MODERN TELEVISION SYSTEMS
to HDTV and beyond

Jim Slater

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Modern Television Systems to HDTV and beyond

Jim Slater
I. Eng., AMIERE
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Television viewers are understandably reluctant to face the expense of replacing their receiving equipment at frequent intervals. This simple fact puts considerable constraints on research and development engineers who would ideally like to introduce new and improved television systems from time to time, which they know could provide better pictures and sound as well as a whole range of new facilities. It is thus a fact of life that television transmission systems must, by their very nature, exist for a long period of time if they are to be commercially viable. There is nothing new about this, and the three currently used colour television standards of the world, NTSC, SECAM, and PAL, have been in use for over a quarter of a century and look set to continue in use for almost as long again before they are finally discontinued. As an example of this, the transmitting authorities in the United Kingdom are currently replacing their existing PAL transmitters with new ones which, it is anticipated, will have lifetimes of at least twenty years, and broadcasters throughout the world are continuing to expand their transmitter networks using the existing standards.

It is no surprise then that television transmission standards have stayed fairly static over the last couple of decades, and many of the excellent books that were written at the time when the existing systems were just being introduced have now become classics, and are regarded as the 'bibles' of the television art, even by engineers who are new to the business. Quite simply, since the systems have stayed static, the need for new books on television transmission systems has not really arisen. This rather dull scenario is, however, about to undergo meteoric changes, since the coming of satellite broadcasting has brought the key which is opening up new opportunities for higher-quality television systems and the eventual dissemination of High Definition Television signals throughout the world.

Over the past few years development laboratories have been humming with ideas for new and better ways of transmitting television signals, and topics such as digital television, multiplexed component transmission systems, and the dozens of ideas for enhanced definition television pictures and sound that are now being put forward have led to the need for this book, which attempts to give a comprehensive overview of this fast-moving and exciting field.
Aimed primarily at the television engineer who wishes to gain an up-to-date understanding of the basic tenets of the new television transmission systems, the book provides a sound appreciation of the various topics whilst avoiding unnecessarily detailed mathematical considerations. The author hopes that it will also prove of interest to students, to non-technical professionals in the communications industry, and to the intelligent layman who wishes to broaden understanding of these novel techniques which will eventually affect us all.
'If men could learn from history, what lessons it might each us!' This cry from the heart of Samuel Taylor Coleridge in 1831 will still be echoed by the world’s television engineers two hundred years later if they refuse to learn from mistakes of the past. ‘What mistakes?’, you might ask, ‘don’t we have excellent television pictures, bright, sharp, and in colour; aren’t our transmitters reliable and our receivers trouble-free and inexpensive?’

All those things are true, but just try taking your portable television receiver the twenty miles across the English Channel to France, or from the USA across either the Pacific or the Atlantic, and you will begin to get just an inkling of the problems that really face television. Your British receiver, although it was probably manufactured on the other side of the world, will not be able to make any sense of the French television signals, and a French receiver will be useless over the border in West Germany. No European receiver will be the least bit of use across the Atlantic or in Japan, and no American set will work in Europe. The problem is compounded when you think of all the videorecorders, computers and other add-on devices which can only be used with one specific television standard.

We might expect a television standard to conform to a dictionary definition concerning something of uniform size or shape, but in real life nothing could be further from the truth. A television standard is defined in the International Electrotechnical Vocabulary (IEV) as ‘A technical specification giving the characteristics of a television system adopted by a qualified organisation’ (ref. 1), and looking further into the IEV we find that a television system is a ‘system defining the permanent features of a television signal...’ (ref. 2). In other words it seems that a television standard, far from being something that has been standardised throughout the world, is the name we give to virtually any type of television system that has some form of official approval, and it will therefore come as no surprise to learn that the international body which attempts to coordinate standards for broadcasting, the CCIR (Comité Consultatif International Radio), lists no fewer than eleven different television standards, together with some variations on these eleven (ref. 3). This listing used to be even longer, since it no longer contains details of the obsolete French 819-line system, which was discontinued in 1984, or of the venerable 405-line system that was used in the United Kingdom until 1985.
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* VHF band only
Some of the systems listed are very different, with different numbers of lines or picture frames, but others are so similar that it seems ridiculous that two separate standards should have ever been agreed upon when it would have made so much more sense for the two countries to adopt a common standard. Sometimes the only difference between two standards is a marginal difference in the widths of the vestigial sidebands, and in other cases there is just a small difference in the bandwidths of the video signals, but in each case the countries concerned have had some reason to refrain from adopting an existing system. This was either because their engineers were convinced that the small change to the existing specification would bring about a worthwhile improvement in picture quality or, less worthily, and one suspects more frequently, because one of the countries concerned saw some commercial advantage in not having the same television system as its neighbour.

The nearest that broadcasters and administrations have come to acknowledging the need for an international television broadcasting standard is the rather weak statement in CCIR recommendation 470 (ref. 4): ‘for a country wishing to initiate a colour service, one of the systems, defined in CCIR report 624, or any compatible improved version of these systems is to be preferred. However, other systems based on the use of video components ...can be considered.’

Things are not quite as bad as they might seem from the foregoing statement, however, because out of sheer self-interest the broadcasters of Europe have managed to agree upon the video-frequency characteristics only of television pictures which they are going to interchange between their own studio centres. Recommendation 472 of the CCIR (ref.5) gives details of an interchange standard that may be used between different countries which use no fewer than 9 different versions of a 625-line television system; this includes all of the European nations, but of course excludes all the 525-line countries.

After more than fifty years of television it would be reasonable to expect that engineers and politicians would have learned from their past mistakes, and would be working towards a single worldwide television standard. Much work is in fact going on in the international standards committees which meet around the globe, but, as we shall see later, even the advent of completely new broadcast media such as high-definition television signals radiated from satellites, which could have presented a unique opportunity to achieve our goal of a universal standard, looks likely to end up once again with a plethora of different standards, making the ideal of being able to use one television receiver anywhere in the world yet again an impossible dream.

*Figure 1 Television systems used in different countries of the world (courtesy ITU)*
Early television systems

Our main concern is with modern television systems, and so there is no place here for a detailed discussion of the pioneers of television and of the systems that they used, but it is perhaps worthwhile to cast our minds back to the early days of television, if only to remind ourselves that development in the field of television has been more or less continuous, and that the standards of yesteryear have always, eventually and inevitably, given way to newer and better methods of broadcasting. This may perhaps encourage us to look forward, and to foresee the eventual replacement of our present NTSC, PAL, and SECAM systems by Multiplexed Analogue Component systems, by higher-definition wide-screen systems, and perhaps one day by a single worldwide digital high-definition system which will, by comparison, make present-day pictures seem as blurred and faded as the hieroglyphics on an ancient tombstone.

The cathode ray tube

The cathode ray tube, upon which all television images have been shown until very recent times, when small liquid crystal displays have started to appear, was invented in Germany by Ferdinand Braun, and first became available to other experimenters in 1897. I think it is appropriate to start any brief history of television at this point, since without the CRT display, the other pioneers would have had difficulty in producing a moving image. Around about 1907, a Russian scientist Boris Rosing successfully demonstrated the transmission of images by using a series of mirrors around a drum to reflect light at the sending end, and a cathode ray tube at the receiving end. In 1908 an English scientist, A.A.Campbell-Swinton, who did not know of Rosing’s work, conceived and started to try to build an experimental system which used cathode ray tubes for scanning the image at the sending end as well as for display at the receiving end (ref. 4). It was several years before Campbell-Swinton could turn his ideas into a working system, but he must take the credit for originating the electronic system of scanning images.

A student of Rosing’s, Vladimir Zworykin, migrated to the United States of America, and there developed electronic scanning techniques, and Isaac Shoenberg, who had worked with Zworykin, joined EMI in the United Kingdom, and led a team which eventually developed the 405-line television system that was to be used in the UK for the next forty years.

Prior to the decision to use 405 lines in the UK, which was made in 1935, experimental systems using 30, 60, 90, 120, and 240 lines were demonstrated by John Logie Baird, who doggedly persisted in developing mechanical scanning methods, both before and after it became obvious that electronic scanning techniques would prove superior. Although any mention of being the first in any scientific field seems to raise the hackles of many
scientific historians, I think that we must at least credit Baird with having been the first to demonstrate a workable television system whose pictures had both movement and greyscale (different shades of grey, between white and black).

By 1926 Baird had used a BBC medium wave transmitter for experimental broadcasts, and in 1928 he managed to transmit a picture across the Atlantic. Incredible though it seems, in the same year he showed a system of colour television which used a fairly simple form of field-sequential colour, and gave demonstrations on what was reported to be a ‘large screen’.

The first Baird television ‘standard’ was 30 lines with 12.5 pictures per second, which must have caused a few headaches and no little eyestrain to those who watched for long periods. This system was developed and improved until in 1936 Baird offered his 240-line 25 pictures per second system for comparative tests with the all-electronic system developed by EMI, which had 405 lines and also displayed 25 pictures per second. The EMI pictures were however built up in a different manner, by interlacing

Figure 2 Cathode ray tubes (courtesy Philips Components)
two fields each consisting of half the total number of lines, first transmitting
the odd-numbered lines and then transmitting the even-numbered lines
and arranging for these to lie between the odd-numbered lines when
displayed on the tube (figure 3). This technique is known as interlacing, and
reduces the visible flicker for a given bandwidth, and continues to form an
integral part of virtually all present-day television systems. In the EMI
transmissions, as in current systems in use in Europe, there were only 25
complete pictures transmitted each second, but the screen was refreshed
every fiftieth of a second, so that a flicker was much less noticeable.

Interlaced scanning

At this point it is perhaps worthwhile making clear the distinction between
a television frame and a television field, since these terms are so often
confused, even by television engineers.

Figure 3 Interlaced Scanning: showing how two fields are interlaced to make one
complete picture, or frame
A frame is one complete television picture, the ensemble of scanning lines which corresponds to the complete exploration of the picture (ref. 7).

A field is a subdivision of the complete television picture in the vertical sense, consisting of equidistantly-spaced sequential scanning lines covering the whole picture area, the repetition rate of the series of scanning lines being a multiple of that for the picture (ref. 8).

The television waveform

Another clever feature of the EMI system was the novel use of a television waveform which included a time division multiplex of the picture signal with all the line and field synchronising pulses necessary not only to ensure picture synchronisation, but also to automatically provide the interlacing of the alternate fields. This is taken for granted in modern systems such as the 625-line system I, whose line and field waveforms are shown in figure 4, but it is important to note that many of the features of this type of waveform were first introduced by the EMI team.

The amplitude (voltage) of the waveform at any instant determines the brightness of each part of the displayed picture, and the cut-off point of the tube, where the electron beam is effectively turned off, is arranged to coincide with a voltage shown as *blanking level*. Thus any parts of the waveform that have an instantaneous voltage greater than that of the blanking level will appear on the screen as some level of grey between black and white, whereas parts of the waveform with instantaneous voltages less than that of blanking level will not appear on the screen. Thus the various synchronising pulses can be carried along with the picture information, but they are blanked and are not seen by the viewer.

In the CCIR System I which we are using as our example, blanking level is also usually the same as the *black level*, i.e. the voltage which it is agreed will represent a specified minimum level of luminance (brightness) on the display tube. Notice, however, that this does not have to be the same as the theoretical cut-off point of the electron beam in the display tube, which we have defined as being the blanking level, and in systems where there is difference between the blanking level and the black level this difference is known as the *pedestal*.

The maximum ratio of the picture voltage to that of the synchronising pulses, that is the ratio of the voltages above and below blanking level, is generally 70:30. This ratio was originally arrived at after tests which showed that in poor reception conditions, with noise or interference in evidence, the sync pulses would become useless at about the same time that the picture signals became unwatchable, so long as this 70:30 ratio was maintained. In a typical studio things are usually arranged so that the maximum peak voltage from the bottom of the sync pulse to the top of the waveform which represents the brightest white that the system can represent, known as *peak white*, is one volt. Our ratio of 70:30
Figure 4 TV line waveform. System I: showing the waveform of a typical television line, with synchronising signals; pulse duration is measured at the half amplitude points.
means that the sync pulses will occupy the voltage range from 0 to 0.3 volts, whilst the picture information will take from 0.3 volts (black level) to 1.0 volts at peak white, an amplitude range of 0.7 volts.

The time taken for the scanning spot to trace out a horizontal line and return ready to begin scanning the next line is 64 microseconds in the system being described, but notice that only 52 microseconds of this time is available for picture information, the so-called active line time. The rest of the 64 microseconds is required for flyback, the time needed for the spot to move quickly back from the right edge of the picture to the left-hand side. The electron beam in the display must be cut off (blanked) during the flyback period, and the line synchronising pulse occurs during this time, ensuring that the receiver starts every line scan in synchronism with the scanning spot of the camera. A short time interval is allowed after the end of the line sync pulse before picture information is transmitted, called the back porch. This ensures that the pulse does not interfere with the start of the picture information and also allows a short black level signal to be transmitted, which can be used as a reference by the receiver circuitry. Similarly, a small portion of the line blanking period immediately before the line sync pulse is kept at blanking level to prevent any of the picture information from interfering with the leading edge of the sync pulse; this period is known as the front porch.

**Vertical synchronisation techniques**

The complex waveform ensures that the electron beams in the camera and the receiver’s display tube scan from top to bottom of the picture in 1/50th second, whilst at the same time scanning from left to right 312½ times. On the second scan the timing is arranged so that the second set of lines interleaves with the first set.

The period of time from when the scanning spot has completed one field scan of 312½ lines and has to move from bottom right to the top left of the picture to start scanning the next field is known as the vertical blanking interval. During this period the line synchronising pulses must be kept going, and field synchronising signals must also be provided. The field sync signal actually consists of five negative-going broad pulses during a period of two and a half lines, the pulses being separated by short (4.7 microsecond) returns to blanking level. The leading edge of each alternate broad pulse also acts as a line sync pulse. Because odd fields, i.e. fields 1, 3, 5, etc., end halfway through a line of video, whereas the even fields 2, 4, 6, etc. end with a complete line, in order to allow interlacing to take place, the vertical synchronising signals are different on odd and even fields, as shown in figure 5. Five equalising pulses are placed before and after the field sync pulse signal to assist in receiver synchronisation, and to ensure that the receiver circuitry derives an identical sync pulse from either odd or even fields.
**Figure 5 Vertical synchronising waveforms for a typical signal, System I (courtesy IBA)**
Baird v. EMI—electronics the winner

Coming back to our brief history, after our diversion showing just how much present-day systems owe to the pioneers, it was after some months of transmitting programmes on the Baird system and on the EMI system on alternate weeks, that the inevitable decision to favour the EMI all-electronic system was made, and from February 1937 the 405-line system, described at that time as ‘high-definition’, became the UK standard with the BBC claiming to provide the ‘world’s first public television broadcasting service’. Things had been happening elsewhere, however, and two years earlier the German Broadcasting Service had introduced their own system of television, again called ‘high definition’, but using only 180 lines. Much work was being done in America and Russia, and the French had also been carrying out tests, but these transmissions ceased with the advent of the second world war, as did those of the other countries. In these days when up-to-the-minute detailed television pictures of wars and disasters beamed to virtually every home are the norm, it seems incredible that the UK government closed down the BBC’s television transmissions altogether for fear that they would provide direction-finding assistance to the German airforce, but we must remember that there were only 23000 television receivers in use in the UK on 1st September 1939 when the service closed down.

Although there were some experimental television transmissions carried out from the Eiffel tower whilst the German occupation of France took place, television took a back seat during the war as engineering efforts were directed towards more bellicose matters, and immediately after the war television was not considered as a major priority anywhere in the world. By 1946 just seven transmitting stations were operating worldwide, one in Britain, one in France, one in Russia, and four in the United States. Regular television broadcasting began in the USA in 1941, and within a period of ten years the 525-line, 30-pictures/60-fields per second standard was used throughout America. During the 1950s a 625-line 50 fields per second system became the norm in most European countries, although the French chose to be different,
using a unique 819-line system which provided excellent pictures, and the United Kingdom continued with its original 405-line transmissions.

The different 50 and 60 fields per second systems used in Europe and America originally came about because it was convenient for the television system to be locked to the frequency of the electricity mains, and this was different on each side of the Atlantic. The need for the frame scanning frequency to bear a close relationship to the mains frequency has long ago disappeared, but the dichotomy between 50 Hz and 60 Hz television systems remains and is likely to continue to be one of the major stumbling blocks to achieving a worldwide high-definition television system.

The television picture—a radio-frequency signal

The television waveform which we considered above was examined line by line and field by field, but the net result of the rapid changes which take place as a television picture is scanned is that the output signal from the camera actually takes up a good deal of bandwidth and can be regarded as a radio frequency signal around 5.5 MHz wide. This signal, known as the baseband signal, is shown in figure 6.

Figure 6 shows the amount of radio frequency spectrum required by a typical baseband video waveform; it corresponds to the CCIR System I waveform that was used as our earlier example of a current television system.

Transmitting the signal

The baseband signal is fine for sending along cables for short distances, but is no good as it stands for getting the pictures into peoples homes. In order to broadcast the television picture we must arrange for the video signal, plus any associated sound signals, to modulate radio frequency carrier waves, substantially higher in frequency than the baseband signals, which can then be radiated from the transmitting stations. The signals will be received by aerials on the viewers homes, demodulated to reproduce the original video and sound signals, displayed on the cathode ray tube and heard from the loudspeakers.

Figure 7 shows the radio frequency spectrum occupied by a typical television system, again the 625-line CCIR System I. The vision signal amplitude-modulates the radio frequency carrier, and it has been found that an asymmetric sideband modulation system is sufficient to provide good pictures whilst minimising the bandwidth required to carry the signals.

The sound signal frequency-modulates a separate radio frequency carrier positioned 6 MHz above the vision carrier frequency, and typical radio frequencies used when the signals are transmitted in the UHF band are shown.
Colour television

So far, all the working systems that we have discussed have been monochrome or black-and-white television. We saw, however, that colour television experiments were made by Baird in the late 1920s and it is not surprising that similar work was being carried out in Germany, Russia and America. Research engineers from the BBC carried out many experiments with colour systems in the late 1940s, without finding a practicable system, and in 1950 it was something of a breakthrough for the American CBS company when it managed to get its rotating colour disc sequential colour system adopted as the American Standard by the Federal Communications Commission.

Although it undoubtedly worked, the problems of a mechanical system which also required a tremendous amount of light at the camera end to produce good pictures meant that the CBS system never proved popular in the marketplace and it ceased to be used after just a few years. By 1953 the American National Television System Committee had come up with proposals for a vastly superior all-electronic colour system which was to provide the basis for all today’s colour television broadcasts, a system which was to be named after the committee’s initials—NTSC.

References

1. *International Electrotechnical Vocabulary*, Chapter 723 4.03.
2. Ibid, Chapter 723 4.02.
5. CCIR Recommendation 472, Vol 11, Video-frequency characteristics of a television system for international exchange of programmes.
8. Ibid, Chapter 723 5.16.
December 1953 saw the introduction in the United States of the NTSC system of colour television, upon which all existing terrestrial transmitting systems are based. The National Television System Committee had worked within a well-defined set of requirements, and thanks to close cooperation between broadcasters, manufacturers and government officials they were able to recommend a system of colour television transmission which has proved so satisfactory that it and its variants PAL and SECAM are in use throughout the world thirty-five years later, and look set to continue in use for almost as long again.

The committee were originally asked to ensure that any system which they chose would meet the following criteria:

(i) **Compatibility**
The colour system should be such that when the signals from a coloured picture are received on a standard monochrome (black and white) receiver then high-quality monochrome pictures should be produced, without any modifications to the receiver.

(ii) **Reverse compatibility**
Colour receivers designed to receive colour pictures should also be able to reproduce black-and-white pictures from monochrome transmissions.

(iii) **Frequency usage**
The colour system should take up no more radio-frequency bandwidth than the existing black-and-white system.

(iv) **Technical quality**
The colour system should produce pictures with accurate colour rendition, and these pictures should be as good as those that the black-and-white system already provided.

As we shall see, the NTSC system managed to satisfy all these requirements, and also provided a method of separately processing the brightness (luminance) and colour (chrominance) signals, which was not only useful for transmission, but also permitted the colour television signals to be recorded on tape. Before we look at NTSC in detail, however, let us briefly consider some of the fundamentals upon which any colour television system depends.
Colour vision and colour television—the basic principles

It has long been known that the human eye/brain combination can be made to see a whole spectrum of colours by providing it with mixtures of various amounts of the three primary colours red, green, and blue (figure 8) (ref. 1). This is very fortunate for television engineers, since it enables just a few parameters to represent the many thousands of colours and brightness levels that may be distinguished by the human eye.

The three main characteristics of a coloured scene that the eye makes use of are:

(i) **Brightness** The point on a grey scale from black to white upon which a particular element of the picture lies. It represents the amount of energy that stimulates the eye. Brightness can be considered as independent of the colour part of a picture, and is often called *luminance* in television.

(ii) **Hue** The actual colour, red, or green, or blue, or yellow, for example. Different frequencies or wavelengths of light are recognised by the eye as different colours or different hues, and the visible spectrum ranges from about 400 nanometers (nm) for blue to 750 nm for red.

(iii) **Saturation** The ‘strength’ or ‘vividness’ of colour. A pastel colour is less saturated than a vivid colour. A saturated colour contains no white light.

By finding means of analysing, controlling, and synthesising these three

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*Figure 8 Addition of three primary colours to produce a range of other colours (for full-colour version, see the back cover of the book)*
parameters for each of the elements of a television picture, a method was worked out for building a colour television transmission system.

In monochrome television only one channel is required to carry all the information about the television picture; only brightness is varied, and so only this one parameter needs to be carried from studio to home.

Following the same reasoning, then, a basic colour television picture would require three channels of information, one each for brightness, hue, and saturation. This would seem to imply that the transmission of a colour picture would require three times the bandwidth needed for a monochrome picture, and this would obviously be undesirable, as well as failing to satisfy one of the fundamental requirements of the National Television System Committee, so methods of overcoming this disadvantage had to be found.

Three colour signals are obtained from the scene being televised by splitting the light incoming to the camera into separate components of red, green and blue by the use of dichroic mirrors or prisms (figure 9). The amounts of red, green, and blue will depend upon the actual colours of the scene, and the electrical signals produced by the red tube, the blue tube, and the green tube will be proportional to the amounts of these colours in the original scene.

We have seen that if the three primary colours red, green, and blue are added in the appropriate proportions, white light can be obtained. In a similar way, if the three electrical signals corresponding to the red, green and blue signals produced during the scanning of the image, $E_k$, $E_G$, and $E_b$, respectively, are added together in the proportions

$$0.299E_k + 0.587E_G + 0.114E_b$$

then the result is white (ref. 2), or more correctly, the luminance signal voltage:

$$E_Y = 0.299E_k + 0.587E_G + 0.114E_b$$

In an ideal world the response of the television system would be linear, a
change in the brightness of the image giving a linear change in camera
tube voltage, and a linear change in the display tube input voltage giving
a linear change in brightness. In reality neither camera tube nor display
tube is linear, and it is necessary to apply \textit{gamma-correction} to compensate
for this. In simplified terms, the relationship between the luminance of the
input signal and the luminance of the output signal is called the gamma
of the system, and this is more precisely defined in ref. 3 as: The slope of
the curve representing, on a logarithmic scale, the luminance of a display
element as a function of the luminance of the corresponding element of
the original object. Thus gamma would be unity for a linear system. In
practice the gamma of all colour CRT display tubes is made to be 2.2, and
the gamma of each of the signal channels is the reciprocal of this,
approximately 0.45.

The ‘dashed’ terms $E_k$, $E_k^\prime$, etc. are the gamma-corrected voltages
 corresponding to the red, green and blue signals. To simplify the following
discussion we shall refer to the luminance signal as $Y$ and to the red, green,
and blue signals as $R$, $G$, $B$ respectively. We say that $R$, $G$ and $B$ are three
component signals which are used to make up the complete colour picture.

Thus the $Y$ signal consists of the $R$, $G$ and $B$ signals added in the
appropriate proportions:

$$Y = 0.299R + 0.587G + 0.114B$$

The luminance signal voltage is obtained in practice by adding these signals
in an appropriate resistive matrix. The $E_Y$ or $Y$ signal is thus for all practical
purposes the same as the black-and-white signal, and would be recognised
as such by a monochrome receiver. It would therefore be possible to
transmit the three signals corresponding to red, green and blue, and this
would not only allow colour receivers to function but would also provide a
monochrome picture for those viewers with black-and-white receivers. Such
a system would, however, require three times the bandwidth of a
 corresponding monochrome system, i.e. three full-bandwidth channels, one
each for red, green, and blue, which is not practicable, and would be
outside the terms of reference of the NTSC.

\textbf{Colour-difference components}

The hue and saturation information of the image are not dependent upon
the summation of the $R$, $G$ and $B$ signals, but upon their ratios. All the
information about hue and saturation can be obtained from the two \textit{colour-
difference signals}, $(R-Y)$ and $(B-Y)$, which themselves contain no brightness
information, since the $Y$ signal has been subtracted.

It has been found therefore, that all the information to describe a colour
picture can be carried in three signals; $Y$, $(R-Y)$, and $(B-Y)$.

The advantage of these component signals over the $R$, $G$, $B$ components
is that both $(R-Y)$ and $(B-Y)$ can be low-bandwidth signals, since they
contain only information about the colour of the picture, all the detailed picture information being carried in the $Y$ signal, the luminance component. The human eye is relatively insensitive to detail in coloured parts of the image, and television engineers have taken advantage of this fact to reduce the bandwidth required for the transmission of a colour picture.

Our colour television picture can therefore be represented by three component signals: $Y$, the wide-bandwidth brightness signal, and two colour-difference signals $(R-Y)$ and $(B-Y)$, both of which can be significantly less than half the bandwidth of the luminance signal.

Notice that, although it might at first appear that $Y$, $(B-Y)$ and $(R-Y)$ would give no information about the green signal, we know that

$$Y=0.299R+0.587G+0.114B$$

and if we know both $(B-Y)$ and $(R-Y)$, we can therefore obtain $G$. The only reason that $(B-Y)$ and $(R-Y)$ were chosen in preference to $(G-Y)$ is that the maximum value of $(G-Y)$ would be smaller.

**Compatibility considerations**

Another advantage of using this colour-difference signal technique is that when a monochrome picture is being transmitted the only signal that is required is the luminance signal, $Y$, so that there is no possibility of any colour signals interfering with the pictures seen on monochrome receivers. When desaturated colours are being transmitted, and statistically this turns out to be for most of the time, the colour difference signals will be only very small in amplitude, again improving the compatibility with monochrome receivers.

Similarly, any change in the relative gains of the amplification stages carrying the colour signals will have no effect on the grey scale of monochrome or colour receivers, because whenever a grey signal is being transmitted the value of each colour-difference signal is zero.

We have seen that the two colour-difference components $(B-Y)$ and $(R-Y)$ are narrow-bandwidth signals; advantage is taken of this fact in all the different types of current television system, since it is found that these narrow-band signals may be used to modulate a specially chosen subcarrier within the normal black-and-white video spectrum. This subcarrier, which is carrying all the information about the hue and saturation of the coloured parts of the picture, can then be combined with the existing luminance signal, to create a *composite waveform*. This composite waveform thus carries both the black and white and the coloured information within the original bandwidth taken up by the black-and-white signal. The composite signal is used to amplitude-modulate a radio-frequency carrier signal in the usual way, and the end result is that we have managed to carry all the information needed to recreate a colour television picture, within the same radio-frequency bandwidth that is needed to carry a black-and-white image.
We have not, however, obtained something for nothing; what the early pioneers of colour television realised was that the existing monochrome transmissions took up rather more bandwidth, or frequency spectrum, than was theoretically necessary for the amount of detail in the picture, and also that most of the information was concentrated in short bursts regularly spaced throughout the frequency channel being used. Figure 10 shows the energy spectrum of a monochrome picture, and it can be seen that the bursts of energy are centred around the harmonics of the line frequency of the television system being used. The gaps between energy peaks could therefore be regarded as redundant space in the television waveform, and it was the realisation that these gaps could be used to carry the additional colour (chrominance) information on a modulated subcarrier, without spreading outside the normal bandwidth of the channel, that made the development of compatible colour and monochrome broadcasts possible. A viewer with a monochrome receiver will be able to watch monochrome pictures as before, whereas the viewer with a colour receiver will be able to make use of the extra chrominance information that the television signal carries to display colour pictures.

**Constant luminance problems**

We have so far made the assumption that the information in the luminance and colour-difference signals is quite separate, so that the colour-difference signals carry no information about the brightness (luminance) of the picture. When such a situation exists we say that the system conforms to the
constant luminance principle. We saw earlier, however, that it is necessary to individually gamma-correct the $R$, $G$, and $B$ signals. Unfortunately this means that the luminance signal $E'_Y$, which we have called $Y$ for simplicity, will not, in practice, contain all the luminance information, since some of this luminance information will be carried in the chrominance signals.

This has various practical effects upon the picture displayed in the home. No problems arise when white or grey parts of the picture are being displayed, since the colour-difference signals are zero, and thus both black-and-white and colour receivers display the white and grey parts of the picture with the correct brightness and contrast. Problems do, however, come about with coloured parts of the picture, whose brightness is not properly represented on a monochrome receiver.

As an example, consider what happens when we are transmitting a pure Red signal with maximum amplitude.

We then have $R=1$, $G=0$, $B=0$, and after gamma-correction, because of the numbers which we have chosen, $R'=1$, $G'=0$ and $B'=0$ where the dashed terms represent the gamma-corrected signals. But

$$E'_Y \ (Y \ for \ simplicity) = 0.299R' + 0.587G' + 0.114B'$$

therefore $Y=0.299$ on transmission.

If we then apply gamma-correction to this signal in a black-and-white receiver, we will obtain a luminance value that is equivalent to

$$Y^\gamma$$

and with gamma=2.2 this means that the luminance signal actually displayed will be

$$0.299^{2.2}=0.070$$

We thus have a situation where, on a black-and-white receiver, the red signal is displayed with only about one quarter of the transmitted luminance level. This illustrates clearly the failure of the constant luminance principle. In a colour receiver the brightness of the same part of the image will be correct because the luminance of the display is the resultant of both the $Y$ signal and the two colour-difference signals. Since some of the brightness information is carried by the narrower-bandwidth chrominance channels, however, there may be a reduction in the resolution of the detail that is visible in the brightly coloured parts of the picture.

In practice the black-and-white viewer is actually at less of a disadvantage than might be supposed from the above, since when the colour subcarrier is present, i.e. on coloured parts of the picture, it is rectified because of the non-linear characteristic of the display tube and actually produces a DC voltage which increases the brightness of the display in coloured areas of the picture, thus offsetting to some extent the loss of brightness due to constant luminance failure in the system.
The failure of constant luminance also has other minor effects in the television system, including a small reduction in noise performance, and although we have so far implied that the undesirable effects are restricted to black-and-white receivers there are in fact also some problems with colour receivers. Since some of the luminance information is carried in the chrominance channels, and the chrominance channels are narrow-band (around 1.3 MHz maximum), compared to the luminance channels (typically 4.5–5.5 MHz), bandlimiting of that part of the luminance signal which is carried in the chrominance channels will take place. This gives rise to a perceptible lack of detail on coloured edges in the picture.

A full discussion of the theory and of the practical effects of not complying with the principles of constant luminance can be found in ref. 4. It is interesting to note that the subject of constant luminance, which many people felt to be something of a theoretical anachronism with little importance to practical television systems, has recently been resurrected by some of the technical groups looking at the development of high-definition television signals. Since their brief is to develop systems which are as good as possible, some of them have actually gone back to first principles and are looking at the possibilities of making future enhanced systems conform with the principle of constant luminance, and initial studies show that this may indeed be possible.

Composite colour systems

The principles of colour television that have been described are common to all present-day terrestrial colour television systems, and the basic colour theory will apply also to future colour television systems, although as we shall see later not all such systems will need to use a subcarrier. The three major systems currently in use throughout the world, NTSC, PAL, and SECAM, are each composite colour systems using the techniques outlined above, but each uses a different method of modulating a subcarrier with the chrominance information. Each has its own particular advantages and disadvantages, and we shall take a look at each system in turn, beginning with the system that was agreed upon by the American National Television Systems Committee, NTSC, the first practical colour broadcasting system.

References

The prime purpose of this book is to look at new television systems which are currently being developed, and it is, therefore, not necessary for us to consider the minutiae of the various existing systems, since the classic reference books can be relied upon to provide full details of these. We do, however, need a basic understanding of the existing systems if we are to be able to comprehend their limitations, and if we are to be able to look at newly developed systems with a critical eye to their advantages and disadvantages. Not only do we need to be able to assess the new systems as far as technical quality is concerned, but we also need to understand the requirements of those new television systems that claim to be compatible with existing receivers, something that is always extremely hard to achieve. We will, therefore, take a broad look at the existing systems so as to understand the basics of any television system, and this understanding should help us to analyse the advantages and disadvantages of the various new systems that are under development in broadcasting research laboratories around the world.

The *International Electrotechnical Vocabulary* (IEV) defines the NTSC system precisely and concisely as

A simultaneous colour television system using, in baseband, a composite colour signal comprising a luminance signal and two chrominance components, which are transmitted as quadrature amplitude modulation of a subcarrier (ref. 1).

It is the various different methods used to modulate the subcarrier with the chrominance signals that differentiate between the three variants, NTSC, PAL and SECAM.

**Baseband spectrum**

We saw in the last chapter how it proved possible to add the colour information to a subcarrier within the normal bandwidth of the television channel and to include this information in the gaps in the energy spectrum of the black-and-white picture signal. In terms of the baseband frequency spectrum such an arrangement can be displayed as shown in figure 11.

The black-and-white (luminance) signal takes up the band from DC to
4.2 MHz, and a sub-carrier is added in the higher-frequency portion of the band, at 3.579545 MHz; the modulated subcarrier can be thought of as riding up and down on the luminance signal (figure 12).

The frequency of the subcarrier is very important and it is chosen to bear a precise relationship with the line and field frequencies. The effect of the subcarrier is to produce a fine regular pattern of dots on the screen. In general the higher the frequency the finer and less noticeable will be the interfering dot-pattern effect which can be seen on monochrome receivers. If the subcarrier frequency is locked to the line frequency and is chosen to be an odd multiple of half the line frequency, any line will contain a whole number of cycles of subcarrier plus an odd half cycle. Thus on any two adjacent lines in a field the peaks of the subcarrier on one line will lie next to the troughs in the subcarrier on the next line and will thus tend to cancel each other out. This technique is sometimes described as ‘giving the subcarrier a half-cycle offset’. The subcarrier frequency is in fact also chosen to be an odd multiple of half the picture (frame) frequency so that the dot pattern on one field lies exactly between the dots of the pattern produced by a complete picture (i.e. two fields) later. The eye will tend to integrate the dots, and the brain will think that the pattern has disappeared.

If the frequency chosen for the subcarrier is too low, there will be a large amount of luminance energy in the middle frequencies of the average picture, which will interfere with the nearby colour subcarrier. If the subcarrier frequency is too high there will not be enough bandwidth available within the television channel for the sidebands of the modulated subcarrier, and there is also the possibility that interference will occur between the subcarrier and the sound carrier, which is normally 4.5 MHz above the vision carrier frequency.

Figure 11 Diagram showing a baseband frequency spectrum of a composite colour signal which shows how frequency sharing (frequency division multiplexing) is used to carry chrominance and luminance signals.
This subcarrier is modulated by the two chrominance components and the sidebands of this signal effectively overlay a chrominance signal upon the higher-frequency parts of the luminance signal. The subcarrier is amplitude-modulated in accordance with changes in the saturation of the colour signal, and it is also phase-modulated, the phase changes corresponding to changes in the hue of the picture signal. The phase changes can perhaps be best envisaged as small shifts in the timing of the cyclic alternations of the subcarrier. As the camera scans along the different lines of the image, the different hues and saturations of picture elements along the line are conveyed as corresponding changes in the phase and amplitude of the subcarrier. The chrominance signal is, therefore, modulated simultaneously in amplitude and in phase, and this doubly modulated signal is superimposed on the radio-frequency carrier that is also transmitting the luminance signal.

Radio frequency spectrum

The radio frequency spectrum allocation for an amplitude-modulated television signal is shown in figure 13. It is not necessary to transmit both side-bands, since they are nominally identical, and double-sideband transmission
would use up a great deal of spectrum space. Although single-sideband transmission would be technically possible, receiver circuitry would need to be far more complex to cope with this, so as a compromise most television standards now use vestigial sideband transmission.

Looking at the spectrum usage, it can be seen that the chrominance signals overlap part of the luminance signals, which could cause interference under certain circumstances. This potential interference does not generally occur, because the frequency of the chrominance subcarrier has been specially chosen to bear a precise relationship to the line scanning frequency (455/2 times the line frequency for NTSC). This ensures that the energy from the colour signal lies exactly within the gaps in the energy spectrum of the black-and-white signal, a system known as frequency interlacing. In the usual American NTSC system, the line frequency itself is specified to be 2/572 times the standard sound/vision carrier frequency spacing of 4.5 MHz, all these relationships having been calculated to minimise the effect of adding colour information on viewers using monochrome receivers. Other small changes were made to the transmission system to minimise the visibility of beats between the subcarrier and sound carrier, whilst maintaining compatibility with the monochrome transmissions, with the result that the monochrome line frequency (nominally 15.750 kHz) was changed to 15.73426 kHz, and the field frequency (nominally 60 Hz) was changed to 59.94 Hz.
Cross-colour and cross-luminance

Problems can arise, however, when parts of the picture contain highly detailed black-and-white information, perhaps a herringbone pattern on a suit, or a finely-striped tie. Parts of the luminance signal containing much detail are at the high-frequency end of the spectrum. These parts of the picture may correspond to frequencies close to those of the colour subcarrier and in some cases the receiver’s decoder will be unable to separate this black-and-white information from the colour information, giving rise to the generation of spurious coloured patterns. This phenomenon is known as cross-colour (see figure 26). Another similar effect, cross-luminance, is caused by the residual colour subcarrier causing brightness variations where sharp colour transitions occur. This shows itself as a dot patterning along edges where rapid changes of colour take place. The NTSC system was designed to minimise the visibility of these effects; the subcarrier signal is zero for white and small in amplitude for the pastel colours that occur statistically most frequently. Earlier it was mentioned that the subcarrier frequency is locked to an odd multiple of the line frequency, and this produces an effect which is integrated by the eye so that the visibility of any dots is reduced. Even the cross-colour effects, which it is impossible to remove entirely from some pictures, are minimised by the chosen relationship between the subcarrier and line and frame frequencies; spurious colours generated on one field are integrated by the eye with the complementary spurious colours occurring on the next field, so that the effect tends to cancel itself.

Subcarrier modulation

The subcarrier is modulated in amplitude and phase by signals which, as we shall see later, are not strictly the colour-difference signals \(B-Y\) and \(R-Y\), but the closely related signals that we shall later define as \(Q\) and \(I\). For the time being, however, to help our understanding, let us assume that the \((B-Y)\) and \((R-Y)\) signals are used as the modulating signals, and we will make the necessary amendments later.

In order to add the information from the two colour-difference signals to the carrier wave that is already used to carry the luminance signal, two subcarriers are effectively used; these are, however, of the same frequency, but they differ in phase by 90 degrees. One of the subcarriers is then amplitude-modulated by the \((B-Y)\) signal and the other amplitude-modulated by the \((R-Y)\) signal.

From figures 11 and 13 it will be seen that it would not be practicable for the subcarrier modulation to take up as much bandwidth as the luminance signals, and so the bandwidth of the chrominance signals is deliberately restricted, to as little as a quarter the bandwidth of the luminance signals. The colour picture will, therefore, be made up of a sharp monochrome
picture over which is laid a relatively fuzzy coloured image. The fuzziness will only be noticeable in a horizontal direction. As we have seen before, however, the human eye cannot make use of fine detail in colour, and so our television system will be quite acceptable to the eye. This feature, sometimes known as proportioned bandwidths, is one of the basic building blocks of a compatible colour television system.

Chrominance signal amplitude restrictions

When the modulated subcarrier is added to the monochrome signal, the peak amplitude of the composite signal will be greater than that of the monochrome signal, but in order to forestall possible transmitter overload problems, whilst at the same time not reducing the signal-to-noise ratio of

![Figure 14 Relative levels of monochrome and composite colour signals, using colour bars. The waveforms show the weighted and unweighted chrominance components together with the luminance signal, using full-amplitude 100% saturated colour bars. The waveforms are marked with normalised values, but voltage values are shown on the y-axis.](image-url)
monochrome pictures, this peak amplitude must be restricted. In the NTSC system, the maximum total excursion of the composite signal is restricted to 33% above peak white level, i.e. 1.33, where peak white is 1.00, as shown in figure 14.

If saturated full-amplitude signals of both yellow and cyan, which have the greatest luminance amplitude, as shown on the diagram, are not to be allowed to exceed 33% above peak white, then this means that the \((R-Y)\) signal must be reduced to 87.7% of its original value, and the \((B-Y)\) signal must be reduced to 49.3% of its original value. We say that weighting factors of 87.7% and 49.3% are applied to the \((R-Y)\) and \((B-Y)\) signals. These weighted signals are

Weighted value of \((B-Y)=0.493 \ (B-Y)\)

or, as we saw in the previous chapter, it is more strictly accurate to say that the weighted value of \((B-Y)\) is

\[0.493 \ (E_b - E'_y)\]

and similarly the weighted value of the \((R-Y)\) signals is

\[0.877 \ (R - Y) \text{ or strictly } 0.877 \ (E_r - E'_y)\]

**Chrominance signal bandwidths**

We saw earlier that the colour subcarrier had to be placed towards the high-frequency end of the luminance frequency spectrum in order to ensure that only fine dot-patterning would be visible on monochrome receivers, and so that the low-frequency luminance signals, which contain most of the energy in a typical video signal, would not interfere with the subcarrier signals and cause cross-colour effects. This means that the amount of bandwidth available for the sidebands of the modulated subcarrier is restricted in the high-frequency direction, i.e. towards the sound carrier, and the effect of this is shown in figure 15.

There is thus not sufficient bandwidth available for both the chrominance components to be carried in double-sideband form, although it would appear at first sight that asymmetrical-sideband modulation could be used, in a similar manner to the vestigial sideband system used for the main vision signal. If asymmetrical modulation of the two chrominance signals, which are separated by a phase angle of 90 degrees, is used, it is found that spurious signals known as quadrature crosstalk are produced, each chrominance signal producing a spurious signal at right angles to itself, and, therefore, interfering with the other chrominance signal (ref. 2).

In order to overcome this problem, whilst still making the best possible use of the limited bandwidth available to the colour signals, one of the components is modulated in double-sideband form, using a fairly narrow bandwidth, whilst
the other component is modulated asymmetrically, taking up a wider bandwidth below the subcarrier frequency than is available above, thus providing a wider band signal. Since this second modulated component signal is effectively a double-sideband signal over the whole of that part of the frequency spectrum that is already occupied by the first signal, no cross-talk is generated over this part of the band. In the part of the spectrum below this we effectively have an asymmetric transmission, but the crosstalk signals can be made to fall outside the bandwidth used by the first signal and eliminated by means of a suitable filter. We, therefore, have a situation where both colour components can be transmitted and received without mutual interference.

It may seem strange that the bandwidth of one of the colour components is wider than that of the other, but it has been found that the human eye is able to see more detail in certain colour combinations than in others, and the NTSC pioneers were quick to realise that, once again, they could take advantage of a proportional-bandwidth technique to transmit colour pictures which would be perfectly acceptable to the eye, whilst taking up only the minimum of bandwidth. Reducing the required bandwidth in this way enables a higher frequency to be used for the subcarrier, with the attendant advantages that this can bring, as discussed earlier.

The eye can detect more detail in the orange and cyan colours than it can in hues of green and magenta (ref. 3) and to take account of this the NTSC system does not in fact make use of the \((B-Y)\) and \((R-Y)\) components which we have considered so far, but instead it uses two other components, \(Q\) and \(I\), which are obtained by advancing the phase of the \((B-Y)\) and \((R-Y)\) signals by 33 degrees, which can be shown (figure 16) as a simple rotation from the \((B-Y)\) and \((R-Y)\) axes.
Projecting the \((R-Y)\) and \((B-Y)\) signals onto the \(I\) and \(Q\) axes it can be calculated (ref. 4) that
\[
I = 0.74 \, (R-Y) - 0.27 \, (B-Y)
\]
and
\[
Q = 0.48 \, (R-Y) + 0.41 \, (B-Y)
\]
which in terms of \(R\), \(G\) and \(B\) become
\[
I = 0.6R - 0.28G - 0.32B
\]
\[
Q = 0.21R - 0.52G + 0.31B
\]
In the NTSC system these two signals are then modulated onto their subcarriers which are of the same frequency but in phase quadrature and the resulting signal is, therefore, modulated in both amplitude and phase. The proportioned-bandwidth technique used means that we have a highly detailed black-and-white picture, reasonable detail in parts of the picture from orange to cyan, and only coarse detail over the rest of the colour spectrum, but since this meets the requirements of the eye, it is a perfectly satisfactory system. The \(I\) chrominance signal has a bandwidth of around 1.5 MHz, whereas the \(Q\) chrominance signal is only about one third of this,
around 0.5 MHz. In these days when we are conscious of the need for more
detail in our pictures it is interesting to note that many of the early NTSC
receivers did not even take advantage of the increased bandwidth available
in the $I$ signal, and had two identical chrominance channels each of which
had only the bandwidth required for the $Q$ signal. This was presumably to
keep the cost and complexity of the receivers down, but it cannot have done
anything to enhance the reputation of the NTSC system.

The complete video signal

To obtain the complete video signal for transmission then, the luminance
signal is used to amplitude-modulate the main carrier, whilst the $I$ and $Q$
signals are modulated onto their different subcarriers of identical frequency
but in phase quadrature, using a technique known as *suppressed carrier
modulation*, which is frequently achieved by using a balanced ring
modulator circuit. If the receiver is to be able to decode the information
carried in this suppressed carrier signal, it must have some means of
knowing what the phase of the colour signals is at any instant, so as to be
able to regenerate the two original carriers with their correct phasing. In
order to allow the receiver to do this, a colour synchronising burst of ten
cycles of the subcarrier of a predetermined constant phase is added to the
transmitted signal. This burst is carried in the back porch of the line
blanking interval of the television waveform, but is omitted during the
period immediately following the equalising pulses and the field sync
pulses. This reference burst, the frequency of which is very precisely
specified as 3.579545 MHz±10 Hz, with the rate of change of frequency not
to exceed 0.1 Hz/sec (ref. 5), provides a reference which allows the
synchronous detector circuitry in the receiver to determine the
instantaneous phase of the subcarrier. This gives the receiver the
information it needs in order to determine which colour-difference signal is
being received at which instant, from which the appropriate colour signals
can be calculated and the colour pictures synthesised.

Disadvantages of the NTSC system

We have mentioned already that the frequency multiplexing techniques used
to interleave the colour information with that of the monochrome picture in
NTSC could give rise to cross-colour and cross-luminance with certain types
of picture, but until such times as very large screen receivers come into
general use, these phenomena are unlikely to present major problems.
Although the effects are well known to those in the television business, they
have not been found to be a major source of complaints from viewers.

Far more disturbing to viewers of NTSC pictures are phase errors which
arise on transmission and reception and which give rise to the cruel, and
somewhat unfair, jibe that NTSC stands for Never Twice the Same Colour!
In any television system, phase distortion is bound to occur when signals of different frequency have to be passed through a piece of transmitting equipment, a distribution network, or a transmitting channel. This is because signals of different frequencies will take different amounts of time to pass through any piece of equipment. This phase distortion is probably the most undesirable side-effect of the NTSC system.

It will be remembered that it is the phase of the subcarrier, or more precisely, the relative phase between the subcarrier transmitted during the picture and the colour reference burst which determines the hue of the displayed picture. Phase changes can take place as the signal passes between transmitter and receiving aerial, especially over paths which are subject to multipath interference or ghosting, and this can give rise to the wrong colours being displayed. Similarly, we would expect changes in the amplitude of the subcarrier to alter the saturation or intensity of the colour, something that can readily be corrected by automatic gain control circuitry, often known as automatic colour control. It is important, however, to note that changes in the amplitude of the signal can also give rise to phase errors. If the phase of the subcarrier varies with changes in its amplitude, or with changes in the luminance level, which can be caused, for example, by clipping in any of the many different amplifiers which form part of the broadcast chain, the signal is said to be subject to differential phase distortion.

This differential phase distortion gives rise to serious errors in the displayed colours, a phase error of as little as 5 degrees giving rise to a noticeable colour change on many pictures, although the effect is very dependent upon the content of the original picture. For this reason, NTSC receivers were invariably fitted with a hue control, to allow viewers to alter the colours to suit their taste, a situation that is far from desirable if accurate colour reproduction is required! Much of the trouble noticed in the early days of the NTSC system was in fact caused by problems with the broadcasters’ equipment, which used thermionic valve circuitry that was very prone to drifting, and the present-day NTSC system provides satisfactory results for most viewers who have taken the trouble to install a suitable receiving aerial system.

When, in the late 1950s and early 1960s, European nations began to consider the introduction of colour television systems, there was an understandable initial intention on the part of some broadcasters to use the well-proven NTSC system, and the BBC, for example, carried out many tests on a version of NTSC modified for use with the 405-line television service then in use in the United Kingdom. Although other ‘improved’ systems were being proposed, there was a general feeling that only the NTSC system had actually proved itself in practice and that there was a huge difference between a proven system and one which had merely been shown to give better results under laboratory conditions. Nevertheless, the known problems that phase distortions could give rise to when using the NTSC
system led research engineers to continue to search for a solution to these problems, and when the European Broadcasting Union set up a special group with the task of choosing a colour system for Europe, a full investigation was carried out into the merits of, and the problems that might be encountered with, various different colour systems.

References

1. International Electrotechnical Vocabulary, Chapter 723. 08.10.
The SECAM and PAL systems were designed so that they would make use of the basic tenets of the NTSC system, but would avoid the two most objectionable shortcomings of this system, its susceptibility to phase errors, and the consequent need for receivers to be fitted with a hue control. It should, however, be stressed that under most conditions NTSC is capable of providing very good results and that the improvements obtained in these other systems, whilst significant, have not been great enough to prevent a large part of the world’s population from being very content with NTSC pictures. In addition, the benefits of the newer systems have only been achieved at the expense of some increase in the complication of the receiver.

SECAM—SEQUENTIAL COULEUR À MÉMOIRE

In the years between 1956 and 1959 the French research engineer Henri de France took the proportioned-bandwidth techniques that had been used in the development of NTSC a step further when he realised that the vertical definition of the colour components of the picture need not be as high as that of the black-and-white parts, and he therefore proposed a system where the two colour components would be transmitted alternatively on successive lines of the picture. The system became known as SECAM, an acronym for Sequentielle Couleur à Mémoire and many different versions were developed before 1965, when the French settled on SECAM III, which is the version nowadays known simply as SECAM.

The basics of the SECAM system

SECAM is defined internationally as

A simultaneous sequential colour television system using, in baseband, a composite colour signal comprising a luminance signal and two chrominance components, each of which is transmitted sequentially as frequency modulation of a separate subcarrier. The receiver is provided with a line-period delay line to permit the simultaneous display of the three components (ref. 1).
Figure 17 Block diagram of simplified SECAM coder and decoder
SECAM is effectively, therefore, a modified version of NTSC in which the two colour difference signals \((R-Y)\) and \((B-Y)\) are sent quite separately on alternate lines of the picture. Instead of the colour subcarrier being amplitude and phase modulated, as in NTSC, the colour signals are carried by frequency modulation of two different subcarriers, one for each colour-difference signal.

We thus have an arrangement where the \((R-Y)\) signal is transmitted on one line, the \((B-Y)\) information for this line not being transmitted at all, whereas on the next line the \((B-Y)\) signal for this second line is transmitted, the \((R-Y)\) signal being dispensed with.

The receiver is, therefore, only receiving half of the original colour information, which results in a reduction of the vertical chrominance detail, but because of the limited response of the eye to colour signals the overall effect is acceptable. In the receiver there is a delay line and an electronic switch, which allows the sequentially transmitted information to be displayed simultaneously by storing the colour information from one line and displaying this at the same time as the colour information for the next line arrives at the receiver. In figure 17 it can be seen that the incoming signal is applied to both input poles of the switch, being connected directly to one input and via a delay line (64 \(\mu s\), one TV line) to the other input. Note that the direct connection actually has an attenuator in circuit which has a similar loss to that of the delay line, typically about 5 dB. The switch is driven by a half-line-frequency square wave and the position of the switch is synchronised with the incoming signal by means of line identification circuitry. The switch thus connects the incoming signal directly to the \((R-Y)\) channel and the delayed signal to the \((B-Y)\) channel, or vice-versa.

With the SECAM system there is no crosstalk between the different colour signals, since they are never transmitted at the same time and there is no need for a complex synchronous detector in the receiver. Because the FM system does not require any external reference for demodulation to take place it is immune to most timing errors. This means that the effects of differential phase distortion are negligible, so the system cannot produce wrong colours under conditions where the amplitude or phase of the subcarrier vary and, therefore, it overcomes the principal problems of NTSC. Differential gain problems, where the amplitude of the subcarrier varies with the level of the luminance signal, will have little effect on SECAM signals, since each subcarrier is frequency-modulated and changes in amplitude will make very little difference to the final picture. This advantage over NTSC is particularly noticeable in videotape recording.

**Colour synchronisation methods**

The receiver must, however, have some means of identifying which line it is receiving at any time, so as to be able to determine whether it is the \((B-Y)\) or \((R-Y)\) signal which is being dealt with. If the lines were to be wrongly
identified at any time the hues of the various parts of the picture would be reversed, which would be a most serious picture defect. Originally, line identification information was sent prior to each field, by means of a special signal which occupied nine lines of the vertical blanking interval, but it was soon realised that since the different colour-difference signals are on subcarriers of different frequencies, a simpler method of line identification could be used. This has the incidental advantage that the field blanking period can now be left free for teletext and test signals.

The two subcarriers are at 282 times line frequency (4.406 MHz), carrying the \((R-Y)\) information and often called \(f_0R\), and at 272 times line frequency (4.250 MHz) carrying the \((B-Y)\) information, called \(f_0B\). These frequencies have been carefully chosen to minimise the dot-pattern effect on monochrome picture areas, which is especially important in a system which, unlike NTSC or PAL, still has some subcarrier present even when the colour-difference signals are zero.

It should be noted that the amplitudes of the two bursts are also different and that these amplitudes are much smaller than those of the colour subcarriers and synchronising bursts used in both the NTSC and PAL systems. This has the further advantage that when SECAM signals are video-recorded the lower level of subcarrier in areas of highly-saturated colour, as compared to NTSC or PAL, means that moiré effects are much reduced.

In the SECAM system some subcarrier is present throughout, except during a large part of the blanking intervals. There is a fairly short subcarrier burst prior to the start of video information on each line, similar to that of the NTSC system, but the SECAM burst continues throughout the whole of the back porch and even on to the beginning of the active line (figure 18).

![Subcarrier burst and line sync pulse](image)

*Figure 18 Subcarrier burst and line sync pulse, showing how the SECAM burst continues through back porch and into the active line period*
In the older versions of SECAM which used frame identification signals the subcarrier would be blanked for the whole of the field blanking interval except during the frame identification signals, but most countries using SECAM have now abandoned the frame identification signals and so the subcarrier is now blanked for the complete duration of field blanking. The major European user of SECAM, France, decreed that after 1979 all new receivers for sale in that country must be capable of using the line identification method and the CCIR has stated that this method is preferable, because it helps with international programme exchanges (ref. 2).

As we have seen, the frequency of the burst is 4.250 MHz on the lines containing \((B-Y)\) signals and 4.406 MHz on the lines that contain \((R-Y)\) signals. If the different SECAM burst signals are fed to a discriminator circuit it is possible to arrange for a positive going pulse to be produced on lines containing \((B-Y)\) information, and a negative-going pulse to be derived from the lines containing \((R-Y)\) information and these pulses can then be used to drive the electronic switch in the decoder, thus ensuring continuous synchronisation.

As well as permitting synchronisation of the colour sequence information, the burst ensures that in the receiver the two subcarrier frequencies are accurate, which is vitally necessary to ensure that grey/black/white signals are correctly reproduced—this is not as simple as in NTSC or PAL where the subcarrier merely vanishes in areas of the picture that contain no colour.

**Differential weighting**

Difference weighting factors are used for the two colour-difference components, and that for the \((R-Y)\) signal is arranged to be negative. We thus end up with a situation where an increase in the deviation of the \((R-Y)\) signal moves the signal towards a lower frequency, whereas an increase in the deviation of the \((B-Y)\) signal causes a move towards a high frequency. This arrangement minimises the bandwidth required. The need to pre- emphasise the video signals in order to improve their signal-to-noise ratio is discussed in the following section, but it is worth noting here that the pre- emphasis leads to the asymmetric deviation of the colour subcarrier for both \((R-Y)\) and \((B-Y)\) signals. This proves to be perfectly acceptable in practice, since the eye is less critical of rapid chrominance transitions at high luminance levels than it is at low luminance levels.

**Disadvantages of SECAM**

There are, of course, disadvantages to SECAM since it is indeed rare to get something for nothing in the field of engineering! It will be remembered that NTSC used suppressed carrier modulation for the colour signals. Since the SECAM system uses FM there is always some subcarrier present, except for brief periods during flyback, so that the signal-to-noise ratio of the overall
signal must be worse than that of an equivalent NTSC signal and the poor noise performance, especially of the chrominance channel, was one of the major hurdles that the early protagonists of SECAM had to contend with. It was found that this problem can be overcome to some extent by using video pre-emphasis so that the signal-to-noise ratio of the higher modulating frequencies is improved, in a similar way to that in which pre-emphasis is used on FM radio signals.

Another potential problem with SECAM is that the constant presence of the subcarriers during the active picture time (i.e. except during flyback periods) can give rise to a dot pattern on black-and-white as well as coloured parts of the picture, which leads to difficulties in getting good compatibility with black-and-white receivers. In order to minimise the dot pattern effect the amplitude of the subcarriers is kept to a low level when they are undeviated, and their amplitudes are increased by using radio-frequency pre-emphasis (in addition to the video pre-emphasis mentioned earlier) whenever chrominance signals are being transmitted. The effects of the dot patterning are further reduced by reversing the phase of each subcarrier on consecutive fields and by also reversing the phase on every third line.

**Fading and mixing SECAM signals**

NTSC (and PAL) signals can be faded up and down merely by altering the amplitude of the complete signal. Altering the amplitude simply changes the level of the signal without affecting either the hue or saturation of the picture, so that fading and cross-fading from one picture to another can be performed simply and effectively by means of variable attenuators, provided that the two signals to be mixed have their subcarrier frequencies accurately synchronised, i.e. locked together.

Since the SECAM signal uses frequency-modulated subcarriers, the amplitude of the chrominance signals is not related to the overall level of the picture signal, so it is not possible to directly mix or fade SECAM signals, which means that far more complex processing is necessary in a SECAM studio. The usual method used in earlier days was to carry out all the necessary operations on the Red, Green and Blue components of the signal, which means using three separate channels. These $R$, $G$, $B$ components can be obtained directly from cameras, telecines, caption generators, etc., but where composite SECAM signals are to be mixed or faded they must each be decoded, their subcarriers being demodulated, and the mixing or fading operation must then be carried out on the $R$, $G$, $B$ colour separation signals separately. Three distinct channels are, therefore, required around the studio, which means three times as much cable and three times the complexity in the innards of the vision mixing equipment. The circuitry of the three individual faders which made up the one complete fader needs to be precisely matched or else changes in hue may be noticed.
as the relative levels of the three components are unintentionally varied. Using three sets of cables can give rise to timing problems, since great care must be taken to ensure that the timings of the three separate signals are equalised throughout the studio, right up to the point where they enter the SECAM coder at the studio output.

A better alternative to RGB mixing is to use what is generally known as component mixing, using separate switching and processing of the luminance signal and the line-sequential chrominance signals. This gives the advantage of only requiring two channels all around the studio, rather than the three required for RGB, thus reducing cost and simplifying timing problems. There is an additional advantage that only the luminance signal path needs to be able to handle the full bandwidth of the video signal, which simplifies the construction of the mixer or switcher.

Using this method, any composite SECAM signals to be mixed or switched must first be decoded and the subcarriers demodulated. The switching is then carried out on the luminance and chrominance signals separately. Just prior to the studio output the chrominance signals are remodulated on to new subcarriers and re-combined with the luminance signal to provide a composite SECAM signal once again.

To avoid all these complications some French studios and facilities houses actually produce their programmes using PAL-equipped studios and only convert to SECAM just prior to transmission.

SECAM developments

SECAM has proved to be a rugged system, relatively unaffected by differential gain distortion or by differential phase problems, and it has considerable advantages over NTSC as far as videotape recording is concerned. Marginal problems of compatibility and signal-to-noise ratio performance were overcome by a great deal of development work and many modifications to the system in its early days.

It was mentioned at the beginning of this chapter that the system known as SECAM in most parts of the world is more accurately named SECAM III. A further variant, which came along too late to be considered for use as a European system, although it has some very attractive features, is SECAM IV. The major difference from earlier versions of SECAM is that the two chrominance components are transmitted together on alternate lines, whilst a subcarrier reference is transmitted on the intermediate lines. This provides a very rugged system and does away with the need for a colour reference burst in the back porch at the beginning of every line. Some engineers believe that if this system had been developed in time to be considered by the Ad-hoc Group of the EBU, which was trying to find a common colour television standard for Europe in the early 1960s, the experts would have seen that SECAM IV had enough attractive features to become that single standard. Unfortunately this was not to be, and a mixture of chauvinism and
nationalistic engineering prestige led to the current situation in Europe where no one standard applies. France adopted SECAM, whilst most of the rest of Europe chose PAL, and the United Kingdom, although deciding upon PAL, also decided to make various other engineering changes to the specification. Although these undoubtedly made small improvements to the quality of the picture, they also meant that a PAL receiver from the UK could not be used in West Germany without modification and vice-versa. Was the small engineering improvement worth the incomparably greater disadvantage of losing direct compatibility with our European neighbours?

**PAL—AN ALTERNATIVE ENGINEERING SOLUTION TO THE PROBLEMS OF NTSC**

Dr Walter Bruch of the Germany company Telefunken had been working for some time on methods of overcoming the shortcomings of the NTSC system, when in 1963 West Germany proposed the PAL (Phase Alternation Line) system, which Bruch had developed, in the hope that it would prove acceptable as a standard for Europe.

The key feature of the PAL system is that it avoids problems of wrong hues occurring due to differential phase errors by reversing the polarity of one of the two chrominance components on alternate lines. Nowadays using a delay line in a similar way to the SECAM system, although originally some ‘simple PAL’ receivers managed without this, PAL receivers are able to effectively cancel out phase errors, and changes in the amplitude of the chrominance signals give rise only to modest changes in saturation on the received picture, which can be minimised by the use of Automatic Gain Control techniques.

The PAL system is a development of the NTSC system, with many similarities, as the IEV definition makes clear (ref. 3).

PAL is defined as

A simultaneous colour television system using, in baseband, a composite colour signal comprising a luminance signal and two chrominance components which are transmitted as quadrature amplitude modulation of a subcarrier, and in which, on each line, the polarity of one of the chrominance signals is inverted.

The basic idea which is central to the PAL system, that of periodically reversing the phase sequence of each subcarrier so that any phase errors produce opposite colour errors on adjacent lines, which will then be averaged by the human eye/brain combination to give the appearance of the correct colours, was not in fact new when PAL was developed. In 1951, before the NTSC system had been finalised, an engineer by the name of B.D.Loughlin suggested that if the phase of the colour subcarrier were reversed on alternate fields, the wrong colours due to these phase errors would appear on adjacent lines in the interlaced television display and would appear to cancel (ref. 4). He described the technique as an
Oscillating Colour Sequence (OCS), although it was also known as Colour Phase Alternation (CPA), and Loughlin went on to try out the effects of using OCS, not only at field frequency, but also at line frequency, and he even tried using the technique on adjacent dots. Although Loughlin showed that this method of cancelling out errors due to phase distortion did work, and that it might be particularly useful in overcoming phase errors caused by multipath interference (ghosting), it was not thought practicable to adopt his ideas at the time because it was found that synchronising the sequence-reversing switches at transmitter and receiver was difficult and even small errors gave rise to 30 Hz flicker problems. This means that the NTSC system did not, in the end, make use of OCS and it was not until over ten years later that Walter Bruch, working for Telefunken in Germany, revived the idea and the PAL television system was born.

**Basics of the PAL system**

As with NTSC, the PAL colour signal comprises a luminance (brightness) component, and two chrominance (colour) components which are transmitted simultaneously as the amplitude modulation sidebands of a pair of suppressed subcarriers which are identical in frequency but are in phase quadrature. Where PAL differs from NTSC is that the phase of one of these subcarriers is switched through 180 degrees at the end of each line, which

![Figure 19 Subcarrier phases for the two modulation axes U, V](image)
gave rise to the name of the system, Phase Alternation Line, from which the initials PAL are derived. The two colour-difference signals used in the PAL system, \((B-Y)\) and \((R-Y)\), are of equal bandwidth, unlike the \(I\) and \(Q\) signals used in NTSC. It is the phase of the \((R-Y)\) signal that is reversed on alternate lines to provide the error correction described below. As in NTSC, weighting factors are applied to the colour difference signals and the weighted signals are known as \(U\) and \(V\) (figure 19).

\[
U = 0.493\ (B-Y) \quad \text{and} \quad V = 0.877\ (R-Y)
\]

**Vector representation of PAL signals**

If the two subcarrier components are demodulated and applied to the \(x\) and \(y\) amplifiers of a special type of oscilloscope, known as a vectorscope, a useful phasor display is provided, which can show the amplitude and phase for any particular colour, which allows any errors or problems to be readily identified (figure 20).

In figure 21 the solid line represents the phase and the amplitude of the transmitted colour signal. The dotted line shows the received signal on a particular line which we shall call \(N\), which is lagging in phase by an angle \(\alpha\). From our diagram it can be seen that the received signal has had its \(U\) signal increased, and its \(V\) signal reduced, compared with the

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*Figure 20 Vectorscope type of display showing the phases of the subcarrier for the primary colours and their complements on alternate lines of the PAL colour system (ref. 5)*
transmitted signal, by the distortion that has been introduced. If the received signal from the next line \((N+1)\) is now reversed in phase and added to the original dotted line signal, we see that the resultant signal has had the phase error cancelled, and that the only difference from the transmitted signal is that its saturation, represented by the length of the line, has been reduced. The reduced saturation is equal to the original saturation multiplied by the cosine of the angle alpha.

In the PAL system the phase reversal is accomplished by electronic switching in the PAL coder, and a synchronised reversing switch in the receiver restores the colour signal to normal as well as correcting any phase errors over a period of two lines.

**Figure 21** Showing how signal phase errors can be effectively cancelled in the PAL system by reversing the phase of one of the signals on the adjacent line and summing the signals.
Simple PAL receivers

The simplest form of PAL receiver, no longer manufactured today, but originally called Simple PAL, uses a synchronous detector and an electronic reversing switch operating at half-line frequency to compensate for the switching of the $V$ component that has taken place in the PAL coder. The switching is synchronised by the transmitted colour reference burst which consists of ten cycles ($\pm1$) of colour subcarrier. The burst itself alternates in phase on successive lines, moving plus or minus 135 degrees about the $U$ axis. As can be seen from the vector scope display diagram (figure 20), immediately before lines where $V$ is positive the burst will be 135 degrees ahead of the $U$-axis, and immediately before lines where $V$ is negative the burst will lead by 225 degrees. This provides a means for the receiver to identify the lines on which $+V$ and $-V$ signals are transmitted in order to synchronise its chrominance demodulators.

We have seen that any hue errors due to differential phase problems will be in different directions on adjacent lines, and in the Simple PAL receiver it is left to the eye to integrate the two hues into approximately the correct hue. Under many circumstances the eye is quite happy to average out these hue errors on adjacent lines, but unfortunately brightness variations also occur when there are hue errors, due to non-linearity in the system, and although the eye averages out the hue errors it is by no means as tolerant of brightness errors and these manifest themselves as horizontal patterning. Since interlaced displays are used, the horizontal patterns appear to move vertically up and down the picture, giving rise to an annoying strobing effect known as Hanover Bars, which becomes increasingly noticeable as phase errors

![Block diagram showing basic principles of a Simple PAL decoder](image-url)
increase. In chapter 2 we discussed the problems that the failure of constant luminance can cause, and it is instructive to notice that the Hanover Bars are actually a result of this deficiency. If the system was linear, the information in the chrominance channels would not make any contribution to the luminance of the final image. Since the system, in common with all other existing systems, does not conform to the principle of constant luminance, however, the luminance of the displayed image is affected by the colour information and any phase errors in the chrominance signals will, therefore, give rise to the brightness variations known as Hanover Bars.

The Simple PAL receiver (figure 22) uses synchronous demodulators for the $U$ and $V$ signals and an electronic reversing switch operating at half the frequency. The transmitted colour burst is used to synchronise the demodulators and to keep the reversing switch in synchronism with the PAL switching that has taken place in the coder.

**Delay-Line PAL receivers**

To overcome the problem of Hanover Bars, which was basically due to the method of relying on the eye to average out the hue errors on adjacent lines, a more complex type of receiver, known as a Delay-Line PAL receiver, was developed. There were worries in the early days that the cost of the necessary delay line would make receivers too expensive for the domestic market and this was one of the so-called disadvantages of PAL and SECAM, but the miracles of mass production very soon gave us precise glass delay lines at economical prices so that since the late 1960s virtually all receivers have been of this type.

The delay line circuit, shown in block schematic form in figure 23, is used to delay one of the incoming subcarrier components by almost 64 microseconds, i.e. the duration of one line, so that the component signals from each of two successive lines can be brought together at the same instant. In fact the delay is made to be very slightly less than 64 microseconds, since it must be an exact number of subcarrier half-cycles so as to prevent the introduction of a phase shift in the delayed signal, compared with the direct signal, which could give rise to chrominance/luminance signals being mistimed. Using this technique of delaying and adding the signals from two successive lines it becomes feasible to electrically average the two signals on adjacent lines, rather than having to rely on the eye to perform this task.

If we assume that the same signal is transmitted on each of two successive lines, remembering that the phase of the $V$ signal is reversed on alternate lines, then the addition of the delayed signal and the direct, or undelayed signal (along the bottom path shown in figure 23), will cancel out the alternating $V$ components and will leave only the $U$ signal, with twice its normal amplitude, i.e. $2U$.

If the signals from the two successive lines are subtracted by inverting one of them before addition, as takes place along the top path shown in figure 23, then the $U$ components will cancel, and the remaining subcarrier signal will
Figure 23 Block diagram showing basic principles of a delay-line PAL receiver.
be +2V on one line and -2V on the next line. This alternation has to be compensated for by the inclusion of a reversing switch in the path of the V signal. The theoretical changes in amplitude of the U and V signals to 2U and 2V are unimportant, since the adder circuits are arranged to provide sufficient attenuation to restore the amplitudes to their original values.

Our U and V signal outputs are, therefore, each made up from a combination of the signals transmitted on two lines, the line currently being received and the line which immediately preceded this. The vertical chrominance resolution is, therefore, reduced, but as we have seen previously, the eye will not be worried by such a reduction. We have thus achieved the theoretical objective detailed earlier—any potential hue errors due to differential phase are automatically cancelled and a small decrease in saturation will be the only result of these errors. The electrical averaging of the colour signals on two lines eliminates the undesirable Hanover Bars that were produced in Simple PAL receivers where the eye was expected to carry out the integration.

**A problem on horizontal edges** Since the displayed colour is inevitably the result of the colour information from two lines of the transmitted picture, problems can arise under certain circumstances, notably when a block of colour is shown on a background of black, white or grey. In this instance the first line of the coloured block will be wrongly displayed, since its preceding line, being part of the neutral, let us say grey, background, contained no colour information and, therefore, no colour information would reach the adder circuitry from this line. In a similar way, the first line of the grey background underneath the coloured block will not be plain grey, but will be contaminated with some colour information originating on the previous line.

**Compatibility and the choice of subcarrier frequency**

In an earlier chapter the importance of choosing a precise subcarrier frequency for NTSC signals was discussed and it was explained that the chosen frequency needed to be an odd multiple of half the line frequency in order to minimise dot pattern effects. The situation for the PAL system is more complex, because the reversal of the V component on each line gives rise to an alternating change in the phase of the subcarrier and this switching at half the line frequency gives rise to components at harmonics of line frequency. Since we have seen earlier that the energy spectrum of a television signal is such that most of energy in a monochrome picture is gathered around the harmonics of line frequency, it is not surprising that this arrangement gives rise to an annoying dot pattern effect on monochrome receivers. For the PAL system, therefore, we add an extra quarter of the line frequency to the value of the subcarrier frequency which we would use if we were dealing with NTSC, thus effectively obtaining a three-quarter line frequency offset for the V signal, which ensures that any
energy resulting from the subcarrier is moved away from the harmonics of line frequency, thus reducing the visibility of any dot pattern.

Additionally, if the subcarrier is made to be an odd multiple of the frame (picture) frequency, the dots appearing on adjacent fields will interlace with one another, which reduces their visibility so, in addition to the offset described above, an extra component at picture frequency is added, so that in the European 625-line/50-fields per second PAL systems an extra 25 Hz is added to the subcarrier frequency that would be calculated from the previous paragraph. This 25 Hz offset means that any patterning caused by beating between the subcarrier and picture signals will repeat only every eight fields. This so-called eight-field sequence, where the phase of the subcarrier and the leading edge of the line sync pulse are only in exact synchronism once every eight fields, gives rise to complications when PAL video recordings are being edited; if no account is taken of the eight-field sequence, random picture shifts can occur at edit points.

Taking into account the need which we have established for the colour subcarrier to bear a particular relationship with the line frequency and for a 25 Hz offset to be added, the colour subcarrier frequency finally chosen for the European PAL system is

\[ f_{\text{subcarrier}} = \left[ \text{Line frequency} \times \left(284 - \frac{1}{4}\right) \right] + 25 \text{ Hz} \]

which, with the line frequency of 15.625 kHz, gives

\[ f_{\text{subcarrier}} = 4.43361875 \text{ MHZ} \]

**Frequency spectrum characteristics**

The baseband video signal for the UK 625-line PAL television system using CCIR system I is shown in figure 24 together with figure 25 showing the frequency bands occupied by the transmitted signal after modulation, as an example; other countries use similar signals with slight modifications to the video bandwidth, the width of the vestigial sideband and the sound carrier frequency. Full details of the systems used in other countries can be found in CCIR Report 624, published by the International Telecommunications Union, ITU. It is important to note that any particular television system such as System I could be used with different colour systems and as an example of this, we can see from ref. 2 that several European countries use CCIR System G with PAL, whereas Tunisia and Saudi Arabia use System G with SECAM. Since we are looking at the existing modern television systems in order to be able to understand clearly what the advantages and disadvantages of proposed future systems are likely to be, it is necessary for us to consider not only the details of how a particular system works in the studio, but also to look at the implications of using that system for radio-frequency transmission. We shall see later how the bandwidth necessary to
Figure 24 Baseband video signal for CCIR system I

Figure 25 Radio frequency spectrum occupied by the vision and sound signals of a PAL system I transmission
transmit a television signal is critical in many instances, especially when we are attempting to produce a higher-definition television picture signal that needs to be to some extent compatible with existing transmissions. For this reason it is important for us to consider a complete system, including such factors as the characteristics of the radio-frequency signal that is produced on transmission.

### Comparison of some different television systems used with PAL

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<td>N</td>
<td>6 MHz</td>
<td>4.2 MHz</td>
<td>+4.5 MHz</td>
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For System I the width of the complete channel that contains both the video signal and its associated sound channels is 8 MHz. A monophonic frequency-modulated analogue sound carrier is placed at 5.996 MHz above the vision carrier. A separate digital dual-channel sound carrier is added at 6.552 MHz above the vision carrier frequency, and this can be used to carry either a pair of stereophonic sound signals or two separate sound channels, perhaps in different languages, in addition to the monophonic audio channel.

The vision signal is asymmetrically modulated, the bandwidth of the upper luminance sideband being 5.5 MHz and that of the lower luminance sideband 1.25 MHz. The bandwidth of the chrominance signals is around 1 MHz (a theoretical maximum of 1.3 MHz) for both U and V and since the luminance bandwidth of System I is 5.5 MHz, it is possible to accommodate the complete double sidebands of the chrominance subcarrier. This is a notable difference from Systems B and G, where only 5 MHz luminance bandwidth is used. For these systems, the chrominance signals must be of vestigial sideband form which can mean that the saturation is reduced on areas of fine chrominance detail.

The ratio of the peak vision carrier power to the sound carrier power is 10:1.

### Disadvantages of the PAL system

Most of the disadvantages of PAL shown here are in fact disadvantages
shared by other composite television systems, but it is probably worth
detailing some of these so that we will be in a position to be able to know
which of the disadvantages it should be possible to eliminate in the more
modern systems that are to be discussed in the following chapters.

The first and inherent disadvantage of the PAL system has already been
noted. Phase distortion errors give rise to variations in the colour saturation
of parts of the picture. Although this can cause noticeable visible
degradations under certain viewing conditions, in general, viewers do not
notice any problems, because the variations in saturation are generally kept
within fairly narrow limits, and the automatic colour correction circuits in
the receivers have an automatic gain control type of action which
compensates for any changes.

We saw in the previous chapter that since NTSC is a composite colour
television system which uses frequency division multiplexing to carry both
luminance and chrominance signals within the same frequency band, certain
picture material will give rise to the phenomena known as cross-colour (figure
26) and cross-luminance, the most common manifestation being the
spurious colours that are generated when the picture contains much fine
detail, such as can happen when the presenter wears a check-patterned suit
or striped shirt. These effects are noticeable on any composite signal, where
subcarriers are used to carry the chrominance information and they are one
of the so-called ‘artefacts’ of the PAL system which engineers would like to
eliminate from future broadcast television systems.

As was discussed earlier, PAL suffers from the disadvantage that the
system does not conform with the principle of constant luminance but
remember that this is not a fault unique to PAL, it is inherent in all existing
television systems, although some of the enhanced systems now under
development may well be designed to conform.

Another disadvantage of PAL (and other composite television systems)
only came to light when the possibility of using satellites for direct
broadcasting to homes was first mooted. Satellite transmissions need to use
frequency modulation to make the best possible use of the limited power
that is available on spacecraft because of practical limitations on the
physical size of the solar-cell arrays. It has long been known that FM
transmissions have a so-called triangular noise spectrum, as shown in
figure 27, and this implies that the system noise will be concentrated in the
high-frequency parts of the spectrum. Since PAL pictures carry their colour
information in the high-frequency parts of the picture spectrum, PAL
signals carried over FM channels are subject to chroma-noise which is
particularly objectionable in large areas of saturated colour.

It was to overcome some of these problems, and to provide a television signal
which would be more suited for satellite broadcasting and as a basis for higher-
quality future systems, that engineers from the United Kingdom Independent
Broadcasting Authority developed the completely new system that will be
described in the next chapter—MAC, or Multiplexed Analogue Components.
References

2. CCIR Report 624.
4. *Proc IRE*, October 1952, Loughlin, B.D.

Figure 27 Triangular noise spectrum of an FM signal showing why noise will be most apparent in highly saturated coloured areas of a PAL picture

![Diagram showing amplitude vs frequency with Luminance, Chrominance, and Noise (FM) labeled](image)

Figure 26 Off-screen photograph showing the effects of cross-colour when using a composite colour television system: (a) composite system PAL, (b) MAC system (courtesy IBA)
5

MAC—the first of a new generation of
television systems

Introduction

The previous chapters have described the existing television systems that are currently in use throughout the world, and have explained their advantages and disadvantages. Although the various disadvantages such as cross-colour and cross-luminance are not usually regarded as very serious by present-day viewers, most of whom watch on small screens, broadcasters are well aware that if these existing systems were to be used with the large-screen displays that are expected to become available in the nineteen-nineties, their failings would become painfully obvious to even the least discriminating of viewers, and might well lead to a situation where viewers, for the first time, were dissatisfied with the technical quality of the pictures being offered by the broadcasters.

We have already discussed how it would be practicably impossible to expect the mass of television viewers to throw away their existing receivers in order to take advantage of some new television system, even if it promised better, clearer pictures, and although much work had been done by the broadcast research organisations to investigate how existing systems such as PAL could be upgraded to provide better pictures, this problem of dealing with the millions of existing receivers always proved the stumbling block. It was the World Administrative Radio Conference in 1977 (WARC ’77) that eventually, indirectly, and quite unexpectedly, provided the solution that broadcasting engineers had been looking for.

The WARC ’77 Conference provided a highly-detailed plan (ref. 1) giving the technical characteristics for the implementation of a service of Direct Broadcasting by Satellite (DBS) to the countries of the ITU’s Region 1, covering mainly Europe, Africa, and the USSR, and it also produced a provisional frequency plan for Region 2, the Americas, and Region 3, Australasia and the Far East.

The main characteristics of the WARC 77 plan for region 1 are shown below and in figure 28, and the important points for our purposes are that the frequency band to be used is from 11.7 to 12.5 GHz, a band that is much higher than the frequencies currently used for television transmission, which are well below 1 Ghz, and that the DBS satellite transmissions use frequency modulation, FM, instead of the amplitude modulation, AM, that is universally used for vision transmission
on existing terrestrial broadcast services. FM transmission allows the satellite transmitter to provide an adequate signal-to-noise ratio at the receiver with only about one two-hundred and fiftieth of the power that would be required to provide the same signal-to-noise ratio using amplitude modulation (ref. 2), and since power is difficult to generate on a spacecraft, there was really no option but to choose FM for the DBS transmissions.

Main Provisions of the WARC '77 Conference
Frequency Band 11.7–12.5 GHz
Frequency Modulation
Orbital Spacing 6°
40 Channels at 19.18 MHz centre spacing
Channels 27 MHz wide, overlapping
Circular Polarisation

Power Flux Density at edge of service area -103 dBW/m²

At first sight this apparently meant that existing television receivers would not be capable of receiving DBS transmissions, but in fact the WARC planners envisaged that any viewer wishing to make use of the new DBS services would be able to buy an adaptor unit. This equipment (figure 29) would convert the
12 GHz incoming signals into UHF signals which could be accepted by the aerial socket of an existing receiver, and at the same time it would change the frequency-modulated satellite signals into amplitude-modulated signals which could be demodulated by the television receiver's normal circuitry.

This concept of every viewer who wishes to receive satellite broadcasts having to purchase an adaptor unit led some research engineers, and notably those of the UK Independent Broadcasting Authority (ref. 3), to feel that this might present the opportunity which they had long been looking for—the chance to introduce an improved system of broadcasting, without making viewers throw away their existing receivers.

The argument which they put forward suggested that any adaptor box intended to provide viewers with DBS services would need to contain a number of specialised very-large-scale integrated circuits (VLSIs), no matter what system would eventually be chosen for satellite broadcasting (and the assumption made in the WARC plan was certainly that PAL and SECAM would be used), with individual countries using the same system for satellite broadcasting as they use for terrestrial transmissions.

Since an adaptor box would be essential, and since this adaptor box would contain integrated circuits, the argument went that it would cost
little or no extra to introduce a new, improved broadcasting system at the same time as the introduction of direct broadcasting by satellite, since the integrated circuit chips that would be required for this, although they would undoubtedly be more complex than those required for decoding PAL or SECAM, would in practice incur virtually no cost penalty, since it costs hardly any more money to manufacture very complex ICs than it does to manufacture those of only moderate complexity, once the ICs are made in very large quantities.

It was further argued that there would be great advantages for the future development of television broadcasting in introducing an improved broadcasting system in this manner, since the system chosen for the satellite broadcasts, which were only just coming into service in the late 1980s, is likely to be still in use well into the next century. It therefore seemed to many forward-looking research engineers that it would be shortsighted to adopt PAL or SECAM for satellite broadcasting, since their disadvantages are well known.

There could be another potentially significant advantage of making a change of this sort; since nearly all the countries of Europe are committed to satellite broadcasting in some degree, the introduction of a completely new system, without any historical links to PAL or SECAM, might make it possible for all the European nations to adopt the same system. As well as providing the almost Utopian situation where the same satellite receiving equipment could be used all over Europe, such a common approach would give tremendous economic advantages. It is well known that complex integrated circuits become cheaper as they are fabricated in larger quantities, and if manufacturers could think in terms of a European market of more than 200 million receivers using the same chip sets, rather than one of perhaps only 20 million for the UK alone, significant mass-production cost-savings would be possible.

We have seen already how petty nationalism and political infighting in the nineteen-fifties and sixties prevented a single television standard being achieved for Europe. It was felt by many that, as progress had been made in the growth and development of the European Community, the time might be right in the nineteen-eighties to achieve this aim of a common European television standard. Unfortunately this laudable aim was not to be achieved completely, but some progress was made, and instead of achieving the goal of one European system, the countries of Europe in fact agreed upon a so-called ‘family of systems’ (ref. 4). The outcome of this idea was that all the countries agreed to use the same basic system for the vision part of the signal, but to permit flexibility, and to obtain a multi-national agreement, it was found necessary to allow for some important differences between the sound and data components that go to make up the complete television signal in different countries.

Even this partial success was not achieved without a great deal of discussion and argument, reminiscent of the earlier years when NTSC, PAL,
and SECAM had been extolled by their protagonists and depreciated by
their detractors. Most European broadcasters were initially unwilling to
consider a change from their existing PAL or SECAM standards, and in the
United Kingdom even the two major broadcasters, the BBC and the
Independent Broadcasting Authority, could not agree on the best system to
be used for satellite broadcasting. The BBC favoured an enhanced version of
the PAL system (E-PAL) that could provide pictures with better definition
and fewer luminance/chrominance crosstalk effects than standard PAL,
whilst providing a fair degree of compatibility with existing receivers. The
research engineers at the IBA had come up with an entirely new system,
Multiplexed Analogue Components (MAC), which they were convinced was
superior to any sort of improved PAL, and in the end the UK government set
up an official committee to consider the two contenders. After much
listening to evidence and critical viewing of television pictures, the decision
to use MAC for the UK DBS service was made (ref. 5). Some countries
argued that as the WARC planners had obviously intended that PAL and
SECAM should be used for DBS, and the interference protection
calculations had been made on that basis, it was not legally permissible to
use other systems. Careful study of the wording of the WARC plan revealed
that the use of other systems was not in fact precluded, provided that their
use caused no more interference to other users of the spectrum than that
allowed for under the plan. To enable the effects of co-channel and
adjacent-channel interference to be assessed, the WARC plan provided the
interference template shown in figure 30. In essence, any system which
keeps its potentially interfering signals within this template is acceptable,
and the MAC protagonists soon showed that their system complied (ref. 6).

After much discussion and many demonstrations the broadcasters and

![Figure 30 WARC spectrum mask—interference protection template](image)
administrators of the European Broadcasting Union and the governments of its member states finally agreed that MAC would be used for DBS broadcasting in Europe, although, as we saw earlier, it was necessary to include various versions of the MAC system in order to gain the agreement of all the countries concerned.

THE MAC (MULTIPLEXED ANALOGUE COMPONENTS) SYSTEM

From the late nineteen-seventies engineers in the Experimental and Development Laboratories of the UK IBA had been looking at the disadvantages of composite television signals like PAL and SECAM. They had seen that problems such as cross-colour and cross-luminance, which occur because the colour and the luminance components of a television signal are made to share a common band of frequencies, using a technique called frequency-division multiplexing, could be overcome by the use of an entirely different technique. The term that they coined for the new system was Multiplexed

Figure 31 Illustrating the difference between frequency-division multiplexing and time-division multiplexing

A Illustrating frequency-division multiplexing, (a) as used in conventional composite television systems, and (b) as could theoretically be used for transmission of separate component signals.

B Illustrating time-division multiplexing, (a) as used for MAC signals on transmission, and (b) as used in studios.
Analogue Components, now known universally as MAC. Figure 26 shows off-screen photographs comparing the image quality obtainable with PAL and MAC, and it will be seen that the MAC picture is completely free of cross-colour.

Strictly speaking, the term ‘multiplexed analogue components’ describes just the vision part of the television signal, which consists of the analogue chrominance components (the colour information), and the analogue luminance component (the black-and-white information) of the picture, which are transmitted in sequence, during separate periods of time, using a technique known as time-division multiplexing. (See figure 31.)

Figure 32 shows one line of the MAC signal, and it will be seen that since the luminance and chrominance signals are never transmitted simultaneously, there is no chance that cross-colour or cross-luminance can occur, so that the MAC system straightaway overcomes some of the major faults of the existing composite systems.

A special technique has to be used to enable the separate chrominance and luminance component signals to fit into a standard 64 microsecond television line period (for 625-line systems), which is essential if compatibility with existing television receivers is to be maintained, since it is difficult to conceive of an add-on box plugging into the aerial socket of a conventional television receiver which could automatically alter the line scanning period of that receiver.

Both luminance and chrominance signals are therefore time-compressed on transmission so that they can be packed into less than 64 microseconds, and once they reach the MAC decoder circuits in the satellite receiver’s adaptor box the signals are expanded in time so that both the black-and-

---

Figure 32 One line of the basic MAC signal, showing how luminance and chrominance are transmitted separately
white and the colour parts of the picture once again fill a complete line of the television display. Figure 33 shows how such a MAC picture would appear on a conventional receiver (i.e. one without a MAC decoder) if the synchronising circuits were adjusted to provide a recognisable image; the time compression of the chrominance and luminance parts of the picture can be clearly seen.

Since the MAC system was designed from its inception to suit the characteristics of a DBS satellite channel, considerable care has been taken to control the amounts by which the colour and monochrome components are compressed, with the result that the system noise is spread relatively evenly throughout the whole picture spectrum; this overcomes the problem that occurs with frequency-modulated PAL or SECAM signals, where all the noise is concentrated in the highly-saturated coloured parts of the picture. Theoretical calculation and practical observations showed that optimum results could be obtained with the luminance time-compressed by a factor of 3:2, and the colour information compressed by double this amount, a factor of 3:1.

The colour information is transmitted in the form of the colour-difference signals \( (B-Y) \) and \( (R-Y) \) that were discussed in an earlier chapter, and on each line just one of the colour-difference signals, either \( (B-Y) \) or \( (R-Y) \), plus the luminance signal is transmitted, the other colour-difference signal being transmitted with the luminance signal on the next line. If both of the colour-difference signals were transmitted on each television line then more time-compression would be required to squeeze in the three signals. The more compression that is used, the worse will be the signal-to-noise ratio of the picture that results after the components have been expanded in time again, so it is desirable to use no more compression than is absolutely necessary. Practical tests showed that pictures resulting from this technique of transmitting only one colour-difference signal per line were perfectly acceptable, in spite of the reduced chrominance resolution that must occur. Once again the eye’s inability to see fine detail in coloured images comes to the rescue of the colour television engineer!

In studio centres which use MAC techniques, and where a considerable amount of picture processing and recording takes place, it would not be acceptable to throw away half the colour information on each line; most post-production operations need both colour-difference components, so special versions of MAC have been developed which enable both colour components to be squeezed onto each line, by using extra compression (ref. 7). In a studio, unlike over a transmission path, the signal-to-noise ratio of the signals will be extremely high, so that the small amount of extra noise due to the extra compression will make no significant difference to the picture quality from that studio. These special forms of MAC are discussed in more detail later in this chapter.

It will be seen from figure 32 that a period of around 10 microseconds in the line-blanking interval before the transmission of the colour-difference
component is used to carry a digital data burst. Line synchronisation is provided by the first few bits of this burst, and the rest of the data is available to carry digital sound signals or any other data required for transmission.

Having looked briefly at the MAC waveform as a whole, now let us consider in more detail each part of the signal.

The three basic analogue components are \( Y \), the luminance signal, and \((B-Y)\) and \((R-Y)\), the colour-difference signals. Since the MAC system parameters were designed to conform, whenever possible, with the digital studio standard format described in CCIR 601 (ref. 8), the bandwidth of the luminance signal (before compression) has been arranged to be 5.75 MHz, and that of each colour-difference signal 2.75 MHz.

The matrix used to convert the original \( R \), \( G \), \( B \) components (which become \( R' \), \( G' \), \( B' \) after gamma-correction in the studio) to provide the luminance component of the MAC signal is the same as that used in the PAL system (figure 34):

\[
Y' = 0.2997R' + 0.587G' + 0.1145B'
\]

The matrix used to obtain the MAC colour-differences signals is, however, different. The two compressed and weighted colour-difference signals in MAC are known as \( E' U_m \) and \( E' V_m \), and sometimes as \( C_B \) and \( C_R \). It should be noted that although these signals are also sometimes colloquially called \( U \) and \( V \), this is strictly incorrect as the terms \( U \) and \( V \) should be reserved for use only with the PAL system.

Similarly, although we will use the terms \( C_B \) and \( C_R \) because they are currently used in much of the literature relating to MAC, this is not strictly

![Figure 34 Matrix of resistors used for deriving the luminance signal \( Y \) from the \( R \), \( G \), \( B \) signals](image)

\[
R_r = \frac{0.701}{0.299} R_r, \quad R_o = \frac{0.413}{0.587} R_r, \quad R_g = \frac{0.886}{0.114} R_r
\]
correct, and alternative nomenclature is currently being discussed in international standards committees. The colour-difference signals $C_B$ and $C_R$ are correctly defined in CCIR Recommendation 601–1 Annex II, but this document makes it clear that these are strictly digital signals and are unipolar. The SMPTE has recommended and defined two alternative terms for use when referring to analogue colour-difference signals which are bi-polar, such as we are using in the MAC systems, and these terms, $P_B$ and $P_R$, may soon be accepted as the correct terms to use for the compressed and weighted colour-difference signals used in analogue component systems.

$$C_B = 0.733 \ (B' - Y)$$
$$= 0.733 \ (-0.299R' - 0.587G' - 0.886B')$$
$$= 0.2192R' - 0.4303G' + 0.6495B'$$

Similarly,

$$C_R = 0.927 \ (R' - Y)$$
$$= 0.927 \ (0.701R' - 0.587G' - 0.114B')$$
$$= 0.6498R' - 0.5441G' - 0.1057B'$$

The maximum amplitude of the baseband luminance signal is 1 volt peak-to-peak, varying from -0.5 volts to +0.5 volts, where the level of -0.5 volts is taken as black level and that of +0.5 volts as peak white (figure 35). The corresponding maximum values for the colour-difference part of the waveform are 1.3 volts peak-to-peak, from -0.65 volts to +0.65 volts. All

![Figure 35 A D-MAC line, showing signal amplitudes](image-url)
voltages are measured with reference to the zero-volt clamping level period which follows the data burst. The data burst itself has an amplitude of 0.8 volts peak-to-peak, varying from -0.4 to +0.4 volts with respect to the clamping level.

A notable difference between the MAC signals and the conventional television signals is that, since there are no sync pulses needed, the whole of the amplitude range can be used to carry the signal information, rather than having to reserve a large part for the synchronisation information. This gives rise to a better signal-to-noise ratio with MAC signals.

We have seen that each MAC line consists of just one colour-difference signal, followed by the luminance signal. Alternate lines carry the two different colour-difference signals alternately. $C_B$ is sent on odd-numbered lines and $C_R$ is sent on even-numbered lines, as is shown in figure 36. This ruling simplifies the decoding problems that can occur in other sequential colour systems such as SECAM, where the particular colour-difference signal occurring on any particular line will differ according to the frame being received.

Since only one of the colour-difference components is transmitted on any one line, the other colour-difference signal has to be generated within the receiver by taking an average over three lines, obtained from an interpolating filter. In order to reduce the amount of storage in the receiver the particular colour-difference signal relating to any particular line must be transmitted one line before the luminance signal to which it is spatially related. This means that the luminance signal must be delayed by one-line time period at the encoder.

A block diagram of a fairly basic encoder is shown in figure 37. The incoming analogue signals are first filtered, so that the bandwidth of the

![Figure 36 Showing how the MAC components are time-multiplexed together](image-url)
Figure 37 Block diagram of a basic MAC encoder
luminance signals does not exceed 5.6 MHz and that of the colour-difference signals does not exceed 2.75 MHz, to prevent aliasing components being produced, which would degrade the pictures. The signals are then passed to analogue-to-digital converters (ADCs) where they are converted to 8-bit (256 level) digital signals. The sampling frequencies used, i.e. the clock rates of the ADCs, are 13.5 MHz for the luminance, and 6.75 MHz for the colour-difference components, these tying in with the sampling frequencies recommended in the CCIR digital studio standard (ref. 8). The clock rates used in all the subsequent stages have been chosen so that they relate to the compression ratios that will be used, and to the line and field frequencies, and it will be seen how these relate to the fundamental clock frequency that has been chosen, 20.25 MHz (13.5+6.75=20.25):

Fundamental clock frequency=20.25 MHz
Luminance sampling frequency=(2×20.25)/3=13.5 MHz
Chrominance sampling frequency=(20.25)/3=6.75 MHz
Line frequency =((2×20.25)/(3×64)=13.5/864
=15 625 Hz

N.B. 864 is the number of samples in a complete television line that has been digitised according to CCIR Rec. 601.

Field frequency =((2×line frequency)/625
=(2×15 625)/625
=50 Hz

The digital components pass straight from the ADCs to a frame store, which effectively isolates input and output signals, so that no timing synchronisation is necessary between input and output signals.

The luminance signal then passes through a one-line delay stage (we saw earlier that the colour-difference signal relating to any particular line must be transmitted one line before the luminance signal to which it is spatially related). This delay is usually achieved by reading the information into one of two random-access memories (RAM), each of which delays the signal by one line period. One of the memories is used to store the luminance information for the current line, whilst the luminance information from the previous line is being read out of the other memory. Although not shown in figure 37, in a practical coder extra luminance delay is added to compensate for the unavoidable delays that occur in the vertical prefilters through which the chrominance signals pass, in order to prevent aliasing occurring. After the chrominance output signal from the frame store has passed through these vertical prefilters, it is applied to a line-sequential switch, and things are arranged so that the compressed and weighted (R-Y) signal $C_R$ is eventually sent out on even-numbered lines and $C_B$ is sent on odd-numbered lines.
The luminance and chrominance signals are then separately time-compressed by different amounts. Although time-compression may appear a rather complex thing to do, and engineers of as little as ten years ago would have been hard-pressed to achieve it, the coming of modern digital storage has rendered it readily feasible. In essence the digital signal samples are read into a one-line shift-register type of random-access memory, arranged in a first-in first-out manner (FIFO). If the samples are then read out of the FIFO at a faster rate than they were read in, the output samples will be closer together in time than the input samples were, so that we have effectively time-compressed our signal.

The luminance signals go into their FIFO at 13.5 MHz and are read out at a clock rate of 20.25 MHz, giving an effective compression ratio of 20.25/13.5=3:2. The chrominance signals are clocked into their FIFO at 6.75 MHz and again clocked out at 20.25 MHz, this time giving a compression ratio of 3:1.

In the final stage of our much simplified MAC coder, the luminance and chrominance signals are time-multiplexed, so that on each line of the resulting MAC television signal there is a luminance signal and one of the two chrominance signals.

At this point it is probably worth emphasising that although we have described a digital technique for achieving MAC coding, and this seems to be the most likely method that will be used in practice, the basic MAC vision signals are, as their full name indicates, ANALOGUE component signals, and we must remember this; as we shall see in a later chapter, it is not yet possible to transmit high-quality digital signals within the radio-frequency bandwidths that are currently available for television. Since the basic signals are analogue, therefore, instead of digitising the signal in the decoder, we could merely take analogue samples, and read these samples into an analogue shift register constructed from charge-coupled devices. If we read the analogue samples out at a faster rate than they are read in, then once again we achieve our objective, a time-compressed signal.

A time-compressed analogue waveform

Whenever you come across MAC waveform diagrams you will see that they are labelled, not by accurately defined timing information given to fractions of a microsecond, but with numbers of ‘samples’ along the X-axis. We have seen before that the whole development of MAC as a television system with a great deal of potential for future enhancement has been arranged so that the system ties in with the internationally agreed sampling frequencies for digital television, as detailed in CCIR Recommendation 601 (ref. 8). When the recommended sampling frequencies, 13.5 MHz for luminance and 6.75 MHz for chrominance, are multiplied by the compression ratios used in MAC (3:2 for luminance and 3:1 for chrominance), we obtain a common sampling rate of 20.25 MHz. We shall see shortly that this is the same data
rate that has been chosen for the burst of data that forms the first part of each D-MAC line, so we can think of a digital clock ticking away at 20.25 MHz throughout the whole of the D-MAC line period, whether it is video or data that is being transmitted at any particular time.

Bearing these factors in mind, it has been found helpful to consider the MAC waveform as an analogue waveform which is sampled at a rate of 20.25 MHz, effectively dividing the waveform into time slots which are each $1/20.25$ MHz, or about 49.4 nanoseconds long. Since the length of one line of the MAC waveform is the standard 64 microseconds used with 625-line systems, we arrive at

$$64/(1/20.25) = 1296 \text{ samples per line}$$

(as figure 35 indicates)

Using this method of measurement we find that, as shown in figure 35, the colour-difference signal occupies 349 sample periods, around about 17 microseconds, and the luminance information occupies 697 samples, or about 34 microseconds. It is much simpler to use the number of samples as a timing reference, rather than to have to specify precise timings to within a few nanoseconds, and we shall see later on what further advantages of using sample numbers become apparent when we come to scramble the signals, as part of a conditional access system.

**Bandwidth considerations**

The effect of time-compressing a signal—let us take a sine-wave for simplicity—will be to increase the number of cycles of that sine-wave that occur in a given period of time. The number of cycles which occur in a given time period is a measure of the frequency of the signal, and therefore by compressing the signal we have increased its frequency, or to look at it from another point of view, we have increased the bandwidth necessary to carry that signal. The bandwidth increases in proportion to the compression applied, so that a luminance signal with a bandwidth of 5.6 MHz will take up a bandwidth of $5.6 \times 3:2 = 8.4$ MHz when compressed by a factor of 3:2, and a chrominance signal with a bandwidth of 2.75 MHz will occupy a bandwidth of 8.25 MHz when compressed by 3:1.

**Wide-screen pictures**

In the MAC/packet family of systems, the normal ratio of the width of the image to the height of the image, known as its *aspect ratio*, is 4:3, as in nearly all existing television systems. Research into viewers’ preferences, which ties in with developments in the cinema over the past few decades, has however shown that, when viewers watch large-screen pictures, they prefer a wider aspect ratio. Since it should be possible to provide large-screen television displays in the home within the next few years, the
Figure 38 Wide-screen MAC

(a) Comparison of standard 4:3 aspect ratio with wide-screen 16:9 aspect ratio
(b) Showing how a 4:3 picture may be panned within a 16:9 picture area so as to include the most important information
(c) Showing areas of the MAC picture frame which could be used to carry luminance and chrominance extensions in the form of add-on sides to the picture
(d) Wide-screen picture with edges made up from luminance and chrominance extensions
Add-on sides (picture extension) which change aspect ratio to 5 : 3

Normal 4 : 3 picture

Complete 5 : 3 aspect ratio picture
developers of the MAC system have taken account of this by making provision for wider aspect ratio pictures to be broadcast, but since there will initially be a large majority of viewers using their existing 4:3 receivers, this has had to be done in a way which ensures compatibility between wide-screen and normal receivers. Figure 38(a) shows comparison of ‘standard’ and ‘wide-screen’ pictures.

The MAC system therefore allows for the transmission of pictures with an aspect ratio of 16:9 (5.33:3), and also enables receivers with a 4:3 aspect ratio to extract an appropriate undistorted image from the widescreen original. The MAC/packet specification allows for several different methods of providing compatible wider aspect ratio pictures, called extended pictures in the specification.

One method is to use the normal time-division multiplex structure, with the active line time remaining the same for the 16:9 images as it would normally be for the normal 4:3 images. Signals are transmitted in line 625 of each picture to indicate to the receiver whether 4:3 or 16:9 images are being transmitted.

When a 4:3 receiver receives the wider aspect ratio transmissions it can effectively choose a 4:3 window from the whole 16:9 image, by selecting the correct portion of the luminance and colour-difference components. This can be thought of as ‘panning’ the 4:3 window within the 16:9 picture, as shown in figure 38(b).

The most appropriate positioning of the 4:3 window can be chosen by the director of the programme, and signals are once again transmitted in line 625 to indicate to the receiver exactly where the 4:3 window should be placed. The receiver will then apply alternative expansion ratios of 2:1 for luminance and 4:1 for the colour-difference signals, to provide an undistorted 4:3 aspect ratio picture.

Exactly how the 16:9 picture is displayed on a 4:3 receiver could however be a receiver option; for example, when the 4:3 receiver discovers from line 625 that wide-screen pictures are being transmitted, the scanning circuits could be modified to provide the whole of the 16:9 image in a ‘letter-box’ format, with a blank area at the top and bottom of the screen.

Another permitted method of providing extended pictures is to increase the amount of time compression that is applied to the luminance and colour-difference components of a 16:9 picture. Two different sets of compression ratios form part of the MAC specification, and once again the receiver will use data from line 625 to identify that it is receiving signals representing an extended picture of this type. The 4:3 receiver will need to make use of alternative expansion ratios to provide a ‘normal’ picture.

A third option for providing compatible wide-screen pictures, which now seems unlikely to be used in practice, was in fact the first method to be demonstrated, by UK IBA engineers. This scheme utilises the fact that it is possible to use part of the vertical blanking period and part of the line blanking period to carry extra information, corresponding to the chrominance
and luminance signals required to describe add-on strips at each side of the 4:3 picture. Figure 38(c) shows the areas of the transmitted frame which could be free for this purpose, and figure 38(d) shows how adding strips at the sides of the picture could increase the aspect ratio, without affecting the 4:3 viewer in any way. The data burst on each line has to be shortened to only 68 bits, which in practice reduces the number of sound channels which can be broadcast from eight to two, but this limitation would probably be acceptable in many instances. A more serious reason for not using this method is that, if we were to use the frame blanking intervals to carry this wide-screen information, it would not in the future be possible to use it to carry extra data which may well be used to provide ‘digital assistance’ to enable advanced receivers to provide enhanced quality pictures. This idea forms part of the European Eureka project, a scheme intended to provide a step-by-step compatible approach to high-definition television, as we shall see in a later chapter.

Although it proved possible to obtain 5:3 aspect ratio pictures using this method, there are difficulties in going even wider, since greater amounts of compression are needed to squeeze in the extra information, and this can result in the edges of the picture being noisier than the central part of the picture.

The specification also makes mention of a fourth scheme whereby all the MAC sound and data would be transferred to the field-blanking interval, so as to allow the whole of the line period except for the synchronisation word to be given over to extended video information, but so far this idea has made little progress.

The complete MAC signal—adding the data burst

A complete television signal needs not only the luminance and colour-difference components of the picture, but also line and frame synchronisation signals to enable the received picture to be reassembled, as well as one or more channels of audio information to accompany the pictures. These days it has also become the norm to expect teletext data and engineering test signals to form an integral part of the complete television signal. To accommodate all these requirements the two time-multiplexed analogue components that we have so far considered have been put together with a burst of data and some clamping information to form what has become known as a MAC/Packet baseband signal (see figure 35).

The time-division multiplexing techniques which we have discussed have also been used to squeeze this burst of digital data into a short period of time at the beginning of each MAC line. Notice that the long time period necessary for synchronising conventional television signals (around 5 micro-seconds for the PAL system, for example) is no longer needed when digital signals are used for synchronisation. Just six bits of data occupying only a few hundred nanoseconds are now required for line synchronising.
purposes, and the complete data burst that is inserted at the start of a MAC line, shown in figure 32, is capable of carrying not only line and frame synchronising information, but also enough extra data to allow for the transmission of several high-quality digital sound signals plus additional data for engineering or commercial purposes.

**MAC variants, but a common vision signal**

There are various different versions of the MAC system that can be used for transmission, the most common ones being known as A-MAC, B-MAC, C-MAC, D-MAC, D-2 MAC. Probably the most important basic fact to grasp about these different systems is that, in all the variants, the vision signals, which consist of the two components, a luminance signal followed by one of the two colour-difference signals, are virtually identical, and it is only the data part of the signal that is different in each version of MAC (figure 39).

The A, B, and C variants were so named because they were the first three types to be developed, and they tie in with the three letters generally used to describe the various options which may be used for combining sound/data with video signals, (ref. 9), but the letter D in D-MAC and D-2 MAC actually indicates that these systems use Duobinary coding of their associated data, an idea which we shall explore later on. It is perhaps worth noting at this point, in order to avoid any confusion later on, that in the early 1980s a system that was then called D-MAC was envisaged, which used frequency-multiplexed data at RF, with the video signal being radiated on one frequency, and the data being radiated on a separate radio-frequency carrier. Such a system would allow the data and the video to be uplinked to the satellite from two different locations, but the receiver required could be very complex, and interference problems might occur. This system is not now used, and it is not the same as the D (for Duobinary) systems which we shall be considering.

![Figure 39 The basic MAC format; all versions of MAC have this basic format for the vision signals—only the data/sound part differs](image-url)
A-MAC (figure 40)

An A-MAC signal carries its data on a separate radio-frequency carrier, just as sound signals have a separate carrier in conventional television. We have seen earlier that having several carriers present in a television signal can

Figure 40 A-MAC transmission format and baseband spectrum: diagrammatic representation of A-MAC signal, showing the frequency multiplex of the vision and digital data, and the time-division multiplex of the colour-difference and luminance signals.
lead to spurious interference, and the fact that the sound carrier is present just a little higher up the band than the vision signal means that it would prove difficult to extend the video bandwidth for an extended definition system in the future. Therefore, although A-MAC was used in the very first MAC trials, it was soon decided by European broadcasters that since they were looking for a system that would last well into the next century, it would be better to do without separate carriers.

The B-MAC, D-MAC, and D-2 MAC systems carry digital data containing synchronising information and the accompanying sound signals in the line-blanking period at the beginning of each television line. The base-band signal for these variants therefore can be seen to include the digital information followed by the luminance and chrominance components, as we have seen in figures 32 and 35, and both vision and data are processed together in the modulation circuitry.

**B-MAC (figure 41)**

The B-MAC system has been marketed commercially by Scientific-Atlanta (ref. 10), and was the first MAC system to become available on the market. Its developers took what turned out to be the wise commercial decision to go ahead with the manufacture of encoding and decoding equipment to their own specification, without waiting for agreement from other manufacturers or broadcasters, and this gave B-MAC a start of several years on the competition, which in Europe took until October 1986 for agreement to be reached on the full specification of the MAC family of systems (ref. 4), and until 1989 to produce suitable chip sets in quantity.

The Scientific-Atlanta B-MAC system is currently used by a number of companies for the transmission of video and data to small satellite terminals owned by businesses such as bookmakers, whose success depends upon high-quality information being received quickly and accurately, whilst this information remains confidential, so that competing companies cannot make use of it.

Since early 1986 B-MAC has been used in Australia, which was the first country to inaugurate a regular MAC satellite service. The Aussat service uses a medium-power satellite, which transmits the programmes of the Australian Broadcasting Corporation to receiving terminals in remote areas which feed transmitters which then rebroadcast the signals to local communities. Some of these signals were previously carried on the low-power Intelsat communications satellites, but the higher-power Aussat allows some viewers in remote areas of the outback to receive signals directly on modest dishes, a service that has become known as HACBUS—The Homestead And Community Broadcast Satellite Service. The data that is carried along with the B-MAC signals is also used for teletext, educational information, and even emergency warnings of potential hazards such as hurricanes.

B-MAC uses a special data burst during the line-blanking period of the MAC signal. The data takes the form of a multi-level code. Most of the data symbols
which are transmitted use four-level (quaternary) coding, but some of the more important control data, which is considered to require more protection against interference, uses two-level (binary) data, the binary signals being a sub-set of the quaternary ones. Multi-level data transmission of this kind allows more data to be carried within a given bandwidth, as will be explained more fully when we consider the D-MAC system later in this chapter, and B-MAC carries its data at a rate of about 1.8 Mbit/s within a bandwidth of only 6 MHz, the same bandwidth that is occupied by the multiplexed luminance and

Figure 41 B-MAC transmission format and baseband spectrum
chrominance vision signals. This has the more important advantage that B-MAC signals can be received from a satellite and passed directly through a standard cable distribution system to individual subscribers, and since the data is going directly to each receiver it is possible to control the access which each receiver has to any particular service. The proponents of B-MAC also point out that it has the further advantage that, since there are no separate carriers for sound and data, it should be possible to readily provide a wider bandwidth for future enhanced television systems (figure 42). This claim could, however, be made for any of the MAC systems except A-MAC.

C-MAC (figure 43)

C-MAC, however, uses a somewhat different system, in that the baseband signal carries no data, and there is effectively a gap in the baseband waveform at the times when the data is to be inserted. The vision components are frequency-modulated, as described earlier, but during the 'gaps' in the FM signal that have been left to accommodate the data, the carrier signal is modulated quite separately, using 2–4 phase-shift keyed (PSK) modulation (see ref. 11 for further details of PSK). We thus have a system where the carrier is frequency-modulated during the transmission of the luminance and chrominance components, and digitally-modulated during the sound/data period; the vision and sound/data signals are not brought together until they modulate the radio-frequency carrier.

Until mid-1987 the UK Independent Broadcasting Authority, which had been responsible for much of the early development of MAC, considered that the C-MAC variant was the optimum version of MAC to use for satellite broadcasting, since they felt that it made the best possible use of the satellite channel, the 2–4 PSK modulation system allowing for the transmission and accurate reception of large quantities of data at the rate of 20.25 Mbit/s.

Figure 42 Showing how a B-MAC signal (or any other MAC signal that does not have its data on a separate carrier) could provide extra bandwidth for a future enhanced definition television system
French engineers, however, considered that it was more important to provide signals from DBS satellites that could easily be passed through existing cable distribution networks than it was to carry the maximum possible amount of data. They had found that many of the early French cable systems could cope only with channel bandwidths of around 7 MHz, and it was quite obvious that data at the rate of 20.25 Mbit/s could not be cajoled into passing through these systems. The French therefore decided that it was very important to have their DBS satellite broadcasts using a standard that could easily be used on their terrestrial cable systems, and so they chose to use D-2 MAC, which can transmit data at only half the rate of that which can be utilised by the C-MAC and D-MAC systems; the D-MAC and D-2 MAC systems are explained in detail later in this chapter. For reasons owing more to political solidarity and the desire for their neighbouring countries to adopt the same system than to engineering soundness, the West Germans also agreed to use D-2 MAC.

In what was to prove a vain attempt to try to reach a single European standard, however, the IBA decided that it would be acceptable to use D-MAC. They had hoped that giving up their previous insistence on C-MAC would encourage the French to adopt D-MAC as well, but this was not to be. The change from C-MAC to D-MAC by the UK was not, however, without its advantages. The Franco-German D-2 MAC system is effectively a subset of the D-MAC system, with its data at half the rate of D-MAC; this allows for dual-standard receivers to be manufactured relatively easily. In addition, the adoption of the D-MAC system allowed simpler and therefore cheaper receivers to be used, since to achieve the full advantages of C-MAC it was necessary to have a digital demodulator for the data signals and a separate FM demodulator for the vision signals.

The only real agreement to have been reached over satellite broadcasting standards in Europe, therefore, was the October 1986 decision that the
various members of the EBU would all use a member of the so-called MAC/Packet family for their DBS transmissions (ref. 4). The EBU’s ‘family’ includes only the C-MAC, D-MAC and D-2 variants, and since it seems that most European countries will actually be using either D-MAC or D-2 MAC, we shall concentrate on these, although full details of the other systems can be found in CCIR publications (ref. 12).

The D-MAC/packet system

We saw earlier on in this chapter why a sampling rate of 20.25 MHz made sense when we were processing the video signals in the MAC coder, and for similar reasons this same clock frequency is utilised for the burst of data that occupies the first 10 microseconds or so of each line of the D-MAC signal. Each burst carries 206 bits of this data, and therefore each line of the D-MAC signal carries 206 bits. Since one line takes approximately 64 microseconds, the average data rate over a line is 204 bits in 64 microseconds, which works out at just over three million bits per second, 3 Mbit/s.

One problem with using a data rate of 20.25 MHz for the data accompanying the MAC vision signal is that according to Claude Shannon of Bell Telephone Laboratories, usually considered the expert on these matters (ref. 13), binary data at a rate of 20.25 MHz will require a bandwidth of at least 10.125 MHz, and in practice, perhaps as much as 15 MHz for error-free transmission.

We saw earlier how the compressed MAC vision signal could be fitted into a bandwidth of about 8.4 MHz, and it would therefore seem very wasteful to have to use more bandwidth than this just to carry the sound, syncs, and data. To overcome this problem television engineers rediscovered an old three-level coding system known as DUOBINARY coding (ref. 14).

Duobinary coding

This specialised form of binary coding enables a given signal to be carried in a narrower bandwidth than would be possible with ordinary binary coding. Duobinary signals are three-level, or ternary signals, which have a greater data capacity for a given bandwidth than standard binary signals (figure 44). This capacity is theoretically about twice that of binary, but in practice somewhat less. Using duobinary, the 20.25 Mbit/s of the D-MAC data signal can be carried within a bandwidth of just over 8.4 MHz, which corresponds well with the 8.4 MHz required for the compressed vision signal.

When duobinary coding is utilised, a binary zero in the input data stream will always be represented by a binary zero in the output stream, but an incoming binary 1 can cause a change in the level of the output pulse stream which depends upon the number of zeros that have occurred since the
previous 1 was received. Thus a zero-level of voltage always represents a zero bit in the output pulse train, whereas a 1 bit can, for example, represent a positive voltage level if the number of zeros since the previous 1 bit is even, or a negative voltage level if the number of zeros since the previous 1 bit is odd. Strictly speaking, if the number of zeros since the last 1 bit is even, no change occurs (i.e. if the previous 1 pulse was positive, the next 1 pulse is also positive). If, however, the number of zeros since the last 1 is odd, a change takes place, so that if the previous 1 pulse was positive, the next 1 pulse would be negative.

The incoming binary data has therefore to be processed into a ternary form which will pass through the standard MAC channel bandwidth. The binary data is converted into three-level duobinary by means of a two-stage process in the coder. The D-MAC specification (ref. 15) provides a method for achieving this coding, as in figure 45.

In essence, the data is first of all ‘preceded’ but kept in a two-level format, and then it is converted to the three-level duobinary signal. The preceding enables the decoder to decide whether a bit should be read as a 1 or a 0, even if one of the pulses is in error.

The incoming stream of binary data [① on the diagram] is first passed through an exclusive-OR gate, and the output from this gate is delayed by one clock period and then fed back to its input. This preceded data stream [② on the diagram] is then fed to the two inputs of a simple adder circuit,
whilst delaying one of the input signals by one clock period. This addition provides an output signal that can have three levels [on the diagram].

The actual levels chosen for duobinary output data of the D-MAC system are 0.9 volts for what we have considered as the positive-level 1 output, 0.5 volts

Figure 45  Block diagram of a simplified duobinary coder with waveforms (courtesy IBA)
for what we have called our zero output, and 0.1 volts for our negative-level 1 output. This enables the duobinary data to occupy a similar voltage range to that used by the luminance and chrominance parts of the video signal.

The duobinary output signal is then band-limited before being transmitted, usually by passing the signals through a fairly complex low-pass filter, although a digital technique known as oversampling is used in some D-2 MAC systems to achieve the same effect.

Duobinary signals have another advantage over binary signals. If more sophisticated data recovery techniques are used, it is possible to achieve improved decoding performance under difficult reception conditions, when signal-to-noise ratios are poor. A special duobinary decoder can look at the incoming data and use a variable data-slicing level together with a so-called Viterbi algorithm (ref. 16) to detect errors due to noise, which would otherwise be read as false 1’s. A standard decoder with a fixed data-slicing level will give acceptable results on normal signals.

**The video and data structure**

The structure of the video and data in D-MAC and D-2 MAC systems will now be considered, but it is important to remember that we are using these systems only as examples of probably the most-used MAC systems, and the detailed information for other MAC systems will differ (ref. 12).

At the beginning of each of the 625 lines that make up a complete picture, or frame, there is some data transmitted, but it is important to note that not all the lines carry video information. As figure 46 shows, the first 22 lines of each field form the vertical blanking period, as in conventional television systems; no teletext or test data has yet been allocated to these lines, which have deliberately been left free in case they are required for future developments such as enhancements to the MAC system. Line 23, and line 335 in the second field, carry a black-level reference signal during the luminance period, but also carry the chrominance information for the following line, one line ahead of the corresponding luminance signal; it will be remembered from our earlier discussion that in order to reduce the amount of storage in the receiver it is necessary for the colour-difference signal related to any line to be transmitted one line before the luminance signal to which it is specifically related.

The next 287 lines of each field (24–310 and 336–622) are the so-called active lines which carry the video information. Lines 312 and 623 carry test signals, whilst line 624 (but not its partner in the corresponding field) carries reference level information, grey, white, and black. The whole of line 625 carries special high-priority digital data which is used to control the organisation and operation of the whole of the digital multiplex structure. As well as providing frame-synchronisation information, this data that line 625 carries tells the receiver how to interpret the incoming data bursts at any particular time, for example whether eight mono sound channels or three stereo sound channels plus data are being radiated.
Figure 46 The frame structure of the D-MAC/packet system (courtesy IBA)
Line synchronisation

Line syncs are provided at the very start of the data-burst period on every one of the 625 lines, in the form of one of two six-bit words, each preceded by a run-in bit. The word is either 001011 (W1) OR 110100 (W2), and the words W1 and W2 alternate line by line, except at the end of the frame where there is a break in the regular sequence so that the odd and even frames may be identified.

The alternating two-line sequence W1-W2 not only provides the receiver with line synchronisation information but also allows the receiver to count line numbers, the line number counter being set to zero every time a new frame occurs. The line number count is used to provide the information needed to generate the interlaced field structure, there being no actual field synchronising signals at the -line point, as might be expected with a conventional television system.

Frame synchronisation

There are two methods of achieving frame synchronisation. The first, and simplest from the point of view of receiver manufacturers, makes use of the W1-W2-W1-W2 line-by-line sequence that we have just considered. Things have been arranged so that, in even frames, odd-numbered lines begin with W1 and even-numbered lines begin with W2. In odd frames, odd-numbered lines begin with W2 and even-numbered lines with W1. It is therefore very simple to identify individual frames. When we come to lines 623 and 624, however, the regular W1-W2 or W2-W1 sequence is broken, and a special pattern is generated to signal that the end of the frame is nigh. The new sequence is W1-W1-W2-W2 for odd frames, and W2-W2-W1-W1 for even frames. Figure 47 shows how this system works in practice.

The second method of obtaining frame synchronisation is to decode a special word transmitted on each line 625 of the MAC signal. Immediately after the line sync word on line 625 a unique 64-bit frame synchronisation word is transmitted, and this is followed by a 32-bit clock run-in pattern. The synchronisation word and the clock run-in word are carried in inverted form on odd-numbered frames.

Data structure

The initial data burst on each line, except for lines 624 and 625, is just over 10 microseconds long, although the specification does allow for this to be altered for special purposes. During this period we have already seen that the first seven bits on each line consist of the six-bit line-sync word preceded by a run-in bit. The remainder of the data burst period is taken up with 198 bits of data in the case of D-MAC, but only 99 bits in the case of D-2 MAC, where, it will be remembered, the data is transmitted at only 10.125 MHz, half the
Figure 47 Showing how the pattern of line sync words is used to identify frames and to provide frame synchronisation
20.25 Mbit/s rate of D-MAC. This means that a bit of D-2 MAC data will take exactly twice the time of a D-MAC bit, and to ease compatibility problems between D-MAC and D-2 MAC, and to make dual-standard receiver design easier, the 198 bits of the D-MAC data are divided into two blocks, known as subframes, of 99 bits. The rules of operation laid down for the MAC standard ensure that users of D-MAC who are carrying multiple sound/data channels carry all the data for a particular service channel in just one of the subframe periods, so that a D-2 MAC receiver trying to decode a D-MAC signal will be able to do this by discarding or ignoring one of the subframes. Arrangements also have to be made to ensure that all the essential service data for the main programme is carried in the subframe that will be used by the D-2 MAC receiver. After the 198 (99 for D-2 MAC) bits there is a spare bit inserted, so that the total number of bits in the data burst is

1 (run-in)+6 (line-sync)+198 (data)+1 (spare)

which makes up the 206 bits shown in figure 35.

Packet organisation

The data that is carried on lines 1 to 623 can be used for many different purposes, but whether the data represents sound, teletext, or other coded information does not matter as far as the coding circuitry is concerned. All the data is organised into sequential blocks which are known as packets, and it is this form of data organisation that has given rise to the official title 'The MAC/packet family'.

A packet is a block of data of a fixed length, 751 bits in our case. The first 23 bits of the data in a packet are known as the header, and they identify which programme service or datastream the packet belongs to. We can thus transmit an effectively continuous stream of data (usually interrupted on each line for the vision signals, of course!) carrying many different sound programme signals, for example. Suppose that we transmit, in time-division multiplex, data representing a French programme, data representing an English sound programme, and data representing a German programme. The packet data stream might look something like figure 48.

A listener wishing to listen to the German transmissions, for example, would switch the receiver so that it ignores any data packets that do not contain the ‘German’ header, whereas a French listener would have the receiver set to collect all data packets that contain the ‘French’ header. Provided that the data is sent at a rapid and frequent enough rate the listeners will not be aware that they are ‘sharing’ the transmission channel.

Advantages and disadvantages of packet multiplexing

Packet multiplexing has the advantage over a continuous data multiplex
that it can operate with combinations of asynchronous signals, so that in our case, where we might wish to carry several sound channels and some extra data, it would not be necessary to ensure that the various sources are synchronous, which might be difficult. Similarly, the bit rates of the individual input data streams need not necessarily bear a strict relationship to the final data rate of the output bit-stream. Packet multiplexing allows the signals from various sources to be inserted asynchronously into the bit stream, and the content of the multiplex can be changed at any time, so that eight sound channels could be transmitted at one instant, and only four sound channels plus lots of data transmitted a few milliseconds later.

The cost of the increased flexibility that a packet multiplex system gives is a greater data overhead, since the packet headers must contain, as well as any necessary error-protection data, information about the address of the data channel that is currently being carried. A typical packet multiplex system might have an efficiency (i.e. the amount of useful data as a percentage of the total data transmitted) of around 97%, whereas a continuous multiplex could achieve 99%.

A system that managed to achieve most of the advantages of the packet system whilst retaining the efficiency of the continuous multiplex was developed by several European broadcasters in the early 1980s and used by the UK Independent Broadcasting Authority on tests of its C-MAC system. The ‘structure map’ system carried information indicating the particular configuration of data being used at any instant, and this information could be used by the decoder to work out which bit of data belonged to which service. Although the system worked well, it was abandoned by British broadcasters in an attempt to reach agreement on one common MAC system, and the packet multiplex was then adopted instead, and became an integral part of the MAC/packet family of systems.

Figure 48 Simplified diagram showing the arrangements when French, English, and German sound programmes are transmitted in time-division multiplex (note the appropriate header preceding each block of useful data)
The packet header

The typical MAC packet is illustrated in figure 49, the header information being shown towards the left of the diagram.

Twenty three bits might at first seem rather a lot to devote to just the header, but it should be remembered that it is vital that the header information is always decoded correctly, since any errors here could well interfere with all the channels being received. The header has the task of ensuring that all the data forming part of each particular programme or data stream (one of several digital sound channels for example) is correctly identified, and in order to do this it must have the capability of spotting any errors that occur, perhaps due to noise.

The first ten bits of the header are known as the address, and each packet belonging to a particular programme or data stream will have the same address, whereas packets belonging to other data streams will have different addresses. The packet decoder in the receiver will use the address information to identify which sound channel should be directed to which loudspeaker, for example.

Since the address is made up from 10 bits there are $2^{10}$, i.e. 1024, possible addresses which may be used to identify different sound channels or data services, but two of these addresses, zero (i.e. the binary address is ten 0’s) and 1023 (binary address ten 1’s) are reserved for special purposes.

The service identification channel

The packets with address zero are used to make up a data stream known as the service identification channel. This carries information which tells the
decoder what type of information is being carried in all the other packets.

Examples of the sort of information transmitted in the service identification channel (packet address zero) are shown below:

- Network identification
- Network origin
- Network name
- Date
- Time
- List of services
- Types of service
- Service identification
- Service name
- Programme information
- Conditional access information

**Dummy packets**

Packets with the address 1023 (decimal) carry ‘dummy packets’ which are used to fill a complete data frame whenever the useful data is insufficient to fill it. The receiver will then ignore any information it receives in a packet with address 1023.

**The continuity index**

Immediately following the ten address bits of each packet header is a pair of bits known as the continuity index. These bits are used to provide a continuously rotating index which counts in binary, from 00 to 01 to 10 to 11, and back to 00. This rotating index is tied in to the continuous stream of data which represents one programme stream, so that for each given address the decoder should be able to identify a continuous binary count from 00, 01, 10, 11, 00 etc. If this count is interrupted for any reason, the decoder will know that a packet has been missed, and will be able to take the appropriate action.

**The protection suffix**

The last part of the header is made up of an 11-bit protection suffix. This code word, different for each packet, is generated in the encoder, and is calculated from the address and the continuity index of each packet. The protection suffix allows for the correction of up to three bit-errors in the 23 bits of the header, and provides a reliable method of error protection for both the address information and the continuity index. The error protection/correction scheme uses a 23, 12 Golay code, a triple-error-correcting systematic code using checksums, details of which can be found in ref. 17.
The ‘useful’ data

Only after the twenty three bits of the header have been transmitted do we come to transmit the data that we are really trying to send—the useful data. There are 728 bits available, in the form of 91 8-bit bytes, but the first of these bytes is sometimes needed to carry packet-type (PT) information. One example of the need for this would be that, when carrying packets belonging to a particular sound channel, only some of these packets will actually carry the digital sound information proper, i.e. the audio samples; other packets with the same header (because they belong to the same service) will carry information about the way in which the audio has been coded, since there are various options for this permitted by the MAC specification. The audio samples will be given the PT code BC, whereas the audio coding information will have PT code BI.

The remaining bits, either 720 if the PT bit is needed or 728 if it is not, can be used to carry audio coded in accordance with any of the agreed coding systems, or data for any other purpose.

Interleaving of data

Noise in digital transmission systems usually takes the form of a burst of errors, a contiguous group of wrongly-received bits. In order to minimise the effects that these multiple bit errors might have, the various bits making up a packet are interleaved before transmission. This has the effect of turning the multiple contiguous errors into a number of spatially separate single-bit errors which can readily be corrected using the Golay code system for error detection and correction, which is built in to the packet header. The interleaving process thus reduces the effect of noise, and the decoder carries a de-interleaving algorithm which puts the data back into its correct order before decoding.

As well as the data in the packets being interleaved, all the data except the first seven bits on each line and the data on lines 624 and 625 is scrambled or ‘randomised’, so as to spread out the spectral energy over the whole of the satellite channel. This prevents all the energy being concentrated at a number of fixed frequencies, harmonically related to the data rate, which could lead to interference being caused to other users of the satellite broadcasting band. Note that this ‘scrambling’ for energy dispersal purposes is entirely separate from the scrambling used to prevent unauthorised access, which is described later. The decoder reverses the process, and puts the bits back into their correct order.

Fitting the data packets into the MAC/packet signal

We have seen that a complete packet consists of 751 bits, and that the packets form a continuous data stream except for when the video is being
Figure 50 Showing how data packets are built up in the D-MAC subframes (courtesy IBA)
transmitted. We have also seen that the data burst on any one line can only carry a maximum of 198 bits of sound or data for D-MAC and 99 bits for D-2 MAC, and that in the case of D-MAC the data is divided into two subframes of 99 bits each to improve compatibility with D-2 MAC receivers. A complete data packet of 751 bits cannot therefore be transmitted on just one line, and so the various parts of each packet are carried in their interleaved order in the data bursts of several adjacent lines until the whole packet has been transmitted. The data is fitted into the subframes as shown in figure 50.

**The data capacity of the D-MAC and D-2 MAC/packet systems**

We can obtain a rough idea of the data capacity that will be obtainable in the D-MAC and D-2 MAC/packet systems by remembering that the data burst at the start of each television line carries 198 bits in the case of a D-MAC signal, and 99 bits for a D-2 MAC signal. Usable data is carried on 623 lines, since lines 624 and 625 are reserved for special purposes, as explained earlier.

For **D-MAC** we therefore have

\[
198 \text{ bits} \times 623 \text{ lines per picture} \\
= 123354 \text{ bits/picture period}
\]

But there are 25 pictures per second, giving

\[
123354 \times 25 = 3.083850 \text{ Mbit/s}
\]

For **D-2 MAC** we have

\[
99 \text{ bits} \times 623 \text{ lines per picture} \\
= 61677 \text{ bits/picture period}
\]

and with 25 pictures per second we have

\[
61677 \times 25 = 1.541925 \text{ Mbit/s}
\]

In practice the useful data rate is somewhat less than these theoretical figures suggest, since in our calculations no account has been taken of the overheads of the MAC/packet system that we discussed earlier, consisting of such things as the 23 bits required for each packet header, and the other ancillary bits needed to organise the multiplex. The generally accepted figure for the average data rate of the D-MAC system is 2.952 Mbit/s, but in general we speak of D-MAC having a useful mean data rate of about 3 Mbit/s, and D-2 MAC having 1.5 Mbit/s.

It is instructive to think of the whole data burst section of the MAC signal not as a certain number of sound channels or data channels, but as a data resource carrying some 3 Mbit/s of data, which can be used to provide whatever services are required. The broadcaster thus has full control over
the mixture of audio and data services that are provided. Although we have considered the situation that will exist for most of the time, when television pictures and their accompanying sound are being broadcast, the MAC/packet system has been designed with sufficient flexibility to allow for the data multiplex to be carried in almost any part of the frame, information about the particular layout being used being carried in line 625.

It would therefore be possible to carry data packets in the space normally occupied by picture information, or even in the field blanking period. If the MAC/packet system is used to carry data without picture information, the data can be sent at the continuous rate of 20.25 Mbit/s, allowing a great deal of useful information to be transmitted quickly and relatively cheaply. Some calculations have been done recently which suggest that the costs involved in sending messages via the satellite data channels could be low enough to enable a typical letter to be sent for a cost of about one English penny, which would mean that satellite broadcasting could be responsible for the return of the old 'penny post', at a time when a conventionally delivered letter costs some twenty times as much!

**Sound coding options with MAC**

The specifications of the MAC/packet family of systems (ref. 4) allow for twelve different options when coding the sound signals that accompany the MAC vision signals. The differences include a choice of sampling rates and a choice of coding method, and different methods of error protection and correction are also included. It was found necessary to include all the different versions as the price of reaching agreement on the standard, since some engineers felt very strongly that their preferred option had to be included.

**Sampling frequency**

The sampling frequency used when converting the analogue sound signal into its digital equivalent may be 32 kHz, which results in high-quality sound channels with an audio bandwidth (±3 dB) of 40 Hz to 15 kHz, or, where a less-good audio signal may be tolerated, 16 kHz sampling may be used. This gives an audio bandwidth of 40 Hz to 7 kHz, which should be sufficient for many speech programmes.

**Coding methods**

Linear coding may be used to provide the highest possible quality, 14 bits being used for each sample.

Alternatively, to make more efficient use of the data transmissions whilst still providing excellent sound quality, NICAM (Near Instantaneously Companded Audio Multiplexing) may be used. This system may be coded
using only 10 bits, compared to the 14 required for linear coding. In this system, fully described in ref. 18, the signal is originally sampled to 14 bits, and the ‘companding’ circuitry reduces the number of samples to be transmitted from 14 to 10, but does this in a manner that allows the ‘missing’ samples to be reinstated in the receiver. The technique used is to divide the digitised signal into five broad ‘coding ranges’, which correspond to particular ranges of amplitude of the original analogue signal. Within the coding range containing the loudest sounds, i.e. the largest amplitude signals, the four least significant bits of the digital word representing the amplitude of the signal may be discarded at the coder, without noticeably affecting the sound. During the times when quiet passages are being transmitted, i.e. when the samples represent small signal amplitudes, the most significant bits may be discarded, provided that they can be reinstated at the receiver.

A similar NICAM digital sound system has been developed in the United Kingdom for use with its terrestrial television transmissions.

Error protection and correction

The basic protection method provided for MAC/packet signals, known as first-level protection, is to add a parity bit to each digital sample of the audio signal. This allows the receiver to detect, but not to correct, a single error that occurs in any sample. The extra overhead incurred by using first-level protection is small enough that the method may be used to protect up to eight NICAM-coded sound channels or up to six linear-coded sound channels in the case of D-MAC signals, these numbers being halved when D-2 MAC is used.

A higher order of protection known as second-level protection, may also be used. This makes use of an extended Hamming Code (ref. 19) in which five protection bits are added to each sample; this enables the receiver not only to detect when several errors have occurred, but also to correct any single error that occurs in a sample. The cost of this higher-level protection is a greater data overhead, and second-level protection may only be applied to a maximum of four linear sound channels or six NICAM-coded channels in the D-MAC system, or two linear or three NICAM channels for D-2MAC.

Four main sound coding options

A sound channel can therefore use high-quality stereo, high-quality mono, or medium-quality mono. It can also use either NICAM or linear coding, and it can utilise either of two protection systems, thus giving twelve different possibilities.

With so many permutations of data rate, coding system, and protection system possible, it proved difficult for the manufacturers of integrated-circuit chip-sets to include every possible variation of sound coding, and
after a great deal of discussion between broadcasters and manufacturers it was decided that the first MAC chip-sets would include the four options shown below:

(H) **High Quality (40 Hz–15 kHz) main sound programme channels**
   Linear-coded, second-level protection, mono or stereo.
   NICAM-coded, first-level protection, mono or stereo.

(M) **Medium Quality (40 Hz–7 kHz), ‘commentary’ channels**
   Linear-coded, second-level protection, mono only.
   NICAM-coded, first-level protection, mono only.

**MAC—a good basis for future systems**

We have seen that the MAC/packet family of systems can provide higher-quality pictures than COMPOSITE systems such as NTSC, PAL, or SECAM. Because the colour and luminance information are sent as separate COMPONENT signals the problems of cross-luminance and cross-colour that are an unavoidable part of the composite systems do not occur with MAC, and since the noise present in the system has been carefully arranged to be spread evenly throughout the picture spectrum, it is less noticeable than with conventional systems. The opportunity has also been taken to provide a slightly higher bandwidth for the luminance signals (5.6 MHz) and a much greater bandwidth for the chrominance signals (2.8 MHz compared with a maximum of 1.3 MHz for PAL).

The MAC/packet system has very few inherent deficiencies, and is therefore very suitable for use as the basis of future, enhanced systems. Much work is already being done in Europe to develop improved services based on MAC, and details are given in a later chapter.

The MAC/packet family of systems has been developed with transmission by satellite in mind, but its advantages have now become so apparent that work is going on in various countries to see how a similar system could be applied to terrestrial transmissions in the future. The advantages of using component signals in a time-division multiplexed format are not, however, restricted to the transmission of such signals, and many engineers believe that similar techniques could be utilised to advantage in studios.

**MAC for studio centres—S-MAC**

One of the problems with replacing composite equipment for PAL or NTSC in studio centres with component analogue equipment becomes apparent when you try to distribute these signals around the centre. Whereas a complete PAL or NTSC picture containing luminance, chrominance and syncs can be carried along just one wire, so that interconnections between
individual pieces of studio equipment require only this one co-axial cable, the analogue component signals, whether R, G, B or the now more usual Y, C_R, C_B, will require three separate cables. To try to overcome this difficulty, whilst retaining the considerable advantages of the component analogue format, the American Society of Motion Picture and Television Engineers (SMPTE) (ref. 7) developed a system called S-MAC, which allows the three component signals to be carried around studio centres on one cable, without degrading the quality of the resulting pictures. This initial SMPTE work was later taken up by a working group of the European Broadcasting Union (EBU), with a view to making modifications to the system to make it more suitable for the timings utilised by European 625-line systems, and a joint 525/625-line version of the specification for S-MAC has now been submitted to the various standards organisations.

As figure 51 shows, in an S-MAC signal all three component signals are time-compressed and squeezed into the 52 microseconds or so of the conventional active television line. The time-division multiplexing gives excellent separation between the components at the cost of a wider bandwidth, which can usually be easily accommodated by the existing studio distribution circuit wiring. To ensure good separation of the components a short period of time, sometimes known as a guard-band, has been left between each of the components; during these periods the signals return to a reference level.

The other main cost of the system, compared with a standard MAC system as designed for transmission via satellite or cable, is reduced noise performance due to the extra compression needed. In practice, however, it is found that the signal-to-noise ratios of the signal paths in a studio are very high, so that there is no noticeable degradation of the quality of the pictures, even under the most critical viewing conditions.

The compression ratios chosen for S-MAC are 13:6 for the luminance
component, and 13:3 for each of the colour-difference signals. These rather peculiar-seeming ratios were adopted as modifications of the original SMPTE proposals of 2:1 and 4:1, which could only squeeze all the components into a standard line time if the sync pulses were reduced in width. It was eventually decided that it would be better to use standard sync pulse timings at the expense of slightly higher compression ratios.

The bandwidths recommended in the world standard for digital studio signals, CCIR recommendation 601 (ref. 8), upon which most systems are being based, are 5.75 MHz for luminance, and 2.75 MHz for each of the two colour-difference components. The maximum bandwidths required by the S-MAC video signals are thus 12.46 MHz (i.e. 5.75 MHz×13:6) for the luminance signal, and 11.92 MHz (i.e. 2.75 MHz×13:3) for the colour-difference components. Most existing studio distribution systems should be able to cope with these.

The synchronisation signals for S-MAC must be different from those used in systems such as D-MAC and D-2 MAC, because the conventional MAC digital multiplex will not exist in the studio at the time the pictures are being put together. Instead the synchronisation uses a standard line sync pulse, whose leading edge is taken as the timing reference for all the transitions along the line. A reference burst at 288 times line-frequency, about 4.5 MHz, is inserted in the back porch of the line sync pulse; this is intended to assist clock phasing, but may not always be strictly necessary. The field synchronising waveform, nominally the same for 525-line and 625-line systems, is modified slightly from the standard layout to take account of the field-blanking requirements of CCIR Recommendation 601 (ref. 8).

**Sending MAC signals along contribution and distribution links**

At the present time much programme material from sports events and Electronic News Gathering (ENG) sources is sent from remote programme origination points to the studio centre in the form of PAL or NTSC signals, which pass along single composite links, either cable or microwave. We have seen in the previous section how it would be very convenient and have many advantages for the quality of the pictures if the three component signals also could be passed along a single link. Although it might at first seem that the S-MAC system described above could be used, we must remember that this required a bandwidth of 12.46 MHz to pass the component signals without distortion. Although the normal studio distribution system will pass this type of signal without problems, the existing links from programme contribution points to studio centres have been designed to pass PAL signals, and so have a bandwidth of only about 6 MHz, although this could probably be extended to about 8 MHz if some of the ancillary signals that are usually carried as well (talkback, etc.) were removed. Even so, this would not allow the S-MAC signals to pass without reducing the resolution of the luminance and colour-
difference signals, to as little as 2.8 MHz and 1.4 MHz respectively, which was felt to be unacceptable.

To overcome this problem, a version of MAC has been developed which is suitable for carrying component signals over the cable and microwave links originally intended for carrying PAL signals between remote programme sources and studio centres; it rejoices in the name of ACLE—Analogue Component Link Equipment (ref. 20).

The ACLE line waveform is shown in figure 52, from which it will be seen that there are several differences between ACLE and S-MAC. Initial work on the ENG links showed that, on the type of material being transmitted, a luminance bandwidth of around 4 MHz and a colour-difference bandwidth of around 1 MHz gave subjectively acceptable picture quality. This could be achieved if compression ratios of 3:2 for luminance and 6:1 for colour-difference (i.e. a ratio of 4:1 for the luminance/colour-difference compression figures) was used. Such an arrangement is sometimes called a 4:1:1 system, reflecting the relative compression ratios used for the single luminance signal and the two colour-difference signals. To achieve compression ratios of this order whilst still managing to squeeze the three components into the normal active line-time period, figures of 14:9 for luminance and 56:9 for colour-difference were eventually settled upon.

There is no synchronising burst in the ACLE signal, so that clock synchronisation has to be taken from the leading edge of the line-sync pulse, and the field synchronising signals are virtually identical to those used by a standard PAL system. This means that standard sound-in syncs signals could be carried by this waveform if required. ACLE has proved to be very tolerant of distortions which arise in the transmission path. Bandwidth restrictions at the high-frequency end of the transmission band cause some

![Figure 52: Simplified line waveform of the Analogue Component Link Equipment (ACLE) MAC system](image-url)
loss of definition of both luminance and chrominance, but the saturation of the pictures remains sensibly constant.

An alternative MAC system for ENG links—T-MAC

TDF and MATRA in France have come up with another method of sending MAC signals over standard ENG links that were originally intended for composite signals (ref. 21). The line waveform, shown in figure 53, is much closer to that of the D and D-2 MAC signals than the ACLE waveform, in that only one of the colour-difference signals is transmitted on each line, along with the luminance component. This means that the ‘standard’ MAC compression ratios of 3:2 for luminance and 3:1 for colour-difference signals can be utilised, thus easing the bandwidth requirements. The horizontal and vertical synchronisation signals are virtually identical to those used in the PAL or SECAM systems, but a burst of about 4.5 MHz (288×line frequency) is inserted in the back porch of the line-sync pulse to help with receiver clock synchronisation. Sound-in-syncs signals can be carried in the normal manner.

Since this system is very close to the D and D-2 MAC members of the MAC family, and yet can be transmitted readily over ENG links, it has some advantages over ACLE, in that the normal MAC scrambling system could be used, if required. Protagonists of the system claim that the balance between the chrominance and luminance bandwidths of T-MAC is better than that of the 4:1:1 system used by ACLE.

Conditional access: a built-in scrambling system

It has been found that MAC television signals, because they are made up from individual components transmitted in time-division multiplexed form,
are much simpler to scramble and unscramble without distortion than the more usual composite signals.

Scrambling is usually understood as the process by which pictures are rendered unintelligible to the viewer without an appropriate descrambling device, whereas encryption is required in more complex systems to protect the electronic keys, signals which are transmitted in order to allow the receiver to understand how the pictures were originally scrambled, so that they can be reassembled.

The basic principles of how any encryption and key distribution method of scrambling works are shown in figure 54. The whole process is nowadays usually known by the 'buzz-words' conditional access, which simply mean that you must satisfy some specified conditions before you are allowed access to the programme being transmitted. Although the most usual condition is that you must pay money before you are allowed to watch, other conditions might be that you must belong to a certain user group, perhaps doctors for specialised medical programmes, for example, or even that you live in a particular country, if the owners of the copyright of the programme wish to restrict those rights to specified countries.

The specification of the MAC/packet family of systems (ref. 4) gives full details of the methods of scrambling and encryption that have been agreed, and the chip-sets that are necessary for the reception of the MAC signals include in-built circuitry to provide for the decoding of scrambled and encrypted MAC signals. No extra add-on box will therefore be necessary for viewers wishing to make use of the various pay-television channels that are available. This is in contrast to the direct-to-home satellite services that are provided by satellites using the FSS (fixed satellite service) band, where viewers initially had to obtain an additional separate decoder box for each different scrambling system that is used.

The scrambling and encryption system defined in the MAC/packet family specification is known as Active Component Rotation, and figure 55 shows the basics of how it works.

The luminance and chrominance components of each line are separately cut into two parts, the cut-points being determined as part of the

Figure 54 Basic principles of how an encryption and key distribution scrambling system works
encryption mechanism by a pseudo-random number generator. Each of the two parts is then interchanged, i.e. effectively rotated about the cut-point, so that the chrominance and luminance information on each line is scrambled before transmission. Each different line of the picture will be cut at two different points which are determined by the pseudo-random number generator, there being a choice of 256 different cut-points during each of the luminance and chrominance transmission periods.

This is one of the occasions when it is most useful to regard the MAC waveform as being made up of analogue samples, since the cut points can be made to apply at particular sample numbers, making for a much simpler implementation than if every random cut point had to be defined at a precise number of nanoseconds.

When both luminance and chrominance are cut, as described above, the technique is known as **double-cut active line rotation**, but the MAC/packet system does allow for the simpler option of just scrambling the luminance component, in which case the system is known as **single-cut**. The double-cut system is the most secure, but provision was made for the simpler method to allay the fears of operators of cabled distribution systems who were worried that the double-cut method might give rise to problems when signals scrambled in this manner were passed through cable systems which

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**Figure 55 Active Component Rotation: simplified diagrams of (a) the non-scrambled waveform, showing possible cut-points, and (b) the waveform scrambled by double-cut component rotation**
have a less-than-perfect amplitude/frequency response and a tendency to cause line-tilt. Theoretical work showed that line-tilt would have to be less than 0.5% if the components were to be put together without error when using the double-cut system, but practical work on a real cable system (ref. 22) showed that any transient effects due to line tilt affecting the scrambling system were masked by the small amount of noise that is present in any practical network. No significant difference could be detected in the pictures whether single-cut or double-cut scrambling was used.

The system of conditional access developed for use with the MAC/packet family of systems has been designed to be as flexible as possible, and as Hamper-proof as possible, with an extremely comprehensive range of facilities, and it is therefore far more complex than the inevitably brief description already given might suggest. Readers needing fuller details should consult ref. 4.

MAC in practice—the chip sets

The built-in scrambling capabilities of the MAC system have proved popular with a wide range of programme providers who appreciate the fact that the

Figure 56 Block diagram of the MULTIMAC decoder chip-set
MAC chip-sets incorporate all the necessary descrambling facilities, so that their customers will not need to purchase separate, expensive descramblers. It is for this reason that some of the distribution satellite transmissions intended for reception at the head-ends of cabled distribution systems are now using MAC. The other benefits of MAC, such as its lack of cross-effects and its improved noise performance, are regarded as something of an incidental bonus.

A group of European semiconductor manufacturers has designed the MULTIMAC decoder chip set shown in simplified form in figure 56. It has been designed to cope with all members of the MAC/packet family of transmission systems, and since it will therefore have an enormous potential market, it should not only allow viewers to reap the benefits of the higher-quality pictures that MAC provides, but also enable the benefits of a complex scrambling and conditional access system to be made available at very low cost to the viewer.

**Progress with MAC**

It was mentioned earlier that the B-MAC system is in regular use in Australia, and for specialised distribution services elsewhere. Regular D-2 MAC broadcast transmissions now take place from the German TV-SAT 2 and the French TDF1 satellites, positioned at 19° W. The UK DBS satellites at 31° W, owned and operated by British Satellite Broadcasting (BSB), were the first satellites to provide a regular broadcast service in D-MAC, one of the five channels being used to carry wide-screen transmissions of films, thus taking advantage of one of the extra facilities that the MAC system can provide. At the present time only a few wide-screen receivers are in existence, and these are very expensive, but several manufacturers have announced plans to make wider aspect-ratio cathode-ray tubes and television receivers available in quantities that will make them affordable by many domestic consumers. The wide-screen display of films is regarded by MAC users as one of their key advantages over competitors using conventional PAL transmissions from distribution satellites.

The MAC system was designed from its inception to be particularly well suited to transmission from satellites, and its advantages such as lack of cross-colour and improved noise performance, together with its capability for compatible wider aspect ratio transmissions, have, as we shall see in later chapters, led to its being used as the basis of several more advanced systems, providing a truly compatible approach towards higher-definition television.

**References**

In strictly chronological terms the developments covered in this chapter came before the development of MAC, but it seemed better to deal with all the various current transmission standards together before moving on to this vitally important standard, which is known throughout the world as ‘Rec 601’. This is, of course, a colloquialism used as shorthand for CCIR Recommendation 601–1, which is entitled *Encoding Parameters of Digital Television for Studios* (ref. 1).

Although it is virtually the only major standard affecting television which has been agreed by broadcasters and administrations throughout the world, Rec 601, as its full title suggests, suffers from the restriction that it currently applies only to studios, and programme production equipment. As we shall see later, at the present time the high bit rates that would be required for the transmission of digital television signals render digital transmission impractical, but the significant advantages that digital processing can bring to television studios have made a knowledge of Rec 601 essential for any studio engineer.

**Digital television**

Digital television began, not in studios, but with the networks carrying television signals between studio centres and transmitters. Although analogue television systems have served us well, and will continue to do so for the foreseeable future, they only give first-class pictures provided that all the equipment in the broadcasting chain is kept in first-class condition, something that requires eternal vigilance, much measuring, and a good deal of maintenance. This is the major reason why broadcast engineers originally became interested in digital techniques, and why they became keen to adopt a system that offers a way of providing more rugged and reliable signals. The analogue television system works only if each piece of equipment is precisely lined up to work within very narrow tolerance limits.

Just consider the number of amplification and equalisation stages that a television signal originated in London must go through before it arrives on the screen of a viewer in the Outer Hebrides. Unless every care is taken at each stage of that signals’s journey to ensure that the amplitude and frequency response of the signal remains constant, there is very little
chance that the shade of grey that appears on the viewer’s screen in Scotland will be the shade that was generated in London, and it is something of a tribute to the engineers of British Telecom, the company in the UK responsible for providing common-carrier services, that the received analogue pictures are usually excellent.

In this book about modern television systems, and in a chapter intended to look at one particular television standard, it is perhaps not appropriate to go deeply into the basics of digital television, as details of the techniques of quantising and analogue-to-digital conversion are readily available elsewhere, but it might be useful to remind ourselves of the basic techniques of pulse code modulation which are used when converting an analogue signal, perhaps from a television camera, to its digital equivalent.

In an analogue-to-digital conversion system like that in figure 57 there are two main factors of importance:

(i) The number of bits which we use to describe each sample, or in other words, the number of levels of brightness which we need to provide,

(ii) The rate at which we take samples of the analogue waveform.

The number of sampling levels required was decided upon after much careful examination of digital pictures made with different numbers of bits per sample, and it was found that eight bits per sample, giving $2^8$, i.e. 256 levels, gave excellent results, although we shall see later in this chapter that the wisdom of this decision has since been questioned.

**Sampling frequency**

It can be seen from figure 57 that the more samples that are taken in a given time, the more bits of information will be available to rebuild the analogue signal at the end of the coding and decoding process. We therefore need as high a sampling frequency as practicable, but have to remember that the higher the sampling frequency the greater the amount of memory required to store each picture, and this has economic implications. Sampling rates are discussed in more detail later in this chapter, but a fundamental limitation which gives the minimum possible sampling rate for any signal was laid down by the Swedish mathematician Nyquist. His work (ref. 2) showed that in order to sample an analogue signal so that it can be reconstructed from the derived samples without distortion, the samples must be taken at a rate greater than twice the highest frequency contained in the signal. For a typical modern television system, CCIR system I, which has video components up to 5.5 MHz, this implies a minimum sampling frequency of $2 \times 5.5 = 11$ MHz. Since, as we shall see later, it is often convenient to use a sampling frequency which is a multiple of the subcarrier frequency, the first multiple of the CCIR System I PAL subcarrier frequency (4.43 MHz approx.) which exceeds the 11 MHz Nyquist limit is
three, which is why three times the subcarrier frequency (13.3 MHz approx.) was much used in the early days of digital television.

Sub-Nyquist sampling

Whilst we are discussing sampling frequencies it is worth noting that in 1975 the BBC Research Department published a paper (ref. 3) which showed that, because of the repetitive nature of the television video signal, under certain specified conditions it is actually possible to sample the PAL signal at a frequency below that stipulated by Nyquist, with very little loss of quality. Although this at first sight seems paradoxical, it is not in fact an example of Nyquist’s rule being defied. What happens is that the television signal is sampled at below the Nyquist rate (usually at twice the frequency of the subcarrier), and as the theory would predict, various distortions do arise. It is, however, possible, because the video waveform is very repetitive, to calculate in advance what these distortion products are likely to be, and it is therefore possible to design filter circuits which remove the distortion. We are then left with the original signal undistorted, but considerably reduced in amplitude.

The advantages of digital television

Digital techniques allow a television picture to be broken into individual picture elements, *pixels*, and instead of transmitting an analogue signal, i.e. a varying voltage waveform, which directly represents the brightness and colour of a television picture, what is sent along the microwave links or cables to the transmitters is a coded message which effectively says ‘picture element number *x* has brightness level *y* and colour *z*’. At the far end of the

---

*Figure 57 The various stages in digitising an analogue television picture and then returning it to its analogue state. Note that a four-bit sixteen-level code is used for simplicity, whereas in a real system eight bits, 256 levels are used.*

(a) shows the original waveform and the samples which are taken and then converted to the nearest whole number, a process known as quantisation.

(b) shows the quantised numbers converted into a four-bit binary number code, the digital system proper.

(c) shows the signal as it might be received after it has been transmitted over a typical path, and it can be seen that the original signal has been subjected to much distortion.

(d) shows the regenerated code after the incoming signal has passed through a threshold detector and appropriate new pulses have been generated.

(e) shows how the decoded samples may be reconstructed to form a representation of the original analogue system. Notice that the regenerated signal has been delayed by the period of one digital word, since decoding cannot begin until all the digits have been received. (Courtesy IBA)
link the message can be decoded, and a completely new picture can be reconstructed, a pixel at a time, by rebuilding each pixel according to the brightness and colour levels specified in the coded message. The received picture should therefore be a perfect re-creation of the original. In the case of the analogue signals, any variation of the voltage level between the transmitting end and the receiving end of the link would result in an alteration of the grey level of the picture, i.e. distortion. In the digital case, the actual level of the digital signal should make no difference to the quality of the received picture; provided that there is sufficient signal to allow the decoder to distinguish between the coding pulses, the picture can be rebuilt into a clone of the original. As a further advantage, whereas a small amount of drift in an analogue circuit, perhaps due to temperature changes, would cause noticeable distortion, the same amount of drift would be most unlikely to disturb a digital circuit to the extent that the pulses cannot be decoded. (See figure 58.)

It was soon realised that similar advantages could be obtained if digital video recorders could be made. When a composite analogue television signal is recorded on tape, it is subject to noise and distortion, which increases significantly with each generation of recording, giving noisy pictures with moiré patterning in the highly-saturated coloured parts of the picture. A digital recorder, on the other hand, would allow just the pulses representing the brightness and colour of each picture element to be laid down on tape. When the tape is played back there will inevitably be noise produced from the record/playback process, but provided that the level of this noise is not sufficient to mask the signal levels representing the coded pulses, the picture can once again be rebuilt as new. It is rather like listening to a very weak Morse-code message from a distant part of the world; although there will be a great deal of background hiss on the received radio signals, provided that your ear can make out the individual dots and dashes from amongst the noise, the original message can be written down without

![Figure 58 A comparison between the accuracy needed to decode analogue signals and digital signals](image-url)
Digital video recording was first shown to be practicable by engineers of the UK IBA in 1979 (ref. 4) and (ref. 5), and there are now two recognised digital VTR formats on the market, known as D1 (ref. 6) and D2 (ref. 7), which use 19 mm wide tape. Prototypes of a third digital format, D3 or DX, using half-inch tape in VHS-type cassettes, are currently being displayed at exhibitions of broadcasting equipment (ref. 8).

The need for a digital standard

During the late 1970s and the 1980s studios started to make use of many individual pieces of equipment, notably time-base correctors, special effects units, and noise reducers, which made use of digital techniques as an indispensable part of their internal operation. Unfortunately, there was virtually no co-operation between different manufacturers as to the digital coding techniques used, each wishing to keep its commercial secrets from its competitors. This meant that in a PAL studio, for example, each item of digital equipment had to have a PAL-to-digital coder at its input, and a digital-to-PAL coder at its output, in order that these units could be connected as part of the normal chain of PAL equipment in the studio. In a studio using time-base correctors and digital special effects units it was not uncommon for the signal to be converted from analogue PAL to digital form and then back again to analogue PAL several times during the course of its journey through the studio equipment, and each time a television signal passes through the coding-decoding process it is unavoidably degraded to some extent. Several passes through the inevitable ‘codecs’ (coder-decoders) caused noticeable picture impairments, basically caused because studios were using what came to be known, in unusually poetic language for engineers, as ‘digital islands’ in an ‘analogue sea’. What was needed was to be able to connect all digital processing units together directly, without going through the analogue-digital conversion process every time, and it was this realisation that led the world’s broadcasters to get together to try to agree on a standard for digital equipment in studios.

Composite digital video

All the early research work on digital television was done on composite signals such as NTSC and PAL, because these were the signals in day-to-day use in the studios. The earliest tests suggested that it would be advantageous for the sampling frequency to bear a simple relationship to the horizontal line frequency. When this is the case the individual samples will automatically be arranged in equally spaced vertical rows, i.e. the sampling pattern will be orthogonal and spatially static, as shown in figure 59.

Research engineers soon found, however, that there were big advantages if the horizontal sampling frequency used bore a simple relationship to the colour-subcarrier frequency of the system, in that this minimised impairments...
resulting from sampling and quantisation errors, and also made life easier in the design of colour coders and decoders, reducing patterning between the subcarrier and harmonics of the digital clock (ref. 9). In the NTSC system both requirements could easily be satisfied, since the colour subcarrier frequency is $455/2$ times the line frequency, as we saw in chapter 3. The PAL system lacks this simple relationship between line frequency and colour subcarrier, because of the subcarrier offset, and the simplest relationship we can obtain is

$$f_{sc} = (1135/4 + 1/625) \times \text{Line frequency}$$

For Secam there is no direct relationship at all between line frequency and subcarrier frequency, because the frequency-modulated subcarrier is continuously varying with the modulation.

In most of the early research work frequencies such as $2f_{sc}$, $3f_{sc}$, and $4f_{sc}$ were used for different purposes, and many digital timebase correctors and field-store synchronisers which used $3f_{sc}$ were built and sold; in America, broadcasters developed a specification for the interconnection of digital equipment in studios which used four times the NTSC subcarrier frequency and eight bits per sample. The search for a common standard was headed by engineers of the American SMPTE (ref. 10) and of the European Broadcasting Union (EBU). Much of the initial work towards digital standardisation was concerned with trying to find ways of coping with the three very different colour subcarrier frequencies used in NTSC, SECAM, and PAL systems, and a lot of time and effort was spent on this, before the researchers set off on a completely different track.

Digital special effects units came into being as engineers realised that a digitised television picture need no longer be thought of as a complete image, but that each picture element was effectively represented by a group of numbers (address, brightness, colour), and that these numbers could be and were being stored inside what were effectively just large computer memories. Once you have numbers inside a computer store you can then
treat those numbers like any other numbers, reading them in and out at
different rates, carrying out mathematical operations upon them, or
selecting just some of the numbers to create your final display with the
desired effects. The manufacturers of these digital effects units found that
it was very difficult and restrictive to try to obtain many of the effects which
they were seeking if they used composite signals, and so inside the digital
special effects units that were being manufactured, virtually all the
processing was done on signals that had been decoded from composite to
component form. The realisation that this was happening inside digital
special effects units led to a rethink among those engineers who were
seeking a common standard.

Component digital video

It was realised that all existing television systems began with the
component signals Red, Green, and Blue \((R, G, B)\) in common. Some work
was done on digitising these \(RGB\) signals, and excellent pictures resulted,
but the problem with this way of doing things was that each of the \(R, G,\) and
\(B\) signals requires the full video bandwidth, as we discussed in chapter 2.
As we saw in that chapter, it was possible to use a different set of
components, \(Y\), the luminance signal, which is a full bandwidth signal, and
the two colour-difference signals \((B-Y)\) and \((R-Y)\), which are narrower-
bandwidth signals. The first step along the road to standardisation was
therefore for engineers to agree that the sought-for digital television
standard should be based on digitising the three component signals, \(Y, (B-Y),\)
and \((R-Y)\), and that eight bits per sample would provide an adequate
number of video levels. Tests were done at different numbers of bits per
sample, and it was generally agreed that eight bits, offering 256 quantizing
levels, or about 220 usable grey levels, provided excellent pictures under
the standard conditions for critical viewing laid down in CCIR
Recommendation 500 (ref. 11). The agreed aim of those trying to decide on
the parameters of a digital standard was that the resulting pictures should
be of a quality to match the original \(R, G, B\) source pictures, which would,
of course, be a considerable improvement on the picture quality provided by
the current NTSC, SECAM, or PAL systems.

Although this was a significant step, it still left major items such as the
sampling frequency and the necessary bandwidths for the component
signals unresolved, and much experiment and debate was to take place
before the final agreement was reached. It should be remembered that the
higher the sampling frequency, the greater the overall bit rate that would be
required, and the greater the amount of storage that would be required in
every piece of digital equipment, so that the choice of sampling frequency
has significant financial consequences.

Although we have so far just spoken of sampling frequency, i.e. the
frequency with which we take samples along a television picture line, it is
important to notice that another way of looking at the same thing is to consider the number of samples along each line of a television picture which result from the sampling process. Both ideas will be used as we discuss the choice of a sampling frequency.

In 1980 the EBU proposed that the luminance (Y) signals should be sampled at 12 MHz, and that each of the two colour-difference signals should be sampled at 4 MHz. This type of system became known as 12:4:4 in the engineers’ shorthand, and an American proposal to use 14 MHz for luminance sampling and 7 MHz for colour-difference signals was similarly known as 14:7:7.

Sampling a 64 microsecond television line at 12 MHz gives

\[ 12 \times 10^6 \times 64 \times 10^{-6} = 768 \text{ samples per line} \]

The Americans carried out a series of tests which showed that picture quality improved as the sampling frequency was raised from 12 MHz to 14.35 MHz, and so they were not prepared to adopt the EBU idea of 12 MHz. Experiments and demonstrations were carried out by EBU and SMPTE groups, and after much work and a good deal of horse-trading, and not without some misgivings on the part of some of the Americans who felt that 14.3 MHz, a multiple of the NTSC subcarrier, would be better, the two groups agreed to recommend a luminance sampling frequency of 13.5 MHz, and colour-difference sampling frequencies of 6.75 MHz. After discussions and demonstrations, the Japanese, the Russians, and various other broadcasting organisations supported the proposals, and the various parameters were adopted as a world standard, Recommendation 601 of the CCIR, in 1982.

The choice of 13.5 MHz as the luminance sampling frequency was an interesting one, since as well as being a compromise between the initial 12 MHz EBU proposal and the 14.3 MHz that some SMPTE members wanted, it gave rise to some very useful figures when compatibility between the 525-line and 625-line systems was considered, and was one of the very few figures that could have permitted the same sampling frequency to be used for both systems.

The first interesting feature of 13.5 MHz was that it was the only frequency within the range being looked at which gave rise to an integer or whole number of samples per line for both 525 and 625-line systems.

The 625-line system has a total line time of 64 \( \mu \)seconds.

At 13.5 MHz this gives 13.5 \( \times 64 = 864 \) samples

The 525-line system has a total line time of 63.56 \( \mu \)seconds.

At 13.5 MHz this gives 13.5 \( \times 63.56 = 858 \) samples

In the 625-line system the line banking period is 12 \( \mu \)seconds, so that the active line time is 52 \( \mu \)seconds.

In the 525-line system the line blanking takes 11.56 \( \mu \)seconds, giving an
active line time of 52 $\mu$seconds, so that we have the same nominal active line time for both systems.

In terms of samples per active line, then, we have, for both 525 and 625-line systems:

$$52 \times 13.5 \text{ MHz} = 702 \text{ samples per active line}$$

Thus the choice of 13.5 MHz for a common sampling frequency gave the advantage of an identical number of samples per active picture line, and allowed the current line blanking periods to remain the same for each system.

It was these features that finally led to the adoption of this ‘magic number’ of 13.5 MHz for the luminance sampling frequency.

Tests showed that a rate of half this, i.e. 6.75 MHz, was sufficient for sampling the colour-difference signals in order to provide excellent pictures.

Although the length of a complete television line in each system must be kept the same as in the existing standards, corresponding to 864 bits for a 625-line system and 858 bits for 525-line systems, using a 13.5 MHz sampling rate, so long as the length of the active line, in terms of numbers of samples, is kept the same for both systems, there is no real reason for it to remain at 702 bits long, which corresponded to the usual 52 $\mu$seconds active line. Instead, the researchers working to develop the standard felt that it would be a good idea to have an active line slightly longer than the 52 $\mu$seconds, with the line beginning slightly earlier and ending slightly later than a standard 52 $\mu$second line.

The reason for this was to allow for a short period of a reference black level at each end, and to reduce the rate of change of transients when a picture line starts or finishes at peak white. For these reasons, then, it was decided to use a larger number than 702, and 720 was chosen because it had a large number of factors, which it was felt made it a number that would be suitable for conversion if other higher or lower order members of the Rec. 601 family were used.

The colour-difference signals each have 360 samples per active picture line, for both 525 and 625-line systems. These sampling arrangements give rise to an orthogonal line and field sampling structure, and the colour-difference samples are arranged so that they are effectively co-sited with alternate, odd-numbered luminance samples.

The basic features of the world standard for digital television studios, CCIR Recommendation 601, are shown in figure 60, and in order to allow equipment using signals of this type to be connected together, an 8-bit parallel digital interface has also been specified in a separate CCIR Recommendation, number 656 (ref. 12). Interconnections take place via 25-pin subminiature D-connectors, carrying eight separate pairs of conductors, each carrying a time-multiplexed stream of bits of the three component signals, in the order $C_B$, $Y$, $C_R$, $Y$, where $C_B$ and $C_R$ are the two
**Figure 60 Basic details of CCIR Recommendation 601**

<table>
<thead>
<tr>
<th></th>
<th>525-line, 60 field / sec systems</th>
<th>625-line, 50 field / sec systems</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coded signals: Y, C_R, C_B</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Number of samples per total line:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- luminance signal (Y)</td>
<td>858</td>
<td>864</td>
</tr>
<tr>
<td>- each colour-difference signal (C_R, C_B)</td>
<td>429</td>
<td>432</td>
</tr>
<tr>
<td><strong>Sampling structure</strong></td>
<td>Orthogonal, line, field and frame repetitive. C_R and C_B samples co-sited with odd (1st, 3rd, 5th, etc.) Y samples in each line.</td>
<td></td>
</tr>
<tr>
<td><strong>Sampling frequency:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- luminance signal</td>
<td>13.5 MHz</td>
<td></td>
</tr>
<tr>
<td>- each colour-difference signal</td>
<td>6.75 MHz</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The tolerance for the sampling frequencies should coincide with the tolerance for the line frequency of the relevant colour television standard.</td>
<td></td>
</tr>
<tr>
<td><strong>Form of coding</strong></td>
<td>Uniformly quantized PCM, 8 bits per sample, for the luminance signal and each colour-difference signal.</td>
<td></td>
</tr>
<tr>
<td><strong>Number of samples per digital active line:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- luminance signal</td>
<td>720</td>
<td></td>
</tr>
<tr>
<td>- each colour-difference signal</td>
<td>360</td>
<td></td>
</tr>
<tr>
<td><strong>Correspondence between video signal levels and quantization levels:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- scale</td>
<td>0 to 255</td>
<td></td>
</tr>
<tr>
<td>- luminance signal</td>
<td>220 quantization levels with the black level corresponding to level 16 and the peak white level corresponding to level 235. The signal may occasionally exceed beyond level 235.</td>
<td></td>
</tr>
<tr>
<td>- each colour-difference signal</td>
<td>225 quantization levels in the centre part of the quantization scale with zero signal corresponding to level 128.</td>
<td></td>
</tr>
</tbody>
</table>
colour-difference signals. Ancillary data is also carried on these pairs, and a ninth pair carry a 27 MHz synchronous clock signal.

**Quantisation levels**

As mentioned earlier, the system utilises eight bits per sample, which, in a binary coded system, would permit a maximum of $2^8$, which is 256 quantising levels. Rather than use all these levels for the grey scale, black level is chosen to correspond with level sixteen, and a further 220 quantising levels above this are given to the grey scale, peak white normally being at level 235. Levels above 235 allow for occasional white overshoots.

The colour-difference signals use 225 of the 256 possible quantising levels.

At the time that the standard was being developed, prior to 1982, most of the test sources used were cameras, telecines, and test generators where the signal-to-noise ratios were poor enough (although the equipment was then state of the art) to mask some of the effects of low-level quantising errors arising in the eight-bit analogue-to-digital convertors that were used. Quantising errors arise when the number of steps available to describe the brightness of the picture is insufficient. For example, if the sample of the analogue brightness signal actually gave a value of 201.5 on the scale of 256 which is available on an eight-bit system, then it is just not possible to describe 201.5, and we have to approximate to either 201 or 202, and it is this type of approximation which gives rise to quantising errors, which generally show up as noise on the picture. Some digital processing effects were tested at this time, but the main emphasis was on chromakey, and the sophisticated digital processors that we have today were no more than a twinkle in the designer’s eye.

Since the introduction of the CCIR Recommendation 601, it has become the norm to use electronically generated graphics and characters as part of the normal studio output, and many special effects generators are also now used routinely as day-to-day equipment, rather than purely being utilised for exceptional special effects as they were in earlier years. Such electronically generated signals can be virtually noise-free, so that there is not enough noise to mask any quantisation errors, and when multiple generations of these very clean signals are utilised, it has been found that undesirable effects can occur. One of these effects is known as *contouring*, because what are effectively contour lines are seen between adjacent areas of brightness or colour, which seem to indicate that the number of brightness levels, that is the number of bits per sample, is inadequate under certain circumstances.

**Rounding errors**

The problem is that mathematical rounding errors occur as the digital signals are passed from one piece of digital equipment to another, or
through the same analogue-to-digital conversion equipment several times. To illustrate the effect of rounding errors in a field other than television, try the effect of using a basic electronic calculator to work out the simple expression

\[
(10/3) \times 3
\]

Although the correct answer should obviously be 10, many calculators give the answer 9.9999999 due to the microchip being unable to cope with enough digits to give the correct answer. A more sophisticated calculator or a computer will often be able to utilise more bits for its calculations, and so will give the correct answer.

During multi-stage digital processing the numbers representing the brightness and colour of individual picture elements can be subject to these rounding errors. When an eight-bit digital word is multiplied by another eight-bit word, sixteen bits will be required to store the answer, and this is readily achievable within any individual digital device. Unfortunately, when CCIR Rec. 601 digital signals are passed from one piece of equipment to another they must be passed via the eight-bit digital interface detailed in CCIR Recommendation 656, and so the internal signals must be truncated or rounded so that only an eight-bit signal is presented at the interface.

These problems have led some manufacturers to say that Recommendations 601 and 656 are inadequate for present-day circumstances, and they have increased the number of bits which they use to ten, and have used two spare connections on the 25-pin D-connector specified in Rec. 656 to carry the extra bit streams. Unfortunately this solution can only work if pieces of equipment made by the same manufacturers are used, and whilst it is undoubtedly true that ten bits give better results than eight in some circumstances, many people are unhappy with this idea, since even ten bits may not necessarily be sufficient to ensure perfection under all conditions, and since it goes completely against the idea of the hard-won world standard laid down in Rec. 601.

One of the largest manufacturers of complex digital picture processing equipment, Quantel, has demonstrated a technique called Dynamic Rounding, which removes the unwanted contouring effects of multiple processing without resorting to changes in the specification of the digital standard, and many broadcasters have been convinced by demonstrations that this technique will prove adequate for some time to come. A somewhat different technique discovered by the Research Department of the BBC, known as Error Feedback Rounding, has been shown to achieve similar improvements with the standard eight-bit digital signals (ref. 13).

In the longer term, however, it now seems likely that more bits will eventually be required, as more and more processing of the digital signals takes place, and the reduction in cost of semiconductor memory makes it practicable to accommodate sufficient storage at a realistic cost. CCIR
Recommendation 601 actually makes provision for future higher-level systems, as explained below, and it seems likely that there will eventually be a supplementary standard for a digital system using at least 16 bits per sample, with a corresponding parallel digital interface.

**The 4:2:2 shorthand**

We have seen already the use of a shorthand notation such as 12:4:4 or 14:7:7 to describe digital component systems. In those systems that used sampling frequencies tied to the subcarrier frequency it was common to refer to them as 4:2:2, meaning that the luminance was sampled at \(4f_{sc}\) and the colour-difference signals were sampled at \(2f_{sc}\). As the work on digital standardisation progressed, a different notation came into use, and the Recommendation 601 system is not known as 13.5:6.75:6.75, but as 4:2:2. The 4 in this coding scheme is used to mean the universal luminance sampling frequency of 13.5 MHz, and any other numbers, such as 2, refer to appropriate proportions or fractions of that frequency, so that 2, which is half of 4, indicates a sampling frequency of 6.75 MHz.

An advantage of this notation is that it can be used to describe other members of a digital hierarchy of systems, based upon 4:2:2, but including higher-quality and lower-quality systems as well, for specialised purposes. Recommendation 601 does in fact provide for an extensible family of compatible digital coding standards, any of which may be simply interfaced with any other.

An example of a lower-level system would be 2:1:1, a narrower-bandwidth 6.75:3.375:3.375 MHz system which might be suitable for newsgathering purposes, where the highest-quality pictures are not essential. A future higher-quality digital system might be described as 4:4:4, having equal sampling frequencies for luminance and chrominance signals, and CCIR Recommendation 601 actually provides a tentative specification for a digital system of this type, as shown in figure 61.

To add to the possible confusion over this shorthand notation, it should be noted that in some research papers occasional use is made of a fourth component in the ratio, e.g. 4:4:4:4. The extra number denotes a special key signal channel that may be used to provide the very highest-quality special effects, where one television signal is to be keyed into another.

Recommendations 601 and 656 have certainly provided the breakthrough needed to persuade manufacturers to undertake the costly business of making many different items of digital studio equipment, and it is now possible to build virtually all-digital studios, although the economics of changing from existing standards make it likely that it will still be some years before such studios are the norm.
Figure 61 Tentative specification for a 4:4:4 member of the REC 601 family

<table>
<thead>
<tr>
<th>Coded signals: Y, C_R, C_B or R, G, B</th>
<th>525-line, 60 field / sec systems</th>
<th>625-line, 50 field / sec systems</th>
</tr>
</thead>
<tbody>
<tr>
<td>These signals are obtained from gamma pre-corrected signals, namely: E'_Y, E'_R - E'_Y, E'_B - E'_Y or E'_R, E'_G, E'_B</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Number of samples per total line for each signal: | 858 | 864 |

| Sampling structure | Orthogonal, line, field and frame repetitive. The three sampling structures to be coincident and coincident also with the luminance sampling structure of the 4 : 2 : 2 member. |

| Sampling frequency for each signal | 13.5 MHz |

| Form of coding | Uniformly quantized PCM. At least 8 bits per sample. |

| Duration of the digital active line expressed in number of samples | At least 720 |

<table>
<thead>
<tr>
<th>Correspondence between video signal levels and the 8 most significant bits (MSB) of the quantization level for each sample:</th>
<th>0 to 255</th>
</tr>
</thead>
<tbody>
<tr>
<td>- scale</td>
<td>220 quantization levels with the black level corresponding to level 16 and the peak with level corresponding to level 235. The signal level may occasionally excursion beyond level 235. 225 quantization levels in the centre part of the quantization scale with zero signal corresponding to level 128.</td>
</tr>
<tr>
<td>- R, G, B or luminance signal</td>
<td></td>
</tr>
<tr>
<td>- each colour-difference signal</td>
<td></td>
</tr>
</tbody>
</table>
The transmission of digital signals

Much work is going on in the CCIR to find practicable ways of transmitting digital signals between studio centres, initially along PTT links, although this work could also lead eventually to methods of transmitting signals digitally to the home. If a component television signal is digitally encoded according to Recommendation 601, this will result in a data rate of \((13.5 \text{ Mbit/s} + 6.75 \text{ Mbit/s} + 6.75 \text{ Mbit/s}) \times 8\) bits per sample which is equal to 216 million bits per second, 216 Mbit/s. Even using the most optimistic of options, this will require a bandwidth of over 100 MHz to transmit; compare this with the 5.5 MHz that is adequate for the analogue version of a television signal, and the price of digital systems becomes clear—it is the extra bandwidth requirements.

Such a wide bandwidth makes it impracticable to transmit these digital signals over the air, and even sending the digital signals along PTT links has problems. Most of the transmission circuits around the world comply with standards laid down by the CCITT, an organ of the International Telecommunications Union (ITU), which is the international body responsible for regulating the world’s telecommunications systems. CCITT standard digital transmission circuits offer nominal capacities of 140 Mbit/s, 68 Mbit/s, 45 Mbit/s, or 30 Mbit/s, so if 216 Mbit/s digital television signals are to be sent along these circuits, some form of bit rate reduction will be required. In addition to the technical problems, there are often cost disadvantages to using these digital circuits, and the cost of using a 140 Mbit/s circuit to carry a single digital video signal generally compares unfavourably with the cost of sending an analogue video signal. These digital circuits can only be used economically if several digital video signals can be squeezed down one 140 Mbit/s circuit, which again requires significant amounts of bit rate reduction.

Bit-rate reduction

Fortunately, television pictures contain a large amount of redundancy, in that pictures do not change very much from picture element to picture element, or even from field to field, and it turns out that there are various techniques which can be used to reduce the necessary bit rate, whilst still providing acceptable pictures that show only a small loss of quality from the original. All the bit rate reduction methods require processing of the digital signal at the transmitting end and a corresponding process at the receiver. At the present time the processing circuitry is complex and expensive, and although it could be practicable for professional use over telecommunications circuits, it is likely to be many years before the same type of circuitry is cheap enough to make digital transmission to the home practical.

There are two main techniques for bit-rate reduction, DPCM and DCT.
Differential Pulse Code Modulation is a technique in which only the difference between a predicted sample value and its actual value is transmitted. The value of the predicted sample can be obtained by intrafield sampling, i.e. looking at adjacent samples in the same field, or by interfield sampling where the prediction is based on adjacent sample values from adjacent fields. The second technique, Discrete Cosine Transform coding, takes the data from a complete block of picture elements and uses mathematical processes known as orthogonal transforms, which are similar to the better known discrete Fourier transforms, to convert this data into an equivalent form from which any redundant information can be removed before transmission.

With both of these techniques some degree of bit rate reduction is also achieved by removing the horizontal and vertical blanking periods before the main coding is begun. Another useful tool is an ancillary technique known as variable-length coding which can be used to supplement both DPCM and DCT. Whereas in normal coding methods a fixed number of bits is allocated to each sample, this method gives the most-commonly occurring sample values short code words, longer words (i.e. more bits per sample) being given to those sample values which occur less frequently.

Unfortunately, there is no one technique that gives the best results at all times; different types of picture respond best to different bit rate reduction methods, and it always seems possible to find some exceptional picture which can be used to ‘crack’ even the most sophisticated bit reduction system. In spite of this, however, the tests which were carried out in 1989 and 1990 by the CCIR/CCITT working party showed that it is possible to obtain very good picture quality on nearly all types of material. It looks as though it will prove to be a version of the DCT technique that is finally adopted as the world standard for the lowest bit-rate system, which will work at approximately 34 Mbit/s for Europe and at approximately 45 Mbit/s for the USA.

Bit rate reduction to only 140 Mbit/s would also be very useful at times, especially for contribution circuits where the highest possible quality is required; this has been, found to be far less complex than the systems operating at lower data rates. DPCM is used, and with intra-field prediction techniques excellent results can be achieved.

Standards

Standards for bit rate reduction are currently being discussed by the CCIR and the CCITT, and following practical tests on various different coding schemes in 1989 and in early 1990, agreement on a common standard is near, but not yet finalised. References to this work cannot yet be given, since the proposed recommendations are still in draft form, but Volume XII (CMTT) of the CCIR Reports and Recommendations of the CCIR will in due course carry the final recommendations.

Most of the standardisation work so far has been based on digital
component signals corresponding to CCIR Recommendation 601, which means that composite signals such as PAL, NTSC, or SECAM will have to be coded before transmission and decoded after transmission; this is likely to give rise to some degradation.

It will be seen from the following section, however, that digital composite video-recorders which record PAL or NTSC pictures directly have recently become available. These are likely to prove popular with broadcasters as they can be used in studios as direct replacements for older analogue recorders. Taking note of this development, and considering that there is likely to be a need for the composite digital signals from these machines to be transmitted directly through PTT circuits, the relevant standards committees are currently considering the best method of providing bit rate reduction to 140 Mbit/s for these composite signals.

**Composite digital reappears**

We saw earlier that the initial work on digital television was carried out on composite signals such as NTSC and PAL, but that this work was discontinued when it was agreed that to carry out digital processing on the individual component signals was likely to give better results, as well as to make it easier to reach an international standard. The first major triumph of the component digital system described in CCIR Rec.601 was probably the component digital videotape recorder, using what became known as the D-1 format (ref. 6). These machines, which can cope with 525-line 60 Hz and 625-line 50 Hz signals without modification, thanks to the efforts taken to achieve standardisation, and can produce virtually transparent copies over as many as fifty generations, will revolutionise studio post-production. Unfortunately these machines are very complex, difficult to manufacture, and therefore very expensive, perhaps two or three times the cost of the 1 inch C-Format recorders that have been the standard studio machines of the nineteen-eighties. They also suffer from the disadvantage that being component machines, requiring luminance and colour-difference signals at input and output, they are difficult to install in a standard studio which has been built to deal with composite PAL signals. Indeed, to make full use of the D1 format the whole studio distribution system must be replaced, at considerable expense.

Realising this, the Ampex Corporation, whilst carrying out its research and development on the component digital D-1 machines, also carried out parallel work on a composite digital video recorder, which records composite NTSC (or PAL) signals directly, using the sampling frequency of $4f_{sc}$ that we discussed at the beginning of this chapter. This type of machine, using what has now become known as the D-2 Format, is cheaper to manufacture than the D-1 machines, and also has the immense advantage that since it uses composite signals, which are carried along one wire, the machine can be used as a direct plug-in replacement for a C-Format NTSC machine, without making
any modifications to the studio wiring. Another important plus factor is that it is predicted that the price will eventually be about the same as that of C-Format machines. Since the machine is a digital recorder it gives excellent multi-generation performance, perhaps up to the twenty generations claimed by the manufacturer, and this is probably the major requirement in many production centres. Since the D-2 machine is recording composite signals it does still suffer from some of the disadvantages of composite signals, such as cross-colour effects, although the use of $4f_{sc}$ sampling does help to minimise some of these effects. Sony have also begun to make and sell these composite digital D-2 machines, which many people are predicting will become the standard workhorses of television studios for the next decade, although I would guess that some new digital mini-format from the far East is likely to take over long before then.

(See the Appendix on page 295 for the most recent developments in digital television.)

References

6. D1 format video recorder, Draft specification.
8. D-3 videorecorder format.
11. Viewing conditions, CCIR 500–2, Reports and Recommendations of the CCIR, vol. XI.
Is there a need for better-quality television?

It is probably true to say that most present-day television viewers are quite satisfied with the technical quality of their television reception, although their views on the quality of the programme material would be very much more diverse. It is even true to say that most viewers are satisfied with a quality rather less good than that provided by the broadcasters. The CCIR grading scale for the subjective assessment of pictures grades pictures from one to five, using the following definitions (ref. 1):

<table>
<thead>
<tr>
<th>Grade</th>
<th>Quality</th>
<th>Impairment</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Excellent</td>
<td>Imperceptible</td>
</tr>
<tr>
<td>4</td>
<td>Good</td>
<td>Perceptible but not annoying</td>
</tr>
<tr>
<td>3</td>
<td>Fair</td>
<td>Slightly annoying</td>
</tr>
<tr>
<td>2</td>
<td>Poor</td>
<td>Annoying</td>
</tr>
<tr>
<td>1</td>
<td>Bad</td>
<td>Very annoying</td>
</tr>
</tbody>
</table>

Whereas broadcasters strive to provide pictures of as near to grade five as possible, and viewers can usually achieve something better than grade four in a domestic environment fitted with a good-quality receiving aerial and properly adjusted receiver, many viewers are equally happy to watch programmes that have been recorded on a VHS video recorder. The typical VHS machine provides pictures that are no better than grade three, and yet viewers regularly demonstrate that they are content with this quality of picture by repeatedly going along to the local video shop and renting a tape, handing over real money on each occasion. In these circumstances one has to ask whether there is a demand from viewers for something better than they have now, and the probable answer is that currently there is not; the average viewer, watching television in the living room on a 59 cm diagonal screen, is
quite content with the quality of the picture signals received from the broadcasters.

If the size of the television display is increased, however, whether by using large tubes or projection techniques, even the least expert viewer starts to notice that the picture quality seems worse; the scanning lines are visible, and the colour appears fuzzy. This suggests that it would probably be possible for the television industry to sell a higher-quality system to viewers, if the assumption could be made that the screen sizes of future television receivers are going to be larger than they are at present. This is not a straightforward assumption, since fashion and the size of modern homes, as well as the receivers that are available in the shops, play a part in the viewer’s choice of receiver. When colour television was first introduced into the UK in the late 1960s, the colour television receiver was an item to show off and to boast about, and many families who could afford a large screen receiver would ensure that it was placed in a prominent position in the room. Since the late 1970s, however, there has been a falling off of large-screen (26 inch or 66 cm) sales in the UK, but it is difficult to decide whether this is because smaller sets are significantly cheaper, or whether it is merely that the fashion has changed, and that it has now become socially more acceptable to relegate the television receiver to a less-prominent position in the home; rising sales of 14-inch portable colour receivers suggest that more and more families are buying several sets, so that teenagers can watch their own programmes in their own rooms, for example.

Recent trends from the United States and demonstrations of larger-screen television receivers in stores and at exhibitions are suggesting that the time may now be right for an increase in the sales of larger-screen receivers. Some European manufacturers have reported that they have sold significant numbers of 32-inch receivers in the last couple of years, but even so it is believed that these sales represent less than one percent of all colour receiver sales, and most of these large receivers have gone into hotels and industrial training areas.

In 1989 the IBA carried out a small survey of about 1000 people who watched enhanced and high-definition television pictures on large-screen monitors at an exhibition. It was interesting to find that, in spite of the fact that many people said that they would like large screens, in general the viewers placed improved quality, i.e. clearer, sharper pictures, before larger pictures in their order of preference (ref. 2).

The acceptability of television pictures in terms of quality is a fairly complex matter, and much work has gone into investigating it. Some of the important factors, in relative order of significance, are programme content, display phosphor resolution, display persistence, viewing distance, and numbers of scanning lines.

It is interesting to see that by no means all of these factors are technical; if the programme material is attractive enough to the viewer, the actual technical quality may be disregarded. Examples of this have been noted when audiences have shown themselves very willing to watch pornographic
material that has been recorded by amateurs and is of a very poor technical quality, and when low-quality pirated versions of the latest movies have been made available on the video black-market. Time and again it has been found that it is the programme content which matters, and those engineers who are convinced that high-definition television will succeed purely because of its technical brilliance should continuously remind themselves of this basic fact.

Satellite broadcasting will provide the first real test of whether viewers will be prepared to pay for an improved quality picture, and the initial soundings do not seem encouraging. During 1990 viewers in the UK were given the choice between receiving satellite programmes radiated in the PAL system, and those radiated using the higher-quality MAC system, and similar situations are occurring in some other parts of Europe. The Astra satellite, a medium power (45 watts) distribution satellite, radiates six PAL channels in English, and viewers can buy 60 cm dishes and suitable receiving equipment from about £199. The official UK Direct Broadcast Satellite, Marcopolo I, owned by the five different programme channels using the higher-quality MAC system, and its film channel can actually broadcast wide-screen MAC pictures to the very few viewers who have the necessary special widescreen receivers. The French Thomson company has plans to make these receivers more widely available during the next couple of years, but it seems that they will inevitably be rather expensive.

Wide-screen viewers apart however, BSB viewers have, up to the present time, the chance to watch MAC pictures in their own home, and can take advantage of the improvements which the MAC system can bring, which were discussed in chapter 5. The most obvious improvement over PAL is the lack of spurious cross-colour patterns, but broadcasters rarely get any complaints about this from viewers using the terrestrial PAL transmitters, and so it remains to be seen whether the better picture quality available will actually make viewers choose MAC rather than PAL. It seems to me to be far more likely that their choice will be made on the basis of the programmes that the two competing satellites offer, rather than on any difference in technical standards.

As if to fulfil the final words of the previous paragraph, at the time of writing, the BSB company has just announced that it will, for commercial reasons, combine with Sky Television, the company which broadcasts four of the English language programmes on Astra. The joint company, British Sky Broadcasting, has announced its intention to transfer all its programmes from Marco Polo to Astra, where they will be broadcast in PAL in order to serve the large number of viewers who have already invested in Astra receivers. The future of the Marco Polo satellites and of UK DBS broadcasting in MAC is currently being considered by the various broadcast regulatory bodies, and it is to be hoped that the significant longer-term advantages of adopting the MAC system, to be discussed in later chapters on HDTV, are not lost because of short-term commercial decisions.
High-definition television—what do we mean?

Before we go on to examine various possible systems in detail, it is sensible to ask what is meant by HDTV, and rather than looking at the various official definitions, which we shall consider later, it is perhaps appropriate to ask what we would expect of an HDTV system that our current systems do not provide. The four major features that any HDTV system would require can be summarised as

- Large Screen size
- Better Resolution
- Wider Aspect Ratio
- Lack of Spurious Effects

We shall now consider these points in turn.

Large screen

Although at the present time the practicability of achieving large-screen displays in the home at prices that the consumer will be prepared to pay is a subject of much discussion, those who believe in HDTV are convinced that large-screen displays will become available. Just how large is yet another question; it seems that there may well be two distinct large-screen markets, the first using money-no-Object giant screens for use in the electronic cinemas of the future, the second using screens of perhaps one-metre diagonal, which would become the norm in the living rooms of the future. Most experimenters in the field of HDTV have chosen this size as representative of what may be both practicable to manufacture and acceptable in the home within the next few years. If we assume that the cathode ray tube display will continue to be the norm, and that is by no means certain, then an extension to perhaps one metre from the largest present-day 68 cm tubes seems feasible, and if the development of flat-screen displays should make screens of this size practicable within the next few years, then a ‘picture on the wall’ with a one-metre diagonal is probably as large as most people would want. If such a screen had an aspect ratio, i.e. the ratio of the width to the height of the picture, of 5:3, as will be suggested later, then the screen would be about 86 cm wide by 52 cm high (figure 62).

Figure 62 Approximate dimensions of a one-metre diagonal screen with an aspect ratio of 5:3
Viewing distance

The size of picture that is acceptable in the home is intimately connected with the viewing distance. The most popular screen size in the UK throughout the 1980s has been 56 cm (22 inch), the figures representing the size of the diagonal of the picture tube. The height of such a screen is about 36 cm, and the aspect ratio is 4:3. In current television systems it is recommended by the CCIR that for critical viewing the viewer should sit between four and six times the screen height (i.e. \(4H-6H\)) from the television screen (ref. 1). These figures are intended to apply to professional viewers who are assessing the technical quality of pictures, but a survey in the early 1980s showed that the average domestic viewer actually watched from a distance of more than \(7H\) (ref. 3). If we make the reasonable assumption that our room sizes are unlikely to change in the short term, then if larger screens are introduced into our living rooms we will be unable to avoid effectively sitting nearer to the screen, in terms of screen heights. Practical tests suggest that if a viewer is watching a one-metre screen in the home, the most pleasing results are obtained when the screen is at a distance of \(3H\) from the viewer, and interestingly enough, cinema buffs say that it has long been known that the best seats in the cinema, the stalls, are those which are situated at a distance of about \(3H\) from the screen (figure 63).

*Figure 63 Comparison between viewing distances of standard television and large-screen television in terms of screen heights*
Research into cinema layouts in the USA that was carried out way back in the 1950s confirms this, since it showed that the centre of the auditorium was on average just over $3H$ from the screen (ref. 4).

Wider aspect ratio

Those involved in research into HDTV are convinced that any future system must provide the viewer with an experience closer to that which is currently obtained at the cinema. Work in Japan showed that when people were shown a selection of pictures with different aspect ratios, then, in general, the larger the screen, the wider the aspect ratio that was preferred. In particular, when viewers watching one-metre diagonal screens from a distance of $3H$ were offered pictures with various different aspect ratios, they chose aspect ratios of around 5:3 as the most pleasing (ref. 5). The first experimental HDTV systems therefore used 5:3, but following subsequent work in America (ref. 6) which also took into account the various aspect ratios currently used for cinema film displays, this has now been superseded by the slightly wider-screen aspect ratio of 5.33:3, or 16:9, as was mentioned in chapter 5 when discussing the MAC system. It is believed that 16:9 will make the best use of the numerous existing cinema film formats when these films are used as HDTV source material.

It is interesting to note that the classical artists of ancient Greece used a ratio of 1:0.618 as the one found most pleasing to the eye, based upon their

Figure 64 Comparison between 4:3 and 16:9 aspect ratio pictures
so-called ‘golden section’, and this ratio turns out to be just a little over 5:3.

 Watching a 16:9 aspect ratio picture at a distance of $3H$ gives a far more cinema-like effect than watching a relatively small screen from $7H$.

 One other factor about receivers with different aspect ratios that is relevant to the commercial market, although rarely mentioned in the technical papers, is that such receivers will actually look noticeably different from normal standard receivers. Marketing people think that this would appeal to the ‘Super-Joneses’ and then to the ‘Joneses’, and they like to think that this will be a significant factor in developing wide-screen receiver sales; ‘Widescreen is great—you can even tell the difference when the receiver is switched off!’ said one salesman at a recent seminar.

Better resolution

Present-day pictures run out of resolution when it comes to very fine detail, and if 525 or 625-line pictures are shown on large screens, by projection for example, this lack of resolution becomes obvious and annoying. We could make use of more detail in pictures if some means could be found of providing this.

 In order to try to calculate the amount of detail that the human eye/brain combination can actually make use of, we have to first of all look at the characteristics of the eye. Under conditions where a test chart is well illuminated, the resolving power of the eye is limited to about 30 seconds of arc, or an angle of one half-minute (ref. 7). This is equivalent to saying that the eye can resolve about 60 cycles per degree of arc, which is the more usual method for television engineers to measure resolution.

 At a distance of $3H$ from a one-metre diagonal screen the vertical angle subtended by the eye will be about 19 degrees, as shown in figure 65. If we are to design a television system to match this resolution on our screen we therefore need $19 \times 60 = 1140$ cycles per degree height. In order to display this number of cycles we need a minimum of two lines per cycle, so that a minimum of about 2280 lines would seem to be required for an HDTV system that matches the resolution of the eye.

 Fortunately, it turns out in practice that this number of lines is not actually necessary. Subjective tests have been carried out to determine the optimum number of scanning lines required (ref. 8), and these have shown that, under the viewing conditions described earlier, the line structure cannot actually be seen when the number of lines is greater than about 1000. Very small improvements in the sharpness and detail visible in the picture were noticed when the number of lines was increased further, but virtually all expert observers now agree that, if a viewing distance of $3H$ is used, a figure of just over 1000 lines will be very acceptable. In general, it is found that the sharpest pictures are obtained when the horizontal resolution matches the vertical resolution (ref. 9), and the two are usually related by a simple
Figure 65 Showing that the vertical angle subtended by the eye when viewing a 1 metre diagonal screen from a distance of $3H$ is about $19^\circ$

Angle subtended by eye at $3H$ is $2\alpha$

$$\tan\alpha = \left(\frac{H}{2}\right) + 3H = \frac{H}{2} \times \frac{1}{3H} = \frac{1}{6} = 0.167$$

$$\therefore \alpha = \tan^{-1} 0.167$$

$$\alpha = 9.46^\circ$$

$$\therefore 2\alpha = 18.92^\circ$$
formula which takes the aspect ratio of the picture into account.

Chrominance resolution

Another resolution problem with our present system comes about as a result of the low chrominance bandwidth that systems like PAL use. As we saw earlier, the PAL system effectively provides a detailed black-and-white picture with a much fuzzier colour image superimposed, and this is a state that the eye normally finds quite acceptable. There are some occasions, however, notably when red captions are shown on a green background for example, where the chrominance bandwidth can be seen to be short of something—the edges of the coloured captions appear all fuzzy. An increase in chrominance resolution would provide a useful improvement in this case, and in pictures of flower gardens and the like.

Picture frequency—temporal resolution

A television receiver displays what appear to the eye to be moving images, but these are actually a series of individual fields or frames which can be considered as samples of the complete picture taken at regular intervals of time. For any acceptable television system, and certainly for a high-definition system, the series of samples must be capable of reproducing movement without jerkiness, and must also provide pictures without flicker and without annoying effects such as interline flicker, which is caused on an interlaced picture by the scanning lines of the two different fields interacting with horizontal edges in the picture.

For smooth motion portrayal it has been found that a repetition rate of greater than 45 Hz is required (ref. 10). As we saw in chapter 1, television pictures to date have used interlaced scanning to give the effect of a greater number of pictures per second whilst using a smaller bandwidth than would be required without interlace. Both the 50 Hz and 60 Hz field rates used in the different parts of the world will therefore satisfy the motion portrayal requirement under most circumstances, although some work has been done (ref. 11) which suggests that the relatively long exposure period of each television field can lead to a form of blurring which is particularly noticeable when the eye tries to follow moving objects such as a racing car speeding around a track. In general, however, the eye/brain combination does not try to resolve fine detail in fast-moving objects, so that the 50 Hz and 60 Hz field rates should be satisfactory.

Large-area flicker is a different matter, however, since tests have shown that for very bright images it is necessary to use a field frequency of around 80 Hz if flicker is to be completely eliminated. The increased cost of using 80 Hz in terms of bandwidth and the increased complexity of production equipment have led most workers in this field to conclude that 60 Hz, and even perhaps 50 Hz, will represent the same sort of workable compromise.
as did 1000 lines rather than the 2200 theoretically required. Technical improvements in receivers will soon allow for several incoming fields to be stored in a semiconductor memory, and for the actual displayed picture to be read out from the store at perhaps 100 Hz, after some processing of the moving parts of the picture. The display frequency will therefore be independent of the transmitted signal frequency.

Interline flicker, which is seen as a series of small vertical movements on horizontal edges in interlaced displays, is noticeable even on 50 Hz and 60 Hz displays, and although the annoyance value reduces as the number of lines is increased it may well be that the eventual goal of an HDTV picture should be to display a non-interlaced, sequentially scanned picture.

**Kell factor**

In 1940 Kell of RCA carried out work on the subjective and objective resolution of television displays, and we now describe the result of a combination of features at both source and display which limit resolution as the Kell Effect. This is defined in the *International Electrotechnical Vocabulary* (ref. 12) as ‘the ratio between the maximum number of horizontal lines distinguishable in the reproduced picture and the number of scanning lines in the raster’. This effect on vertical resolution has come to be seen as particularly relevant to HDTV studies, and it is important to notice that we are not referring just to the physical limitations of a system, but also to the perceived effect of those limitations, in essence what the visual system can distinguish. One of the most significant aspects of these limitations is line interlace.

**Interlace**

All other features of a television display being equal, a sequential display will provide a subjectively sharper picture than an interlaced display, and the difference is surprisingly large, meaning that an interlaced display needs about 1.5 times more lines to subjectively produce the same resolution as a sequentially scanned display. As an example, a 625-line per frame display with sequential scanning, i.e. all 625 lines scanned one after the other at twice the normal rate, will give the same subjective effect as a standard interlaced display with some 940 lines. This is an important feature which is largely based on the averaging that the eye performs between lines and over fields. The process is believed to be largely to do with the persistence of vision, and the inability of our visual system to distinguish between the interlaced lines from alternate fields presented every fiftieth of a second. In practical terms if the viewer is presented with a grating which has progressively finer and finer detail in the vertical plane, there will be a limit at which the eye can no longer distinguish detail, i.e. the difference between adjacent lines in the grating. This threshold is
extended if sequential scanning is used. We shall see in a later chapter that
this is the basis of some of the European arguments for an extended
definition television system which uses the advantages of sequential
scanning to provide an improved system compatible with the existing 625-
line services. (See figure 66.)

Lack of spurious effects

The most noticeable effect of this type is cross-colour, which was discussed
in chapter 4, and which can be seen in figure 26. The PAL television system
transmits both the colour and the black-and-white parts of the picture at
the same time, using frequency-division multiplexing. The colour
information is effectively interleaved with the black-and-white picture as it
is transmitted, and the receiver has the job of sorting out the colour signals
from the black-and-white and then reassembling them to form a complete
colour picture. Most viewers are familiar with this effect when finely striped
shirts or checked suits cause spurious coloured patterns which move about
with any picture movement. The same problem in reverse, so to speak,
occurs when there are sharp colour transitions in the picture. The
luminance information breaks through into the chrominance channel,
causing a fine crawling dot pattern, known as cross-luminance.

Any higher-quality television system should ideally be free of both of
these effects.

The beginnings of HDTV

It was as long ago as 1974 that the Japanese broadcaster NHK, their public
service broadcasting equivalent to the BBC in the UK, began work on a
system of high-definition television, and they were joined by Japanese broadcasting equipment manufacturers shortly afterwards. Further details of the Japanese system, as of the other systems which were later to be suggested, will be given in later chapters, but basically their system, developments of which have come to be known as Hi-Vision, uses 1125 interlaced scanning lines and sixty fields per second.

In essence this system provides extremely-high-quality pictures, even on cinema-sized screens, and by the early 1980s the Japanese were able to offer a complete range of broadcast equipment using this system. Cameras, telescopes, videorecorders, mixers, monitors, and projectors were all designed and developed to work with the 1125/60 system, but although the 1125/60 system represented a huge leap forward in picture quality, it also had and still has two major disadvantages. Firstly, and probably most importantly, the system is significantly different from any of the world’s existing television standards, which means that anyone wishing to make use of the better quality pictures needs to buy an expensive new receiver, and also that viewers with existing receivers will not be able to make use of the 1125/60 pictures, without very complex conversion equipment which seems unlikely to be economically practicable.

The second problem with this HDTV system is that it requires large amounts of bandwidth to carry all the extra information that is needed to provide the excellent pictures which the system can undoubtedly provide. For the highest-quality transmission a video bandwidth of around 30 MHz is required, compared with the 5 MHz needed for most European PAL and SECAM systems. In radio-frequency transmission terms this means that an HDTV picture of this type would take up four to five times the transmission bandwidth required by conventional systems, so allowing a typical DBS satellite, which has the bandwidth to carry five standard pictures, to carry only one HDTV channel instead. As we shall see later, the Japanese have worked hard on this problem, and have developed a ‘black-box’ known as MUSE, which can overcome this bandwidth problem at the cost of some deterioration in the final picture quality; whether this will provide an acceptable solution in the long term still remains to be seen.

Several other broadcasting organisations around the world, and notably the BBC in the UK, had research programmes looking at future HDTV possibilities, but only the Japanese actually went ahead and developed a complete working system. NHK is compelled by the Japanese government to spend around 1.8% of its total turnover on research; it has been estimated that up to the present time NHK has invested some $300000000 in its Hi-Vision project, and that the various Japanese manufacturers have also spent a similar amount. The fact that only Japanese HDTV equipment was available for sale led to a situation where in 1984 the Japanese submitted their 1125/60 HDTV system to the world standards making body for broadcasting, the CCIR, asking for it to be ratified as the world standard for high-definition television.
The knowledge that this was to happen concentrated the minds of the rest of the world’s broadcasters who had an interest in HDTV, and encouraged them to focus upon what the acceptance of the Japanese standard would mean in real terms. It was felt by many that the acceptance of the Japanese system would inevitably give the Japanese manufacturers an unassailable advantage when it came to the supply of broadcasting equipment, right through from studios to transmitters, and in a world where many of the television receivers already come from Japanese sources this would be going too far. Several of the most influential American broadcasters originally supported the adoption of the Japanese system as a world standard, on the practical grounds that it was the only system actually up and running, as opposed to the various laboratory concepts favoured by other broadcasters. The system was actually officially adopted in 1988 as the recommended HDTV production standard by the American Advanced Television Standards Committee, which accepted the proposals prepared by an SMPTE working group (ref. 13) and proposed to submit the decision to the American National Standards Institute. Although this proposal was agreed by a majority of the forty-five organisations in membership of the ATSC, the support from some of the other major broadcasters was, however, luke-warm, and the National Association of Broadcasters refused its approval; it was quickly realised that the decision to adopt 1125/60 was something of a red-herring. The Japanese-based system might be acceptable as a production standard, but as a transmission standard to provide the population of America with higher-definition pictures it definitely left a lot to be desired. American companies woke up to the fact that the commercial outcome of accepting the Japanese system might be disastrous for the US economy, and finally decided to look for an improved television system which would be particularly well suited to the needs of the United States.

European broadcasters realised the problems that accepting a Japanese standard would bring commercially, but they were also able to play a technical card to avoid having to vote for the adoption of the 1125/60 system. All European television systems, and about 60% of all the world’s viewers’ use 50 Hz, i.e. 50 fields of 312½ lines per second, a number that was originally related to the 50 Hz mains electricity frequency, although there is now no longer any need for a direct relationship between the two. European broadcasters were able to claim that the use of the Japanese 60 Hz system would cause various problems, including a 10 Hz flicker between mains-powered studio lighting and 60 Hz studio production equipment. Although the Japanese explained that they had been using the 60 Hz NTSC system in parts of Japan that use 50 Hz electricity for over thirty years without any noticeable problems, and although they even designed, built and demonstrated a reasonably effective adaptive 10 Hz filter, known as a ‘flicker-licker’, it became obvious that Europe was not going to be in favour of adopting the 1125/60 system as the world HDTV standard.
The biggest argument against the adoption of 1125/60 was and is that the system is so vastly different from any existing system that its lack of compatibility would be a very real problem. This could mean that those viewers who want and can afford the HDTV services would need to have two television receivers in the same room, since although it will be possible, technically, to include the circuitry for a conventional receiver within the cabinet of the HDTV receiver, this is likely to add a substantial amount to the already considerable cost of an HDTV receiver. Preliminary work in the United States has concluded that a one-metre diagonal receiver is likely to cost more than $5000 initially, and it suggests that because the single most expensive component will be the cathode-ray tube, the price cannot be expected to fall as quickly as for most electronic equipment, and that receivers with one-metre screens may still cost over $3000 after five years of production. As far as the price of the receiver is concerned the actual electronic circuitry included in the receiver is considered to be relatively unimportant, so that the price may be little different whether a full HDTV system or one of the many proposed enhanced systems is used (ref. 14).

Reports such as this naturally do their best to extrapolate from the currently known facts, but can take no account of some completely new technology that may, unknown to us, be just around the corner. A lovely example of a new technology changing all previous conceptions came about in the last few years of the last century. From 1850 onwards people were complaining about the rapidly growing amount of horse-manure clogging the streets, and there were various dire predictions that if road traffic kept on growing the streets would be rendered impassable by the depth of the ordure. With hindsight we know that the motor-car came along, so that the predicted problem never materialised, although nearly a century later we are finding very different problems due to the growth in the numbers of cars. Let us hope that the television industry can come up with some brand new, cheap and simple method of producing large-area displays that will confound those who are predicting that the HDTV receiver will always be a high-cost item.

There are very great difficulties involved in introducing a completely new television system, even if we ignore the technical complications. In order to provide a high-quality service that the viewer would find desirable enough to pay for, any HDTV service will need to provide high-quality programming, and experience with subscription services elsewhere shows that this generally means that recently-released feature films must be offered. Such programme material is very expensive, because of the competition from cinema chains, and it would not be realistic to broadcast HDTV programmes using this material if, in the initial stages, there were no more than a few thousand viewers equipped to receive the service; the cost per viewer would be phenomenal. Far more desirable would be a scenario in which the HDTV transmissions could also be received by the millions of existing viewers on their existing receivers; although they would not gain
the benefits of HDTV they would be able to watch the expensive programme material to the normal viewing standards that they expect, and this would enable the programme provider to amortise the cost of the film material over millions of ordinary viewers, as well as the relatively small number of those watching in HDTV. Such an approach would also appeal to advertisers, who need to be assured that large numbers of people are watching the programmes which they sponsor or during which they buy advertising time.

It was no surprise, therefore, that the Japanese failed to have their system adopted as the world standard for HDTV, and instead it took its place in the CCIR Reports and Recommendations as a Report (ref. 15). As indicated earlier, the Japanese proposal stirred Europe and America into action to develop their own individual proposals, many of which we shall be discussing. An enormous amount of work has been put into trying to find a common standard for HDTV which all the world's broadcasters will be able to agree upon, but it now looks very unlikely that the members of the CCIR will be able to reach such an agreement, and the most likely scenario for the next few years is that there will be three HDTV standards. These will be the original Japanese 1125/60 standard, a European 1250-line 50 Hz standard, and an American standard, possibly 1050-line 60 Hz, which still has to be decided upon. Both the European and American systems have been designed from the outset to provide a substantial degree of compatibility with existing receivers, in order to try to ease the problems of introducing a completely new high-definition system. The European system offers a step-by-step approach to HDTV, with the various intermediate steps providing different amounts of enhancement to the television picture, depending upon the complexity of the receiver being used. In the following chapters we shall be taking a look at the various systems, and also considering the ongoing work to try to bring at least some degree of commonality to the multiplicity of different standards that are to be used.

Terminology

We will end this chapter with a look at some of the terminology and definitions which are applied to the various enhanced and high-definition television services, although it must be stressed that in such a fast developing field as this the vocabulary is also changing fast, and some standards bodies have not yet adopted exactly the same definitions as others, which can lead to confusion.

CCIR definitions

**Enhanced Television** The term Enhanced Television designates a number of different improvements applicable to 525/60 and 625/50 television systems, providing an aspect ratio of 4:3, either with unchanged or new emission standards (ref. 16).
**Extended Definition Television** The term Extended Definition Television implies new systems that are based upon 525/60 or 625/50 scanning, but providing a wider aspect ratio and increased resolution (ref. 16).

**High-Definition Television (ref. 17)** A high-definition system is a system designed to allow viewing at about three times the picture height, such that the system is virtually, or nearly, transparent to the quality of portrayal that would have been perceived in the original scene or performance by a discerning viewer with normal visual acuity. Such factors include improved motion portrayal and improved perception of depth.

This generally implies in comparison with conventional television systems:

- spatial resolution in the vertical and horizontal directions of at least twice that available with Recommendation 601;
- any worthwhile improvements in temporal resolution beyond that achievable with Recommendation 601;
- improved colour rendition;
- a wider aspect ratio; and
- multi-channel high-fidelity sound.

**Definitions from the International Electrotechnical Vocabulary**

**Enhanced Television System** Television system which retains the scanning standards of the existing 625-line 50-field or 525-line 60-field systems, whilst providing various improvements in the quality of the picture and additional features as a result of new processes of analysis, synthesis, and signal processing, with or without modification of the transmission standards (ref. 18).

**Extended Definition Television System** Enhanced television system which may include a change in the transmission standards, to obtain effectively greater resolution than existing systems (ref. 19).

**High-Definition Television System** Television system in which the scanning standards are improved over those of the existing 625-line 50-field or 525-line 60-field systems, and in particular the number of scanning lines per image is appreciably higher than in these existing systems. And, in principle, higher than 1000 (ref. 20).

**Definitions from the United States Advanced Television Systems Committee (ref. 21)**

These definitions refer specifically to developments taking place in the USA, as references to NTSC and to the FCC (Federal Communications Commission) imply.
IDTV—Improved Definition Television The term Improved Definition Television refers to improvements to NTSC television which remain within the general parameters of the NTSC emission standards and, as such, would require little or no FCC action. Improvements may be made at the source and/or at the television receiver and may include improvements in encoding, filtering, ghost cancellation, and other parameters that may be transmitted and received as standard NTSC in a 4:3 aspect ratio.

EDTV—Extended Definition Television The term Extended Definition Television refers to a number of different improvements that modify NTSC emissions but that are NTSC receiver-compatible (as either standard 4:3 or ‘letter-box’ format). These changes may include one or more of the following:

1. Wide aspect ratio.
2. Extended picture definition at a level less than twice the horizontal and vertical emitted resolution of standard NTSC.
3. Any applicable improvements of IDTV.

HDTV—High-Definition Television The term High-Definition Television refers to television systems with approximately twice the horizontal and vertical emitted resolution of standard NTSC. HDTV systems are wide aspect ratio systems and may include applicable improvements from IDTV and EDTV. Terrestrial HDTV systems must be NTSC receiver-compatible. This may be achieved through simulcasting or through the use of an NTSC-compatible main channel accompanied by an augmentation channel.

Note: Improvements in audio may be incorporated in IDTV, EDTV, and HDTV.

ATV—Advanced Television A collective term embracing the terms IDTV, EDTV, and HDTV, described above.

References

1. CCIR Recommendation 500/3: Method for subjective assessment of television pictures, Reports and Recommendations of the CCIR, Volume XI.
13. SMPTE Specification 240M.
Introduction

Surprising as it may seem to those who still see HDTV as something for the distant future, it was some twenty years ago, in 1970, that the Japanese broadcaster NHK began to research into the possibilities of developing a High Definition Television System, and they gave it the name HDTV.

The standards which their system was to use were decided upon after much basic research, not only into television engineering, but also into the basic characteristics of the human eye/brain combination and into the effects which viewing conditions would have on the total viewing experience (ref. 1). Since, as we saw earlier, the acceptability of a picture depends to some extent upon its content the Japanese researchers were careful to use a wide range of pictures in their tests, many of them computer-generated images of carefully controlled characteristics.

Ten years after the project began, in 1980, the first HDTV tests via satellite were carried on Yuri, the somewhat curiously named Japanese experimental satellite. By 1982 the system, which had 1125 lines, 60 fields per second, and an aspect ratio of 5:3, which was later to change to 16:9, was being demonstrated on large screens, and much of the equipment necessary to equip a studio had been built by NHK and the Japanese manufacturers. NHK was able to show HDTV cameras, telecines, videotape recorders, and both cathode ray tube and projection displays, and some of the pictures were comparable in quality with those from 35 mm film.

A range of 1125/60 systems

It is important for readers to note that in the 1990s it is an oversimplification to talk about ‘the Japanese HDTV system’, because the basic system that will be described in the next few paragraphs has been subject to considerable changes over the two decades of its existence, and there have really been three main phases in the life of the 1125/60 Hz HDTV television system.

Originally the system was put forward as a standard to be used both for studio production and for transmission over the air and via cable. Criticism of the enormous bandwidth requirements for transmission led to the...
development of the MUSE system, described below, which allows for 1125-line/60-Hz pictures to be transmitted over standard bandwidth satellite or cable channels at the cost of a small reduction in the quality of some pictures. It has now become generally accepted that any transmitted 1125/60 HDTV signals will use one of the variants of MUSE.

The third phase has really come about as a result of the so-far unsuccessful struggles to achieve a world standard for HDTV, the politics of which were described in the previous chapter. Realising that it would not be possible to achieve their original goal, which was to get the whole world to adopt the 1125/60 HDTV system for both production and transmission, and seeing that they were many years ahead of competing systems when it came to the availability of HDTV studio equipment, the Japanese have adopted another approach. They have begun to make a complete range of HDTV studio equipment available to programme makers around the world, and are attempting to make the full-bandwidth highest-quality 1125/60 Hz system the de-facto world studio standard for HDTV. Already facilities houses in the United States and in Europe have bought HDTV production equipment, and even the BBC, which is nominally committed to the development of the competing European 1250/50 HDTV system, has utilised the Japanese equipment to gain experience of HDTV production, although the resulting programme, The Ginger Tree, had to be standards-converted to 625/50 before its transmission in 1989.

The basic parameters of the Japanese HDTV system

The basic standard adopted for the Japanese HDTV system had the following characteristics, although it is important to note that some characteristics were changed as the system developed, and some parameters have been changed to suit particular applications:

- Scanning lines per frame: 1125
- Number of active (picture) lines per frame: 1035
- Aspect ratio (later changed to 16:9): 5:3
- Interlace ratio: 2:1
- Field frequency: 60 Hz
- Line frequency: 33750 Hz
- Luminance ($Y$) bandwidth: 20 MHz
- Chrominance (colour-difference signal) bandwidths:
  - (i) wideband signal ($C_w$): 7.0 MHz
  - (ii) narrowband signal ($C_N$): 5.5 MHz

Note that the field frequency is precisely 60 Hz, not the 59.94 Hz which is used in the American and Japanese NTSC terrestrial systems in order to
improve compatibility for black-and-white television viewers.

The original RGB signals from the HDTV source are passed through a resistive matrix to provide a luminance signal $Y$ and two colour-difference signals of different bandwidths, $C_W$ and $C_N$. These were originally derived from the following matrix equations, but changes in some colorimetry characteristics have already taken place and further changes may be expected as the attempts at standardisation progress:

$$\begin{bmatrix}
Y \\
C_W \\
C_N
\end{bmatrix} = \begin{bmatrix}
0.3 & 0.59 & 0.11 \\
0.63 & -0.47 & -0.16 \\
0.03 & -0.38 & 0.41
\end{bmatrix} \begin{bmatrix}
R \\
G \\
B
\end{bmatrix}$$

These first HDTV signals were intended for transmission over satellite radio-frequency channels, and numerous transmissions were made using both composite colour signals, the luminance and chrominance signals being frequency multiplexed, and using time-compressed analogue component signals. This form of transmission was known not as MAC, but as TCI, Time Compressed Integration, and in this system the compressed luminance and chrominance signals are time-division multiplexed on a line-sequential basis. In a further series of tests (ref. 2) the Yuri satellite was also used to transmit luminance and chrominance signals on completely separate satellite channels, but although this was an interesting experiment, it is unlikely to have practical applications.

The composite form of this HDTV system, using a form of wideband PAL known as HLO-PAL (Half-Line Offset PAL) with a colour subcarrier at 24.3 MHz and a baseband spectrum occupancy shown in figure 67, was tried over FM satellite broadcast channels, but had poor noise performance,
especially noticeable in the coloured parts of the picture, as might have been expected. This composite system was, however, found to perform well over SHF terrestrial transmitter paths using both AM-VSB and FM, and over wide-bandwidth optical fibre cable systems.

The TCI component system was, however, found to give much better results over low-power FM satellite paths, and it has the same advantages as other multiplexed analogue component transmission systems.

In our earlier discussions of the MAC system we saw that using time-compression increased the signal bandwidth, and to take account of this, care was taken in the NHK TCI system to ensure that the bandwidth of the compressed chrominance signals did not exceed the 20 MHz of the uncompressed luminance signal (figure 68).

The original TCI system used no processing of the luminance signal, which took up about 79% of the normal line time. Another 19% of the line time was used to carry the chrominance components, either both together or line-sequentially.

![Figure 68 Basic details of the TCI line waveform](image)

\[ H = \text{duration of one line} \]

**Signal bandwidth**

\[
\begin{align*}
Y & \quad 20 \text{ MHz} \\
C_w & \quad 5 \text{ MHz} \times 4 \to 20 \text{ MHz} \\
C_n & \quad 4 \text{ MHz} \times 5 \to 20 \text{ MHz}
\end{align*}
\]

*Figure 68 Basic details of the TCI line waveform*
The expressions TCI-LI (time-compressed integration of line colour signals) and TCI-LSI (time-compressed integration of luminance and line-sequential colour signals) are used to denote the two different systems. (See figure 69.)

The bandwidth of the two chrominance signals is altered from that originally specified in order that the compressed $C_W$ and $C_N$ signals can be fitted into the 20 MHz bandwidth required for the luminance signal. For the TCI-LSC signal we thus have

- Bandwidth of the $Y$ signal = 20 MHz
- Bandwidth of the compressed $C_W$ signal = 20 MHz
- Compression ratio applied to $C_W$ signal = 4:1

Thus maximum bandwidth of uncompressed $C_W$ signal

$$= \frac{20}{4} = 5 \text{ MHz}.$$  

Similarly

- Bandwidth of the compressed $C_N$ signal = 20 MHz
- Compression ratio applied to $C_N$ signal = 5:1

Thus maximum bandwidth of uncompressed $C_N$ signal

$$= \frac{20}{5} = 4 \text{ MHz}.$$  

As the $C_N$ signal takes up less line time than the $C_W$ signal, there is time for a horizontal synchronising pulse to be fitted in at the beginning of each alternate line.

Figure 70 shows a simplified version of the circuitry by which such a TCI signal can be achieved. The $RGB$ signals are matrixed to produce the luminance signal $Y$ and the two colour-difference signals $C_W$ and $C_N$ and then these signals are low-pass filtered to prevent aliasing and then digitised. The time compression is achieved by reading the signals into a line store at one frequency, and then reading them out at a higher frequency; the actual combinations of frequencies for the $C_W$ and $C_N$ signals are shown on the diagram. The time-multiplexed colour signals are then combined with the luminance signal, and the completely multiplexed signal is then changed back to analogue form in a digital-to-analogue convertor.

---

**Figure 69** Distinguishing between TCI-LC and TCI-LSC systems
Figure 70 Simplified TCI encoder

Figure 71 Modified TCI-LSC signal

**LPF** Low-pass filter
**DAC** Digital-to-analogue convertor
**ADC** Analogue-to-digital convertor

$H =$ duration of one line

*Signal bandwidth*

$Y_L + Y_H$ 
$20$ MHz

$Y_L$ 
$10$ MHz $\times 2 \rightarrow 20$ MHz

$C_W$ 
$10$ MHz $\times 2 \rightarrow 20$ MHz

$C_N$ 
$5$ MHz $\times 4 \rightarrow 20$ MHz
More complex TCI-LSC systems were then developed, in which the luminance signal was subjected to processing, being divided into high and low-frequency components, $Y_H$ and $Y_L$. The low-frequency component is transmitted on every line, whereas the high-frequency component is only transmitted on alternate lines, as indicated in figure 71. The main advantage of the modified system is to allow the chrominance bandwidth to be higher, so that when different compression ratios are used we achieve a bandwidth for $C_w$ of about 10 MHz and about 5 MHz for the $C_N$ signal.

Various other modifications of the basic HDTV signal have been worked on, and the aim seems to have been to provide systems for all possible situations.

**The HDTV studio production standard**

When HDTV signals are being used in production studios, in closed circuit areas such as the televising of medical operations, or as source material for the printing of high-quality still pictures, there is no need to worry about bandwidth constraints, since the signals are only being passed over short distances around the studio. To take advantage of the large available bandwidths in these situations there is a version of the HDTV system which has been designed to provide for a studio production standard. This has nominal bandwidths of 30 MHz for each of three parallel, time-coincident component video signals, which may be based upon Red, Green and Blue components or upon luminance and colour-difference components. Each component signal carries its own synchronising pulse waveform. The basic characteristics of the 1125/60 studio standard are shown below, and it is instructive to compare these with the characteristics of the 1250/50 HD-MAC system described in chapter 9.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total number of lines per frame</td>
<td>1125</td>
</tr>
<tr>
<td>Number of active (picture) lines</td>
<td>1035</td>
</tr>
<tr>
<td>Interlace ratio</td>
<td>2:1</td>
</tr>
<tr>
<td>Aspect ratio (horizontal:vertical)</td>
<td>16:9</td>
</tr>
<tr>
<td>Field frequency</td>
<td>60 f.p.s.</td>
</tr>
<tr>
<td>Line frequency</td>
<td>33 750 Hz</td>
</tr>
</tbody>
</table>

**Bandwidth considerations**

We can see from the wide bandwidths required for the baseband luminance and chrominance signals, something of the order of 30 MHz, that the radio frequency bandwidth requirements will be even greater, and it is generally assumed that to transmit such an HDTV signal will require perhaps four or five times as much RF bandwidth as a normal PAL or NTSC television signal.
Although it is possible to imagine future transmission systems where enough bandwidth could be made available for an HDTV system of this type, perhaps using fibre-optic-based cable systems or satellites radiating on frequency bands above 40 GHz, at the present time it would seem totally impracticable to devote such bandwidths to television transmission, since any HDTV signal could only be transmitted at the expense of a reduction in the number of conventional channels that could be carried.

Even in such a futuristic world it will undoubtedly be important to continue to make the best possible use of the necessarily finite amount of spectrum space that will be available for television purposes, and in these conservation-minded times it surely makes sense to use no more bandwidth than that absolutely necessary for the satisfactory transmission of HDTV signals. With this object in mind the Japanese have developed techniques and equipment whereby wide-bandwidth 1125-line 60 f.p.s. HDTV signals may be converted into baseband signals which take up no more than about 8.1 MHz at baseband, so that what are ostensibly 1125/60 HDTV pictures may be transmitted over standard satellite channels. This bandwidth-reduction system, of which there are several variants, has been given the name MUSE, Multiple Sub-Nyquist Sampling Encoding.

**Sampling and subsampling principles as applied to television**

In the explanations of the workings of the MUSE system which follow, and in our consideration of other HDTV systems, we shall be discussing how the system makes extensive use of sampling and subsampling techniques, so before embarking on this it may be useful to look at some of the basic principles of sampling television images.

A television picture can be considered as a two-dimensional representation of an original image, which varies with time. It is easy to see that the television picture is already sampled vertically, because of the way in which the picture is made up from horizontal lines, but perhaps it is less obvious that there is also a time-based (temporal) sampling taking place because the image is made up from successive fields, repeated at regular intervals. If we now also take samples of the television signal at regular intervals along the length (i.e. during the period) of each line, we can effectively represent our image in the form of a three-dimensional pattern of samples.

In the previous section we saw that an HDTV picture is likely to give rise to a great many samples per second, which will require a wide-bandwidth signal to carry it. The aim of MUSE, and of other HDTV systems such as HD-MAC, which will be considered in the next chapter, is to reduce the bandwidth required by HDTV picture signals, and this is done by throwing away, in a carefully controlled manner, some of the samples from which the...
(a) Original TV signal

(b) Result of sampling at frequency $f$
   - infinite number of repeats at multiples of $f$

(c) What happens if sampling frequency $f$ is
    less than twice the frequency of the original signal
    - overlapping signal spectra causes aliasing

(d) If the original signal is bandlimited to $f/2$ before
    being sampled (by filtering) no aliasing takes place

(e) To subsample the signal by a factor of 2 in order to reduce
    the data rate, the sampling frequency is reduced to $f/2$.
    This requires the original signal to be filtered again, reducing
    the band occupied by the signal to $f/4$, if aliasing is to be avoided.
The process of subsampling, or re-sampling an already sampled signal in order to reduce its data rate, will require the sampling frequency to be reduced, and this will therefore create a whole new set of repeat spectra. In figure 72(e) it can be seen that, if the signal is to be subsampled by a factor of two, the sampling frequency will need to be reduced to $f/2$. If we are to avoid aliasing, therefore, the original sampled signal must be filtered again, reducing its bandwidth to $f/4$.

Thus wherever we wish to sample a television picture signal we will first need to appropriately filter that signal, in order to avoid aliasing; the large number of low-pass filters that can be seen in the block diagram of a MUSE coder shown in figure 75 illustrates this point.

The MUSE system

The MUSE system is an essentially analogue television transmission system that uses a clever technique of sampling all the individual elements of an interlaced picture, and then selecting a fraction of these to form the actual signal that is transmitted. Stationary parts of the picture are sampled using a frame and field offset sampling technique, whereas moving parts of the picture use line offset sampling. Figure 73, provided by NHK in an early explanatory paper on their plans for satellite broadcasting, provides a useful illustration of how the MUSE system works in principle, but as we shall see later there have been many developments in this system, and there are some significant differences between the system shown in figure 73 and the current system. The main difference is that with the current system the pictures are

original image is built. The process of discarding these samples is known as **subsampling**.

If a radio frequency signal is sampled at a frequency, known as the sampling frequency $f$, then the sampling process will unavoidably generate a theoretically infinite number of repeats of the original signal at multiples of $f$ throughout the spectrum. In the case of a television signal, as shown in figure 72(a), this means that the first of the repeated spectra will be at $f$ MHz above the centre frequency of the original spectrum, as shown in figure 72(b).

Looking at figure 72(c) it can be seen that if the sampling frequency chosen is less than twice the frequency of the original signal, then the original spectrum and the repeated one will overlap, causing aliasing, i.e. interference between the two signals, which shows up as some form of patterning on the sampled picture. In order to prevent this happening when we sample a television picture, we must first of all filter the picture signal so that it does not contain any components above half the sampling frequency; this will ensure that no aliasing occurs, as shown in figure 72(d).
Figure 73 Principles of operation of the MUSE (Multiple Sub-Nyquist Sampling Encoding) system (courtesy NHK)

Number of scanning lines: 1125
Interface ratio: 2:1
Frame frequency: 30 Hz
Image aspect ratio: 5:3

Subsampled pattern at the first field: ①
Subsampled pattern at the second field: ②
Subsampled pattern at the third field: ③
Subsampled pattern at the fourth field: ④

Note: At the subsampling stage, inter-field offset and inter-frame offset subsamplings are adopted.

Blank areas indicate interpolated points on the reconstructed raster.

Only the sampled picture elements are transmitted during a period of four successive TV fields.
At the receiver, four successive fields are stored in a frame-memory; and for still-pictures, two successive frames are combined. Then the missing picture elements are interpolated.
subsampling by a factor of three, as shown in figure 74, rather than by the factor of four shown in the explanatory sketches of figure 73.

In figure 73 we can see that the original raster produced by scanning the picture with 1125 lines, at a frame frequency of 30 Hz and with a 2:1 interlace, is first of all sampled at 48.6 MHz and then the various subsampling patterns for each of the fields are generated as shown. During each of four successive television fields only the sampled picture elements which are indicated on the diagram are transmitted, and in the receiver it is therefore necessary to store four successive fields.

**Still picture areas**

For still pictures, two successive frames, i.e. four fields, are combined, and then any missing picture elements are obtained by interpolation in the receiver; the interpolated points are shown as the white squares on the diagram.

**Moving parts**

For moving parts of the image, advantage is taken of the fact that the resolution of the human visual system is much less for moving objects than for stationary ones. In practice, the human eye/brain combination does not try to keep all parts of a moving image in sharp focus, so if the eye is looking at the pattern on a man’s suit, for example, all the fine detail will be seen whilst the suit is stationary, but if the suit moves, the eye is quite happy to endure the situation where the detail in the pattern just disappears; this type of motion blur is quite acceptable.

In the MUSE system the moving parts of the picture are subsampled at a fraction of the main sampling rate, giving a poorer resolution, but as we have seen, the effect is generally quite satisfactory as far as the eye is concerned. There is, however, one particular type of television picture which seems to catch out the MUSE system, leaving the visual system feeling that something is not quite right. This occurs when a fast-moving object, perhaps a racing car, suddenly comes to a halt. Whilst the car is moving the eye is quite happy with the slight motion blur, but as soon as the car stops the whole image appears to instantly come into sharp focus, giving a rather unnatural effect. Some people feel that this problem is sufficiently troublesome to say that the MUSE system does not provide a good enough basis for an HDTV system which is to last for at least a generation, but most people accept that this effect will be rare in normal viewing, and it is generally felt that the disadvantages of MUSE are more than compensated for by the massive reduction in bandwidth requirements.

There is no doubt that the resolution of the MUSE picture is less than that of the original sampled picture, for both moving and stationary parts of the image, but once again television engineers have adopted the old adage that
what the eye doesn’t see the TV system doesn’t need to provide. In the original picture the resolution in directions corresponding to the diagonals of the picture can actually be shown to be twice the resolution in the horizontal and vertical directions. This is in spite of the fact that the human visual system actually has a poorer resolution along diagonals than in either horizontal or vertical directions. The reduced diagonal resolution of the MUSE pictures actually makes a very good match with the characteristics of the human visual system.

**Panned and tilted pictures**

A third type of image is actually the most complex for MUSE to deal with, and that is when the whole picture needs to move, as when the scene is panned or tilted. In these cases a motion compensation vector is calculated for each field, indicating the speed and direction of the panning motion, and this extra information is transmitted during the frame flyback period so that the receiver can make use of it to accurately reconstruct the image.

Figure 74 shows diagrammatically what effectively happens in the current versions of the MUSE system. Starting with a full-definition HDTV signal of the Hi-Vision type, we subsample the picture elements by three, so that the resulting signal can be transmitted over a satellite channel that can handle baseband signals of about 8 MHz. At the same time, information about the movement of the picture is sent from transmitter to receiver in the vertical blanking period of the picture. This *motion vector* information is then used to enable the sophisticated receiver to reconstruct an HDTV image.

Figure 75 shows a much simplified block diagram of a MUSE coding system. The *RGB* input signals from the camera are digitised at a sampling frequency of 48.6 MHz and then turned into linear form by removing the gamma correction. They are then converted into luminance (*Y*) and colour-difference (*C*) signals in a matrix, and the *Y* and *C* signals are combined into a Time Compressed Integration (TCI) format. The colour channel signals are time-compressed by a factor of four to one compared with the luminance, so as to provide the most acceptable noise performance. The TCI signal is then processed in different ways for the static and moving parts of the picture.
Figure 75 Simplified Muse coding system (courtesy NHK)
For moving parts line offset subsampling at 24.3 MHz (i.e. 48.6 MHz/2) is used, and for stationary parts frame and field offset subsampling is used. The three-stage sampling of the stationary parts of the image is carried out as follows:

- Original sampling 48.6 MHz (orthogonal sampling pattern)
- First subsampling 24.3 MHz (field offset)
- Second subsampling 16.2 MHz (frame and line offset)

The static and moving parts are then combined pixel by pixel, according to the amount of motion that has taken place, and the signal is subsampled at 16.2 MHz, the MUSE sampling frequency. Notice that the 16.2 MHz sampling frequency will allow the final MUSE signal to fit into a bandwidth of about 16.2/2=8.1 MHz. The original sampling frequency of 48.6 MHz was in fact chosen so that the 16.2 MHz figure would be achieved after the subsampling processes.

The signal then undergoes gamma correction and non-linear pre-emphasis to improve the noise performance, and the control signal (motion vector information) and synchronisation signals are then multiplexed together, as well as the digital audio signals, which are carried in the vertical blanking period.

In addition to the digital sound and the motion vector signals that are carried in the vertical blanking interval, special vertical interval test signals are included to give automatic equalisation of the transmission channel, allowing the receiver to compensate for any transmission deficiencies.

MUSE has been carefully developed to provide a very practical means of transmitting HDTV signals over relatively narrow bandwidth channels, and it includes other desirable features such as a very rugged synchronisation system, and a quasi constant luminance system which, as was discussed in an earlier chapter, is very desirable for an HDTV system.

The hardware for the coding and decoding of MUSE signals is fairly complex, and has up to now been very expensive. During 1989 the first large-scale integrated circuits for MUSE were produced, and it is expected that these will soon be available in quantity, which should make it possible to market MUSE equipment at prices which will appeal to the consumer market. The Japanese satellite BS3 began the transmission of regular MUSE transmissions in 1990, and it will be interesting to see if the availability of MUSE equipment at reasonable prices will lead to the Japanese public being the first to buy HDTV equipment in quantity. It is important to remember, though, that, as we saw in chapter 7, research suggests that the price of an HDTV receiver is more likely to depend upon the cost of the large-screen display than upon the cost of the complex electronics, so it may well be that these receivers will still remain too expensive for the mass market.

Although the Japanese HDTV production system and the transmission of its pictures via MUSE is currently far in advance of other systems in terms
of the development and availability of equipment, there are still big question marks as to whether such a completely different system, which is totally incompatible with any existing television transmissions, can possibly achieve market acceptance. The problems of this incompatibility and of having only a very small initial audience for programmes transmitted on such a different system have led other countries in Europe and America to adopt a different approach. They see the ideal HDTV system as being downwards-compatible with existing television systems, so that the same transmitted signals would provide HDTV pictures for those viewers equipped with HDTV equipment, whilst viewers with existing receivers could receive normal definition pictures on their existing equipment. This different approach is discussed in subsequent chapters.

The MUSE technique for obtaining significant reductions in bandwidth whilst still being able to regenerate acceptable HDTV pictures is being utilised in other ways, and we shall see when we come to discuss the various proposals for ATV systems in the USA that various different forms of MUSE are being developed to allow ATV signals to be carried on fairly narrow-bandwidth terrestrial transmitters.

References

There is now a general assumption throughout the television industry that one day in the indeterminate future HDTV will have replaced present-day television systems. In chapter 7 we discussed whether or not it was likely that viewers could be persuaded to spend money on higher-definition television receiving equipment, especially since there is currently very little evidence that television picture quality plays a major part in a typical viewer’s choice of programme. The industry is now convinced, however, that the arguments against HDTV are very much short-term ones, since the average life of a colour television receiver is well under ten years, so that between now and the end of the century, which is when HDTV will be becoming widely available, almost all existing viewers will have had to replace their existing television receivers. This means that the decision to buy an HDTV receiver will actually become a decision between buying a conventional receiver or an HDTV set, a marginal decision that may very well depend to a large extent upon the price at which HDTV receivers are available.

We have seen already, however, that there are several major considerations, both technical and commercial, which make it unlikely that there will suddenly be a technological revolution which persuades all the people to throw away their existing equipment and rush around to the local shop to buy brand new HDTV receivers. It is therefore very important to give the strongest consideration to the various ways in which HDTV might be introduced, assuming that in the longer term HDTV will become the normal method of watching television.

In the studies of HDTV that have been going on around the world, three main approaches to its implementation have been prominent. The first approach, typified by the Japanese 1125-line/60 f.p.s. system, is to produce a format with a completely new emission system, that is not compatible with any existing system such as PAL, SECAM, or NTSC. The general idea is that such signals would be radiated via satellite or cable systems, although there is no reason why, in principle, such a system could not also be adopted for terrestrial transmission. New receivers specially designed for the HDTV system would be required to provide the higher-quality pictures and sound. Conventional receivers would only be able to make use of these signals if they were to be provided with complex transcoding
standards conversion equipment, which would be very expensive, and even then the viewer with a conventional receiver would only see the new programmes at a quality determined by the existing receiver.

The second approach, which has proved of particular interest to American broadcasters, is to produce a so-called compatible emission system format which consists of a signal that is compatible with a conventional television system plus an augmentation signal that provides the additional information that is required to produce an HDTV picture. Such systems enable conventional receivers to pick up the compatible part of the programme material from the HDTV emissions at the same quality as their normal pictures, whilst viewers with special HDTV receivers can make use of the full quality of the HDTV signal. This type of system can be considered as truly compatible, since an existing viewer needs no adaptor to receive the HDTV programmes, although they are only received at the same level of quality as the conventional programmes.

The step-by-step or multi-step systems are those which make use of an improved quality television system as the first step towards HDTV, this first step not being compatible with an existing standard. The introduction of MAC systems for satellite broadcasting in Europe can be considered as an example of a first step in this type of system. Once the first step has been taken, the scene is set for the later introduction of an HDTV system which is fully-compatible with the new system introduced in the first step.

Receivers that could receive first-step signals would automatically be able to receive the second-step HDTV pictures, but at reduced quality, and HDTV receivers would be able to receive full-quality HDTV step-two transmissions as well as the first-step transmissions.

In this type of system conventional receivers would not be able to receive the HDTV transmissions, and could only receive the first-step transmissions if a fairly complex adaptor is used, and even then receivers using such adaptors may not be able to make use of all the technical advantages of the new transmissions. The HDTV receiver would not be able to receive conventional transmissions unless it was fitted with extra circuitry, but some people feel that this will not be a significant disadvantage since it may take so long for this stage to be reached that conventional transmissions will have come to the end of their natural life. This writer tends to feel that conventional transmissions still have a great deal of life left in them, and that the extra cost of including conventional decoding circuitry for PAL signals would perhaps make little difference to the total cost of an already expensive large-screen HDTV receiver.

Using this step-by-step approach it seems that at least three different generations of receiver hardware would be involved:

- **step 1** conventional receivers:
  - existing 525/60 and 625/50 NTSC, PAL, SECAM receivers
- **step 2** improved systems that retain 525/60 and 625/50 displays (MAC systems, for example)
Figure 76 HDTV delivery—the future environment (CCIR Report 801–3)
step 3 full HDTV receivers

There may also be several other intermediate steps introduced, allowing developments such as wide-screen enhanced receivers which are capable of improved 525 or 625-line displays, without providing full HDTV quality.

Figure 76, based on a drawing from Professor Krivosheev of the CCIR study group which is examining possible routes towards HDTV (ref. 1), gives a broad overview of the various options which will become available as the change from conventional services to HDTV takes place. It illustrates the various linkages that must be taken into consideration between the different elements of the television system of the future, from studio, via the transmission channel, to home.

The key part of the future broadcasting environment will be the HDTV production centre which is shown at the top of the diagram. Whilst most of the productions will be made in the HDTV format, it will, for the foreseeable future, be necessary to use other contribution formats as well, since archival material in 525 and 625-line formats, analogue and digital, as well as films in various formats, will provide much of the necessary programme material.

From the production centre the HDTV programme material will pass to the broadcasting network via a multi-purpose distribution interface, at which point there will be a number of convertors to change the HDTV source signals into the various forms that are necessary for the various broadcast systems. The convertors will provide outputs suitable for standard 525 or 625-line transmissions, enhanced television transmissions, bandwidth-reduced HDTV transmissions, for use over satellites perhaps, and the full bandwidth HDTV signals which may be passed over fibre optic networks.

The outputs from the different delivery systems are then sent to the viewers, and here it is worth noticing that the diagram also offers the possibility of physical delivery of HDTV programme cassettes to the home as one of its alternatives. The quality of the picture that the viewer actually sees will depend to a great extent upon the receiving equipment that is installed in the home. Signal quality could range from full-bandwidth HDTV through reduced-bandwidth HDTV to various levels of enhanced television as well as the basic 525 and 625-line services, and the diagram shows that it will be necessary for an HDTV receiver to be able to receive the normal 525 and 625-line transmissions in addition to the HDTV signals.

EUREKA—the European approach to HDTV

After the Japanese proposals in the early 1980s for the adoption of their 1125/60 HDTV system as a worldwide standard were rejected by European broadcasters, the EBU Technical Committee, which had been studying HDTV since 1981, suggested various ways in which a worldwide agreement
on HDTV standards might be reached. A major plank of their proposals was that an 80 Hz interlaced HDTV studio standard should be introduced, 80 Hz having the merit that it would allow relatively simple standards conversion to and from both 50 Hz and 60 Hz systems. Unfortunately, this idea was not accepted by the rest of the world’s broadcasters, and the goal of reaching a common standard seemed to be getting no nearer, as those countries using 60 Hz field rates felt that it would be a backward step to adopt 50 Hz, and those using 50 Hz felt that it would be too much of an upheaval to have to make the change to 60 Hz. Even some of the members of the European Broadcasting Union disagreed as to the field rate to be used.

All this gave rise to the formation of a European multi-national research and development project aimed at bringing together interested parties to combine their research efforts in the field of HDTV; the project was named Eureka EU95. The project was the joint initiative of Bosch (West Germany), Philips (Netherlands), Thomson (France), and Thorn EMI (U.K.), but many other European industrial companies and public and private sector organisations also joined, so that there are now over thirty participants (ref. 2).

The main aims of the project were to propose a compatible HDTV studio standard of the highest quality, suitable for use in 50 Hz countries and designed in such a way that the HDTV signals can, in the future, be transmitted, but can also be used as the source from which lower-quality signals may be derived, which can be carried by present-day satellites, terrestrial transmitters, or cable systems and displayed and recorded with existing receiving equipment. Another well-understood aim was to have this system, rather than the Japanese 1125/60 system accepted as the world standard, but as has already been indicated, this aim was much less likely to succeed.

The project did succeed in its aim of submitting a proposed standard, or more properly, a detailed specification of such a standard, to the CCIR plenary assembly in 1990, and of building a full range of equipment to demonstrate that the system really does work. This standard can provide pictures which are a significant improvement on anything seen so far in the HDTV field, and it has also been designed to be readily compatible with film, since it is felt that 50 Hz systems are superior to 59.94 Hz or 60 Hz systems when it comes to transfer to and from film, and to make possible the exchange of programme material between 50 Hz and 60 Hz countries.

The system is of the step-by-step type detailed above, in which a full-quality HDTV signal is generated in the studio, whilst a specially processed version, known as HD-MAC, is transmitted, a signal that is compatible with the MAC family of standards, so that people who have bought the first generation of MAC satellite receiving equipment will be able to make use of the HD-MAC transmissions at lower than HDTV quality. In this sense, compatibility means that existing equipment is not immediately made obsolete as the new transmissions begin; ‘old’ receivers (only back as far as the first generation of MAC receivers though, which in 1990 is not very far
back!) will be able to make use of the new HDTV signals, and new receivers will also be able to pick up straightforward 625-line MAC signals (figure 77). This also means that existing videorecorders will not need to be made obsolete, although once again the initial compatibility will be limited, as current videorecorders can only record PAL/SECAM/NTSC signals. It is worth noting however that some work has been done to investigate whether domestic videorecorders could be made to record MAC signals, and the outcome was that this should present few problems for the manufacturers.

The Eureka HD-MAC approach to HDTV is a genuinely evolutionary approach that will allow viewers to change up to better standards of display as they wish. The key to all this is the realisation that no longer do receiver standards have to be the same as the production studio standards; it is possible to have a very high quality production studio source, and to derive from this a less-good version of the studio signal which may be transmitted over a standard bandwidth transmission channel. Once this signal is received in the home, it can be displayed on an ordinary MAC receiver, or it can also be displayed on a receiver that is fitted with advanced signal processing equipment, which can provide enhanced-quality pictures (ref. 3). Readers who have difficulty in understanding how studio and transmission paths may have different standards should think of what happens in a studio today, when a 35 mm film is being used as the programme source. The 35 mm film is capable of producing pictures of a much higher technical standard than the 625-line PAL network can transmit, but a picture of somewhat lower quality than could have been produced from the original film is transmitted via the transmitting network and is received in the viewer’s home.

Figure 77 Simple illustration of HD-MAC compatibility with 625-line MAC
In the same way, it is clear that pictures could be transmitted at a field rate of 50 Hz and yet displayed with a field rate of 100 Hz if suitable storage and processing circuitry was built into the receiver. The simplest way of achieving this field rate upconversion would be to repeat each field of the incoming picture to produce 100 fields/sec, but if this method is to be used with 100 Hz interlaced displays it is necessary to interpolate between the lines of the incoming fields to ensure that the lines appear in their correct places (figure 78). To produce a display with a 100 Hz refresh rate it is estimated that perhaps an extra 3 Mbytes of storage must be included in the receiver, and although this may seem a lot, it is expected that a full HD-MAC receiver will need at least 9 Mbytes for all its picture-processing circuitry. This technology can only be transferred to the domestic marketplace if memory costs fall, and it is fortunate that memory chips are expected to fall in price until the cost of all this storage becomes an acceptable percentage of the cost of the receiver, the ‘ten-dollar frame store’ being something that manufacturers regard as a goal which can eventually be achieved.

**The Eureka family of systems**

As well as being based on the MAC family of systems, the various steps of the Eureka EU95 project have also been arranged so that each one bears a simple relationship, when expressed in digital form, to the international digital studio standard defined in CCIR Recommendation 601 (ref. 4).

The long-term target for the studio standard of the European HDTV system, which has been submitted to the CCIR as a proposed *world* HDTV studio standard, has the following characteristics:
The analogue picture signal is in the form of three, parallel, time-coincident component signals, consisting either of red, green, and blue signals or of a luminance signal and two colour-difference signals. When expressed in digital form the signals have the following characteristics:

**Number of samples per active line**
- Luminance signal: 1920
- Colour-difference signals: 960

**Number of samples per full line**
- Luminance signal: 2304
- Colour-difference signals: 1152

**Sampling frequency**
- Luminance signal: 144 MHz
- Colour-difference signals: 72 MHz

Since CCIR Recommendation 601 assumes interlaced scanning, it was originally thought that the HDTV studio standard might be based upon interlaced scanning, but we have seen already that better performance, with a greater apparent vertical resolution and an absence of interline flicker, can be obtained from continuous (progressive) scanning, although this performance is only obtained at the cost of an increased video bandwidth.

It was therefore decided to base the hierarchical family of studio standards on a 50 Hz progressive standard. The various evolutionary steps as far as studio production is concerned are detailed in figure 79, and it can be seen how each step upwards is based upon the original Recommendation 601 standard; there are three levels of HDTV defined, together with an enhanced 625-line system which has a 16:9 aspect ratio and non-interlaced sequential scanning (ref. 5).

The *high-definition progressive standard* (HDP) thus represents the ultimate in the European HDTV system, but requires a large amount of data processing and storage to cope with its data rate of 1728 Mbit/s. 1920 luminance samples are taken for each active line, but colour-difference
<table>
<thead>
<tr>
<th>Scanning parameters</th>
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<th>Sampling parameters</th>
<th>Gross bit rate (Mb/s) ((Y+2C) \times 8) bits/sample</th>
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</thead>
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<tr>
<td>HDP (1) 1250 / 50 / 1</td>
<td>16 : 9</td>
<td>Luminance Y 144 MHz orthogonal (1920 s/apw)</td>
<td>36 MHz orthogonal (960 s/apw)</td>
</tr>
<tr>
<td>HDQ (2) 1250 / 50 / 1</td>
<td>16 : 9</td>
<td>Colour-difference C 72 MHz quincunx (960 s/apw)</td>
<td>36 MHz orthogonal (960 s/apw)</td>
</tr>
<tr>
<td>HDI (3) 1250 / 50 / 2</td>
<td>16 : 9</td>
<td>Luminance Y 72 MHz orthogonal (1920 s/apw)</td>
<td>36 MHz orthogonal (960 s/apw)</td>
</tr>
<tr>
<td>EDTV (4) 625 / 50 / 1</td>
<td>16 : 9</td>
<td>Colour-difference C 36 MHz orthogonal (600 s/apw)</td>
<td>9 MHz orthogonal (480 s/apw)</td>
</tr>
<tr>
<td>REC601 (5) 625 / 50 / 2</td>
<td>4 : 3</td>
<td>Luminance Y 13.5 MHz orthogonal (720 s/apw)</td>
<td>6.75 MHz orthogonal (360 s/apw)</td>
</tr>
</tbody>
</table>

(1) HDP: High Definition Progressive scanning
(2) HDQ: High Definition Progressive scanning and Quincunx sampling pattern
(3) HDI: High Definition Interface scanning
(4) EDTV: Enhanced Definition Television
(5) Rec 601: CCIR Recommendation 601

Note: s/apw = samples per active picture width

*Figure 79 The proposed family of studio standards (courtesy Eureka)*
samples are taken at half this rate, and only on alternate lines, giving the sampling pattern shown in figure 80.

Figure 81 is drawn to illustrate the limiting resolutions, horizontally and vertically, that a system of this type gives; we can see that the vertical resolution for the luminance part of the picture is 576 cycles per active picture height, and if we say that we can carry two bits of information per cycle this is equivalent to $2 \times 576 = 1152$ active lines. For the colour-difference part of the picture signal, since we only have the colour signals on alternate lines we have only 288 cycles per picture height. In the horizontal direction there are 1920 samples per active picture width for luminance and half this number for the colour difference signals.

The next level down in the hierarchy shown in figure 79 is known as HDQ (High Definition Progressive Scanning and Quincunx sampling), and this

![Figure 80 Luminance (+) and colour-difference (o) sampling pattern for the HDP system](image)

![Figure 81 Limiting resolutions for luminance and colour-difference components of the High Definition Progressive Scanning system](image)
The system manages to preserve the benefits of progressive scanning whilst reducing the data rate and signal bandwidth required, making it a practical way to provide progressive scan HDTV pictures. This is achieved by sampling the signal ‘quincunxially’, so that the resulting samples appear in sets of five, like the arrangement of five dots on the sides of poker dice, as shown in figure 82. In order to do this the picture must first be diagonally filtered, but as we saw when we were considering the MUSE system, the eye is happy with the results of this, since it is not very sensitive to lack of detail in diagonal directions, and the effective horizontal and vertical resolutions for both luminance and colour stay the same as for the HDP system.

The limiting resolutions for the HDQ system are shown in figure 83, from which the effect of the diagonal filtering can be seen.

The sampling frequency of the luminance signal can be reduced to 72 MHz by this technique, but the colour-difference signals are sampled at the same 36 MHz rate as for HDP signals. The total data rate for the luminance signal and the two colour-difference signals of the HDQ system is therefore reduced to

\[(72+2\times36)\times8 \text{ bits per sample}=1152 \text{ Mbit/s}\]

The third level of the hierarchy, and the lowest level of HDTV, has 1250 lines per frame and 1920 samples per active line, but uses 2:1 interlaced scanning. This is called the *interlaced studio standard*, HDI, and the sampling pattern for luminance and chrominance components can be seen in figure 84.

Notice that there are still 1250 lines per frame, but that each frame is now made up of two sets of interlaced 625 line fields. Although the luminance can now be sampled at only 72 MHz, compared with the 144 MHz needed for the HDP system, we still get 1920 samples per active picture width. The interlace makes it unavoidable that there will be colour-difference signals on every line, as shown in figure 84, and this results in
greater colour-difference resolution in the vertical direction, as is shown in the resolution diagram for the HDI system, figure 85.

You never quite get something for nothing, however, and we have to remember from chapter 7 that an interlaced display requires about 1.5 times as many lines as a progressive, sequentially scanned display in order to subjectively give the same resolution. This means that, although the vertical resolution on the diagram appears to be a full 576 cycles per picture height, equivalent to 1152 lines, in practice this will be reduced by a factor of about $1/1.5$, approximately 0.6.
The world production standard, or just one of them?

The 1250/50/1:1 HDP proposal gives excellent pictures and it is felt that this system has enough extra quality in hand to cope with any processing which it is likely to undergo in a studio environment; the Eureka EU95 team would like this to become the eventual world HDTV production standard, and it certainly seems that it will definitely become the standard for Europe. To try to persuade the 525-line countries that a 1250/50 HDTV system would be suitable for them, much work has been carried out on standards conversion techniques. The aim is to show that HDP signals can form an excellent basis for conversion to a 1050-line/59.94 Hz system and then can be further downconverted to provide 525-line NTSC compatible pictures. It seems that most of the technical problems of this type of conversion can now be overcome, but political considerations still make it most unlikely that 60 Hz countries will adopt HDP.

Very good progress has been made with the production of equipment for the Eureka EU95 project, and as long ago as September 1988 the team were able to demonstrate a 1250-line sequential scan camera and a complete HDTV chain sending signals over satellite links, with displays from projectors and cathode ray tubes showing the high-definition MAC signals in many different formats.

Transmitting compatible HDTV signals

So far we have discussed in detail only the production standards part of the European HDTV initiative, but we must remember that one of the key
The starting point, and the sticking point, for anyone wanting to transmit HDTV pictures, is that CCIR Report 801 gives the definition of HDTV pictures as pictures having approximately twice the horizontal and vertical resolution of normal television pictures; this means that they must contain around four times the information of a normal television picture, and will require about four times the bandwidth to transmit. Although it might be feasible in the future to provide enough bandwidth over fibre optic cable networks and satellites in the bands from 20–80 GHz, at the present time, and for the foreseeable future, we just don’t have the radio frequency spectrum available to allow us to transmit HDTV without first of all processing it in some way which will reduce the bandwidth of the signals. Effectively, then, we need some means of taking a 1250-line/50 f.p.s. source picture and compressing it so that it will pass over a normal 625-line MAC satellite channel and produce a usable picture on a standard 625-line MAC receiver. In addition we need owners of HDTV receivers to be able to use the same 625-line signals, plus perhaps some data transmitted in the frame blanking intervals, to be able to obtain a high-definition picture on their display.

The Eureka EU95 HDTV project aims to overcome these problems, and to use the MAC/packet transmission system to provide a step-by-step route to full HDTV in a manner which ensures compatibility with all receivers using the MAC system. The basic principles of the HD-MAC transmission system are shown in figure 86.

Perhaps the first point of interest in this diagram is its similarity to figure 74, which illustrates the principles of MUSE; the same types of technology are being used to provide better picture quality at the receiver than could normally be expected if the transmissions are sent via a relatively narrow-
band channel. The big difference between the two systems is that the HD-MAC system can be introduced in a compatible manner, providing all the commercial advantages that were discussed in chapter 7.

The production standard 1250-line HDTV picture provided by the camera in the studio needs to have some of the information which it contains removed before the picture can be passed through a standard satellite broadcasting channel, which can cope with a baseband signal bandwidth of about 10 MHz. Note that the diagram shows the source as 1250/50 interlaced, since that was the standard used for the Eureka HD-MAC demonstrations in 1988, but further developments in this project will probably see the ‘top-quality’ source eventually providing 1250/50 non-interlaced pictures.

**Characteristics of the working HD-MAC transmission system**

It is important to remember that HD-MAC is still very much under development, and that changes to the original system are almost certain to be made before regular transmissions begin. The HD-MAC studio production standard described in the previous section as the target system is somewhat different from the working system which is actually being used for tests and demonstrations of the HD-MAC transmission system at the present time. This utilises 1250 lines, 50 fields per second and 2:1 interlace, and differs from the system that we have described mainly in that the basic sampling frequency is 54 MHz, rather than the 72 MHz that we have used so far, giving 1440 luminance samples per active picture line (rather than 1920), and 720 colour-difference samples per line (compared with 960). Note that these numbers of samples are twice the samples per line defined for the CCIR 601 digital standard, so that we are still transmitting a true HDTV picture according to the definition given in CCIR Report 801, since we have twice the horizontal and vertical resolutions of the basic 625-line standard.

From figure 86 we see that the pictures from the source are first subsampled by a factor of four, which effectively compresses the 1250-line interlaced signal which has 1440 samples per line and produces a 625-line interlaced signal with 720 picture elements per line. This lower-bandwidth signal is then sent to a MAC coder for encoding as a standard MAC/packet signal, which may be transmitted over a standard direct broadcasting satellite channel.

Although the pictures seen by the viewer with the conventional 625-line MAC receiver who is watching images derived from a 1250-line HD-MAC source will be very good, critical viewing may well show some aliasing artifacts, taking the form of slight patterning in some picture areas. This is an inevitable result of the subsampling of the HDTV signals that has taken place, but is not generally regarded as seriously degrading the pictures, and its effect is probably even less than that which was suffered by viewers of black-and-white receivers when the colour television subcarrier was added to the transmitted monochrome signals in the 1960s.
Digital assistance

Subsampling inevitably leads to some loss of information from the transmitted signal, whereas the job of the HD-MAC receiver is to build an HDTV picture which is as close as possible to the original. It is possible, at the source, to analyse what has happened to the original picture in the subsampling process, and to transmit information about this to the receiver. This will enable an HDTV receiver to control various complex processing circuits, which will enhance the received 625-line picture information and allow an HDTV picture to be displayed. This extra control information, sometimes called digital assistance, can be transmitted during the frame blanking intervals, in a similar way to which teletext is carried on normal terrestrial transmissions, so that the control information is carried as an integral part of the HD-MAC signal. The capacity of the digital assistance channel when a standard 625-line MAC signal is being transmitted over a satellite is about 1 to 1.5 Mbit/s.

Much of the information which we shall want to transmit as digital assistance will be to do with picture movement, and information about the movement of various areas of the picture may be sent to the receiver in various ways. There are two major methods of dealing with motion, the processing systems being known as motion adaptive and motion compensation, the latter being a more complex and more powerful technique. In motion adaptive systems the control information sent merely tells the receiver to switch between two or more processing methods for different parts of the picture, whereas when the motion compensation technique is used the data takes the form of motion vectors which can be used by the processing circuits in the receiver to accurately calculate where each group of picture elements should be displayed. In a perfect world it might be desirable to send information about the speed and direction of motion of every moving picture element, but the available vertical blanking interval data channel is much too small for this, so the picture has to be analysed as blocks of pixels, but this works well in practice.

The motion adaptive technique

The first technique uses an approach similar to that which was discussed when considering the MUSE system, in that each picture is divided into two different types of information, corresponding to areas where there is no movement of the image, and areas which are moving. The processing mode that is utilised then depends upon whether or not the particular part of the picture is static or moving, and switching takes place between the two modes, so as to make the best use of the available bandwidth. It is systems in which this type of switching takes place that are called ‘motion adaptive’.

Whether or not a particular group of pixels is moving or static can usually
be determined fairly simply by comparing the pixels in adjacent pictures. Having divided the areas of the picture in this way, the information from the static areas of the picture is temporally filtered and then subsampled by a factor of two, which effectively throws away every other pair of fields. The remaining pair of fields is treated as four standard MAC fields of 288 lines by 720 pixels, and these are transmitted over a four-field period. Pixels are interleaved using a line-shuffling technique, which improves the effective horizontal resolution. At the receiver, each incoming picture is stored and then displayed twice, which, since the picture elements involved have not moved, provides a satisfactory display. The information from the moving parts of the picture is again filtered and then subsampled by a further factor of two, and then transmitted every field period. The result is a loss of detail in the moving parts of the picture, but as we saw before, this generally proves acceptable to the eye, which is not very sensitive in these circumstances (ref. 6). Motion adaptive techniques need not be limited to just two classes of picture movement.

The motion compensation technique

The motion compensation technique allows for much better results than using motion adaptive techniques when trying to transmit fine detail in moving areas, but this improvement comes only at the expense of considerably more complexity in the coder. Basically, the position of small blocks of picture elements is compared from one field to another, and the centre of the block is seen to have moved in a particular direction at a certain speed. The speed and the direction of movement are then conveyed to the receiver by means of the digital assistance channel in the form of a motion vector, and the position of the displayed pixels is adjusted accordingly. As was mentioned earlier, the amount of data which the DATV channel can carry is limited to somewhere around 1.5 Mbit/s, which means that the number of motion vectors that can be sent is insufficient to cope with very complex movements.

Perfect processing of all pictures is still a long way away, however, and several different schemes are being investigated by the Eureka EU95 team, including a system which uses both of the above techniques, automatically deciding which technique to use according to the type of motion involved (ref. 7). One interesting trick that can be used in the coder, although it is very complex in terms of information processing, is to try each of the available techniques for dealing with motion on each block of pixels, and then to test the results in the coder, prior to transmission, by rebuilding the block in the coder, in just the same way as it would be treated by the receiver’s decoder. The result of the test is then compared with the original information presented to the coder, which is, of course, still available at that point. The technique which provides the best result from these tests is then used for transmission of that particular block.
Widescreen HD-MAC

In chapter 5 the possibilities for achieving compatible widescreen pictures using MAC were explained. Of the various approaches that were considered, HD-MAC makes use of a system in which the decoder can be switched between two different sets of compression ratios in order to cope with pictures having either the standard 4:3 or the wideband 16:9 aspect ratios. To understand how this happens, let us consider three different scenarios, and see what happens at both source and display ends of the broadcasting chain.

Figure 87 shows the simplest case, when the source is a 4:3 aspect ratio picture and the display has the same aspect ratio. This is the situation with the normal standard MAC pictures, and the decoder will therefore need to expand the received picture signals by the standard ratios of the MAC system, 3:2 for luminance and 3:1 for the colour-difference signals.

The second case is shown in figure 88, where the source is using a widescreen 16:9 aspect ratio whereas the display is a conventional 4:3 receiver. In this case using the standard MAC expansion ratios would lead to the decoded picture being distorted, since the original pictures have been compressed by the usual 3:2 luminance and 3:1 colour-difference ratios. It is therefore necessary in the decoder to use the alternative expansion ratios of 2:1 and 4:1 if the picture on the 4:3 display is to maintain the same relative proportions as the original. Unfortunately this leads to the decoded picture being wider than the display screen, and so in this case we have to arrange that the 4:3 receiver only takes in and expands a part of each line,
as shown in figure 89. Effectively, this method discards the sides of the original 16:9 picture, but keeps the remaining 4:3 picture undistorted.

The third case to be considered is that where both source and display have the widescreen 16:9 aspect ratio. In this case the standard MAC expansion ratios of 3:2 and 3:1 produce the correct display, as shown in figure 90.

We thus have a system that allows for different aspect ratio receivers to be provided with pictures of the correct aspect ratio, irrespective of the source aspect ratio, in a very compatible manner. There remains, however, the problem that the person who buys an expensive widescreen receiver will have to put up with pictures that do not fill the screen for much of the time, since it seems unlikely that broadcasters will be able to provide continuous 16:9 programming for some years to come, and the vast amount of archival material shot with a 4:3 aspect ratio will always present this problem. It has been suggested that the areas at the side could be filled with other information, ranging from electronically generated ‘curtain’ patterns to small pictures showing what is on the other channels, but another option that is likely to be offered by manufacturers is to allow for the screen to be over scanned top and bottom, making for a picture that actually fills the visible screen area, but in which the top and bottom of the original display is lost. To television professionals who have been trying for years to ensure that their

![Diagram](image-url)

Figure 89 Showing how only part of the MAC line is used to provide a 4:3 image when the source has a 16:9 aspect ratio

![Diagram](image-url)

Figure 90 MAC decoder expansion ratios with 16:9 source and display
carefully composed pictures are seen in the home as closely as possible to the
originals this may be anathema, but to receiver marketing men it may well be
a way of persuading potential customers to purchase a widescreen receiver.
The French company Thomson is promising that its widescreen receivers will
give the viewer the capability of varying the picture geometry at will—they call
it ‘format control’—so as to provide the choice between filling the screen or
having an undistorted picture with blank edges. Figure 91 shows a
photograph of a prototype of Thomson’s advanced television receiver,
expected to be on sale towards the end of 1990, which, as well as format
control, has internal circuitry which provides a doubling of the lines from a
standard 625-line MAC picture to provide a 1250-line display.

This is to be a multi-standard PAL/MAC/RGB/YC receiver with all the

Figure 91 Thomson 16:9 multi-standard receiver with 1250-line display
inputs and outputs that you could think of, including something with the marketing man’s dream name of a ‘golden SCART’ socket, which will allow HD-MAC signals to be plugged in once they become available. The receiver is not strictly an HDTV receiver, since the tube has less resolution than that required for HDTV, but it will let viewers take full advantage of any extended signals that become available, and will allow them to make use of the widescreen display, even with transmitted 4:3 pictures. It is likely to cost around £3000 initially, according to manufacturers estimates.

**Constant luminance**

In chapter 2 the problems of achieving constant luminance were discussed, and it was seen that no current transmission standard conforms to the constant luminance principle. The coming of HDTV has brought with it the chance to try to improve upon current signals as far as this aspect is concerned, and we have already seen that the 1125/60 system has been designed to operate on quasi constant luminance principles. The HD-MAC system has been designed to use true constant luminance, so that the luminance of highly saturated colours will be conveyed properly, and the chance has also been taken to increase the colour gamut, providing a wider choice of colours. The decision to utilise constant luminance with HD-MAC was taken after the MAC specification had been finalised, so there will be some incompatibility with standard MAC decoders, but tests have shown that this will not seriously degrade the pictures.

**Progress with the 1250/60 system**

Except for the system’s unlikely acceptance as the world production standard, work on the 1250/50 studio standard is going according to plan. The HD-MAC transmission project is also progressing well, with equipment rapidly being developed for both studio and home use. The target date for domestic receiving equipment to be available is 1992, and the various members of the Eureka EU95 team are working hard to meet this target. The 1992 Olympics, which are to be held in Barcelona, Spain, will be covered by HD-MAC cameras, and the aim of the Eureka manufacturers is to have HD-MAC receivers on sale in the shops by that time. Most market estimates suggest that the cost of such receivers will initially put them out of reach of the average domestic viewer, but, as we have seen, there are good reasons for thinking that these costs can eventually come down.

**Enhanced television—the half-way house?**

Since it will be several years before an HDTV system providing widescreen pictures can be introduced, and it will probably be some years after that before reasonably priced receivers appear in the shops, manufacturers are
looking at ways of introducing receivers that can provide improved and enhanced pictures before HDTV appears. It was mentioned earlier that source and display standards can now be independent of each other, and one method of taking advantage of this is already starting to be seen in domestic receivers.

If a receiver is fitted with field storage and interpolation circuitry, then a 625-line progressive scan picture can be built up from the incoming interlaced signals, using the technique that was shown in figure 78. This enhanced television picture provides a significant improvement in perceived resolution, and eliminates inter-line flicker, without any change being made to the basic MAC signal that is transmitted. Effectively, this is making use of the second step of the step-by-step approach to HDTV which was explained earlier in this chapter, whereby an improved system using a 625/50 display is introduced.

**Widescreen without waiting for HDTV**

The marketing men of the receiver industry are keen to see the early introduction of widescreen receivers, because they are convinced that the noticeably different shape of the screens will persuade those people who must have everything that is new and different to rush out and buy such receivers. One of the more cynical salesmen was heard to say that ‘the Joneses’ would buy such a receiver because their neighbours would be able to tell that it is different, even when it is switched off! Fortunately there is no need to wait for HDTV before such widescreen pictures can be transmitted, and the British DBS operator BSB is already providing widescreen transmissions of feature films, which, being originally intended for the cinema, are already originated in a widescreen format. We have seen earlier that as far as viewers with MAC receivers are concerned, these widescreen transmissions are fully compatible with ordinary 4:3 aspect ratio receivers, so audiences for these films should be high, since they will not be restricted to viewers with widescreen receivers.

After seeing demonstrations of 16:9 aspect ratio widescreen pictures on receivers that provide a progressively scanned 625-line display, many viewers have expressed the view that these pictures are as good as they could want, and some people even feel that there is no need to make the final move to ‘proper’ HDTV for home receivers.

**Extended definition without waiting for HDTV**

It is even possible to extend the definition of 625-line MAC pictures so as to provide some increase in the horizontal resolution of the 625-line widescreen MAC pictures, with no loss of compatibility. This work was pioneered by the research engineers of the UKIBA (ref. 8), and the basic idea is to increase the transmitted luminance bandwidth from its normal 5.6
MHz to around 8 MHz, which results in a channel base bandwidth after compression of about 12 MHz, rather than the 8.4 MHz of a normal MAC transmission. Special non-linear pre- and de-emphasis circuitry has been developed, which automatically alters the amplitude/frequency response according to the level of the signal, and using this technique the extended MAC signals can be transmitted over a normal satellite channel with no significant increase in noise or interference to other channels. A standard MAC receiver, which may not initially be fitted with the modified de-emphasis circuitry, still provides first-class pictures, which actually appear slightly sharper than with normal MAC transmissions because of an edge-crispening effect which occurs.

So good are the results that this type of enhanced 625-line MAC system can provide, when viewed on screens with a diagonal of about 1 metre at a viewing distance of three times the screen height, that some people, including an English Member of Parliament (ref. 9), have suggested that the UK government should stop contributing money to the Eureka EU95 project, and should instead concentrate its resources on encouraging British industry to concentrate on the development and production of enhanced television. The argument is that most viewers will not be able to tell the difference between true HDTV and the enhanced pictures, so that it might make sense to begin compatible enhanced 625-line transmissions very soon, delaying the jump to a full HDTV system until such time as new digital HDTV systems are developed. A completely new digital system would not suffer from the political disadvantage of being associated with any current system, so that it might be possible to gain agreement on a single world standard, and even the CCIR groups that are currently working toward a common analogue HDTV system recognise that the long-term future for HDTV lies in the digital domain (ref. 10). Possibilities for future digital HDTV systems are discussed later.

Whatever the final outcome of the suggestions to go no further than extended definition before taking a digital path to HDTV, and it seems to me most unlikely that the UK would take such a different line from its European neighbours, it is beyond doubt that first-class results can be obtained from 625-line MAC pictures, with the techniques described, and it may well be that large-screen improved definition images of this type will prove to be the next commercial step along the road to our eventual goal of HDTV. The Eureka EU95 system with its goal of HD-MAC has many advantages over other systems, but its trump card must surely be that it has compatibility at every step. We have seen the steps up to HDTV from the production point of view, so now we end this section with the step-by-step approach as it may affect the viewer. We must remember that viewers (and manufacturers) will not necessarily have to take every step, they can stay where they are or can jump over one or more steps, as they wish; they can choose the improvements that they want and that they are willing to pay for, at a time that suits their needs and their budgets. We can only hope
that viewers will be able to obtain all the information that they will surely need to help them to make informed choices; at least the MAC chip set will provide the full choice of all the available sound systems, so that the viewer will not have to choose between them!

**A step-by-step guide to receiver improvements towards HDTV for the viewer using the HD-MAC system.**

1. 625-line MAC interlaced 4:3 aspect ratio display, perhaps using an existing PAL receiver with a satellite adaptor feeding the receiver with signals via a peritelevision socket.
2. 625-line MAC progressively (sequentially) scanned 4:3 aspect ratio display.
3. 625-line widescreen interlaced 16:9 aspect ratio display.
4. 625-line widescreen progressively scanned 16:9 aspect ratio display.
5. 625-line widescreen progressively scanned 16:9 aspect ratio display with extra processing in the receiver to improve the display of moving parts of the image.
6. 1250-line HD-MAC HDTV widescreen interlaced display.
7. 1250-line HD-MAC HDTV widescreen progressively scanned display.
8. 1250-line HD-MAC HDTV widescreen progressively scanned display with extra processing to improve the display of moving parts of the image.

**Enhanced television—the Japanese have it too**

In parallel with the European work on enhanced television, the Japanese have been developing a method of providing better quality pictures from their 525-line NTSC system for those viewers who are prepared to buy new television receivers equipped with extra processing circuitry. The system is called Clear-Vision (their HDTV system is Hi-Vision) and the pictures are actually originated using the HDTV 1125/60 studio standard. These pictures are downconverted in the studio to 525-line form, and generally have higher resolution than conventional 525-line pictures. Special signals are inserted in the vertical blanking period of the 525-line pictures, which allow reflections and ghosting that are picked up along the transmission path to be eliminated in the receiver.

The Clear-Vision receiver is fitted with frame stores that allow it to display a 525-line progressive scan picture, giving the increase in perceived vertical resolution that was mentioned in connection with enhanced MAC receivers. The ghost-cancelling circuitry in the receiver compares the timing (position) of the received pulse that was transmitted in the frame blanking interval with the normally transmitted sync pulses and an internally generated pulse, and is able to calculate the delay of the reflected signal and to cancel out the ghost image. The receivers are also fitted with sophisticated filtering which allows for better separation of the NTSC colour from the black-and-white image, and the overall impression is of very much better pictures than are normally seen from NTSC. These transmissions are of course
totally compatible with the existing 525-line receivers; apart from the
ghost cancellation pulses the transmitted signals are virtually the same
as normal NTSC transmissions. It is interesting that, just as with the
European enhanced MAC transmissions, some Japanese pundits are
already saying that the Clear-Vision pictures are so good that there is
no need to progress to the Hi-Vision 1125/60 system. Work has already
begun on finding ways of adding extra sides to the 525-line pictures in
a compatible way, so that widescreen pictures can be transmitted.

Enhanced television—it doesn’t have to be MAC

Enhanced television systems with many different characteristics are being
looked at in broadcasting research laboratories throughout the world, as
broadcasters realise that if their existing PAL, SECAM, and NTSC services
are not to come to be regarded as ‘second-class’ in comparison with
widescreen HDTV pictures from cable and satellites, something must be
done to improve them.

Extended PAL

As far back as 1981 the BBC described and developed an extended PAL
system (figure 92) which virtually eliminated cross-colour from the PAL
signals, and at the same time gave an improvement in resolution for viewers
who were prepared to buy new receivers (ref. 11). The BBC intended these
signals to be carried over the DBS satellite channels, but as mentioned
earlier, the UK government eventually decided that MAC would be used for
this purpose. The system made use of the extra bandwidth that is available
over a DBS satellite channel, and was reasonably compatible as far as
viewers with existing receivers were concerned, but did reduce the detail
visible in some pictures, and gave rise to a small reduction in the signal-to-
noise ratio of the pictures.

The basic idea was to sharply filter the luminance signal at 3.5 MHz,
which meant that the viewer with a conventional receiver would see no
luminance detail above this frequency. Although this gave the disadvantage
of seeing less of the fine detail in pictures, in practice this disadvantage was
overcome by the fact that no cross-colour patterning occurred. The band of
luminance frequencies above 3.5 MHz was not discarded after filtering, but
was frequency-shifted above the normal video frequency band, to the region
8–10 MHz above the carrier, for use by the specially designed higher-quality
receivers, which could provide higher-resolution pictures, again without
cross-colour. As we saw in chapter 4, the noise in an FM satellite channel
is concentrated at the high-frequency end, and since the high-frequency
luminance parts of the extended-PAL signals extend as high as 10 MHz,
these pictures would be subject to a higher level of noise than ordinary PAL
pictures.
In more recent times the BBC has come up with ideas for applying the newer techniques that have been developed for higher-definition MAC-based signals, to PAL pictures. One idea uses the technique of digital assistance, which was discussed earlier in this chapter. At its simplest, the terrestrial transmitter would transmit a basic 625-line picture, which could have been derived from a higher-definition picture by subsampling. Transmitted along with the ordinary 625-line picture, in the field blanking period, are digital signals which tell the receiver which information from the higher-definition original picture was thrown away in the subsampling process, and perhaps some information about the movement of various areas of the picture. Using this type of technique, and receivers containing field stores and sophisticated electronic processing circuitry, it may one day
be possible to transmit 625-line pictures from our terrestrial transmitters in such a way that they can provide almost HDTV quality, whilst continuing to provide viewers with conventional receivers with normal PAL pictures.

Many different methods of compatibly providing improved quality pictures and widescreen displays are being worked on with great zeal in different parts of the world, and much of the technology described in the next chapter with regard to American Advanced Television services can be applied to existing terrestrial transmissions, not only in America, but in other countries as well.

References

Introduction

Large numbers of viewers in the United States of America already have a choice of twenty to thirty different television programme channels available to them, from cable distribution systems and off-air receivers. For this reason there has not been the commercial pressure towards direct-to-home satellite broadcasting which has been introduced in many parts of the world, and especially in Europe, as a method of increasing the number of available programme channels. As an example, the vast majority of the residents of the United Kingdom generally had a choice of only four programmes until the coming of satellite broadcasting in 1989 and 1990 made three times that number readily available. Since the operators of the direct broadcast satellites have to find some method of encouraging new viewers to subscribe, it has not really been surprising that they have tried to offer incentives such as better pictures as well as more programmes, and this led directly to the development of the European enhanced and high-definition television systems that we have discussed in the last chapter, the MAC satellite broadcasts effectively opening the way for these improved broadcast systems.

With the large number of channels already available it is no surprise that there is currently no real demand for direct-to-home satellite broadcasting in the USA, in spite of the fact that it was US viewers who were the first in the world to install ‘backyard’ dishes to eavesdrop on the output of distribution satellites carrying programming intended for cable operators. The satellite route to HDTV therefore seems an unlikely way of bringing improved quality television pictures to the USA, and it is therefore not surprising that the emphasis in the USA has been different. This, plus the vast amount of existing hardware in broadcast studios and transmitters and in homes in the USA (it is estimated that there are about 160 million television receivers in the USA and over 1400 television stations), has led the Americans to seek ways of providing higher-quality and widescreen pictures over their existing terrestrial networks, both off-air and cabled. Rather than use the terms HDTV or EDTV, the American broadcasters prefer the more generic term ATV, Advanced Television, and this has been defined as a collective term embracing IDTV (Improved Definition TV), EDTV (Enhanced Definition TV) and HDTV; precise definitions of these terms and their abbreviations can be found at the end of chapter 7.
In 1983 the Advanced Television Systems Committee (ATSC) was formed from manufacturers, broadcasters, cable and satellite operators, and the film industry, with the aim of coordinating and developing voluntary national standards for Advanced Television Systems. The work of this group has covered both studio production and the transmission of ATV.

Sending improved pictures over the existing networks has the unavoidable corollary that existing viewers to these same networks must be able to continue to receive existing programming, so that the major American requirement is to provide enhanced and higher-definition pictures in a way that is as completely compatible as possible with existing receivers.

All television broadcasting in the USA is regulated by the Federal Communications Commission (FCC), and in 1987 the FCC formed an Advisory Committee on Advanced Television Service (ACATS) to advise the FCC about ATV, and to recommend how best to introduce such a service, taking into account technical, economic, and legal issues (ref. 1). The committee included members from all branches of the television industry, and it issued an interim report to the FCC in June 1988.

The reasonings of the advisory committee led the Federal Communications Commission to state, in a ‘tentative decision’ on September 1, 1988, that in order for any Advanced Television system to be approved by the FCC it must be compatible with existing NTSC standard receivers, or must provide for the existing standard transmissions to be duplicated on another channel, the important point being that existing viewers must be able to continue watching, using their existing equipment, and that no existing sets should be made obsolete (ref. 2). The FCC also said that if any additional spectrum was to be needed for Advanced Television services it must be found in the existing VHF and UHF television broadcast bands. This is likely to prove difficult to implement in many areas without interference being caused to existing transmissions, and the American Office of Engineering Technology (OET) is studying the possibilities for providing additional spectrum in the existing bands. In a 1988 report it concluded that if all the existing stations were to be provided with extra spectrum for ATV operation then there would be no alternative to allowing for substantially reduced interference protection ratios, unless reductions in existing service areas could be tolerated, which seems unlikely.

Studies are continuing to see how spectrum usage might be improved by re-arranging some existing allocations, and whether the existence of a new generation of receivers with improved selectivity and better interference rejection capabilities would make it possible to use particular combinations of channels that have previously been avoided because they are subject to mutual interference, the so-called ‘taboo’ channels.

‘Taboo’ channels

A television transmitter network generally consists of a large number of
different transmitting stations situated all around the country, and since
the amount of radio-frequency spectrum that is allocated to television
broadcasting is invariably restricted, several transmitters in different
locations will have to share the same channels. If the transmitters are far
enough apart then channel sharing should generally be possible without
interference, but in many practical situations transmitters using the same
channels will not be as far apart as would be ideal, and there is always the
possibility of **co-channel interference**. Unfortunately, because domestic
receivers are generally built down to a price, rather than to the highest
possible technical standards, it is found that there are other channels
which could cause interference if they were to be used within a certain
distance of another transmitter.

**Adjacent channel interference** Let us assume that the channel to which
the receiver is currently tuned in order to view the programme is channel \( n \).
Any nearby transmitter radiating signals on the adjacent channels, i.e. \( n+1 \)
and \( n-1 \), would cause interference in the form of patterning or buzz on
sound, simply because the selectivity of the ordinary receiver is not good
enough for it to separate two adjacent signals.

**Local oscillator interference** All modern receivers are of the
superheterodyne type which use a local oscillator to beat with the incoming
signals in order to produce a standard intermediate-frequency signal that
can be readily amplified and demodulated. This local oscillator can be
considered as a small transmitter, and in American NTSC receivers it
generally radiates signals on channel \( n+7 \) when the receiver is tuned to
channel \( n \). The affected channel depends upon the intermediate frequency
used, and is different in the UK for example, where the radiated interference
is on five channels above the channel to which the set is tuned.

Returning to the USA, this means that if a nearby receiver were to be tuned
to channel \( n+7 \) it would suffer interference from its neighbouring set tuned
to channel \( n \), and in order to prevent this from happening we must treat
channel \( n+7 \) as a ‘taboo’ channel. Similar problems apply in reverse if the \( n-7 \)
channels are used, so these too must be regarded as ‘taboo’.

**Intermodulation products** Certain combinations of input signals can mix
together to produce spurious signals which generally appear as patterning
on the wanted picture. If there are several carrier frequencies, say \( a \) and \( b \),
then various combinations of these, such as \( (2a-b) \), can cause problems.
Sometimes a similar phenomenon known as cross-modulation can occur,
where the modulation from one carrier is effectively transferred to the other,
giving the annoying effect of two pictures superimposed, or of the sync
pulses of one picture showing up on the other. The planners of the
television spectrum usage therefore have to ensure that transmitters using
frequencies which are likely to generate these spurious signals are kept well separated.

**Intermediate-frequency beat interference** When two television signals from two different transmitters are separated by the intermediate frequency of the receiver, the two signals can combine in such a way that they produce a beat signal at the difference between the two frequencies, and this signal can be picked up by the receiver’s intermediate frequency amplifier. In the USA this occurs when the two stations are plus or minus eight channels from the station to which the receiver is tuned, so these channels too must be considered as taboo.

**Image interference** Since the front-end selectivity of the average domestic television receiver is poor, signals at twice the intermediate frequency of the receiver from the wanted channel can pass through the receiver. This applies to both sound and vision signals, and in practice means that signals on $n \pm 14$ and $n \pm 15$ also must be considered taboo.

**Overcoming the taboos**

The FCC has had an improved performance experimental receiver specially built for it by the RF Monolithics Inc. company. This receiver has high selectivity, carefully designed filter circuitry throughout, and special precautions have been taken to reduce the local oscillator radiation. The results suggest that, if future receivers could have similar characteristics, all the taboo channels might be usable for ATV (ref. 3), but the large number of existing receivers means that for many years in the future broadcasters will still have to take account of the ‘taboo’ channels.

**The spectrum usage options for ATV**

The basic rule for spectrum usage for ATV, laid down by the FCC (ref. 3), was that no system would be allowed to utilise more than an extra 6 MHz of bandwidth on top of the 6 MHz already used by the normal NTSC signals. Four alternative methods by which ATV might be introduced were suggested by the FCC:

**A** *Provide an NTSC-compatible ATV service within the standard 6 MHz of the normal 6 MHz channel.* Although this might sound impossible, and as though there would be an element of ‘something for nothing’ in such schemes, we must remember that the NTSC system does have a great deal of redundancy in it, and we shall see later that there are techniques which could be perfectly practicable.

**B** *Utilise an extra 3 MHz channel additional to the existing 6 MHz channel, to carry an augmentation signal.*
C  Utilise an extra 6 MHz channel additional to the existing 6 MHz channel, as an augmentation signal.
D  Utilise an extra 6 MHz channel to carry a non-compatible ATV signal, simultaneously broadcasting the same programmes in NTSC on the standard 6 MHz channel.

There are various other features to be considered if the three possible systems that use augmentation channels are used. The simplest form of augmentation channel to introduce might be one where the additional spectrum is provided directly adjacent to the normal spectrum allocation of that television station. Such contiguous assignments might not always prove possible however, if the optimum use of the television spectrum is to be made, and even if they can be permitted, it is likely that much of the present broadcast spectrum will need to be reorganised and reallocated first. It may therefore be necessary to augment UHF television stations using other frequencies in the UHF band, and to use VHP augmentation channels for VHP stations. It would involve more complexity for both transmitters and receivers if the augmentation channel had to be in a different band from the main channel, for example if a VHP augmentation channel were used to provide the extra ATV information for a standard UHF channel, but this is by no means impossible, and is one of the scenarios being considered by the Office of Engineering Technology.

The FCC invited comments on its tentative decision and on the many options for ways of introducing ATV, and many different organisations have submitted proposals.

### Standardisation in America

One thing that has become clear since the FCC decision that ATV broadcasts must be receivable on standard NTSC receivers is that the USA will take a very different path towards higher-quality television systems than either the Japanese or the Europeans. Although it seems to go without saying in Europe that standardisation of broadcasting systems is considered to be a good thing, in spite of the fact that the aim has only been partially achieved, there are real differences in attitudes to standardisation in the USA. Whilst it is appreciated that having a single standard for television broadcasting, such as the NTSC system, which is the only system currently used throughout the United States, can have many advantages, including the provision of more programming for viewers and the benefits of mass-production economies of scale in equipment manufacture and sale, there are also potential disadvantages. It is felt that the choice of a statutory inflexible standard might reduce consumer choice, and might prevent or delay the introduction of improved technology in the future. This argument has made for difficulties for equipment designers and manufacturers in the USA, since fear of falling foul of the anti-trust legislation has made it
difficult for manufacturers to be seen to be collaborating with others in the design of a single standard that might be seen as preventing equipment manufactured to different standards by a competitor from being successful in the market-place. For this reason the FCC has for some years now tended to shy away from any standardisation processes for new radio and television services, its aim being the admirably democratic and capitalistic one of ‘letting the market decide’ upon which new systems would be successful. This idea seemed to reach its peak with the introduction of no fewer than five different technical systems for the introduction of stereophonic sound to medium-wave radio channels. The FCC adamantly refused to come down in favour of just one standard, with the result that at least three systems were marketed, and these were virtually incompatible with one another, so that a driver moving from one State to another would need to have access to different decoders. In this situation it is not surprising that stereo on medium waves has just not taken off in the market.

In the case of ATV, however, the FCC has encouraged manufacturers and broadcasters to participate in the work of the advisory committee which it set up to consider ATV policy issues, and voluntary standards bodies such as the American National Standards Institute (ANSI), the Advanced Television Systems Committee (ATSC), and the Electronics Industry Association (EIA) have all been asked for their views. From this it seems that the FCC may eventually be prepared to endorse a mandatory or at least a recommended ATV standard, although this is by no means certain, and various other ideas were suggested in the FCC’s first statement on ATV (ref. 4). In general the FCC wishes to preserve flexibility in the standards-setting process, and in particular it wishes to ensure that even if a standard is finally recommended, methods of introducing further improvements should be considered.

In 1988 (ref. 2) the FCC said that it felt that it might be too early to adopt ATV transmission standards, and asked those in the industry to consider the pros and cons of adopting one standard, and the best timing for such action. A suggestion was made that it might be better not to set firm standards, but to encourage compatibility amongst ATV systems and perhaps just to provide regulations limiting the amount and type of interference that any new ATV standard could cause to any other transmission. In this scenario the market would be left to decide how to cope with several standards, perhaps in the hope that a de-facto standard might emerge.

Another suggestion, that emanated from the Massachusetts Institute of Technology and was considered by the FCC, was for the industry to adopt open architecture receivers. The argument for this idea is that since all ATV receivers will inevitably have to be able to decode two standards, i.e. NTSC and ATV, the additional cost of providing for reception of more than two standards might well be quite small. If the development of such an Open Architecture Receiver (OAR) were to prove technically and economically
practicable, it might be that this approach would be preferable to setting standards.

The field for the introduction of ATV in America is therefore wide open, with most of the possible systems in with at least a chance of succeeding. More than twenty different systems have been submitted to the FCC for consideration, some fairly similar to each other, and we shall examine a number of these. Before embarking on a tour of the various ATV systems, however, it is worth mentioning that the first HDTV system to gain any sort of a foothold in the USA was the Japanese 1125/60 system, which, thanks to a great deal of lobbying by a few manufacturers and a couple of broadcasters, was actually accepted as the approved HDTV standard by the Advanced Television Systems Committee in their Standard A/27. The Society of Motion Picture and Television Engineers (SMPTE) also favoured this system for HDTV production, and published a studio standard SMPTE-240M, which has since been updated. During the latter half of 1989 the SMPTE began further work to try to reach an agreed studio standard for the USA, and although they stressed that they would be looking at a wide range of different systems it is expected that one of the systems they will be concentrating on will be a standard, originally proposed by the National Broadcasting Company (NBC) at the SMPTE conference in 1988, which seems much more suited to the USA, since it has 1050 lines (i.e. 2×525 lines) and a field rate of 59.94 Hz, which is likely to prove much more compatible with NTSC than the 1125/60 system. Incredible as it now seems, in the mid-1980s it even appeared that the Americans would be supporting the Japanese 1125/60 System in the CCIR deliberations as to the world standard for HDTV. All this changed when US industry woke up to the fact that adopting a Japanese HDTV system might have disastrous longterm effects on the US equipment suppliers; several powerful manufacturers made their disagreement known, and this led to the work which was to result in the eventual FCC rulings on ATV. The Japanese manufacturers have not entirely given up hope of getting the 1125/60 system into the USA, however, and a number of manufacturers of production equipment for HDTV have formed an organisation, The HDTV 1125/60 Group, whose primary purpose is to enhance programme production opportunities by actively supporting and promoting the 1125/60 system as the production standard for programme origination and exchange between HDTV broadcasters. There are currently a number of facilities houses in the USA which use the 1125/60 standard for high-quality productions. In addition to these uses of the 1125/60 system, the Japanese have made several different proposals as to how various narrow-band forms of MUSE could be used to satisfy the FCC criteria, so they have obviously not yet given up the struggle.

At the present time it is therefore difficult to make predictions about either the technical aspects or the timing for the introduction of advanced television in the United States, but there is so much work going on in so
many different places that it seems certain that some form or forms of ATV will be transmitted within the next few years. The Advanced Television Test Centre (ATTC) has been set up in Virginia, and its engineers made a start at the beginning of 1990 testing some of the 23 systems that have so far been proposed. Several different types of test will be carried out on each system, where possible:

(i) Measurements and objective tests to assess the detailed characteristics of system,
(ii) Tests to determine the amount of interference to other users caused by the particular system,
(iii) Radio propagation tests.
(iv) Tests of the system over terrestrial and cable TV paths,
(v) Subjective tests to determine how viewers perceive the quality of the pictures, and whether any problems of compatibility are noticed.

We will first of all give brief technical details of some of the many systems and ideas for ATV which have been proposed, although not all have actually been submitted to the FCC, and then try to make some comparisons and draw some conclusions.

Advanced compatible television (ACTV)

Towards the end of 1987 a team of engineers of the David Sarnoff Research Centre, a contract research organisation, with the cooperation of RCA, NBC, GE, Thomson and others, proposed what is claimed to be a fully compatible system which can provide High Definition Television and which can transmit its signals using only a standard 6 MHz wide NTSC channel (ref. 5). To understand how engineers can manage to squeeze a quart into the pint pot of the 6 MHz wide channel, it is useful to remember that in the NTSC system, colour was added to the black-and-white signals without using any more bandwidth, using the frequency interleaving techniques explained in chapter 3. Effectively, the ACTV system, and several of the other proposed systems, manage to squeeze even more information into the basic channel, and this extra information can be used to improve the quality of the transmitted pictures. (See figure 93.)

Once the initial headline-grabbing hype of ‘HDTV in a 6 MHz channel’ was overcome, and fuller details of the system became available, it became apparent that ACTV is actually an evolutionary family of three systems, and that only the first two of the steps towards HDTV can actually be introduced within the constraints of a standard 6 MHz channel.

All the ACTV signals can be viewed on existing receivers as well as ACTV receivers, so the basic compatibility of the system is very good.
The so-called ‘introductory system’, ACTV-I, is not in fact the simplest possible system, as we shall see later, but its signals can be sent along a normal 6 MHz bandwidth TV channel. ACTV-I cannot provide full HDTV quality, and is more correctly described as an EDTV system, but it can take a wide aspect ratio 1050-line interlaced picture or a 525-line sequentially scanned picture as its source, and provide both higher-quality widescreen pictures for viewers equipped with new receivers, and normal 525/59.94 interlaced pictures for viewers with standard NTSC receivers. Figure 94 shows the basic operating principles of ACTV-I.

A 1050-line 59.94 Hz interlaced picture is recommended as the ideal source signal for ACTV, but to use this signal for ACTV-I purposes it must first be converted to a 525-line progressively scanned image, since this type of signal is the best type to process for transmission over the normal 525/59.94/2:1 transmission network, and it also allows various processing algorithms to be used to derive a signal which contains information about the vertical temporal detail in the pictures.

The first process in ACTV-I, as can be seen from figure 94, is to split the widescreen high-definition picture into four different components. The first component, the main signal, is a signal with the same aspect ratio and bandwidth as a standard NTSC signal; the other three components contain extra information which can be used to provide the viewer with a wider aspect ratio picture and better resolution, when used in conjunction with the main signal. The extra three components are carried along with the main signal channel on sub-channels, in a similar way to which the colour information,
Figure 94 Principles of the coding system used for ACTV-I, a single-channel NTSC-compatible enhanced television system
effectively an extra signal, is made to modulate a subcarrier which is added to the black-and-white signals to provide compatible NTSC colour pictures. Figure 95 shows how this is done, and indicates the positions in the spectrum of the various additional signals, which will be described. The developers of the ACTV system have had to try to match the characteristics of each of the available subchannels with the type of information that each is asked to carry, and the result is a careful balance between the amount of information which can be carried and the minimisation of any noticeable effects on receivers displaying standard NTSC pictures.

Obtaining component 1—the main NTSC signal

The 525-line progressively scanned source picture, with its widescreen aspect ratio of 16:9 (an improvement on the initially submitted 5:3), is horizontally scanned in the normal line-time period of 52 microseconds. Since the widescreen picture has been scanned in the same time that is normally taken to scan a 4:3 picture, the horizontal bandwidth and the amount of detail available on a horizontal line is increased. The source picture is converted to a standard 525-line YIQ (i.e. component format) interlaced signal, which forms the basis of the first component. The YIQ signals are filtered to limit the bandwidth of the luminance information in this first component to 5 MHz, and the colour-difference information to 600 kHz, which are actually slightly better than the resolutions available on standard NTSC pictures. The high-frequency information above 5 MHz, in practice a band stretching from 5–6 MHz, is separated out, and, as we shall see later, is used to form component three of the ACTV system.
To actually form component one, the first step that is taken is to select the central 4:3 part of the original widescreen picture; this is done, line by line, and then the central part of each line is expanded until it takes up to 50 microseconds, almost the full 52 microsecond active line time utilised by an NTSC receiver. Since a signal which has been expanded in the time domain will require less bandwidth, this signal will comfortably fit into the normal NTSC bandwidths for transmission. The remaining two microseconds of the 52 microsecond line time are used to carry some of the information that was previously carried in the ‘side-panels’ of the 16:9 picture which were discarded to form the 4:3 picture. Since this information is carried only for 1 microsecond at the start and finish of each line, and since most conventional receiver displays overscan, a standard NTSC receiver should display only a standard 4:3 picture; the extra information at the edges of the picture will be ignored.

In the case of a widescreen receiver, however, this will have circuitry which can take the information in the one-microsecond-wide strips and expand it to display the side panels along with the 4:3 picture. The amount of information which can be squeezed into the time-compressed 1 microsecond strips is however limited; compressing the side panels by a factor of six results in the maximum frequencies that can be carried within the standard bandwidth NTSC channels being about 700 kHz for luminance and 83 kHz for chrominance. Because of this, it is not possible to carry all the information about the side panels in the 1 microsecond strips, so the side panel information has to be separated into two frequency bands, known as the ‘lows’ and the ‘highs’. Only the low-frequency information about the side panels can be carried in the 1 microsecond strips, but these frequencies carry the direct current component of the television picture and most of the energy of the signal.

All this information, i.e. the 4:3 aspect ratio picture and the low-frequency parts of the compressed side panels, can now be NTSC-encoded, after filtering, and the result is that this information fits into the normal luminance and chrominance regions of the NTSC spectrum, as shown in figure 95.

In order to ensure that the join between the side panels and the normal 4:3 picture will not be visible on 5:3 displays, the transmitted centre panel information is actually made to overlap the side panels, so that a very narrow strip covering the area where the join takes place is actually transmitted twice. This extra information can be used by the decoder in the receiver to provide a smooth transition between the edges and the main picture, so that no hard edge is visible.

An incidental advantage of the filtering process that takes place with ACTV pictures is that ordinary NTSC receivers actually show an improvement in the picture quality; the cross-colour and cross-luminance effects are reduced, and some increase in resolution is also claimed.
Component 2—the high-frequency parts of the side panels

If the displayed side panels were to contain only the low-frequency information that we have transmitted so far, there would be a noticeable difference between the resolution of the central part of the picture and the edges, so some method has to be found of transmitting the side panel ‘highs’. The luminance frequencies between 700 kHz and 5 MHz corresponding to the side panels and the chrominance frequencies from 83 kHz to 600 kHz are filtered, and the chrominance is quadrature-modulated onto the luminance signal at 3.58 MHz. The side panels, which actually take up about six microseconds at each end of the 16:9 widescreen picture, are then expanded in time to fill the part of the active line that is used by the centre panel, about 50 microseconds long, and the time expansion causes the bandwidth requirement for these side-panel highs to be reduced to about 1 MHz. It was found by experiment that if component two was expanded to fill the whole of the 52 microsecond line period, as might seem the obvious thing to do, the resolution of the edge panels was reduced. Figure 94 shows how component two is made up. Because component two is a low-energy signal it can be compressed in amplitude and quadrature-modulated onto a new subcarrier, together with component three, which will be described in the next section, without causing interference to the main NTSC signal.

Component 3—extra horizontal detail

We noted earlier that the scanning of the 16:9 picture in 52 microseconds meant that more horizontal resolution would be available than for a standard NTSC signal. The first two components have only transmitted luminance information up to 5 MHz, however, so in order to allow the widescreen receiver to make use of the potentially greater resolution it is necessary to find a method of carrying information about the luminance detail contained in the band of frequencies between about 5 MHz and 6.1 MHz. After selecting the information within this band by appropriate filtering, the extra luminance detail for the whole of the 52 microsecond widescreen line is time-compressed by the small amount necessary to squeeze it into the 50 microseconds which is used to carry the centre panel of the picture. This reduction to 50 microseconds is necessary because it was found experimentally that doing this gave better resolution in the side panels; it appears that modulation in the region of the side panels causes undesirable effects. The result of this complex arrangement is that an extra 1 MHz of horizontal resolution can be obtained over the whole image.

Component three contains very little low-frequency information and is therefore a low-energy signal, so that it can be compressed in amplitude and quadrature-modulated onto a separate subcarrier at 3.1 MHz, together with the component two signals. Figure 95 shows the effect of this, which is to
include a low-amplitude sub-band containing the information about components two and three within the spectrum of the main signal. The subcarrier frequency of 3.1 MHz is an odd multiple of half the line rate and was chosen so that the energy from the signals relating to components two and three interleaves into gaps in the spectrum of the main signal, and the sub-carrier is made to invert its phase on alternate lines. All these measures ensure that the extra information about the high-frequencies of the side panels and the extra horizontal luminance detail can be carried along with the main signal, without the extra information having any effect on normal NTSC receivers. Effectively the extra subcarrier is hidden in a small portion of the spectrum normally given over to colour signals, but instead this region is dedicated to carrying the high-resolution luminance detail. This technique was first developed by Dr. Fukinuki of Hitachi Research Laboratories, and the region of the spectrum where the extra information is hidden is sometimes called the 'Fukinuki hole'. A brief description of another method by which this technique could be used to improve NTSC is given later in this chapter.

Component 4— the vertical-temporal helper signal

It was explained earlier that one source standard for the ACTV system uses a 525-line continuously scanned display, and we saw that this must be reduced to a 525-line interlaced display if the pictures are to be sent along a standard 6 MHz bandwidth radio frequency channel. It is then possible, as we saw earlier, to include line doubling circuitry in the receiver which can convert the incoming interlaced signals into a progressively-scanned display. Invariably this gives less-than-perfect results on some moving parts of the image, and so component four has been introduced to provide a so-called 'helper' signal to transmit extra vertical-temporal information which a suitable receiver can use to increase the amount of vertical detail present, especially in moving images. For this system to work perfectly the helper signal would enable the receiver to restore the vertical detail in moving parts of the picture that was lost in the original conversion to an interlaced display. In practice the algorithm that the receiver will use to reconstruct the image is known, and it is therefore possible to work out at the source when certain parts of the moving picture will be displayed erroneously by the receiver. It is therefore possible to use the fourth component, the helper signal, to transmit an error signal which carries enough detail to enable the receiver to correct the display. The helper signal could also be used to send control signals to switch in appropriate motion adaptive processing circuitry at the receiver.

Since the information being carried by the helper signal consists only of the error signals, the amount of information to be sent on many pictures will be small, so a relatively narrow bandwidth signal can be used. The helper signal currently used as component four is restricted in frequency to
750 kHz, and the signal is transmitted in phase quadrature with the main vision carrier.

The composite signal—a summary

The ACTV system therefore relies on being able to carry extra components, in addition to the normal luminance and chrominance signals, within a standard NTSC signal, and if this is to happen in a compatible way the extra signals must be invisible to the viewer with an NTSC receiver. In addition, the extra components must be readily extractable from the total signal by an ACTV receiver. The arrangement shown in figure 95 has been demonstrated to work well, but there are many possible detailed modifications which could be made to alter the balance between the above requirements. In particular, the helper signal could take different forms and it may even be possible to add several more such signals for future use. There is even room to accommodate an additional digital audio signal, as is shown in figure 95. The demonstrations have shown that the requirement for the extra components to be invisible on a normal NTSC receiver is generally well met. We saw earlier that the compressed side panels will be hidden by the normal receiver overscan, so that component one provides no difficulties. Components two and three are quadrature-modulated onto a carefully selected subcarrier whose frequency and phase alternation have been chosen for minimum visibility. Component four, the helper signal, has been arranged so that it too quadrature-modulates the vision carrier, and things have been so contrived that the inevitable pattern which this would produce is spatially correlated with the main vision signal. On older NTSC receivers the helper signal is difficult to perceive because of the way it is placed spatially with respect to the vision signals, and in modern receivers using synchronous radio frequency detectors the helper signal can actually be removed before it reaches the display.

ACTV-II—full HDTV in a compatible manner

In the previous section it was mentioned that ACTV-I is an enhanced definition system rather than a full-quality HDTV, but it has the great benefit that it can be fitted into a single 6 MHz standard NTSC channel. The further development of this system has led to the creation of ACTV-II which is a full HDTV system, which uses an extra 6 MHz channel to carry augmentation signals which improve the pictures carried by the ACTV-I system. ACTV-II is therefore effectively an ACTV-I picture plus extra information carried in another channel, and so it is fully compatible with both NTSC and ACTV-I receivers, in that both will provide pictures from an ACTV-II signal, although only at the quality of the appropriate receiver. Figure 96 shows the basic principles of how the ACTV-II system operates. The ACTV-II source picture is a 1050-line 59.94 f.p.s. 2:1 interlaced
Figure 96 Basic principles of ACTV-II system
HDTV picture, and the first step in the process of producing ACTV-II is to compare this source picture with the ACTV-I picture derived from it, using the ACTV-I picture signals in the form that they would be available to produce the display in the receiver at the viewer’s home. In order to obtain a reconstructed ACTV-I picture it is therefore necessary for the ACTV-II encoder to contain an ACTV-I decoder. This takes the ACTV-I component signals and reconstructs them into the form that they would have in a widescreen 525-line progressively scanned EDV receiver, these components being known as $Y'$, $I'$ and $Q'$, as shown in figure 96.

These reconstructed signals are then subtracted from the component signals of the original HDTV source picture, $Y$, $I$, and $Q$ on the diagram, and the resulting signals therefore represent the difference between the original source picture and the ACTV-I EDTV picture. These difference signals will include the resolution that has been lost in the conversion process from HDTV source to ACTV-I picture, and will also contain any spurious signals or artifacts that have been created in the conversion process. If this information could be sent to the receiver it could enable the receiver to reconstruct a full-quality 1050-line HDTV picture, but unfortunately the difference signals require a bandwidth of about 20 MHz, and are therefore much too wide to be carried along even a 6 MHz augmentation channel of the type that the FCC suggested might be made available. Some means must therefore be found of compressing the difference signals so that they can fit into a 6 MHz channel.

When the $Y'$, $I'$ and $Q'$ signals are subtracted from the $Y$, $I$ and $Q$ signals, the resulting difference signals, shown as $dY$, $dI$ and $dQ$ on the diagram, have bandwidths of 20, 10 and 10 MHz respectively. These three difference signals are called the augmentation signals, and they must be compressed and multiplexed so that they will travel in a 6 MHz baseband channel. Figure 97 shows how the compression of the $dY$ signal is achieved.

The 20 MHz $dY$ signal is filtered and split into three separate bands of frequencies, as shown in the diagram. Frequencies above 18 MHz do not pass through the filters, and are effectively discarded. The lowest frequency band is from 0 to 6 MHz, and is called the $dY_L$ signal. The next two bands, from 6–12 MHz and from 12–18 MHz, are frequency-shifted down to DC by beating them with signals at 6 MHz and 12 MHz respectively, and then they are passed through low-pass filters so that we end up with two signals, each taking up from 0–6 MHz. The two signals are then multiplexed together line by line, to give a 6 MHz wide signal called $dY_H$. The resulting two signals $dY_H$ and $dY_L$ are then multiplexed together into another 6 MHz wide signal, $dY_{LH}$. The two signals $dY_N$ and $dY_H$ are then treated differently according to whether still or moving parts of the picture are being transmitted. When still areas of the picture are being transmitted, the two signals $dY_L$ and $dY_H$ are multiplexed frame by frame, but on moving pictures, only the $dY_L$ signal is transmitted. To switch between the two cases, i.e. stationary or moving parts of the picture, a signal called a binary motion signal is used; this is
Figure 97 Compressing the $dY$ augmentation signal
derived from the vertical-temporal luminance helper signal or by examining the differences between frames in the ACTV-I signal. The output signal is then further multiplexed with the compressed $dl$ and $dQ$ signals, which are derived in a similar way, the resultant being a single 6 MHz signal which is split into alternating lines and expanded in time to produce two 3 MHz wide signals. These two signals quadrature-modulate a radio-frequency carrier signal which is placed at the centre of the 6 MHz wide augmentation channel.

The ACTV-II receiver

The ACTV-II receiver is tuned to the main signal and a separate tuner section automatically receives the signals coming along the augmentation channel; information about the frequency of the auxiliary radio frequency signal can be carried in the ACTV-I signal. For the augmentation signal the odd and even lines are quadrature-demodulated, and the $dY$, $dl$ and $dQ$ signals are processed differently according to whether they carry information about still or moving areas of the picture. After appropriate time expansion and demultiplexing, the augmentation information components are added to the components of the ACTV-I picture that has been received on the main channel, and the result is a picture which can have some 18 MHz of horizontal luminance resolution in still areas, and about 6 MHz in moving areas, the corresponding chrominance figures being 2.4 MHz and 1.2 MHz.

Progress with ACTV-II

It must be stressed that the description of ACTV-II given above is intended only to explain the principles of how the system works; the final format of this signal has not yet been confirmed, and other techniques for constructing the augmentation signals could be developed. As figure 96 shows, however, the ACTV-I signal will be transmitted by the main transmitter which provides signals for NTSC, EDTV and HDTV receivers, whereas the augmentation signals are transmitted by an auxiliary transmitter on a different frequency, and these augmentation signals are only of use to HDTV receivers.

Other possible augmentation signal techniques

The engineers at the David Sarnoff Research Centre are currently considering other types of augmentation signal which could be used instead of the signal described above. Although we have so far shown how the ACTV-I signal has been packed with extra information and the ACTV-II augmentation signal has been compressed from 20 MHz to make it fit into a 6 MHz channel, and we have implied that these processes can be carried out without any
corresponding disadvantages, in reality the processed signals will have less redundancy and will be less robust than the originals. If the augmentation signal could be digital instead of the compressed analogue signal described previously it should be more rugged, and so studies are underway to see what form a digital augmentation signal might take. One idea would be to simply digitise the analogue augmentation signal, but in practice it would require a great deal of data compression to fit the resulting digital signal into the available 6 MHz channel, and the compressed data might then be just as susceptible to errors as the analogue signal.

Another, far more futuristic idea from the research centre is that the 6 MHz channel should be used not as an augmentation channel, but as a channel carrying all the information necessary to create high-definition pictures at the receiver. There is obviously not enough bandwidth available in a 6 MHz channel to carry an HDTV picture, but the idea is that the channel could be used to carry a digital signal that represents a complete highdefinition still image. A series of such images would be sent at a reduced temporal sampling rate, together with some extra digital information describing the motion vectors corresponding to moving parts of the image. In the receiver a series of still images would be received at a frequency considerably less than the normal frame rate, and the receiver would use the motion vector information to calculate the positions of the moving parts of the picture, and would then synthesise a complete series of moving images. Although such a technique just might work, it seems that much more research effort will have to be put into it before it leaves the drawing board, and if some of the other techniques used are considered to be ‘putting a quart into a pint pot’, then this idea would be squeezing in a whole gallon!

Entry-level ACTV

The introductory system, ACTV-I, which has been described, provides enhanced definition television in a compatible manner, within the normal NTSC 6 MHz radio frequency channel; a full HDTV system can only be achieved using ACTV-II. Although it is expected that ACTV-I will be the transmission standard that is used initially, the David Sarnoff research engineers realised that some studios may find it expensive to change to ACTV-I straightaway, and they have therefore suggested a simpler, entry-level form of the system, called ACTV-E. Very few details have yet been published, but the major difference seems to be that the ACTV-E signals do not contain the helper signal that is an essential part of ACTV-I, component four being responsible for providing extra vertical-temporal luminance detail. The ACTV-E system uses a 525-line interlaced source, rather than the progressively scanned 525-line or 1050-line interlaced pictures needed for ACTV-I, and this results in a considerable simplification and cost-reduction for the broadcaster; current HDTV cameras require far more light than normal
cameras, and this can in itself cause problems for the broadcaster. ACTV-E provides widescreen pictures by means of the compressed side-panel approach used in ACTV-I, and the increased horizontal resolution is still available. The components one, two and three of the original ACTV-I system are still present, and a suitable receiver will still be able to provide a progressively scanned 525-line display from the incoming interlaced signal, so the viewer can still receive a widescreen EDTV picture.

There is, of course, a price to pay for this simplification of the system, and that price is a lack of vertical resolution in areas of the picture containing movement. Allowing the studio operator to provide 525-line interlace signals initially, and making it possible to transmit widescreen pictures without the complication of the additional helper signal, could make life much easier for small companies who wish to start on the path towards advanced television, and the extra information needed to make a full ACTV-I signal could be added at a later date. The David Sarnoff researchers are keen to stress that ACTV-E is not be regarded as a system in its own right, but should only be seen as a subset of ACTV-I.

Progress with ACTV

The Advanced Compatible Television techniques that have been described allow for the development of an evolutionary system that can initially be introduced compatibly within a standard NTSC channel and which can provide widescreen pictures with enhanced vertical and horizontal resolutions. The later addition of a second 6 MHz channel enables full-quality HDTV signals to be transmitted.

Extended field trials of the ACTV system have not yet been carried out; only tests in practical conditions will confirm whether the signals will be able to stand up to problems that occur due to attenuation over long signal paths, and due to reflections in areas where reception is difficult. Critics of the system have suggested that the presence of a second subcarrier might make for difficulties if stereo sound signals are also carried in the same television channel, and there are still unanswered questions as to whether remodulation of the ACTV signal onto a different frequency channel by a videorecorder would lead to the second subcarrier becoming visible as a patterning effect. Tests are currently taking place, and it is predicted that ACTV receivers could reach the marketplace by 1993.

A development which looks likely to have important implications for the future success of the ACTV system began in 1990; four companies with strong interests in the American HDTV market have joined together in a development consortium to push for the development and adoption of American-designed HDTV technology. Sarnoff Laboratories, RCA (Thomson), NEC, and Philips have agreed to concentrate their research and development efforts on the ACTV system, and they have also made it clear that they would welcome other companies who might wish to take part. This
could turn out to be the point at which the Americans finally agree to ‘get their act together’, and it will be interesting to see what happens in the coming months and years.

SuperNTSC—Faroudja Laboratories

Many broadcasting engineers have been impressed by the demonstrations which have been given of the system developed by Faroudja Laboratories, a major supplier of high-technology circuitry to other broadcasting equipment manufacturers. The Faroudja system is called, without undue modesty, SuperNTSC. It is a 525-line, NTSC-compatible EDTV system which can be carried in just a standard 6 MHz channel, without any augmentation channel being required, and it also has the claimed advantages of using no extra subcarriers or hidden channels, and of using technology that is already fully developed (ref. 6). As might be expected from the name SuperNTSC, Faroudja laboratories have based their system very closely on NTSC, making great efforts to overcome the main deficiencies of the system, which are cross-colour, cross-luminance, and a limited chrominance bandwidth. Although much work has been done to improve NTSC decoders, by the incorporation of complex filters into receivers, even a very complex decoder is not going to be able to completely separate luminance and colour signals which have been superimposed during the frequency-division multiplexing process, and so the Faroudja engineers decided that the basic solution to these cross-colour and cross-luminance problems must lie in making some modifications to the original coding process.

Precoding

The main idea used in the improved encoder is to try to prevent the spectra of the luminance and chrominance components from overlapping, even before the multiplexing process takes place, and this is done by prefiltering the individual components through comb filters. The luminance information is comb-filtered between 2.3 and 4.2 MHz, this being the frequency range that is most likely to suffer from overlap with the chrominance signals. The chrominance is comb-filtered too, and the net result is that the area where the two signals overlap is appreciably reduced, thus reducing the possibility of the creation of the intermodulation effects that cause cross-colour and cross-luminance. The two signals are then frequency-division-multiplexed to produce an NTSC signal, but this time the actual cross-effects on the transmitted signal are much less than usual, and when the signals are again filtered by comb filters in the receiver, the results are very much better than standard NTSC, with the manufacturers claiming that the pictures come close to the original RGB source pictures. In addition to the improvements due to the elimination of cross-effects it is found that the amount of chrominance noise, usually seen as black ‘sparkles’ in areas of
highly-saturated colour, is much reduced. The reason for this is that much of
the so-called chroma noise that is seen in conventional receivers is in fact
due to a combination of high-frequency luminance noise which gets into the
chrominance channel and the chrominance noise proper. The effect of this
luminance noise is especially noticeable at around the colour-subcarrier
frequency, and so the effect of the comb filtering that takes place in the
improved NTSC system described is to reduce the amount of luminance noise
in the area of the subcarrier, the net effect being an apparent improvement in
the signal-to-noise ratio of the chrominance signals.

SuperNTSC builds upon these improvements in the NTSC system, and
the principles of operation of the SuperNTSC system are shown in figure 98.
The source picture is progressively scanned at either 1050 lines or 525
lines, at a 29.97 Hz frame rate. This progressively scanned source image is
then converted to an interlaced signal which is fed, in either RGB or YIQ
component form, to the SuperNTSC encoder. The luminance signal is split
into two, with the complementary filters shown, the signals between 2.3
and 4.2 MHz being comb-filtered as described in the previous section, and
then combined with the remaining parts of the luminance signal in an
adder. The $I$ and $Q$ colour-difference components are fed to a quadrature
modulator, together with the subcarrier, and the resultant signals are
comb-filtered before being combined with the treated luminance signals to
form a SuperNTSC composite television signal in which the potential for
cross-colour and cross-luminance artifacts has been very much reduced.
The output SuperNTSC signal is, of course, 100% compatible with a
standard NTSC signal, and can therefore be transmitted over all the existing
terrestrial transmitter networks, but this signal has the potential to provide
better pictures in the home if special receivers are used.

As can be seen from figure 98 the incoming signal received in a home
could be fed to a standard NTSC receiver without any problems, and the
same signal can be used to feed a special decoder, which can provide better
results than standard NTSC, especially when coupled to a display which
has line doubling circuitry in order to produce a continuously scanned
picture.

The basics of the improved decoder are shown in figure 99. The
chrominance signals are comb-filtered and then subtracted from the
incoming complete video signal, which is delayed appropriately, the
resultant being the luminance component $Y$. The chrominance signals are
then demodulated to provide $I$ and $Q$ signals, and these, together with the
$Y$ signals, are fed into a resistive matrix from which the $R$, $G$, and $B$
components are derived.

The chrominance processing is, however, rather more complex than the
filtering shown in figure 99 would imply. The comb filtering is carried out in
an ‘adaptive’ manner; whenever a sharp chrominance transition is detected
the coefficient of the comb filter circuitry is changed so that its action is
optimised, and this is done continuously in response to changes in the
Figure 98 Principles of operation of the SuperNTSC system
pictures. Also included in the decoder is a second processor which improves the pictures considerably because of its ability to adaptively vary the bandwidth of the chrominance processing circuitry. In determining the optimum bandwidth of the decoder there are two main criteria to be satisfied; rather paradoxically, the bandwidth should be large in order that the receiver will be able to display sharp chrominance transitions, but for minimum chrominance noise and cross-colour the requirement is for a narrow bandwidth. The adaptive decoder of the SuperNTSC system allows both of these requirements to be met; when large chrominance transitions occur the filters are adjusted so that the bandwidth is at its maximum, but when the chrominance signals are low in level and there are no sharp transitions the filtering is adjusted so that the effective bandwidth is narrowed, thus keeping noise to a minimum.

Another technique that is used in the SuperNTSC decoder is called chrominance bandwidth expansion, a method of increasing the positional accuracy and sharpness of colour transitions. The idea is that under most picture conditions any change in colour will occur at the same point as a luminance transition, but in ordinary receivers the chrominance information is blurred or smeared because of the limited bandwidth of the chrominance channel. In the SuperNTSC decoder the luminance transition that is coincident with a chrominance transition is examined, and the colour transition is effectively regenerated in a form which gives a much wider bandwidth, so that sharp colour transitions can now be displayed.

SuperNTSC improved display techniques

As can be seen from figure 98, the signals from the adaptive decoder are fed into an advanced line doubler which has been designed to provide $RGB$
picture signals with either 1050 lines, 2:1 interlaced, at 59.94 f.p.s., or alternatively signals with 525-lines, continuously scanned (ref. 7).

This line doubler uses motion compensation techniques to avoid motion artifacts, and a technique known as horizontal multiplicative enhancement to increase the sharpness on luminance edges. To improve the effective vertical resolution a form of detail processing is used, and aperture correction is used to compensate for the reduction in definition caused by the finite size of the scanning spot, thus providing a sharper image. Faroudja claims (ref. 7) that a picture signal with a basic 8 MHz bandwidth can provide pictures with the appearance of an image that might have originated from a signal of 15 to 20 MHz bandwidth.

**Other applications of SuperNTSC**

The techniques used in the SuperNTSC system have a much wider application than might at first be thought. One example of this is that the researchers working on the ACTV systems described in the previous system have experimented with the use of SuperNTSC pictures instead of standard NTSC pictures as their basic signals, and with the SuperNTSC decoder and display; the use of SuperNTSC should result in better pictures, since the original NTSC cross-colour and cross-luminance effects will be much reduced. In a similar manner the techniques that have been developed by Faroudja could be applied to PAL systems throughout the world with appropriate modifications to the filtering circuitry. Somewhat surprisingly, the one significant ATV feature that the SuperNTSC system does not yet provide is a widescreen display, but the Faroudja paper submitted to the FCC advisory committee on advanced television systems says that an aspect ratio of 4:3 is the first step, and that an eventual second step will be to move towards an aspect ratio of 1.61:1 (i.e. 4.83:3) whilst remaining fully compatible with 4:3 receivers (ref. 8), although there may be the need for a black strip to be displayed at the top and bottom of the picture, the so-called letter-box display. Various techniques could be used to provide the widescreen feature, however, and a few minutes thought about the application of SuperNTSC to the ACTV system, as mentioned at the start of this paragraph, will show just one method by which widescreen SuperNTSC could eventually become practicable.

**The Zenith Spectrum Compatible HDTV system**

Another frontrunner in the race to provide a compatible HDTV system for the United States of America is the Zenith Electric Corporation, whose Spectrum Compatible HDTV System adopts a different and original approach to the subject. According to the company’s claims, its HDTV transmission and encoding system enables a 30 MHz bandwidth HDTV signal to be transmitted through parts of the spectrum that are currently
unusable because of the ‘taboo’ channel problems that were discussed earlier in this chapter. This could result in a second 6 MHz wide channel being made available for every existing NTSC station to use, the extra channel being capable of carrying the HDTV information, whilst the existing channel continues to carry the standard NTSC signals, so that a fully compatible HDTV system results (ref. 9).

In chapter 1, figure 10 showed the energy spectrum of a typical television signal, and it could be seen that the spectrum is most uneven, and that virtually all the energy is concentrated in regular peaks which occur around harmonics of the line frequency. When television signals are transmitted it is these peaks of energy which will tend to cause interference to other transmissions, and the amount of interference is proportional to the peak picture and sound carrier powers; much of the interference is due to the high peak powers transmitted during the sync periods, whilst some is also related to the level of the colour subcarrier that is radiated. The nub of the Zenith system is that their engineers have designed a new type of television transmission system which has a much more even distribution of energy over the complete picture signal, which in turn allows peak energy levels to be vastly reduced, as compared with NTSC, and this allows transmissions to be carried in ‘taboo’ channels that would normally be quite unsuitable for the carriage of standard NTSC signals, because of the interference that they would generate. The energy within these new transmissions is so evenly distributed that the overall mean level can be extremely low compared with NTSC, and Zenith claim that the average transmitter power needed for the extra HDTV channel is only 0.2% of that required by an NTSC transmitter with the same service area (ref. 9).

Figure 100 shows how the Zenith system would be compatible with existing NTSC systems, and it is the fact that the extra HDTV channel can be carried on otherwise ‘taboo’ channels that makes this system practicable; it is most unlikely that the available spectrum would be sufficient to allow for every NTSC transmitter in the USA to be given an extra 6 MHz of bandwidth if the normal taboos have to be complied with.

The key to the idea put forward by Zenith is that, if the energy spectrum of a television signal is examined, it is found that most of the energy is concentrated within the first half megahertz from the carrier frequency, except for peaks which occur at the sound carrier and colour subcarrier frequencies. Figure 101 shows this clearly; it represents the average of an NTSC energy spectrum over a one-hour period (courtesy Zenith).

The Zenith system therefore separates the spectrum to be transmitted into two frequency bands, a low-frequency band with a bandwidth of under 0.2 MHz, and a high-frequency band containing most of the spectrum above 0.2 MHz. From figure 101 it can be seen that the low-frequency band will therefore contain virtually all the signal components with any significant power, whereas the high-frequency band, although containing most of the spectral detail of the television picture, will contain hardly any of the total
Figure 100 Zenith Spectrum Compatible HDTV system

Figure 101 Power spectrum of an NTSC signal averaged over one hour (courtesy Zenith)
Figure 102 Basic Zenith transmission and reception processing system

Figure 103 Principles of Zenith HDTV picture coding system
video signal power. By treating the two bands separately with different types of processing it is possible to generate a signal for transmission which has a much more even spread of energy over the spectrum, and a much lower average level of spectral energy.

Figure 102 shows the basic transmission processing system and the receiving system used by Zenith. The video signals are first passed through a temporal pre-emphasis filter, a sort of comb filter which is designed to reduce the amount of redundant information that is transmitted, i.e. the amount of stationary picture information; this should lead to a reduction in the potential co-channel interference between the HDTV and NTSC signals. The signal is then subjected to another filtration process which separates the low-frequency part of the signal from the high frequencies, and different processing is then used for each of the two signals.

**High frequencies**

The average power of the video signal is much reduced by the removal of the low-frequency information, but high instantaneous power levels will still be generated on picture amplitude peaks; to reduce the power level of these peaks a compressor is used to reduce the level of high-amplitude signals and to increase the level of low-amplitude signals, so limiting high-amplitude signals and making for a narrower spread of levels over the picture, which has the incidental advantage of improving the signal-to-noise ratio, since the level of the lowest-amplitude signals is increased before transmission. The high frequencies are then passed to a linear filter which disperses the energy of any remaining signal peaks over a period of time, a technique which again reduces the peak power of the signals. To improve the signal-to-noise ratio of the high-frequency part of the signal pre-emphasis is then applied, so raising the level of the high-frequency components which are then transmitted as suppressed carrier modulation on two carrier signals in quadrature which are situated at the centre of the television channel.

**Low frequencies**

The low-frequency part of the television signal, having been separated out by the filter, has only a narrow bandwidth, and it is digitally encoded at a low bit rate before transmission. The digitised low-frequency signal, together with the synchronisation information that is needed, is transmitted during the vertical blanking interval, in a similar manner to which teletext information is carried with conventional television pictures. The result of separating the low and high-frequency parts of the signal, and transmitting the high-frequency parts as a processed analogue signal and the low-frequency parts as a digital signal, is a transmitted signal with a flatter energy spectrum and a lower average level.

We have seen how the Zenith System manages to provide an HDTV signal
which can fit into a standard 6 MHz wide radio-frequency channel without causing interference, and how its signal processing allows the signal to make use of what would normally be ‘taboo’ channels, thus simplifying the problem of finding enough spectrum space for each existing broadcast station to use for an HDTV signal. We will now have a look at the proposed HDTV system from the point of view of the picture encoding and decoding system, the principles of which are shown in figure 103.

The number of scanning lines per picture used by the Zenith system is the somewhat peculiar number of 787.5 (525×1.5) which provides a display with 720 active lines, rather less than is provided by some other HDTV systems, but generally regarded as perfectly adequate for an ATV system. The video source that is used is a 787.5-line 59.94 f.p.s. progressively scanned picture, which uses a horizontal scanning frequency of 47.2 kHz, which is exactly three times that of NTSC. In order to take account of the possibility that HDTV pictures from other sources might need to be handled by this system, Zenith have shown that the 787.5-line signal can readily be obtained from a 1050-line 59.94 f.p.s. source picture, as used in some of the other proposed ATV systems. The original submission to the ACATS assumed an aspect ratio of 5:3, but Zenith saw that there are no problems in designing the system to cope with other aspect ratios, including 16:9. A true constant luminance colour system is used, and as well as providing a more accurate rendition of colours this also provides an improved signal-to-noise ratio in parts of the picture containing saturated reds and blues. The basic principle of the Zenith video encoding system is to split the spectrum of the source signal into components, and to analyse those components in order to eliminate those which the eye doesn’t actually need in order to recognise a satisfactory picture. The video encoder converts the HDTV 787.5/59.94 source signal into 480 analogue sampled components every frame period of 1/59.94 seconds. Each of these components occupies 63.56 microseconds and has a nominal bandwidth of 2.675 MHz. The coding scheme is arranged so that parts of a picture which contain movement are sent at a fast rate, 59.94 f.p.s., where the static parts are sent less frequently, at only 11.988 f.p.s., a technique that we have encountered in other HDTV systems.

The 480 components are divided into 240 pairs, equivalent to 240 lines of an NTSC picture, and the pairs are eventually transmitted sequentially as suppressed carrier amplitude modulation on two carriers in quadrature, which are situated in the centre of the 6 MHz HDTV radio frequency channel. Suppressed carrier operation is necessary so that the amount of interference produced will be small enough to allow the signal to be transmitted on ‘taboo’ channels. The various frequencies used in the Zenith system have been chosen so that they are precisely related to the NTSC scanning standards, and this allows the HDTV signals to use precision frequency offsets so that they can be interleaved with the standard NTSC signals.
The processed video signals and the digital data carried in the frame blanking period are time-division multiplexed and then modulated onto the two carrier signals in quadrature; because the data is only transmitted during blanking, it should be completely invisible to anyone with a standard NTSC receiver. The data signals occupy about 23 lines of the vertical blanking interval, which ties in well with NTSC pictures.

The RGB source signal is matrixed into a luminance signal and two colour-difference signals, and these are encoded using different techniques. The luminance signal, which has a bandwidth of about 29 MHz, is first divided into three components which represent different parts of the frequency spectrum. Each frequency band is then vertically filtered, so that there are different vertical resolutions for the different parts of the signal. The lowest frequency band carries most of the information which the eye needs to deal with the moving parts of the picture, and since the moving parts of the picture will require to be updated as frequently as possible, these frequencies are transmitted at 59.94 f.p.s. with a resolution of only 96 lines; the receiver can interpolate between these 96 lines to display a full 720 active luminance lines. To reduce the bandwidth requirements of this component the signals are time-expanded by 3.6:1. Although the information about rapidly changing parts of the picture is carried at a reasonably fast rate, motion compensation techniques similar to those discussed for other ATV systems are also used in the encoder and in the receiver.

The second of the three bands of luminance frequencies is filtered and resampled to give 480 lines of vertical resolution, and the highest frequency band is similarly treated to give 240 lines resolution. These two high-frequency components of the luminance signal are time-multiplexed and only one fifth of each is transmitted. Time expansion is then used to reduce the bandwidth requirements, and these signals are effectively transmitted at a final rate of 11.988 f.p.s. The effect of the different vertical luminance resolutions given to each part of the signal is to reduce the diagonal resolution of the pictures, but as we saw earlier, the effects of this are quite acceptable to the human eye.

The colour-difference components, shown as C1 and C2 on figure 104, are each passed through filters which limit them to a bandwidth of 9.6 MHz. Vertical filtering and resampling gives each signal a resolution of 240 lines, and these signals are then filtered, time-multiplexed so that only one fifth are transmitted, and then expanded in time so as to reduce the bandwidth required. The resolution of the colour signals is one third that of the luminance signals, both horizontally and vertically. The various components are then multiplexed together in stages to provide the final signal for transmission.

The receiver has the complex task of decoding the analogue components and of using the incoming digital signal to restore the low-frequency parts of the luminance signal. The analogue components are interpolated so that
Figure 104 Simplified Zenith HDTV encoding system
they again appear on 720 lines, and the motion compensation circuitry in the receiver is controlled by additional data transmitted during the vertical blanking interval.

Other applications of the Zenith system

Zenith claim that the reduced peak and average power requirements of its system will enable the 6 MHz wide HDTV signals to be carried over standard cable systems, and since such a signal should be recordable using standard FM recording techniques, they feel that Super VHS recorders should, with small improvements in technology, be able to provide domestic viewers with the means of recording and playing back HDTV signals. The ideas which led to the reduced power requirements of the Zenith signal could have applications for many other future television transmission systems; anything that allows the massive power consumptions of the broadcasters to be cut back must be of interest, at a time when energy costs are rising and the environmental benefits of reducing energy consumption are becoming more apparent each day.

HD-NTSC—the Del Rey Group HDTV system

The HD-NTSC system is designed to provide widescreen HDTV pictures to new ATV receivers via a standard NTSC 6 MHz wide radio frequency channel, whilst still providing a compatible picture on standard NTSC receivers, without any form of adaptor. It uses a technique called TriScan Subsampling (ref. 10). Although called HDTV, the basic proposal is for the transmission of a 525/60/2:1 picture, although this can be derived from a 1125/60 studio source if required. A straightforward method of understanding the TriScan technique is to begin with the picture elements that can be utilised on a standard NTSC picture. Ignoring the interlacing that normally takes place there are 483 active lines available, so it is reasonable to say that the smallest vertical picture element will have a height equal to 1/483 of the screen height. The maximum horizontal luminance bandwidth of an NTSC signal is 4.2 MHz, which means that 220 cycles of a sine wave would be displayed during the 52.5 microsecond active line time. If we assume that a complete cycle of a sine wave can carry two picture elements, one black, one white, perhaps, then a maximum of 440 pixels can be squeezed into a horizontal line, or to put this another way, each pixel will have a width of 1/440 of the screen width. The TriScan system effectively uses an original luminance signal of three times the horizontal resolution and twice the number of lines as the standard NTSC signal that we have been considering. To do this, the pixels which we have just described are subdivided into smaller elements that are known as sub-pixels. Although pixels are usually considered to be rectangular, as in figure 105(a), the actual pixel shape displayed on a cathode ray tube is likely to have a
Gaussian form, and for the purposes of our explanation of the system it is convenient to consider them as triangular, as shown in figure 105(b).

Figure 105(c) shows how in the TriScan process each of the NTSC pixels is divided into three subpixels, numbered one, two and three. If the scanning spot in the camera could be made to scan only the subpixels numbered one on its first pass, i.e. as it scans the first frame, and then on the next pass 1/30th second later, to scan pixels numbered two, and then on the third pass pixels numbered three, the amount of information transmitted through the system would be equivalent to that from three times as many pixels as the standard NTSC transmissions.

Figure 105 Pixel shapes for NTSC and for the TriScan subpixel concept
When these signals are received by a standard NTSC receiver, it cannot cope with subpixels, since it was never designed to do so, and it will therefore merely display subpixels one, two and three on top of each other as they are received from subsequent frames, the end result being a picture that looks no different from a normal NTSC display.

If a special HD-NTSC receiver were used, however, it could be constructed in such a way that the phosphor elements on the display tube were divided into three to correspond with the subpixels on the camera scanning tube, and thus could make use of the extra detail that has been transmitted. The scanning spot in the receiver must obviously have some means of synchronising its position with that of the scanning spot in the camera tube, and the normal line-sync pulses will not give enough information to synchronise to a third of a pixel, one subpixel. In order to overcome this problem a special TriSync pulse is transmitted every third frame, so that the receiver will know which of the three scans it is dealing with. Various ideas have been suggested for the location of this pulse, but it could easily be transmitted in the vertical blanking interval, or as part of an extended VBI known as the Auxiliary Data Window. An incidental advantage of having the TriScan pulse is that its presence can indicate to receivers that HDTV signals are being transmitted; this could be useful in enabling HDTV receivers to switch back to standard NTSC processing when the pulse is missing.

**Movement interpolation**

We saw earlier that it takes three frame periods to actually transmit all the three subpixels that make up each pixel, and which are necessary to build a complete high-definition picture. This means that any movement in the HDTV image will cause problems; there is effectively a loss of temporal resolution, since it takes three frame periods to transmit a complete HDTV picture. With the standard NTSC picture rate of approximately 30 f.p.s. this means that it will take 3/30ths or 1/10th of a second before the screen image is completely refreshed. A frame store in the receiver can easily be used to recover the complete signal, but if moving parts of the image are not to appear smeared and blurred some form of motion correction must be applied, such as the motion adaptive technique that we have considered with previous systems, in which the receiver switches its mode of operation whenever moving parts are detected, so that blurring is avoided, but the vertical resolution is reduced. The blurring that occurs in the TriScan system will be present on both vertical and horizontal motion, but the system uses a motion adaptive processing system called Dual Resolution Processing (DRP), and it works by converting the moving parts of the image to a form in which they have lower spatial resolution. Other methods of improving the performance of the TriScan system are currently being worked upon,
including a scheme using motion vectors in a similar way to MUSE, and various forms of digital assistance.

**Wide aspect ratio**

The HD-NTSC system utilises a somewhat unusual method of providing a wider aspect ratio, 5:3 at present, although it may be possible to go to 16:9 using the same techniques. The idea is to keep the width of the pictures the same as with the normal 4:3 display, but to reduce the number of lines in the picture display from 483 to 414, thus giving a widescreen look to the display. In addition the actual NTSC picture area that is visible is increased slightly by reducing the duration of the front and back porch of each line, and a very slight horizontal compression, called an *anamorphic squeeze*, is also used. There is no question that the standard NTSC viewer will lose some of the picture, top and bottom, and it might therefore be thought that this would rule out the proposed system on grounds of compatibility. Del Rey claim, however, that the average NTSC receiver is already overscanned and does not in fact display more than about 435 out of the total of 483 active scanning lines which are transmitted, so that a reduction to 414 lines would only represent a vertical height reduction of less than 5%, evenly distributed as a black strip at the top and bottom of each picture, and they say that viewers may even prefer the clean cut off at the top and bottom of the picture. The slight horizontal squeeze causes no problems on standard NTSC receivers, because of the overscanning that is used.

**The auxiliary data window**

The reduction in the number of active scanning lines in the HD-NTSC system provides an extra 69 lines per frame which can be used for other purposes than transmitting video information. This extended vertical blanking period is actually called the *auxiliary data window*, and it is envisaged that the data that can be sent during this period, about 600 kbit/sec, will be used for the transmission of several channels of digital audio, for teletext, and for ‘digital assistance’ to tell the decoder how to make the best of the transmitted picture, although details of the latter are not yet available.

As well as the basic ideas of the Del Rey proposal, it should be possible to use the ‘improved NTSC’ techniques that are used in other systems, and the sophisticated display arrangements already considered, to improve the overall quality of the final picture; as an example, chrominance resolution can be made much better than in a standard receiver, and complex filtering arrangements can significantly reduce any cross-colour or cross-luminance effects. The HD-NTSC signal is absolutely compatible with standard NTSC receivers, except for the introduction of a thin black line at the top and bottom of the pictures, and this brings the added advantage that it will also work with standard NTSC videorecorders. The resolution that can be obtained from the
system on static pictures is about twice that available on NTSC, and on moving parts of the picture the resolution is considerably less than this, since it takes six fields to carry a complete sequence of all the subpixels, which takes 100.1 milliseconds. Fast-moving parts of the picture can be subject to blurring. It is claimed that the radio frequency transmission performance and coverage characteristics of the HD-NTSC signal are similar to those of NTSC.

**Characteristics of the HD-NTSC signal**

- Lines per frame: 525
- Active lines per frame: 414
- Total line time: 63.56 µsecs
- Active line time: 55.31 µsecs
- Field frequency: 59.94 f.p.s.
- Line frequency: 15 734.264 Hz
- Aspect ratio: 1.67:1 (5.01:3)
- Field period: 16.6833 msecs
- Complete HD-NTSC signal frame rate (6×field period): 100.1 msecs
- HD sequence length (i.e. time for all three subpixels per pixel in the picture to be scanned): 1575 lines (3×525)
- Video bandwidth: 4.2 MHz (luminance)
- Radio frequency bandwidth: 6.0 MHz

It should be noted that, as well as the NTSC-compatible transmission system described, the Del Rey group has put forward an HDTV production format that is compatible with the 1125/60 system, and it calls this production system HD-PRO.

**MITV-CC and MITV-RC—two ‘channel-compatible’ systems from the Massachusetts Institute of Technology**

MITV-CC and MITV-RC are two ATV systems that have been proposed by researchers at MIT, and although they both claim to be channel-compatible, which means merely that either signal can be transmitted within the bounds of a standard 6 MHz NTSC channel, only MITV-RC, the RC standing for ‘receiver compatible’, can actually provide signals that are compatible in the sense that we have used before, i.e. that it can provide the ordinary NTSC receiver with a watchable picture as well as providing the viewer equipped with an ATV receiver with better pictures.

**MITV-CC**

MITV-CC, the CC standing for ‘channel compatible’, claims to have resolution similar to the versions of the MUSE system that have been put forward for use in the USA, but it is not compatible with standard NTSC receivers in any way. The researchers seem to have looked for a method of making better use of a standard television channel, so that it will carry the extra information necessary for HDTV, but it might be thought that compatibility with NTSC had not entered their minds, except for the fact
that the MITV-RC system described in the next section can be used in conjunction with MITV-CC. The television channel is made better use of by utilising double sideband quadrature modulation of a single carrier in the middle of the radio frequency channel, and further information is transmitted through sub-band coding. In a similar manner to other systems such as the Zenith system that has been described, the video spectrum is divided into several components which are selected according to the amount of movement information contained in them, and this ensures a better balance between spatial and temporal resolutions, at the cost of a lower frame rate for higher spatial frequencies, i.e. on fast-moving parts of the image. Even more revolutionary, the sound carrier and the flyback periods are eliminated, so as to waste as little of the channel as possible, and the various picture, sound, and data components are modulated onto the single carrier at the channel centre. Yet another difference between the MITV-CC system and more conventional systems is that the usual wideband luminance and narrowband chrominance component signals are not used. Instead, a narrowband RGB signal is used to carry the low-frequency parts of the picture, and a luminance ‘highs’ signal is used to carry the luminance detail. Adaptive modulation of the various components is used, and this causes any noise in the channel to be suppressed, and advantage is taken of the better noise performance to allow the picture resolution to be improved. The system is ideally suited to transmission over cable networks, and on terrestrial transmission systems the coverage should be greater than for NTSC at the same power level, because of the better noise performance. The protagonists of the system claim that it has much better performance than existing television signals under conditions where the signal-to-noise ratio is poor.

Figure 106 shows the basic idea behind the MITV-CC coding system. Pictures from a high-definition source are digitised and then fed to a bank of filters which produce a number of components, up to forty-five, each one of which has a different spatial and temporal frequency content. RGB information is transmitted with a resolution of 400 pixels wide by 254 lines high, at a rate of twelve frames per second. The resolution of the luminance signals ranges from 1200 pixels wide by 762 lines at 12 f.p.s. to 400 pixels wide by 254 lines at 60 f.p.s. Nine of the components are then selected, six of which are fixed, and three depending upon the content of the particular scene and the amount of any movement which it contains. The six fixed blocks correspond to the lowest resolution signals in R, G, and B, and to the next highest horizontal, vertical, and temporal components. The three further components which are selected are signalled to the receiver by means of digital codes transmitted in the vertical interval. These components are then multiplexed together with digital audio and data signals, and then read into a buffer memory store. The data is read out from the store in two separate streams, one for odd lines, the other for even lines, and is then converted back to analogue form. The two signals are then filtered and quadrature-
multiplexed onto the carrier.

The MITV-CC system is the product of a research department that has tried to develop a completely new design of television system which attempts to extract the maximum possible picture and sound quality out of a standard NTSC 6 MHz wide channel. Although we have seen that it cannot be considered technically compatible with existing NTSC receivers or video

Figure 106 Simplified block diagram of MITV-CC encoder
recorders, it can, under the somewhat peculiar regulations for compatible HDTV that have been laid down in the United States, still count as a compatible system. This is because, as we saw earlier, the ATV rules allow for an extra 6 MHz channel to be used alongside an NTSC channel, which would allow MITV-CC to be carried on one channel whilst the other 6 MHz channel carried a standard NTSC picture to keep existing NTSC viewers happy. Somehow this seems almost cheating!

**MITV-CC attributes**

Simple, rugged signal format.
Can be carried in a 6 MHz wide channel.
Can be carried on cable and satellite systems.
Improved signal-to-noise ratio.
Better picture quality under adverse reception conditions.
Can be recorded on modified video recorders.
Digital data channel.
Digital audio.
Widescreen, aspect ratio 16:9.

**MITV-RC**

This is a more conventional ATV system, which operates in a single 6 MHz channel, and which provides improved picture quality for viewers with ATV receivers, whilst enabling viewers with NTSC receivers to obtain relatively normal quality pictures, except for the appearance of a black bar at the top and bottom of the picture when displaying picture signals transmitted from an ATV source (figure 107).

No video information is carried on the top and bottom 12.5% of the picture, which means that the remaining 75% of the normal 480 active lines are displayed in the form of a picture with a 16:9 aspect ratio. The extended vertical blanking interval, seen as black bars that appear above and below the picture on a standard NTSC receiver, is used to carry luminance enhancement information which can be used to improve the quality of the picture available to the viewer with an ATV receiver. The transmitted luminance resolution is 3 MHz over the NTSC area of the picture and 4.2 MHz over the enhancement area. Extra chrominance resolution on static portions of the picture is obtained by reducing the chrominance frame rate to half of the normal, i.e. 15 f.p.s., but, as we have seen before, this will be at the expense of some reduction in resolution during moving parts of the picture. The transmitted chrominance bandwidth is 0.6 MHz, whereas the displayed bandwidth on an ATV receiver is 1.2 MHz.

The system described is one of the simplest methods of providing ATV in a compatible manner. On transmission the signal behaves just like NTSC, and it is compatible with all NTSC receivers and videorecorders, and can be
recorded and played back as usual. We have seen that some of the proposals for ATV require the extra information to be carried on another channel, whilst others, like the ACTV system from David Sarnoff Laboratories, manage to hide the extra information within the structure of the existing signal, at the expense of considerable complication of the transmitted signal. The MITV-CC system is in essence simpler, in that it makes use of the space freed by reducing the picture height, which provides a great deal of capacity for future improvements. As with many of the other systems, the MITV systems will be also be able to take advantage of motion compensation techniques and specialised displays. The MITV-CC system was designed on the assumption that viewers would eventually use ‘smart’ television receivers, sometimes called open-architecture receivers, which allow for a great deal of flexibility and programmability; open-architecture receivers are discussed in more detail later, but in essence they can be adapted by using different software to cope with a wide range of ATV systems, and any evolutionary changes which may come about.

One scenario for the introduction of the MITV systems that is being considered is for the receiver-compatible MITV-RC to be introduced first; this would allow viewers with NTSC receivers to continue to use their existing receivers, but manufacturers hope that many people would then be persuaded to buy an open-architecture receiver to provide the widescreen EDTV quality pictures that MITV-RC makes possible. At a later stage these same receivers could then be used, perhaps with some modification to the controlling software, to display HDTV pictures from the MITV-CC signals.

Attributes of MITV–RC

Can be carried in a 6 MHz channel.
Compatible with NTSC receivers (although black bands at top and bottom of pictures).
Can be carried on cable and satellite systems.
Aspect ratio of 16:9 for both ATV and NTSC receivers.
Digital data channel.
Digital audio.
Better picture quality.

The VISTA system, from Dr William Glen of the New York Institute of Technology

The New York Institute of Technology (NYIT) has proposed and demonstrated in the laboratory a system known as VISTA, an acronym obtained from Visual System Transmission Algorithm. VISTA is a two-channel system, where the first channel carries an NTSC signal and the second channel an augmentation signal. Some of the techniques used are common to other schemes that we have discussed, and it is understood that other systems actually make use of NYIT patents (ref. 11). (See figure 108.)

As with other systems VISTA has been designed to exploit the human visual system, and it does this by separating the information in the source pictures into components, one set having low spatial resolution and high temporal resolution, corresponding to a standard NTSC signal, and the other having components with high spatial resolution and low temporal resolution, these forming the augmentation signal.

The input signal of the VISTA system is from a 1125-line 16:9 aspect ratio progressively scanned source. One of the reasons why this number of lines has been chosen by NYIT is that there is already an 1125/525 converter available from Japan, as part of the Japanese efforts to show that 1125-line MUSE could be used in NTSC countries. The basic NTSC signal for the VISTA system is therefore obtained from the 1125/525 conversion equipment, but as we have seen in other systems the NTSC signal is actually very much improved by the application of temporal filtering at the source and corresponding comb filters in the receiver; cross-colour and cross-luminance are much reduced. The information to be transmitted over the augmentation channel consists of the high-frequency luminance detail from the source picture and the colour detail, in the form of the higher-frequency R-Y information, but this information is sent less frequently, i.e. at lower frame rates than the basic picture information. To take account of the fact that both 3 MHz and 6 MHz wide augmentation channels are allowed by the FCC rules, alternative specifications have been provided for the two different cases. Assuming that a 6 MHz wide augmentation channel is available, the channel carries information at 15 frames per second, with a maximum video bandwidth of 5.3 MHz, and this is carried on a single-sideband suppressed carrier system. Tests have been carried out to confirm that this information can fit into a standard 6 MHz wide NTSC channel without causing undue
Figure 108 Block diagram of VISTA transmission system
interference, and it has been found that the VISTA augmentation signal produces less adjacent channel interference than NTSC, and can tolerate more interference. If only a 3 MHz channel were to be available, perhaps because of problems with ‘taboo’ channels, then their augmentation information would be sent at the reduced rate of 7.5 frames per second, with a maximum video bandwidth of 2.7 MHz, and code signals in the vertical blanking interval would indicate to the receiver which type of augmentation signal was being used.

Since suppressed carrier modulation is used for the augmentation channel there is no main carrier, no colour subcarrier, and no sound carrier, and its power can be much less than that of the main signal carrier. When receiving a main signal and an augmentation signal care has to be taken to see that the two signals are received at the same time, or else path length variations due to reflections, perhaps from moving aircraft, could cause problems. The augmentation signal therefore has a 3.58 MHz burst at the end of each line to phase-lock the augmentation signal so that it can be accurately loaded into the frame store in the receiver. One line of the vertical blanking interval is also used to carry digital code signals which identify the individual frames, but the level of these signals and of the burst is kept low, so as to avoid interference.

Whenever a two-channel system is used, some method must be found of telling the receiver where the augmentation information is to be found. To ensure that the receiver always tunes to the correct augmentation channel, a digital code is inserted in the vertical blanking period of the NTSC part of the transmission, and this code is used to automatically tune the second tuner in the receiver to the augmentation channel. Figure 109 shows a block diagram of a VISTA receiver.

Wider aspect ratio

In order to obtain pictures with a 16:9 aspect ratio, only 443 of the 448 active lines available in the NTSC system are used in the HDTV receiver; the horizontal blanking interval of the NTSC signal is also reduced by 4 microseconds to help to increase the aspect ratio further. In the receiver the 443 active lines are scan-converted to produce 1024 active lines (1125 lines total) for display. This means that the NTSC viewer would see the full 4:3 image, whereas the VISTA viewer would see an image that is cropped vertically.

The VISTA system can provide an evolutionary path to HDTV which provides existing viewers with NTSC receivers with excellent pictures. VISTA signals are suitable for distribution over cable systems, and could be carried over satellites if two channels were made available. In this case it would be better for the more robust augmentation signal to be carried at the high end of the spectrum, because of the problems which the triangular noise spectrum of FM channels can cause on systems where the colour
information is at the high end of the spectrum; this was discussed in chapter 4 when the suitability of MAC for satellite broadcasts was shown.

The North American Philips proposals—HDNTSC and HDMAC-60

The North American Philips company (NAP) has taken a comprehensive approach to the introduction of HDTV to the United States, and has put forward what is called a ‘hierarchical ATV emission system with full NTSC compatibility and HDTV quality’ (ref. 12). This is effectively a system concept offering several options, but essentially containing two related formats for ATV systems, one particularly suited to satellite transmission, the other intended for terrestrial and cable transmission. The signal to be used for satellite transmissions is a widescreen multiplexed analogue components (MAC) signal, whereas the terrestrial version, which can simply be derived from the satellite version, is a two-channel system. One of the two channels carries a standard NTSC picture whilst the second channel carries augmentation information which includes side panel information for wide aspect ratio operation, higher resolution detail information about the pictures, and digital audio. One idea put forward by NAP is that the MAC signal could be distributed via satellite, and that these signals could be converted to the terrestrial signal format for distribution by cable or for onward transmission by broadcasters. (See figure 110.)

The satellite transmission system—HDMAC-60

The basic pictures required by the NAP system are in 525-line 59.94-frame-rate progressive scan format, with a 16:9 aspect ratio and an active line time of 26 microseconds, but, as we have seen previously, these could be derived from an 1125/59.94 studio source if desired. The choice of a 59.94 frame rate simplifies later conversion to NTSC. HDMAC-60 has been carefully designed to provide a balance between spatial and temporal components of the picture signals that matches the characteristics of the human visual system. The HDMAC-60 system uses different compression ratios on different lines, so that different lines are effectively transmitted with different bandwidths. This technique allows high spatial and temporal resolutions to be achieved in vertical and horizontal directions, with low temporal resolution in diagonal directions, a situation that the human visual system is quite content with. Alternate lines are sent as line difference signals at a lower resolution, using a 2:1 time compression ratio; these transmit the vertical/temporal high-frequency detail of the luminance component of the signal. One out of every two of the remaining lines, i.e. one line of every four of the picture, is expanded in time by a factor of 16/9 so that it can carry a full resolution signal. The other one of the two remaining lines, again one line in four of the picture, is neither compressed nor expanded, and carries information with medium resolution. The \( B-Y \) and \( R-Y \) colour-difference signals are
transmitted on alternate lines, with each signal alternating between 2:1 compression and 4:1 compression. The total bandwidth of the baseband signal, which includes four digital audio channels, is 9.5 MHz, which is suitable for direct transmission over satellite channels.

The terrestrial system—HDNTSC

The HDNTSC system has been designed to carry the same information that is carried in the HDMAC-60 system, whilst remaining fully compatible with
NTSC. It provides a standard NTSC signal using a 6 MHz channel, whilst the augmentation information needed to provide the extra information for HDTV is carried in a separate radio frequency channel. Although the aim of NAP is to squeeze the augmentation signals into a 3 MHz wide channel, at the present time at least 4.6 MHz is required. HDNTSC is based upon a 525/59.94/16:9 continuously scanned source, identical to that used for HDMAC-60, and the system has been arranged so that transcoding from HDMAC-60 to HDNTSC can be carried out simply and without introducing any undesirable artifacts, so that it would be practicable for terrestrial HDNTSC transmitters to use HDMAC-60 signals from satellites as the source of their programmes.

The information in the baseband HDNTSC signal is separated into two signals, the NTSC signal package, a conventional 525/59.94/2:1/4:3 NTSC signal, and the augmentation signal package (ASP). The NTSC signal to be carried on the first channel is obtained by taking a portion appropriate to a 4:3 aspect ratio of every alternate line of the progressively scanned picture. The portion of the original 16:9 aspect ratio picture which is used to provide a 4:3 aspect ratio picture for the NTSC signal is variable, so that the director of the programme can arrange for the picture to be panned and scanned to provide the most appropriate 4:3 picture. The remaining parts of the 5:3 picture will be in the form of side panels, not necessarily of equal size, and the information representing these is carried in the augmentation channel. The augmentation channel is thus used to carry the higher-resolution horizontal and vertical detail of the image, and it effectively carries four signals during each line scan period. The first corresponds to the left-hand side panel and the second to the right-hand side panel; both are processed as a normal NTSC signal. The third signal is a line-difference signal which is used to enable a progressively scanned display in the receiver to provide a higher-resolution display. This difference signal is obtained by taking the average value of two adjacent lines of the NTSC portion of the picture and subtracting this from the luminance part of the equivalent lines which were thrown away when extracting the NTSC picture from the source picture; this signal is time-compressed before transmission. The fourth signal contains digital signals which are used to carry Dolby encoded stereo sound signals, which are additional to the standard NTSC sound signals.

Options

The North American Philips company stresses that the basic ideas used in their system could be modified in various ways to provide the 'optimum' NTSC-compatible HDTV system, and the company has suggested a number of different options. One aspect they are working on is the possibility of utilising a digital augmentation signal. Although this would allow the use of lower power for the augmentation transmissions, and might enable the taboo channels to be used to carry the augmentation signals, sophisticated
bit-rate reduction techniques would be necessary, and these are not currently practicable for consumer equipment.

The Bell Laboratories proposal—the SLSC (Split Luminance/Split Chrominance) system

Bell Laboratories have proposed an HDTV system (ref. 13) which requires two 6 MHz channels to provide an NTSC-compatible system. Figure 111 shows how it works.

The source is a high-definition 1050 line picture, but this is vertically filtered and then scan-converted to provide a 525-line signal which has the same horizontal resolution as a normal NTSC picture. The first radio frequency channel carries this picture signal, which provides standard pictures on standard NTSC receivers. The remainder of the original 1050-line HDTV picture, i.e. the higher-frequency parts of the luminance and the colour-difference signals, are separately encoded and transmitted over the second radio frequency channel. This system is sometimes called the Split-Luminance/Split-Chrominance (SLSC) system, since both luminance and chrominance signals are separated into low and high-frequency areas. Figure 112 shows the baseband radio frequency spectrum arrangements used in the Bell system, and although it indicates that adjacent channels are used for

Figure 111 Block diagram of the Bell HDTV encoding system
the two signals this is by no means essential, and there could be benefits in using quite separate channels. Bell have suggested that a simplified form of SLSC could be utilized in circumstances when adjacent channel operation is possible (ref. 14).

A standard NTSC receiver should be able to ignore the information from the augmentation channel, and this would probably be simpler if the channels used were not adjacent; Bell say that their tests have shown only a very slight degradation of the signal received on NTSC receivers. An HDTV receiver would make use of both the NTSC information coming from the first channel and the augmentation information coming from the second channel. Using the same type of techniques we have seen for other systems, frame stores in the HDTV receiver would be able to provide a 1050-line HDTV picture. Bell claim that the horizontal resolution of their HDTV pictures will be twice that of NTSC, and that there is sufficient capacity available in the second radio frequency channel to carry digital sound as well as augmentation information. Wide aspect ratio pictures could be obtained by using one of the methods utilised by other systems, such as carrying side panel information in the augmentation channel by using suppressed carrier amplitude modulation, but no firm proposal had been made at the time of writing.

**HDB-MAC—the Scientific Atlanta HDTV proposal**

Scientific Atlanta have demonstrated a working widescreen HDTV system based on the B-MAC transmission system that was described in chapter 5. The system allows for the transmission of widescreen HDTV pictures with

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*Figure 112 The spectrum utilisation of the Bell Laboratories HDTV system*
up to six high-quality audio channels as well as teletext and computer data, and the first major public demonstration in December 1989 showed pictures from a world boxing championship on nine-foot-high HDTV projection screens. The source signal can be a 1050-line interlaced-scan HDTV picture or a 525-line progressively scanned picture, but the former must be converted to the latter before the actual signal processing takes place. HDB-MAC is backwards-compatible with B-MAC, so that broadcasters using B-MAC could eventually upgrade to HDB-MAC.

Although a description of the HDB-MAC system is included in this section about the American approach to HDTV, this is more for the sake of completeness than because of a belief that it will be chosen. HDB-MAC is not generally considered to be a contender for the American ATV crown, because of its basic incompatibility with NTSC receivers; only by using a set-top HDB-MAC/NTSC convenor could an NTSC receiver make use of the signals. It seems that it is really intended for satellite distribution, and for use on cable systems; the signals from a satellite can be used on cable systems if two contiguous 6 MHz NTSC channels can be made available. HDB-MAC is being used for teleconferencing and other closed-circuit tasks such as providing doctors with high-definition pictures of live operations being carried out in operating theatres thousands of miles away. As with

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**Figure 113 HDB-MAC coding arrangements**

The original signal is a 525 line progressive scan signal with 750 samples per line.

The signal is first filtered to remove the higher-frequency diagonal components, and then quincunxially sampled, discarding every other sample.

Samples in all even lines are moved into the empty space in the line above.

Resulting signal 525 lines interlaced scan
B-MAC, one of the major reasons for satellite and cable operators using HDB-MAC may be because of its secure built-in encryption system. The basic principles behind the encoding process are shown in figure 113.

The 525-line picture with 750 samples per line is diagonally filtered, and the resulting signal is then quincunxially sampled, using a similar method to that used by the European HD-MAC system, and this means that we are effectively discarding every alternate sample. The resulting samples from each of the even lines are then moved upwards in the picture to the line above, so that samples from alternate lines are placed side by side, and alternate lines contain no samples at all. The lines without samples are of no use and may therefore be discarded, which effectively produces a 525-line interlaced picture, and such a picture can of course be transmitted via a standard satellite channel.

A standard B-MAC receiver would then display the received signal as a normal 525-line interlaced picture, but an HDB-MAC receiver containing a number of line stores could rebuild a progressive scan picture by looking at the incoming samples and processing them so that missing samples could be interpolated from the surrounding samples, and hence the missing lines could be synthesised.

The High Resolution Sciences CCF system

High Resolution Sciences Inc. is a research corporation dedicated to developing technologies that improve the quality of visual displays. They have not so far put forward a comprehensive scheme for advanced television, but they did submit a paper to the FCC Advisory Committee on Advanced Television Service (ref. 15), and the techniques which HRS have developed look as though they could make a significant impact if they were applied to various ATV systems.

The heart of the technology developed by HRS is a system called Chroma Crawl Free (CCF). This is a novel method of encoding and synchronising television pictures so that unmodified existing television receivers will display a picture without the effect known as chroma crawl, and with greatly reduced cross-colour and cross-luminance artifacts. Chroma crawl can be seen along the edges of brightly coloured parts of NTSC images and in some coloured patterns, as colour dots which move slowly up the picture. The effect can be disturbing, especially when looking at titles in saturated colours, or at detailed patterns. It occurs because of the relationship between the line and frame frequencies in the NTSC system, which were originally chosen to minimise the effects of adding the colour signals to the black-and-white pictures, it being particularly important to see that the millions of viewers with monochrome receivers were not disturbed. In order to make the spectra of the colour information interleave with that of the luminance information as was explained in chapter 2, the colour subcarrier frequency was chosen to be an odd multiple of half the frame and line frequencies. It works out that each
NTSC line has 227.5 cycles of subcarrier and each frame 119 437.5 cycles. Since each field ends with the subcarrier 90 degrees out of phase with the one before it each scanning line will begin with the subcarrier 180 degrees out of phase with the preceding one. In consecutive fields, therefore, the colour subcarrier position will appear one line higher, and this causes the ‘chroma crawl’ or ‘dot crawl’ effect.

The CCF System changes from the 227.5 cycles of subcarrier per line that is used in NTSC to 227 cycles, increasing the horizontal frequency by about 2%. This makes every line of the same field have the same subcarrier phase, but an additional half cycle of colour subcarrier is added at the end of each field, with the net effect being that the next field will be 180 degrees out of phase. Fields one and three have the same subcarrier phase on every line, and have the opposite phase from fields two and four, and the result is that dot crawl no longer occurs. As an added advantage, the change in the relative phasing of phase has the effect of reducing cross-colour artifacts. (See figure 114.)

### Compatibility

The difference between the horizontal and vertical scanning frequencies is small enough to be well within the tolerances of television receivers and video recorders, and tests via satellite and cable systems have resulted in no complaints from viewers. There can be problems, however, in some types of studio equipment such as cameras, special effects units and C-format video recorders which derive their synchronising signals by dividing down from the colour subcarrier. To overcome problems of this type, it would be better to install the CCF encoder close to the studio output.

The High Resolution Sciences proposal cannot yet be considered as a
complete ATV system as it stands, but the ideas are worth considering since they may well be applicable to other ATV systems which utilise NTSC as their basic signal, and the improvements which are gained could be added to some of the other improvements to NTSC which we have seen are now possible.

**QuanTV—a new technique from the Quanticon company**

As the Quanticon submission to the FCC ACTS says (ref. 16), ‘QuanTV is not really a television system, but it is a technique which is applicable to both analogue and digital television systems, and which can reduce noise, distortion, and interference.’ Although the submission is naturally intended for a market where NTSC is the chosen standard, the techniques used could equally well be applied to PAL, SECAM, and perhaps even MAC transmissions. The pictures produced by the system are compatible with existing NTSC receivers and can be carried within the existing 6 MHz NTSC radio frequency channel. An advanced receiver can make use of the QuanTV signals to rebuild component signals which provide pictures which are claimed to be free from all impairments due to channel noise, interference, cross-modulation, echoes, and colour distortions. The transmitted signal can be recorded on an existing NTSC videorecorder and will play back into a normal NTSC machine at standard NTSC quality; a better-quality machine would be required to record the higher-quality QuanTV pictures. No change of aspect ratio from the 4:3 of NTSC is involved.

The technique used in QuanTV is called *psychophysical compression*, and figure 115 shows what is done at the transmitting end. After filtration,
luminance and chrominance components are sampled, and carefully designed dither signals, called *cinematic dithers*, are added to the sampled signals before quantisation takes place. The dither signals vary from pixel to pixel and from line to line, and this technique allows fewer bits to be used in the quantising process without the contouring that would otherwise occur being noticeable. If the signals were to be transmitted digitally, which is not currently the case of course, then the necessary bandwidth would be reduced from that required to transmit a digitised standard NTSC signal. In the current circumstances, however, where analogue transmission is to be used, the increased bandwidth can be deliberately sacrificed in order to improve the signal-to-noise ratio of the analogue signals, and to render them more rugged and less susceptible to interference.

The psychophysical compression technique uses luminance sampling having seven or eight levels, but the dither signals cause variations in the level of each picture element between the amplitudes of two adjacent steps. The effect of the dither is thus to give a subsampling effect, i.e. lots of mini-steps for each main amplitude step, and this is especially noticeable in areas of low contrast. The low-contrast parts of the pictures can utilise a trade-off between spatial and temporal resolution and contrast, which turns out to provide acceptable pictures with the improvements in signal-to-noise ratio, distortion, and ruggedness that were described earlier. The dither signals are generated by computer techniques, and it is important to note that the transmitter must be modified before QuanTV can be incorporated.

Standard NTSC television receivers can make use of the NTSC signal that results from the dithered signals without any problems, but in order to make use of the QuanTV signals to generate improved pictures in the home, a special receiver containing frame storage is necessary, and figure 116 shows the general principles.

The QuanTV receiver takes the luminance and colour-difference components from the NTSC decoder and then quantises luminance using seven or eight levels and colour difference using three levels. Appropriate delays are inserted in the luminance and chrominance channels, and the regenerated pictures are free from noise and interference. Clock circuitry in the receiver uses the colour subcarrier to ensure synchronisation between the sampling processes in the transmitter and receiver. It is important to note that such a receiver would not work acceptably if standard NTSC signals were incoming, so the QuanTV receiver has to be a dual-mode design which can switch over to normal NTSC decoding when standard NTSC signals are being transmitted; the diagrammatic changeover switch can be seen in figure 116. It has been suggested by Quanticon that an ancillary signal carried in the NTSC vertical blanking interval could be used to switch the receiver between QuanTV and NTSC modes. Frame stores at the receivers could be used to provide progressive scanning at 60 frames/second to improve the displayed image, as has been seen in other systems.

It seems that the QuanTV cinematic dithering technique, which brings the
benefits of reduced noise and distortion to those equipped with the noise-reducing receivers, is more likely to be applied to other ATV systems, rather than being adopted as a system in its own right; Quanticon have made it plain that licences for their patents will be readily available.

The Osborne Compression System

Osborne Associates Inc. has proposed a flexible system that could be applied to various types of ATV system, and several variants have been detailed. The HDTV signal can be transmitted through a 45 Mbit/sec digital data channel, over a single 9 MHz wide channel, or over two 6 MHz channels. The aim of the system is to optimise the efficiency of digital transmission by bit rate reduction, and by this means to provide a method of moving to HDTV whilst still providing pictures on standard NTSC receivers. The decoder in the receivers would be the same, whichever of the three transmission methods was used.

In each case, the system subsamples a high-definition picture to provide an NTSC picture, and adaptive sampling is used, as in other systems, to make the most of spatial redundancy in the original picture. Figure 117 shows how the system works when two 6 MHz radio frequency channels are
available. The subsampled NTSC picture is transmitted directly on the first radio frequency carrier, so that all standard NTSC receivers would receive a normal picture. In the encoding equipment this NTSC signal is then decoded, but using the same adaptive interpolation algorithm as is to be used in the HDTV receiver, so that an ‘artificial’ HDTV picture signal is present in the encoding equipment, as can be seen from figure 117. The second radio frequency channel is then used to carry an ‘error’ or ‘difference’ signal derived by subtracting the artificial HDTV signal from the original HDTV source signal. When this second signal is received by the HDTV receiver it is added to the NTSC signal received on the first channel, and the receivers can then rebuild a copy of the original HDTV image.

If two 6 MHz channels cannot be made available, then it is possible to transmit the NTSC part of the signal in a standard 6 MHz channel, the error or augmentation signal being transmitted in an extra 3 MHz wide channel.

**Single-channel digital system**

The third option, shown in figure 118, is to go for digital transmission, and the Osborne Digital Compression system, using both temporal and spatial compression together with a digital coding system that uses the minimum possible bit rate, allows the complete NTSC signal and the error signal to be
compressed to a data rate of 45 Mbit/s, and transmitted over a 6 MHz wide satellite channel using QPSK coding, which can be considered as a four-level code which enables a lot of data to be carried in a limited bandwidth (ref. 17).

**The Fukinuki approach to improved NTSC**

Dr Fukinuki of Hitachi Research has already been mentioned in connection with the 'Fukinuki hole', an area or areas of the existing spectrum which are currently being used to carry colour information, but which are not being fully utilised in the NTSC system. Although no official proposal has been submitted to the ACATS, he has suggested a method of carrying the highest-definition parts of the luminance signal in these areas, and has shown that such improvements in definition could be achieved in a manner which existing NTSC receivers would find completely compatible (ref. 18).

The proposal can be understood by considering each NTSC television field as a separate plane, so that an NTSC picture will consist of parallel planes separated from one another by one sixtieth of a second. In the NTSC system the colour subcarrier is different in phase by 180 degrees on adjacent lines, and it can be shown that a similar 180 degree phase shift takes place from

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*Figure 118 Osborne System using a single digital channel*
field to field and from frame to frame. The Fukinuki idea is that when a field starts with one particular phase of subcarrier the information being carried will be the conventional colour information, whereas when a field begins with the opposite phase of subcarrier high-definition luminance information will be carried in the areas normally used for the colour information during that field. In order that the receiver will be able to detect which information is being transmitted at which instant of time, the area of the incoming signals of interest is first selected by filtering, as shown in figure 119, and the resulting signals are then passed through delays of 262 lines and 263 lines, and the signal phases are then compared with those of the incoming signal. Fukinuki has shown that if the signals are in phase after a 262-line delay then the incoming signal will be carrying the colour information, whereas if they are in phase after a 263-line delay the signal will be the higher-definition luminance information.

The changes taking place from field to field mean that such a system would of course need to utilise some form of motion compensation technique, and the Fukinuki proposal is probably best regarded as a technique to be used in conjunction with some of the other proposed systems that we have discussed.

The QUME system—Quadrature Modulation of the Picture Carrier

Although it has not submitted an official proposal to the ACATS the Japanese Matsushita company has suggested (ref. 19) a method of enabling an NTSC signal to carry additional information which could be used to improve the definition of an NTSC picture or to provide an increased aspect ratio. The technique used is called Quadrature Modulation of the Picture Carrier (QUME),
and the name describes the system very well. It is really a development of the way in which a black-and-white picture was made to carry additional colour information by the addition of a subcarrier. Figure 120 shows the basic idea. The vision carrier signal, before modulation is added, is phase-shifted through ninety degrees. This phase-shifted signal is then modulated with the extra information which is to be added to the NTSC signal. The resultant modulated signal is then filtered, and it is added to the standard NTSC modulated vision carrier, effectively providing quadrature modulation of the NTSC vision carrier, and giving rise to what is known as the QUME signal.

Figure 121 shows a diagram of the final video spectrum, and it can be seen that the extra information has been slotted into the normal spectrum at the low-frequency end, an idea which we have come across in other proposals.

A normal NTSC receiver should ignore this extra low-frequency information, and to ensure this, Matsushita have taken considerable trouble
to design the filtering circuitry used when producing the QUME signal so that any potential interference is reduced to a minimum for NTSC viewers. Enhanced receivers designed to utilise this system would contain a synchronous detector circuit which could separate out the standard NTSC information and the additional information and the two signals would then be appropriately combined in order to generate an enhanced picture; the extra information could be used to provide more luminance detail, or to give the amount of detail on a wider aspect ratio display.

**CBS proposal**

An ATV proposal from the Columbia Broadcasting System (CBS), (ref. 20), requires the use of two DBS satellite channels, so it cannot be considered compatible with standard NTSC receivers in the same way as other systems since a special adaptor box would be necessary even to allow NTSC receivers to provide a picture; nevertheless, brief details are included here, for the sake of completeness.

The CBS system uses two channels, each of which carries a Multiplexed Analogue Component signal. These transmissions are not called MAC in the CBS system, but TMC, Time Multiplex Components. Figure 122 shows the basic method of operation.

The source picture can be in a variety of formats, but must be converted to a 1050-line 5:3 aspect ratio interlaced before the actual TMC processing begins. To provide a signal suitable for transmission over channel one, the so-called ‘compatible channel’, every alternate pair of lines from the 1050-line source is averaged, and the result is a 525-line interlaced signal with a 5:3 aspect ratio. The central 4:3 aspect ratio part of this picture signal is then extracted, and it is this signal that is transmitted over the compatible channel.

The second channel carries every other line of the 1050-line 5:3 aspect ratio interlaced picture, and it also contains the information about the side panels which were removed from the pictures in the first channel when the 4:3 portion was selected.

Figure 123 shows the construction of the TMC (MAC) lines used on each of the two channels. The horizontal resolution of the pictures in the first channel is about 1.5 times that of NTSC, since the satellite channels for which the system was designed are of wider bandwidth than that available for NTSC, and the final HDTV picture also has the same resolution. The side panels of the 5:3 picture, however, have lower resolution than the central portion because they must be compressed by a greater amount to allow them to be carried along with the extra information in the second channel.

In the home equipped with only a standard NTSC receiver, a satellite receiver feeding an adaptor box uses the first channel to provide a 525-line 4:3 aspect ratio picture. Where an HDTV receiver is available, however, both signals will be utilised, and the combination of the two allows the receiver to display a 5:3 aspect ratio 1050-line HDTV picture.
Figure 122 The CBS ATV system using two satellite channels
GENESYS—a remarkable proposal from Production Services Inc.

If all the proposed ATV systems are trying to squeeze a quart of information into the pint pot of an NTSC channel, then the GENESYS system from Production Services Inc. (PSI) takes the prize for at least claiming to fit in a whole barreelfull. It claims that using its unique processing techniques it can carry a standard NTSC picture and an HDTV picture and four channels of sound within a single 6 MHz channel. The system that PSI have put forward is not so much a system, more a method of carrying extra information within the NTSC channel, and they claim that their ideas could be utilised to carry MUSE signals or any of the other HDTV signals that have been proposed by other companies. So far they have demonstrated that they are able to carry an additional 3 MHz of information along a standard NTSC channel at the same time as the channel is carrying an NTSC picture, without any visible mutual interference, but it is their remarkable claim that they expect to be able to carry a full-bandwidth 1125/60 production standard video picture along the same 6 MHz channel that has really caused eyebrows to be raised in the industry, some people being openly sceptical of the claims.

Figure 123 The TMC signals for the two channels used in the CBS system
The GENESYS system owes its action to four separate processes or techniques. The first is a ‘new’ modulation technique, called ‘waveform modulation’, and claimed to be completely different from AM, FM, or PM, in that it modifies the shape of the carrier signal in a manner that renders this modulation completely invisible to AM, FM, or PM demodulators in receivers, so that no unwanted artifacts can be seen on the NTSC picture with which such signals are transmitted.

The second technique is an analogue-to-digital conversion technique which is claimed to provide an infinitely small resolution instead of the usual steps that ADCs provide; it is believed that a modified form of Delta modulation is probably involved.

The third leg upon which the GENESYS system stands is a bit compression system that allows 16-bit digital signals to be sent using only three bits, providing a five times increase in the data that can be transmitted over a particular channel.

The fourth process is a novel method of demodulation of the complex signals produced by the GENESYS system. PSI claim that they have a demodulator containing only a few standard components which can detect the modulation used in the GENESYS system down to very poor carrier-to-noise ratios, whilst at the same time demodulating standard AM or FM signals.

The system would allow a broadcaster to carry HDTV and normal NTSC signals on normal transmissions, allowing the viewer to receive either signal, according to whether an NTSC or an HDTV receiver is used. Whilst this sounds to be close to an ideal solution to the American need for a compatible method of providing HDTV, it seems that there is some way to go before the limited demonstrations that have so far been given are supplemented by demonstrations of the full HDTV transmission system, and some engineers have said openly that they believe that the company is extrapolating too far from its proven position, thus seeming to obtain a magical increase in the amount of information that can be squeezed into a given channel.

The Avelex system

A proposal that was submitted to the ACATS but has since received little publicity is a 6 MHz single channel NTSC-compatible system from the Avelex company. Known as the High Definition and High Frame Rate Compatible NTSC Broadcast Television System, the system uses NTSC as its basis, but incorporates sub-Nyquist sampling and uses an eight-field sequence. The proposal suggests that up to 1500 pixels could be displayed on each horizontal line, and that 966 lines could be displayed. Aspect ratios of 16:9, 5:3, and 4:3 can be accommodated, and motion vectors are transmitted by multiplexing them with the I colour-difference signal, and utilised to provide motion compensation information for the receiver.
The Broadcasting Technology Association proposal

Another proposal to ACATS that has since been virtually ignored in the technical press, possibly because many of the desirable features are only offered as future developments, is from the Broadcasting Technology Association (BTA). The system as submitted is really an improved NTSC system rather than a full HDTV proposal. Signals from what could be an HDTV source are first converted to a 525-line interlaced 4:3 format, and the signal processing in the studio consists of adaptive pre-emphasis to improve the detail that can be seen in dark areas of the picture, and quasi constant luminance processing. In addition a reference timing signal is inserted into the video signal and this can be used to cancel ghosting which occurs over the transmission path, by using appropriate circuitry in the receiver. It is assumed that line doubling circuitry would be used in the receiver to convert the incoming picture signals to progressive scan, and the receiver would also use complex three-dimensional filtering to separate the luminance and chrominance signals. Although the initial proposal is only for a 4:3 aspect ratio system, a second phase of development has been promised, which will include wide aspect ratio higher-definition pictures and high-quality audio.

The noise margin method of hiding enhancement information

A group of researchers from the M.I.T. and from Bell Laboratories have put forward details of their experimental work on an ATV system which uses a novel method of hiding the augmentation information within the normal NTSC signal (ref. 21). The result is a signal which can be carried over a standard 6 MHz channel and which gives perfectly acceptable results on standard NTSC receivers, whilst offering enhanced resolution and wider aspect ratio pictures to those viewers with an ATV receiver.

The basis of the idea is the discovery that when an NTSC picture is transmitted over the air and received on a standard NTSC receiver providing a picture that can be seen to have a satisfactory signal-to-noise ratio (SNR), some parts of the picture signal spectrum actually have a higher signal-to-noise ratio than would be strictly necessary to provide an acceptable picture. The difference between the actual signal-to-noise ratio in these parts of the spectrum and that absolutely necessary to provide good pictures is called the noise margin, and this area can be utilised to carry extra information to augment the standard NTSC picture. This extra information can be in the form of extra picture detail and the additional information required to provide widescreen pictures, but if it is to remain compatible with NTSC receivers it must have the appearance of a noise signal as far as the receiver is concerned. For a standard NTSC receiver the only effect of the extra information being squeezed into the channel will be a slight worsening of the signal-to-noise ratio in some areas of the picture, but the system has been
carefully designed so that this noise appears as a very small amount of high-frequency noise which is virtually invisible under most viewing conditions. Nevertheless, the *sine qua non* of the noise margin method of hiding enhancement information is that the original NTSC pictures must have a signal-to-noise ratio sufficiently good to provide noise-free pictures.

Figure 124 provides a simplified explanation of how the noise margin occurs, and how the extra enhancement information can be squeezed in. The human visual system has the characteristic that the signal-to-noise ratio of the pictures that it sees can become lower and lower as the frequency of the detail in the picture becomes higher, whilst still appearing to be satisfactory (ref. 22). The diagonal line in figure 124 is therefore representing this characteristic, and is labelled ‘required SNR’—note that this SNR becomes lower as the frequency rises. The rectangle represents the signal-to-noise ratio of the actual received picture, with all spectral components having the same SNR, as has been found in practice for good-quality NTSC pictures, and is therefore labelled ‘existing SNR’. The top triangle then represents the area of the signal that can be utilised to carry enhancement information, and in the receiver this can be used to construct a higher-definition widescreen picture. This method of obtaining a wider aspect ratio has not yet been finalised, but the authors favoured the technique of vertically cropping the picture, which has been utilised in other systems.

As with other techniques that have been described, this system uses additional tricks to squeeze in even more information. As well as using the noise margin system as described, additional audio information is added to the signal by taking advantage of the fact that the human visual system has a lower temporal bandwidth for colour than for luminance, so that a 15 Hz chrominance flicker is not easily noticed. The temporal rate of the chrominance signals is therefore reduced by half, to 15 f.p.s., by making each successive pair of chrominance frames identical. The digital audio

Figure 124 Basic explanation of how noise margin can be utilised to provide, augmentation information in a compatible manner
signals are then added to the chrominance signals using opposite polarities on successive picture frames. Subtracting the two frames will then provide the audio information, whilst adding them will cancel out the audio and produce the colour information. The added digital information is coherent with the chrominance signals, and should be virtually invisible on an NTSC receiver.

The noise margin method of enhancement can provide an EDTV system with pictures that have twice the normal NTSC resolution in the stationary areas, and as a bonus, digital audio can be added to the chrominance signals.

**Liberty Television/Weaver proposal**

Although it has not yet been officially submitted to ACATS, yet another ATV system was proposed at the NATPE (ref. 23) programming conference at the end of 1989, and if it does nothing else it illustrates that the situation regarding ATV standards in the USA is still very fluid. Jon Weaver of Liberty Television, a New York production house, suggested that if an 1800-line 72 Hz f.p.s system were introduced, this would allow for simple transcoding between 1250/50, 1050/59.94, and 1125/60 standards. No firm technical details have yet been revealed, but it seems that an 1800-line 72 Hz system would be likely to stretch the present state of the art as far as cameras, recorders, and video processing equipment are concerned, so it seems that this is an unlikely contender for the ATV honours.

**The DigiCipher HDTV system**

Although many people were beginning to think that an ATV system based upon some combination of several of the previous systems could eventually win through in the American market, it became plain that new developments are still forthcoming in the ATV field when General Instruments announced yet another proposed system in June 1990. Its DigiCipher system (ref. 24) has resulted in a great deal of discussion amongst engineers, some of whom are extremely sceptical about whether the fascinating proposal can ever be turned into a working system.

DigiCipher is an all-digital HDTV system that, it is claimed, can be transmitted over a standard 6 MHz wide television channel, in either the VHP or UHF bands. Additional advantages claimed are that the decoder complexity is low, and that low transmitting power can be used, allowing the transmissions to make use of otherwise ‘taboo’ channels. Compatibility is achieved by simulcasting the Digi-Cipher information with a standard NTSC signal on another channel.

In order to achieve the miracle of squeezing a digital television signal through a 6 MHz channel a ‘highly efficient unique compression algorithm’ is used to vastly reduce the data rate that is required. In common with
many other researchers in this field, G.I. have decided to use a coding system based on motion-compensated discrete cosine transform (DCT) coding (ref. 25) to achieve this. Such a system can only work because successive television images nearly always contain a large amount of similar information, so that by cutting out the redundant information, i.e. the information which is repeated from one image to the next, only essential data, giving the details of the changes which have taken place from one field to the next, need be sent. As we saw with some other systems, the DigiCipher system compresses the signal by first predicting how the next frame will appear, and then sending the difference between the prediction and the actual image. The simplest way to predict what the next image will be is to use the previous field. Since some parts of pictures contain less redundancy than others, the result is a variable data rate which can sometimes be difficult to handle. This differential pulse code modulation (DPCM) idea works well if there is little movement present or if there is little spatial detail, but can collapse completely under some conditions.

As with many of the other systems using temporal compression, motion estimation and compensation techniques are used with the coding process. The DigiCipher motion estimation system uses large blocks of pixels, called 'superblocks', and provides a motion vector to give information about each of these blocks.

![Diagram of DigiCipher coder](image-url)
DigiCipher coder

Using as its source a 1050-line/59.94 f.p.s. interlaced picture, the DigiCipher digital video encoder takes the Y, U, V signals and samples them at 51.80 MHz, implements the compression algorithm, and generates a video data stream (figure 124A). Four channels of digital audio plus four 9600 baud data channels and the necessary control and synchronizing data are then multiplexed together with the video data, to provide a 15.8 Mbit/s data stream. Forward error correction data is then added, bringing the data rate up to 19.42 Mbit/s, and this data is then fed to a 16-state Quadrature Amplitude Modulator (16-QAM), in which the amplitude and the phase of the transmitted signal are varied. With 16-QAM four amplitudes and four phases are usually used, and QAM was probably chosen in preference to PSK because it has better noise tolerance and therefore better resistance to errors. The multi-level multi-phase 16-QAM signal can then carry the complete audio and video data stream within a bandwidth of only 4.86 MHz.

In the DigiCipher decoder the 16-QAM demodulator receives the incoming signal from the tuner, demodulates it and provides a 19.42 Mbit/s data stream (figure 124B). The demodulator circuitry contains an adaptive equaliser which can compensate for distortions to the off-air signal caused by multi-path reception. The data then passes to the forward error correction circuitry, which can correct random and burst errors and which should provide error-free data to the sync/data selector, which maintains overall synchronisation and demultiplexes the data stream to provide separate streams for video, audio, and data.

![Figure 124B DigiCipher decoder](image-url)
Digital transmission

For transmission, the use of digital modulation permits a much lower transmitter power, perhaps as much as 30dB less, to achieve the same signal-to-noise ratio and therefore coverage area as for analogue NTSC signals. This helps enormously in limiting potential interference to existing

<table>
<thead>
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<th>Parameters</th>
<th>Value</th>
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<td>Dynamic</td>
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</tr>
<tr>
<td>16-QAM Symbol Rate</td>
<td>4.86 MHz</td>
</tr>
</tbody>
</table>

Figure 124C DigiCipher systems parameters (courtesy General Instruments)
transmissions, and allows the system to make use of the ‘taboo’ channels. Since it is claimed that the digital signals take up only a 6 MHz bandwidth, there should be no problems in passing them along existing cable networks, allowing them to carry HDTV signals with the minimum of modifications, and the signals should also be suitable for use over Multichannel Microwave Video Distribution Systems (MVDS) and over satellite links. G.I. even claims that ‘all-digital recording and playback of its HDTV signals is within the reach of current technology for consumer use, since the total data rate is less than 20 Mbit/s’. With DigiCipher claiming so many different advantages, it is no wonder that the sceptics are shaking their heads!

MUSE for the USA—a Japanese hierarchy of systems

The systems proposed by NHK for the American market have deliberately been left until the last part of this chapter, mainly because we have already considered the detailed operation of the MUSE system in chapter 8. The variants of the MUSE system that have been proposed all work using some of the same basic principles as the system described earlier, but they have been extensively modified so that the signals can be squeezed into the bandwidths that the FCC has said will be made available.

The original MUSE system was designed primarily for satellite broadcasting, and uses an 8.1 MHz wide baseband channel to carry a 16:9 1125-line picture with 1440 horizontal picture elements. Such a signal will not fit into a standard NTSC channel, and so three major variations of MUSE have been developed to try and find a system that would be acceptable for the North American terrestrial transmission system. Since the basic MUSE system is totally different from NTSC there is no way in which it could truly be called compatible, since the MAC-like nature of the signals means that a decoder box would be necessary to provide NTSC viewers with a picture; the only way in which compatibility could really be claimed under the rules of the FCC ‘game’ would be if the modified MUSE signals could be fitted into a 6 MHz channel which parallels a standard NTSC channel carrying the same programme material, the so-called simulcast technique. The three suggested ATV versions of MUSE are called Narrow MUSE, which uses the simulcast technique, and MUSE-9 and MUSE-6 which are completely redesigned versions of MUSE that can also provide pictures on NTSC receivers. Figure 125 shows how they fit into the hierarchy of MUSE systems for all purposes, from wideband satellite transmissions to narrowband terrestrial ones.

Narrow MUSE

The essential features of Narrow Muse are that it is an ATV system with four channels of digital audio that can be carried in a 6 MHz wide radio frequency channel, so that it can be simulcast with an NTSC signal on another channel. To
reduce the bandwidth from that of the normal MUSE signal the number of scanning lines is reduced from 1125 to 750, but as we saw in earlier chapters, this should be sufficient to provide an HDTV display if appropriate upconversion is carried out in the receiver. Even this reduction in lines is not sufficient to let the signal pass through a 6 MHz channel, so multiple sub-sampling is used, as described in chapter 8, to provide a further reduction in bandwidth. Stationary parts of the image are subsampled with a combination of field offset and frame offset sampling, whereas moving parts are processed using line offset sampling, which means that moving areas will have lower resolution; as we have seen before, this will be acceptable to the eye. Essentially then, the Narrow MUSE system uses line reduction and multiple subsampling to reduce the spectrum required to just over half of that needed for standard MUSE, giving a baseband video signal with a bandwidth of 4.86 MHz which can then be transmitted using vestigial sideband amplitude modulation within the confines of a 6 MHz wide radio frequency channel, as shown in figure 126. The digital audio is transmitted during the vertical intervals, and there are two options available, giving four channels at moderate quality or two channels at high quality.

Since Narrow MUSE uses the same basic encoding techniques as MUSE,
Figure 126 RF spectrum occupied by a Narrow MUSE signal

Figure 127 Narrow MUSE encoder and decoder using interfaces—block diagram
except for the scanning line conversion from 1125 to 750 lines, Narrow MUSE signals can be obtained by using what are known as **interface adaptors** at the input of standard MUSE coders and in a similar way standard MUSE decoders can cope with Narrow MUSE signals, which should help with equipment standardisation, but is unlikely to assist in keeping costs down. In the receiver the 750-line picture signal is converted to 1125 lines before display (see figure 127.)

The picture quality which Narrow MUSE can provide is better than that available from the MUSE-6 and MUSE-9 systems which will be described next, primarily because the Narrow MUSE system is not constrained by NTSC compatibility.

**MUSE-6**

The MUSE-6 system provides pictures with twice the static resolution of NTSC, a 16:9 aspect ratio, which is obtained by cropping the picture vertically, and improved chrominance resolution, and yet it fits comfortably within the limits of a 6 MHz wide NTSC channel and provides acceptable pictures on NTSC receivers.

The improvement in horizontal resolution is obtained by frequency-multiplexing different parts of the picture information. The parts of the frequency spectrum above 3.9 MHz are divided into two, one extending from 3.9–5.8 MHz and the other from 5.8–7.7 MHz. These two components are interleaved into an NTSC signal by using two frame-offset subcarriers. The multiplexing of the high-frequency components is only carried out on static areas of the picture, so that the resolution of moving areas is about the same as that of standard NTSC pictures.

The 16:9 aspect ratio picture has only 345 basic scanning lines, which would give a vertical resolution around half that required for an ATV picture. Once again, multiplexing is used to improve things, as is shown in figure 128. The first 345 lines of the cropped picture are transmitted normally, but the vertical high-frequency components, corresponding to lines from 346–690, are time-multiplexed during the extended vertical blanking periods, i.e. they are carried in the masked-off portions of the picture area above and below the visible image. There are some 160 lines in the extended vertical blanking period, so to carry the lines from 346–690 it is necessary to compress the information from two lines so that it fits into one of the lines in the masked-off area. In order to permit this, the horizontal resolution of the extra lines (i.e. the vertical high-frequency components of the picture) must be reduced by a half.

In a similar manner, the chrominance signals can be given enhanced resolution by frequency-multiplexing the high-frequency parts of the chrominance signals into the high-frequency luminance signals that are carried in the masked-off parts of the picture.

Digital audio signals can also be added by carrying the digital data in the
line blanking periods, before and after the line sync pulses, and this sound is of course in addition to the normal FM sound that would be carried by an NTSC signal. Figure 129 shows the basic method of operation of the MUSE-6 NTSC-compatible system.

The source, as with all MUSE systems, is a 1125-line 60 Hz 2:1 interlace picture with a 16:9 aspect ratio. The source is sampled at 31.9 MHz for luminance and 15.4 MHz for each of the colour-difference signals, and these sampled signals are then fed into a noise reducer and applied to a motion detector, which examines adjacent fields and determines the difference between them. The prior noise reduction is necessary because the difference signals from the adjacent fields will contain noise, which could lead to the motion detection circuitry becoming confused. The main signal is then converted from 1125 lines to 750 lines, interpolations between fields being used on static parts of the picture and just the current field information for moving parts of the image. It is then necessary to convert the field rate from the 60 Hz of the source to the 59.94 Hz which is required to ensure compatibility with NTSC; the conversion is done by reading the information into field stores at the 60 Hz source rate and then reading it out at the slower 59.94 Hz rate. Information is taken from the motion detection circuitry to improve this conversion. The signals are then passed to a matrix and a non-linear processor to provide signals of an appropriate gamma for the NTSC system, and they then enter the circuitry which carries out the arrangements for ensuring that the masked-off parts of the picture carry the enhancement information.

As shown earlier, the $Y$, $I$, and $Q$ signals from the matrix form a 750-line signal which is divided vertically into two separate components representing...
Figure 129 The MUSE-6 encoding system
the high-frequency and low-frequency parts. The low-frequency part provides
the information for the central part of the picture, whereas the high-
frequency part, after horizontal band-limiting, is compressed, and the
compressed information provides the top and bottom parts of the masked-off
picture. The $Y$, $I$, and $Q$ signals are then pushed into an NTSC encoder, and
the high-frequency component signals are separately encoded. Digital audio
and ghost cancellation signals are added to the vision signals before
transmission. The resulting MUSE-6 signal can be carried in a standard 6
MHz wide NTSC radio frequency channel, and will provide a standard NTSC
receiver with an NTSC picture. ATV receivers will be able to make use of the
extra information that the MUSE-6 signals contain in order to provide a
1125-line widescreen picture with better resolution.

**MUSE-9**

The MUSE-9 system uses a main channel which is identical to MUSE-6, but
in addition it makes use of another 3 MHz wide channel to carry further
augmentation information. MUSE-9 is therefore compatible with existing
NTSC receivers in the same way as MUSE-6. The augmentation channel,
which occupies 2.1 MHz of the baseband channel, provides extra
information which can be used to increase the resolution of the moving
parts of the picture, and to provide extra digital sound channels and an
improvement in the quality of the original digital audio signals. The
augmentation channel signal is transmitted as a 525-line signal in which
the extra movement information about the high-frequency parts of the
picture is time-division-multiplexed with the digital audio signals. Using
vestigial sideband modulation the augmentation information can be carried
within a 3 MHz radio frequency channel, and the main and augmentation
channels can either be transmitted by one transmitter in a 9 MHz wide
contiguous band, or by two separate transmitters, as shown in figure 130.

It is felt that where possible the single 9 MHz channel option would be
preferable, since this is likely to avoid possible problems with amplitude and
phase differences between the main signal and the augmentation signal.

**MUSE for ATV**

All of the three MUSE systems that have been proposed for American ATV
use a 1125-line 60 Hz source. Narrow MUSE provides the highest-quality
pictures and is closest to the original MUSE system in that it does not
produce a signal which can be used by NTSC receivers, although it does fit
into a single additional 6 MHz channel, so that simulcasting has to be used
to provide ‘compatibility’.

MUSE-6 provides NTSC receivers with a fully compatible signal, and can
produce widescreen pictures and two channels of digital audio on an ATV
receiver. By the addition of an extra 3 MHz wide augmentation channel
Figure 130 MUSE-9 transmission options

- Single 9 MHz System
- 9 MHz
- MUSE-6 Signal
- Dual 6/3 MHz System
- 6 MHz
- Augmentation Signal
- 3 MHz
- Two Transmitters
- From Source

Diagram on the left:
- One Transmitter (Tx)
- MUSE-6
- Augmentation Signal

Diagram on the right:
- Two Transmitters (Tx 1, Tx 2)
- MUSE-6
- Augmentation Signal

From Source
MUSE-6 is transformed into MUSE-9, an NTSC-compatible ATV system which has better resolution of the moving parts of the image than MUSE-6 and provides improved audio.

**The US ATV proposals—thoughts and conclusions**

We have looked at over twenty potential ATV systems for the United States, and since many of the techniques used to provide improvements in one of the systems could just as well be utilised to improve some of the other systems, the number of possible permutations is enormous. The work that would be necessary to evaluate and compare all these systems would be time consuming and expensive, and this has led the American Electronics Association, which might be expected to be a bastion of ‘stand on your own feet’ capitalism, to ask for nearly $1.5 million from the government to fund the necessary research, a request that has not been acceded to. In fact it seems that not all the proposals will be submitted for testing; in 1989 the chairman of the subsystems committee of the FCC ACATS invited companies with ATV systems to provide equipment for testing at the Advanced Television Test Center (ATTC) in Alexandria, Virginia, and at the time of writing it seems that towards the end of 1990 only the following companies will provide complete systems for testing, although there is, of course, still time for others to join them:

- Faroudja Laboratories—SuperNTSC
- Massachusetts Institute of Technology—MITV-CC and MITV-RC
- New York Institute of Technology—ViSTa
- NHK (Japanese Broadcasting Corporation)—Narrow MUSE, MUSE-6 1and MUSE-9
- North American Philips—HDNTSC
- Production Services Inc.—Genesys
- David Sarnoff Research Centre—ACTV-I and ACTV-II
- Zenith—Spectrum Compatible HDTV
- General Instruments—DigiCipher

**Sound improvements with ATV**

Improved sound systems have been mentioned in connection with many of the proposed ATV systems, and it has been shown that various digital sound channels can be carried along with the improved picture signals. In addition to this, two companies have submitted complete audio subsystems which they claim could be used to bring further enhancements to the sound of many of the ATV systems. The two companies are Dolby Laboratories and Digideck.
The problems of critical assessment

The author is very much aware that in this chapter the multiplicity of systems has been described fairly uncritically, which is the major disadvantage of having to rely on manufacturers’ descriptions of what their systems can achieve whilst not yet being able to judge the systems in practice. Until side-by-side tests and demonstrations of the various systems have been carried out it will not be possible to reach sensible conclusions on which systems are best, and it is vitally important to remember that a system which performs perfectly in the laboratory may turn out to have severe problems when it is subjected to the many degradations that can occur to a signal when it is transmitted over the air. Practical transmission systems may involve passing the signal over cable and microwave links before transmitting it through several transmitters in tandem before it finally reaches the home by means of a less-than-perfect antenna assembly; received signals are likely to suffer from noise, ghosting, and selective frequency distortions which could play havoc with an ATV signal which has had its complete frequency spectrum packed full of the extra information that is necessary to provide enhanced pictures and sound.

In general the techniques used in the various systems that have been proposed for ATV use some combination of an increased bandwidth, reduced diagonal resolution, and reduced temporal resolution to provide increased vertical and horizontal resolutions when compared with NTSC. It is possible to make some predictions of the likely problems with each type of system, although at this stage it is only fair to manufacturers to say that each would probably claim to have ways of minimising or avoiding these defects. From a normal understanding of engineering principles and the author’s in-built conviction that ‘you don’t get something for nothing’ it seems reasonable to assume that those systems which use the largest amount of bandwidth should be able to provide the best performance, provided of course that the bandwidth has been used optimally. It is important to note, though, that the ATV systems have generally been designed to provide some degree of NTSC compatibility, in accordance with the FCC requirements, and this factor may act as an important constraint on what would otherwise be the optimum usage of the available spectrum. Most of the techniques used in the various ATV systems actually trade off one parameter for another, as we have seen, and it is usually a case of removing information that the human visual system is not too aware of in order to include extra information giving more detail in the parts of the picture that the eye and brain do find important.

We therefore have the situation where the systems which provide improved resolution, whether vertically or horizontally, generally provide reduced performance in one way or another when motion is present in the pictures. Reduced temporal resolution is the inevitable result of some of
these systems; the MUSE and North American Philips proposals need more than one frame to update a picture, using 15 frames per second, whilst the Del Rey system sends only 10 f.p.s. and the Glenn VISTA system has a 7.5 f.p.s. update rate. The system proposals from Bell (SLSC), Scientific Atlanta HDB-MAC, and CBS should all provide full temporal resolution, whilst the David Sarnoff/NBC ACTV proposal is likely to suffer some loss of temporal resolution because of the inter-frame averaging techniques which it uses.

The systems which include the separate transmission of side panels to provide wider aspect ratio pictures for the ATV viewers could suffer from problems; as an example, if the signal-to-noise ratio of the side panels is not as good as that of the main picture, and it often will not be, then under certain reception conditions it may well be possible to see the joins between the main picture and the edges. The systems which use a 16:9 or 5:3 picture as the basic system picture will not suffer from this problem, but may cause compatibility problems with NTSC receivers which will display blank strips at the top and bottom of the picture, as we have seen.

The various subsampling processes work extremely well for much of the time but can cause artefacts in the form of annoying patterning effects and unusual and therefore irritating motion effects on some pictures. Even the display improvements which may be obtained from receivers which can provide continuously scanned pictures from incoming interlaced signals are not always without technical cost—upconverting to higher line numbers can produce visible artefacts. In the same way that the colour subcarrier of an NTSC signal can break through to provide luminance patterning on a picture, systems that use extra subcarriers, such as the David Sarnoff/NBC ACTV system, could result in further interfering patterns if the relative levels of the various signals are not carefully controlled, as can happen when the signals are sent over a difficult transmission path. Opponents of the Genesys system find it difficult to believe that all the extra information needed can be squeezed into a standard NTSC channel without the extra information causing some sort of degradation; only time and stringent testing will show who is right.

It is only right when discussing the disadvantages that some of these systems have to point out that several of the systems will result in the NTSC viewer actually receiving better-quality pictures than before; as just one example it seems that the pre-processing that picture signals will be subjected to in the Faroudja SuperNTSC proposal should mean that NTSC pictures will suffer much less from cross-colour and moiré patterning.

Further implications

The type of research work that is being done to obtain an agreed ATV system will be very relevant to improving other existing terrestrial systems
when the time is right. We have seen already that the Japanese Clear-Vision system uses similar techniques to provide much improved 525-line pictures which can be enhanced and upconverted in the receiver.

In the United Kingdom, as another example, there is some concern that the provision of enhanced widescreen MAC pictures from the DBS satellites might in the long term lead to the existing terrestrial broadcasters losing business, as their viewers come to see the existing 4:3 aspect ratio PAL pictures as rather ‘poor relations’, and advertisers might choose to put their advertisements on the channels providing the best quality. To overcome this the broadcasting research engineers are currently working on methods of enhancing PAL and of providing widescreen terrestrial pictures in a compatible manner; many of the techniques being studied have a great deal in common with the ideas being put forward for ATV systems in the USA. We have discussed earlier the BBC suggestions for Extended PAL (E-PAL) that were put forward when the UK DBS plans were being considered; the BBC is now experimenting with Digitally Assisted Television (DATV), which was discussed in chapter 9 for HDTV applications. By using a separate subcarrier to carry the DATV information, rather than the vertical blanking interval that is to be used for the data in the HD-MAC proposals, it might be possible to transmit 625-line PAL signals which give acceptable pictures to viewers with normal PAL receivers, whilst the DATV information can be used by an HDTV receiver to provide high-quality 1250-line widescreen pictures. The UK IBA also has its own system, called SUPRA-PAL.

In Germany a good deal of research is going on to try to achieve enhanced PAL pictures in a compatible manner. The Institute of Broadcasting Technology (IRT) has developed a system called Improved PAL (I-PAL), and The University of Dortmund has shown Quality PAL (Q-PAL). The systems provide enhanced horizontal luminance resolution, to allow for the requirements of widescreen pictures, and the effects of cross-colour and cross-luminance are much reduced. Grundig is taking part in the tests of these various systems. Other schemes being worked on include the addition of digital sound (Germany does not use the NICAM digital dual channel sound system developed in the UK), and the possibility of providing widescreen pictures, one such idea having the label PAL-Plus. Philips and Thomson are both much involved with this research, which should keep them at the forefront of the technology whether the future of enhanced television turns out to lie with MAC or with PAL.

**How the I-PAL system works**

On any one alternate line of the television picture, say line \( n \), the complete luminance signal is carried, utilising the maximum possible luminance bandwidth (5 MHz) for the German system. On the next line, line \( n+1 \), only the low-frequency part of the luminance information (i.e. up to about 3 MHz) is carried, and this information is frequency-multiplexed with the
usual PAL quadrature modulated chrominance subcarrier. The standard PAL colour burst is carried on every line. In the I-PAL receiver, the high-frequency luminance portion of line \( n \) is delayed by one line period, and this information is then added to the low-frequency luminance information which is carried on line \( n+1 \). In a similar manner the chrominance information carried on line \( n+1 \) is delayed and then added to the luminance information being carried on line \( n+2 \). This rather clever idea means that the received pictures can be free of the various cross-effects, and the higher-frequency luminance information carried on alternate lines can provide an increase in horizontal luminance resolution.

As might be expected, however, the disadvantages of using this technique are that the vertical chrominance resolution is reduced, as is the diagonal luminance resolution; we have seen earlier that the human visual system can generally accept both of these limitations. Unfortunately, the I-PAL pictures produced on conventional PAL receivers appear rather unsaturated, and adjustments are needed. Possibly more significantly, over-air tests in 1988 showed up some significant hue errors, caused by differential phase problems occurring over the transmission path. In order to try to overcome this, a modified version of I-PAL, called I-PAL-M, has been developed, and this does allow the effects of phase errors to be compensated for, as well as providing an improved signal-to-noise ratio. Since I-PAL is essentially a transmission system, however, no improvement in cross-effects will be achieved if the output from a standard PAL studio is used as its input; signals from a component studio will be necessary to make the best of the system.

The Q-PAL alternative

Quality PAL came about as a result of research work at the BBC and at the University of Dortmund, in Germany. Like other proposed systems it eliminates cross-colour and cross-luminance and also permits some increase in the horizontal luminance resolution. The improvements come about because multidimensional filtering techniques are used at both the transmitter end and at the receiver end of the transmission chain. Effectively, the spectra of the chrominance and the luminance signals are filtered far more precisely than in the standard PAL system at the transmit end, and this pre-filtering allows the receiver to make a much better job of separating out the luminance and chrominance components. Even conventional receivers show fewer cross-effects when used to receive Q-PAL signals, and the special Q-PAL receivers give improved results even when receiving standard PAL signals, because of the more precise filtering that is used.
The PALplus system

PALplus is a system which has been designed to provide the compatible picture quality improvements possible with I-PAL and Q-PAL, whilst at the same time offering viewers who are prepared to buy new receivers the chance to receive wide-screen, 16:9 images. This is likely to become more and more important as existing broadcasters have to learn to compete with the widescreen offerings that satellite broadcasters can provide; if advertisers are to continue to support terrestrial transmissions it is important that these services are not seen to be technically inferior.

The technique which the PALplus system uses to provide widescreen pictures in a compatible way is similar to that adopted by some of the American schemes, in that it assumes that ordinary 4:3 viewers will be happy with a ‘letterbox’ style of presentation which gives a black band at the top and bottom of the picture; the method of achieving this, however, is rather different. We have seen that in a standard PAL picture only 575 of the total 625 lines actually carry picture information, these being called ‘active lines’. The PALplus system removes every fourth line from this 4:3 aspect ratio active picture area and then squashes together the remaining 431 lines, which results in a picture of about three-quarters the original height, which then has an aspect ratio of 16:9. The 144 lines which were removed are not thrown away, but are inserted into blank spaces at the top and bottom of the cropped picture, 72 at the top, and 72 at the bottom, but the video information on these lines is processed so that it cannot be seen by viewers with 4:3 receivers. The net result of all this is that a conventional receiver will display only the central 431 lines of the picture, in a letterbox format, but an appropriate receiver with a 16:9 display will use the information in the 72 lines above and below the main picture signal and will rearrange these lines to synthesise a full-height widescreen picture.

There are currently several problems with the PALplus system. Firstly, removing every fourth line can lead to jagged edges along diagonal parts of the picture, and some form of interpolation must be used to correct for this. Additionally, there are difficulties in squeezing the extra information that is being carried into the standard radio frequency channels used by the PAL system, and various ideas are currently being discussed to overcome this. One suggestion is that the information carried in the 72 lines above and below the main picture information could be transmitted in the so-called ‘ultra-black’ range, i.e. that part of the signal that corresponds to the video area between black level and half the level of the synchronising pulse, between 150 and 300 mV in a video signal which usually has a peak-to-peak range of 1 volt from the bottom of sync pulse to peak white.

This idea works well in laboratory tests, but the effective depth of modulation of the video will be reduced, so that the signal-to-noise ratio will be worsened, and this may be important when signals are transmitted over long paths.
It appears that the techniques used in PALplus could equally well be applied to SECAM signals, and work is currently under way to try to find methods of implementing PALplus that would allow SECAM to benefit from the same improvements—some engineers are using the name ‘Colour-plus’ to describe enhancements which would encompass both PAL and SECAM systems.

DBS for the USA—at last? The Sky Cable project

This chapter began with the statement that there was no real demand for high-powered DBS transmissions in the USA, and in fact various unsuccessful attempts to start such a service have in the past been made. In the spring of 1990 moves were made which could change this position and provide DBS services within the next few years, whilst at the same time completely changing the picture as far as ATV and HDTV systems are concerned. Hughes Communications has joined with NBC, Cablevision Systems Corporation, and a company owned by Rupert Murdoch, The News Corporation Ltd., to sign a memorandum of understanding which establishes a partnership for the purpose of providing high-power DBS services to the American public. The plan is to use a Hughes 601 spacecraft, and the somewhat questionable claims from the publicity blurb say that ‘as many as 108 new television channels will be made available using digital video techniques’, and that ‘HDTV signals of any standard’ can be broadcast, along with compact disc quality audio. The initial estimates are that the four partners will provide equal shares of the one billion dollars which will be needed to set up the system, which is to be called Sky Cable. European readers will find this name somewhat reminiscent of Murdoch’s Sky Television from the Astra Satellite, which is directed at the UK market. The Hughes satellite is one of the most powerful currently available, and even radiating large numbers of channels it should be capable of providing viewers with excellent pictures on small dishes of around 50 cm diameter. The consortium says that the receiving equipment will retail at about $300. Many viewers in the USA have installed 3-metre ‘backyard’ dishes, so the new service, which will be aimed at rural areas as well as at existing cable head ends, will provide new pictures at much less expense and with much smaller antennas. The intention to provide HDTV transmissions could turn the current situation regarding ATV on its head, and it will be fascinating to see the effect that this new service will have on ATV developments.

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At the CCIR Plenary Assembly meeting in May 1990, what many considered the last chance to reach an agreement on a world standard for HDTV slipped by for another four years, as the decision was made to defer any agreement until the next CCIR study period, which runs from 1990–1994. We have been careful to distinguish between transmission standards and studio standards in our discussions, but neither one of these has yet been achieved. Although many brave words about the importance of reaching an agreement on an HDTV standard were spoken, practical engineers can see that it now seems unlikely that there will be just one standard, and that for some considerable time ahead we are likely to see the Japanese 1125-line/60-Hz standard competing with the European 1250-line/50-Hz standard and an American standard perhaps based on 1050-lines/59.94-Hz. It is also important to remember that many other countries besides the USA and Japan currently use NTSC and therefore have an interest in an HDTV system that is NTSC compatible; during 1988 a group of thirteen countries using NTSC met to consider the wider implications that the adoption of an HDTV system would have. In spite of what the European engineers tell you, the Japanese 1125/60 system is currently something of a de-facto HDTV studio production standard, with facilities houses in Europe and America making use of it, but this is mainly because there is no other HDTV equipment currently on sale.

Test productions using the Sony High Definition Video system have been made, using equipment supplied (presumably on loan) by the manufacturers, by several European Broadcasters, including the BBC and HTV in the UK, RAI and Canale 5 in Italy, ORF in Austria, SFR in Switzerland, ZDF in Germany, and RTVE in Spain. The EUREKA aim of promoting the 1250/60 system as a studio standard is likely to come to fruition as the project moves from the experimental stage and studio equipment becomes available for sale, but there are no indications that it will become the world studio standard—the Japanese system is unlikely to go away. Compounding the standardisation problems even further, the Russians have said that they do not favour any of the current proposals, and that they certainly do not intend to adopt the step-by-step approach based on MAC. They claim that such an approach would merely delay the onset of ‘proper’ HDTV. Similar sentiments have been expressed by the Australians, who feel that in the longer term
revolutionary change is inevitable due to the coming of digital technology, and they feel that any approach to HDTV that has a heavy emphasis on backwards compatibility can at best provide only an interim solution. Australia advocates a digitally based single worldwide HDTV standard, but accepts that such a proposal must include a practical transitional path from existing systems to this new HDTV standard (ref. 1). Although many other engineers throughout the world would probably agree with these sentiments, it seems that to put these brave ideas into practice would delay the coming of HDTV for many years.

The groups of engineers working on the various HDTV projects have by no means given up their attempts at moving towards standardisation, however, and the currently fashionable idea is to try to reach agreement on some aspects of HDTV which can be regarded as common to all the existing systems, even though agreement on a complete system is unlikely to be reached. In other words, let us not worry about those things which we cannot agree on, but instead let us try to standardise those features of an HDTV system that could be common to all systems; as well as easing the path towards an eventual common standard this approach would make conversion between existing systems much simpler. The cynics say, with some truth, that the only parameter on which agreement has currently been reached is the aspect ratio; the whole world seems to agree that 16:9 could be acceptable, even if their currently favoured system actually uses something rather different. In fact there are agreements on a good many other basic characteristics as well, including things like the number of pixels per active line (1920) and the orthogonal arrangement of those pixels, and much work is currently being undertaken to try to reach mutual agreement on what are known as the Common Image Format and the Common Data Rate concept, the idea being to agree upon as many common parameters as possible; at the moment this work is mainly connected with the HDTV studio production field. The major remaining difference between the various systems is that of field rate, but so fundamental is this difference that it affects many of the other parameters of the HDTV signal.

**Scanning** It seems to be generally agreed that progressive scanning would be the best long-term option, but because of the complexities and the memory requirements when this is used for a full HDTV system, the various parties involved in trying to reach an agreed standard have recognised that 2:1 interlace is probably the most practical method of scanning in the near term. One manufacturer has suggested that it might take as long as ten years to bring a 1000-line progressive scan camera onto the commercial market-place.

**Colorimetry** The CCIR expert group on colorimetry has accepted that in the long-term the agreed HDTV system should have colorimetric parameters which are in full agreement with the constant luminance principle, and
which also allow for the representation of a wider range of colours than is at present possible. The experts are currently recommending (ref. 2) that this eventual goal should be achieved in two steps, first adopting an interim set of parameter values that can be put into practice with today’s technology, leaving the final step to be taken after further discussion and development and when practicable. Some engineers are unhappy with this approach because they feel that it will be difficult to make changes to something as basic as the colorimetry of a system several years after its inception.

**Common image format**

The Common Image Format approach takes the long-term view that television pictures may not always be synthesized by a scanning process, as at present, and that the best way to consider a television picture is as a large number of individual pixels positioned over the whole of the display screen. The desirable number of pixels per active line, i.e. that actually carry picture information on each line, has been agreed as 1920, but since the number of active picture lines has not yet been agreed, other parameters such as the shape of the picture elements cannot yet be agreed. One suggestion was to use 1080 vertical pixels per picture, i.e. 1080 active lines, since this would result in square pixels when a 16:9 display was used, and would provide a satisfactory number of visible lines for use with both 1125 and 1250-line systems. It would not, of course, be possible to use this number of lines with a 1050-line system. To illustrate that there is nothing ‘magic’ about the chosen numbers, an alternative suggestion, that has now been dismissed, was to have 1024 active lines and 1792 samples per line; this also gave square pixels, with an aspect ratio slightly different from 16:9.

The ideal ‘common image’ would have the same aspect ratio, number of active lines, number of pixels per active line and colorimetry irrespective of the frame rate or scanning method utilised. Many engineers like the common image approach because it is rather like the electronic equivalent of film, where all the pictures are based on a single common image—the frame. If a common image approach could be agreed upon then standards conversion between the different HDTV systems would be simpler, since only temporal conversion would be needed. Although the common image concept would mean that the active portions of the image, horizontal and vertical, would be the same for all systems, the blanking periods and total line periods and total numbers of lines could be quite different in different systems, which should enable HDTV to be introduced in a manner that is compatible with existing line and field rates that differ between different systems. The American ATSC favours the common image approach, and has said that it requires its HDTV production system to work at both 59.94 Hz and 60.00 Hz, the former to maintain compatibility with existing transmissions, the latter for use in production centres where NTSC compatibility is not a consideration (ref. 3). Although such a dual frame rate
approach could give rise to complications if attempts were made to edit between tapes using the different frame rates, the common image concept should be able to cope with the basic requirement of producing HDTV pictures at either of the two rates.

The Australians have a slightly different vision of what a common image format should include, and as well as a common image of the type mentioned above they favour a ‘common frame’. [N.B. It is important to notice here that the Australian use of the word ‘frame’ corresponds with the English word ‘field’; two Australian frames make one complete picture.] The common frame would have the same total number of lines (active plus blanking) and the same number of pixels per total line (active plus blanking), whatever the actual frame rate. This would provide for operation at different frame rates, and the Australians favour a so-called ‘agile receiver’ which could cope with different incoming frame rates.

Whatever the small differences in the perception of the common image format, the idea can be seen to imply in essence a commonality of spatial characteristics for the active area of the picture, so that the number of samples per active line, the aspect ratio and the number of active lines are common, whereas the picture rate, the sampling frequency and the data rate could differ between systems.

Although the Common Image approach thus has much to commend it, the fact that the details of the common image cannot yet be agreed could mean that in practice this approach will bring us no nearer to reaching a common standard than using any other approach, and could actually delay the final denouement.

The common data rate

The world standard for digital television studio signals, CCIR Recommendation 601, was discussed in detail in chapter 6, and the reader may remember that the data rates for both 525-line/60 Hz and 625-line/50 Hz systems were the same, adjustments being made to the number of samples carried in the blanking periods in order to achieve this. Effectively, Recommendation 601 is based upon a common sampling frequency, a common sampling mode, a common sampling structure, and a common number of pixels per active line for both 525/60 and 625/50 pictures. The common data format for HDTV builds on the ideas of Recommendation 601, and is essentially a two-step ‘dual-standard’ approach to a single programme exchange standard.

The common data rate approach uses techniques in which the sampling frequency and the data rate are the same for systems which have different picture rates; the aspect ratio and the number of samples per active line are also common. In chapter 6 we saw that the luminance sampling rate for Recommendation 601 was 13.5 MHz, with two colour-difference signals sampled at half this rate, so that at eight bits per sample we ended up with
8×(13.5+6.75+6.75)=216 Mbits per second. Although the first step would be to utilise HDTV standards that were based on the same rates as CCIR Recommendation 601 and therefore using a common data rate for both 525/60 and 625/50, the next step might be to use a higher common data rate, and 74.25 MHz (5.5×13.5 MHz) is one rate that has been suggested. This would allow commonality between 1125/60 Hz pictures and 1250/50 Hz pictures, and the mathematics shows that an even higher standard of 1375 lines at 50 Hz would also fit into the set. Research engineers at the UKIBA have shown that other options are possible, whilst retaining a simple relationship with Recommendation 601, which is important for standards conversion to conventional standards:

1250/50–1050/59.94
1250/50–1125/60
1375/50–1125/60
1200/50–1001/59.94
1200/50–1000/60

Although any of these options could theoretically be used, the set with most of the advantages seems to be 1200/50–1050/59.94, both using progressive scan, since the relationship which this bears to the original 4:4:2 signal of Recommendation 601 corresponds to an increase by a factor of two in both horizontal and vertical directions, and the reader may remember that one of our aims in approaching HDTV was to double the resolution of the existing systems both horizontally and vertically. This scheme could be implemented with either an orthogonal sampling structure, or with the quincunxial structure that was discussed in chapter 9. As was seen in that chapter, the quincunx structure has the advantage of allowing us to retain the detail from a progressively scanned picture even when interlaced transmission is used, and this helps to improve the performance that can be obtained from standards conversion. It could also allow for interlaced scanning to be used as an initial step in the introduction of HDTV, with progressive scanning following later.

One scenario that has been discussed is that dual-standard switchable equipment could be made for both studios and receivers, so that initially both standards could be used in appropriate countries, but leaving open the possibility that one day the overwhelming advantages of one of the systems would become so apparent that it would become the de facto world standard. This argument ignores the probability that such receivers would be more expensive than single-standard equipment.

As might be expected, not everybody likes or supports the common data rate approach to HDTV. It is by its very nature a dual standard system, which means that some desirable combinations of other standards might not be practicable. The Canadians have done some work which suggests that when this type of approach is used it is inevitable that one of the
standards must have a lower spatial resolution than the other, and they feel that this will delay the eventual implementation of a single standard.

Open architecture receivers

The discussion of the idea of dual-standard receivers provides a reminder that in chapter 10 it was mentioned that the Massachusetts Institute of Technology (MIT) had suggested the adoption of Open Architecture Receivers (OAR), making the argument that if dual-standard receivers were being developed it might cost only a little more to develop OAR receivers that could decode lots of different standards, i.e. receivers that were basically independent of the transmission standard used. Such a receiver would use whatever information was presented to it, and somehow build up a suitable picture for display. Looking at this idea in a broader time frame we could envisage a television system using OARs that looked something like figure 131.

Signals from a wide range of sources could be received in the home or at a cable head end and then fed by cable distribution system to the home. The Open Architecture Receiver would consist of appropriate input circuitry to cope with the various incoming signals, some computer-controlled signal processing circuitry, and a display of the highest quality that the customer chooses to buy. Whatever the standard of the incoming signals the computer circuitry associated with the OAR takes control of them and uses them to build the best high-definition picture possible in the circumstances. In addition there might be outputs from the OAR which could feed other small-screen television receivers in the same house.

![Figure 131 Principles of an open architecture receiver](image-url)
Figure 132 The MIT Smart Receiver—showing how open architecture works
The MIT submission to the FCC included details of a possible configuration for a receiver of this type, which they christened The Smart Receiver (ref. 4). Figure 132 shows the block diagram, from which it can be seen to consist of three basic sections.

The input section, shown along the top of the diagram, consists of the necessary tuner(s), RF and IF amplifiers, a demodulator, an analogue-to-digital convener, and a frame store. This section of the receiver is said to be ‘tunable but not programmable’. Whatever the input signal, within the limits of what the tuner and input section can cope with, a complete picture frame is held in what is called the input frame store, although it should be noted that this is not necessarily in a form that could be used directly for display.

The central section of the diagram consists of input and output signal busses which provide the interfaces between the input and display sections and the processing section. The same digital bus lines can be used to connect digital input signals directly to the receiver, allowing it to synthesize a display from digital signals coming from a fibre optic cable, perhaps, or allowing for the connection of a digital video recorder or the input of computer data or graphics. The main function of this middle section of the receiver is to take the information that has been stored in the input frame store and to process it, perhaps rearranging the information corresponding to particular pixels and by carrying out the various interpolation processes that are needed to construct a high-quality picture with the desired aspect ratio. The processing that is carried in this section is controlled by the microprocessor control module, which can be pre-programmed or which can accept messages from the remote control unit operated by the viewer. Effectively we have, in this central part of the smart receiver, a computer processing stage which could be very cheaply mass-produced. The advantage of using such circuitry is that by a change in the programming a picture can be constructed for whatever signal is presented to the receiver; without using complex converter circuitry the receiver can cope with PAL, NTSC, MAC, or wired inputs.

The display section, shown along the bottom of the diagram, takes its input from the central processing section and holds information from which an image can be recreated in the screen-refresh memory, at a line and frame rate suitable for display, but not necessarily bearing a direct relationship with the line and frame rates of the signals that were originally transmitted. It seems likely that this display information could be held in some compressed form. The output from this memory store could then be passed to interpolation circuits before being converted back to analogue form for final display. The display could be a high line rate, high frame rate HDTV format, but different versions of this basic receiver type could also be made available, each having a different type of display, according to the requirements and the depth of the pocket of the customer.

Such an open architecture receiver would, because it is controlled by a
computer program, be easily adaptable to cope with the different types of television signal that will be available during the next few years, as the various steps towards HDTV are taken. It could even cope with new types of signal which were not thought of at the time of its construction—a change in the computer program would be all that would be necessary to allow it to deal with the novel signal.

**Virtual studio standard**

It is recognised by those involved in the long and arduous process of trying to achieve standardisation in the field of HDTV that in the longer term we are likely to develop digital HDTV systems, and that it is in the digital domain that the real key to the future of HDTV lies. Looking ahead to such times when the practical realisation of digital HDTV signals in both production and transmission might be practicable, the concept of a *virtual studio standard* has been suggested (ref. 5). The kernel of this idea is that it should be possible to agree upon a single unique format for carrying the digital data representing an HDTV signal on a digital data bus, which could be used to transport HDTV signals between different pieces of equipment or between studio centres, and which could be used to record the signals. The actual standards used for the pictures and sound at the source and at the destination would then be unimportant, as all the input and output signals would communicate with the universal bus by means of digital gateways, where the standards conversion to and from the universal bus standard would take place. Such a technique would allow broadcasters to exchange programmes made in a whole variety of different standards, but since the possibility of several standards conversions taking place between source and display would then be a real one, the virtual studio standard will need to be of very high quality in order to ensure that it does not contribute any undesirable artifacts to the pictures.

It is generally accepted that using a digital system will provide the most flexibility and allow powerful computer processors to be used, but, having said that, it will be necessary to ensure that the bit rates required for such a system are actually practicable; there would be no point in agreeing upon a theoretical system that did not permit equipment to be made at a reasonable price. In developing such a system, however, care must be taken to allow sufficient ‘headroom’ to cope with future developments that might arise. Up to the present time, the virtual studio standard concept is nothing more than a concept; although much thought is being given as to how such ideas might be turned into something more concrete, and the common image format and common data rate could perhaps be regarded as steps along the way, it seems that we are as far away as ever from a single universal standard and it seems inevitable that the next stage of development will see the introduction of at least three different HDTV/ATV systems to the different marketplaces of the world. Although this rather
depressing scenario might be thought sufficient to dull the ardour of the keenest of research engineers, this is not the case, and in the final chapter we take a longer-term view, and find that once the present-day technological restrictions have been overcome the prospects for the early part of the next century are really exciting.

References

As we enter the twenty-first century, many of the problems and difficulties which are today regarded as basic to the whole subject of HDTV may well disappear or become insignificant and unimportant as changes in the various technologies surrounding electronics, computers, and broadcasting open up a whole new range of possibilities.

Spectrum utilisation

All existing broadcasting systems have been designed to make the best use of a limited amount of frequency spectrum; whether transmitted over air, via cable, or by satellite, the limited bandwidths available in the relatively low-frequency bands that are currently used have meant that it was essential to make any television signal occupy as little bandwidth as possible. During the next few years it will become possible to build consumer equipment that operates in frequency bands much higher than anything currently possible, and the advantage of using these higher frequencies is that since they are currently virtually unused it should be possible to provide much larger portions of the spectrum at these frequencies for broadcasters to use. A good example is the band of frequencies that has been allocated by the UK government for the provision of Microwave Video Distribution Systems; the band from 40.5–42.5 GHz is 2000 MHz wide, which could allow for dozens of different conventional television signals to be transmitted, or even for the transmission of a number of wideband HDTV transmissions, each of which might take up perhaps 100 MHz in its radio frequency form. The availability of such large amounts of bandwidth should also make possible the transmission of digital television pictures; we saw when considering the digital studio standard, CCIR Recommendation 601, that some 216 Mbit/s of data were required, needing over 100 MHz of radio frequency spectrum if no bit rate reduction techniques were to be used, depending upon the modulation system. Digital transmission at frequencies above 40 GHz would therefore be possible—there are already international frequency allocations for television use between 41 and 43 GHz and between 84 and 86 GHz, and as manufacturers improve their ability to produce, in quantity, equipment that works at higher and higher...
Figure 133 The electromagnetic spectrum (courtesy IBA)
frequencies, at prices which appeal to the domestic consumer, digital transmission and reception could become practicable.

**Spectrum conservation**

Just because larger amounts of the spectrum will become usable, however, does not mean that we should begin to treat the spectrum in a profligate way; our current thrifty habits of only using as much of the spectrum as absolutely necessary should be retained. The spectrum is a finite and very valuable resource, and in a world where conservation is now very much in fashion, spectrum conservation and the avoidance of ‘pollution’—interference to and from other users of the spectrum—should be avoided. It is therefore important to note that although a single digital signal can take up more radio frequency channel space than its analogue equivalent, if a completely digital broadcasting network is carefully planned it is possible to interleave digital signals and to use bit rate reduction techniques which permit the overall usage of the spectrum to be extremely efficient. Other advantages of digital transmission could include an improvement in coverage and signal quality—so long as the digital signals can be received with an acceptable number of errors it is possible for the receiver to rebuild perfect pictures, even though the actual field strength of the incoming radio frequency signal is low.

Once a television signal is in digital form it may be regarded as any other digital signal, merely a set of numbers appropriately placed in a large computer store, and such signals can be processed by computer circuitry which was originally intended for ‘number-crunching’ applications. As we have seen already, the numbers to be ‘crunched’ when dealing with digital television are large, but modern computer chips can cope with the data rates involved. Treating digitised television pictures as numbers in a computer allows for the generation of the many special effects that seem to be indispensable to today’s ‘with-it’ programme director by the application of mathematical processes to the numbers in the field stores, but it is the wider implications of this type of treatment that are likely to affect the future of HDTV as we know it.

**Digital storage—the frame store**

Throughout the 1980s the possibility of using complex signal processing in the receiver in order to provide improved displays was well known, but the cost of the necessary field stores proved too great to allow for their incorporation in domestic receivers. As the fabrication skills of the semiconductor manufacturers continue to improve, with line thicknesses down to 0.5 microns now feasible, the amount of digital storage that can be squeezed onto one chip continues to increase, year by year, with 1990 seeing single chips containing 16 Megabytes being developed in research
laboratories, and X-ray fabrication promising line widths of less than one tenth of a micron in a year or two’s time. As the amount of storage per chip rises so the cost per bit stored falls. Although the ‘ten dollar frame store’ has become somewhat mythical in the industry because it has been promised for so long, the early 1990s are likely to see the cost of frame stores reduced sufficiently that manufacturers can afford to incorporate them into the ‘top of the range’ television receivers, and already a few receivers of this type are on the market.

**HDTV—already passé?**

As we have studied the various possibilities for providing HDTV in the next few years we have seen that virtually all the different proposals are merely extensions and developments of existing methods of creating and transmitting television signals; indeed, when discussing the European EUREKA EU95 approach to HDTV and some of the American proposals, we made a positive virtue out of the fact that the systems were step-by-step developments of current systems. The trouble with this approach is that any new system is likely to retain some of the basic disadvantages of its predecessors. Since present-day colour television systems are virtually all based on systems that first saw the light of day in the 1950s, there is a certain amount of truth in the allegation that most current HDTV plans are merely replacing the technology of the 1940s with that of the 1980s, whereas we shall be well into the nineties before HDTV reaches our homes, and probably well into the next century before HDTV becomes the norm. Every scientifically inclined schoolboy knows that the current method of sending television signals is wasteful and that the picture signal contains much redundancy; if we were starting completely from scratch we would surely not send virtually the same picture every twenty-fifth of a second, we would merely send the small amount of information needed to update the changes that occur in the picture from one frame to the next. It is this type of thinking that is leading to the adoption of computer techniques in attempts to provide the HDTV systems for the next century, and it may well turn out that the HDTV systems we are currently having such trouble in sorting out are quickly overtaken by these new techniques as we move through the next decade; if the current HDTV systems have not become well enough established by then some of them may never reach the market.

**HDTV—just another computer program?**

No matter how we dress up the ideas for new HDTV systems, we cannot get away from the fact that they all require computer storage and processing circuitry in the receiver if HDTV images are to be displayed, and this means that the dividing line between television engineering and computer technology is now becoming blurred. The computing power to be found
inside current HDTV receivers is substantial when compared with the small amounts that have previously been required, for teletext and the like, but it is still small when compared with advanced computers. Engineers who have grown up in computing, rather than in broadcasting, are now starting to think about adopting a different approach to HDTV; why not forget the existing television receiver circuitry, which has over the last fifty years evolved from its prehistoric (well, almost!) predecessors which had glowing valves and turret tuners, and instead consider the television receiver as a powerful computer with a high-quality display? We saw earlier that researchers from the Massachusetts Institute of Technology favoured smart receivers, having an open architecture; they have now gone further along this road, and Nicholas Negroponte of their Media Laboratory has been quoted (ref. 1) as saying ‘the TV set will probably have 50 Megabytes of random access memory and run at 40 to 50 millions of instructions per second’. This is basically the equivalent of today’s supercomputers, such as the Cray, and although such figures might seem incredible it is generally accepted that within the next five or six years this level of computing power will be available for image processing in receivers, and that the cost could be within the reach of many consumers.

Consider what happens if such computing power is put into the central stage of the MIT smart receiver discussed in the previous chapter. As well as being able to deal with incoming signals from the usual sources the receiver would be able to take digital transmissions directly into its computer section, and would be able to provide sufficient processing power to synthesize a high-definition picture from many different input signals. Digital compact disc video players which hold their data in a highly compressed form could again be connected directly to the digital bus, and the processor could provide cinema quality pictures on the screen. HDTV pictures could be produced from a wide range of different input sources, the appropriate computer program being used to turn the incoming signals into the best possible displayed images; the viewer selecting an HDTV programme could have his or her actions mirrored by the receiver automatically selecting the appropriate computer program in the processor!

**Telecommunications and HDTV**

We have so far considered various possible sources of digital television signals, from satellite and wideband cabled distribution networks to compact discs, but there is an even more likely contender lurking in the wings. In many parts of the world the telecommunications authorities are currently upgrading the existing analogue telephone networks to digital form, which will not only improve the quality of the received signals but will also allow for the introduction of many new services and facilities. One of the first stages is the introduction of ISDN, the Integrated Services Digital Network, which can generally provide two telephone channels and a limited amount of data
transmission (typically 64 or 128 kbit/sec) using the standard copper telephone cables to bring the services into the home or office. There is insufficient data capacity in the ISDN to transmit standard television signals, but already plans are being laid throughout the world for the eventual introduction of digital broadband networks which would be capable of carrying digital HDTV signals as well as all the telephone-based services. The organisation of data for use in transmission networks such as these broadband ISDN networks has already been well documented by the International Standards Organisation OSI, and the architecture for information transfer is expressed as a seven-layer model (ref. 2). An advantage of using a layered model is that it enables the various parts of the transmission and processing system that will be required for HDTV to be separated so that any particular difficulties may be isolated and dealt with separately.

The transmission of HDTV signals can be seen as just another application which needs data to be transmitted from one place to another, in our case,
from studio to viewer's home. Figure 134 shows the various layers as they
are defined for telecommunications use, on the left and right-hand arms of
the diagram, whilst the ways in which each of the layers might be seen to
correspond with an HDTV system are shown in the centre of the diagram.
This apparently rather abstract approach allows us to deal with digital
HDTV signals that may be transmitted in many different formats, and
which, 'after processing, may be turned into several different types of
display, making use of the open architecture receiver techniques that we
have discussed earlier.

The seventh layer of the model is concerned with the use of information
at application level, effectively the output from the system, or the input
from the source, depending upon the point of view; it is called the
application layer, and this represents HDTV in our case.

The sixth layer, called the presentation layer, is the layer which is
concerned with the conversion and presentation of information. For our
purposes this includes such things as the number and layout of the pixels
which will make up the eventual display (i.e. the active pixels), the number
of lines in the picture, the colorimetry of the display, and its aspect ratio.

The fifth layer, known as the session layer, is concerned with the
selection of information and access to it; for us this means the rate at which
pictures, as defined in level six, pass through the system. Since in television
similar pictures will often occur one after the other, which allows some
spatial/ temporal processing to be carried out, it is usual in this context to
consider pictures as though they were grouped in frames, although it is
important to note that this use of the word 'frame' is subtly different from
the normal usage, which can lead to confusion. In the present case, a frame
may be made up of any whole number of pictures, and if we take the case
of a standard 2:1 interlaced picture as an example, we would consider this
as having two pictures per frame, each one coded so that only every
alternate line was transmitted.

The top three layers, five, six, and seven, are essentially transparent to
the data, i.e. data transfer takes place in the same manner, whatever the
type or source of the original data. Any standards conversions that may be
necessary take place in the lower levels, which can be considered as
interfaces which define the logical and physical ways in which the
information will be carried from transmission source through the
transmission path to the eventual display.

As figure 133 indicates, the fourth layer, transport, is concerned with the
identification of groups of data, which for our television application means
concerned with coding and formatting the video information. It is in this
area that any bandwidth reduction that is needed, for instance to convert a
high bandwidth studio signal to a signal which can be transmitted over a
network of lower bandwidth, is carried out; another way of looking at this
layer is as the area where the matching of the video bit rate to the channel
bandwidth is carried out. We mentioned in the previous paragraph the
concept of pictures being transmitted in ‘frames’ with regard to the session layer, but it is interesting to consider that level four can be used to provide bandwidth reduction, and since the use of interlace can be considered as a simple form of bandwidth reduction, vertical subsampling of a progressively scanned picture in level four could be one means of achieving an interlaced picture.

The lowest levels, three (network), two (data link), and one (physical), represent interfaces between source, transmission and display, and different interfaces can be defined for different transmission requirements, whilst the transparent nature of the higher levels means that a common studio production standard or at least a common studio interface standard could be achieved. This idea would enable different scanning formats, such as 50 Hz and 60 Hz television, to be used, so long as the information in the sixth (presentation) layer could be agreed upon, so that appropriate data formatting could take place in level four.

This necessarily brief overview of the use of the ISO seven-layer model and its possible applications to television is not meant to be anything more than an introduction to the idea that the coming of truly digital television could enable huge strides to be taken towards world standardisation.

The ultimate goal—HDTV without standards

The basic concept of the television system of the future being all digital and utilising computer data transfer methods and receivers which are totally different from today’s, should allow for the dream of a universal television system to be realised. If tomorrow’s receiver is ‘merely’ a supercomputer on a few chips with a vast choice of separate or integrated high-quality displays available to suit every living room and pocket, then no matter what type of digital data is fed into it the computer will be able to synthesize the best picture possible from the available data. Taking this scenario we are effectively letting technology carry out the work that has so far failed to be satisfactorily achieved by the world’s standards committees; in a world where we have become used to allowing the computer to carry out repetitive tasks so that people can be freed for more cerebral activities, surely this computerised approach to HDTV, rather than interminable arguments about whose system is best, represents the real way forward.

References

Although we have intimated that there is no real possibility of transmitting television pictures digitally for years to come, because of the high bit rates and wide bandwidths required, IBA UK research laboratories revealed in September 1990 (ref. 1) that new techniques that they have developed might bring digital TV forward by several years.

Using the acronym SPECTRE

Special
Purpose
Extra
Channels for
Terrestrial
Radio-communication
Enhancements

a project is currently being undertaken in order to try to see whether it might be possible to develop further the already extensive use which is made of the UHF spectrum for carrying television signals. The present situation is that the 44 8-MHz-wide channels that make up the current UHF TV broadcast band in the UK are actually used and reused by something like 3400 different television transmitters, most, of course, being low-power relay stations.

The idea of SPECTRE is to investigate the feasibility of additionally squeezing a large number of low-power digital signals into this same chunk of bandwidth, without affecting the existing analogue signals.

What makes such an idea possible is that although the present UHF band was well planned back in the early 1960s, making various assumptions about receiver technology and transmitter performance capabilities, we can now see, with our more up-to-date knowledge of digital signal performance, that there is in fact some spare capacity, some redundancy in this band that we could now perhaps make use of.

As we saw in Chapter 6, the CCIR 601 standard for digital television requires some 216 Mbit/s for a standard 625-line picture, and since standard coding techniques would require over 100 MHz of radio-frequency bandwidth to carry this, compared with the 5.5 MHz which we need for our
current analogue PAL pictures, it is no surprise that engineers have been rather wary of expecting digital TV transmissions in the near future.

The last few years have seen great strides in the development of bit-rate reduction techniques for television pictures, these usually being based on the well-known fact that most TV pictures carry a great deal of redundant information, since the picture that occurs at any instant is generally very similar to the one that came 1/50th of a second before it. Much work in various research laboratories around the world has crystallised in a general agreement that the way forward is to use a complex technique called motion-compensated hybrid Discrete Cosine Transformation of the original TV picture signal information (ref. 2).

The essence of the technique is that the differences between each two successive frames are calculated, and since it would involve too much data to do this for every individual picture element, or pixel, blocks of eight-by-eight pixels are generally used.

The DCT mathematically transforms each 8×8 block of pixels into blocks of 8×8 numerical coefficients, many of which are effectively zero, since no change has occurred between frames, and these coefficients do not therefore need to be transmitted.

The current state of the art allows perfect decoding of even the most critical picture material with a bit rate of about 30 Mbit/s, a big reduction from the original 216 Mbit/s, and by accepting that it would be practicable in the domestic TV market to accept some reduction in vertical chrominance resolution, and by using improved motion compensation techniques, IBA engineers are confident that high-quality pictures can be transmitted and received at a bit rate of as little as 12 Mbits/s. This was demonstrated at the IBC exhibition in Brighton in September 1990.

Now that we are able to see a possible way forward for the generation of bit-rate-reduced digital television pictures, ways in which we could possibly transmit these pictures have to be found. A most useful aim would be to transmit this digital information, that is extra TV programme channels, in the existing UHF band, sharing it with the existing analogue broadcast programmes. As can be imagined, this is by no means simple, and the first problem to be solved is how to transmit the digital signals without causing interference to the existing analogue pictures.

This can be done, provided that the level of the digital signals is kept extremely low, compared with that of the analogue signals. It is possible to provide digital TV pictures over the same coverage area as the analogue signals even with the digital signals at very low power, because the carrier-to-noise ratios required for the satisfactory reception of digital signals are very much less than those for the existing analogue signals.

Typical C/N figures for a grade four picture, almost perfect, are about 40 dB for our existing analogue PAL service, but only 15 dB for a digital service. With modern receiver front ends and the improved noise figures that have become realistic over the past couple of years, it should be possible to obtain
matching coverage areas from digital transmitters radiating signals 30 dB less power than their analogue coverage areas.

We never get something for nothing in engineering, however, and one disadvantage of the low-power operation is that the digital signal will have to operate in a very hostile, noisy and interference-prone environment. As well as this, there may well be problems with multipath interference, so the choice of modulation method is critical.

IBA engineers believe that the best idea is to use a technique called Orthogonal Frequency Division Multiplexing modulation, using a large number of overlapping digitally modulated carriers, some form of QPSK coding then being used.

*Orthogonal*  
*Frequency*  
*Division*  
*Multiplexing*

We are familiar with the idea of FDM (frequency division multiplexing) where several different signals are modulated onto a group of adjacent carrier frequencies which are then sent along a common channel. OFDM takes this a stage further.

The OFDM technique breaks the digital data stream into sections and uses these multiple signals to modulate a large number of simple carriers, and it is the total of all these modulated carriers that makes up the OFDM signal. The individual carriers are derived from the Discrete Fourier Transform of the original signal.

The essential feature of the OFDM technique is that the frequency spectrum of each modulated carrier is allowed to overlap its neighbour, and careful selection of the carrier frequencies, of the phasing of each of the signals, and of the digital coding system that is used, allows the individual carriers to be separated out again by the application of the Fast Fourier Transform as the signal is demodulated. The same circuitry that can distinguish between the individual carriers is able to take account of out-of-phase reflected signals, such as those that are produced by multipath interference.

The spectrum that is produced by the tightly packed overlapping spectra of each of the individual carriers means that the system makes very efficient use of the available radio-frequency bandwidth.

In practice there is some intersymbol interference caused by the inevitable multipath interference, but the problem is reduced or eliminated by leaving a guard band interval between each symbol; provided that this is long enough to exceed the delay suffered by any of the reflected signals, all the orthogonal carriers can be demodulated without difficulty.

The OFDM spectrum gives excellent results in the presence of multipath interference, and it also turns out to be ideal for use in a hostile interference environment.
The main interference from existing analogue TV transmissions will take the form of two high-power carriers at the sound and vision frequencies. OFDM can cope well with this because the large number of carriers used means that it is possible to decide not to transmit any information on some of them, if we wish. For our purposes this means that we can cut out those carriers that fall in the portions of the spectrum near to the analogue vision and sound carriers. Effectively, then, we can define a spectral template for the digital signal, and get our receiver to look only at the information within that template, ignoring the interference that would be caused by the powerful sound and vision carriers.

UHF TV channels in the UK are spaced 8 MHz apart, so that the frequency spectrum of transmissions from a single transmitting station will, to a first approximation, look like four equally spaced pairs of sound and vision carriers. Whilst it is true that there will also be energy in the form of subcarriers present at the colour subcarrier frequency and at the frequency of the NICAM digital sound carrier, the effects of these are reduced by the dispersal effect of their modulating signals, so that they have much less peak power than the sound and vision carriers. The regular spacing of TV channels therefore makes it possible to fit in extra low-level digital signals, between the existing signals, as the diagram shows.

Theory suggests that we could actually provide eight new digital channels for each transmitting station, but in practice transmitters are not sited on an ideal frequency lattice, and there are various other taboos on the frequencies that can be used. A more realistic outcome will be to be able to

![Spectrum with digital signals inserted](image-url)
provide four analogue and four digital TV signals from each transmitting station, thus doubling the number of possible terrestrial TV programmes.

Whilst this would be some considerable achievement, I must stress that it will not happen overnight. Much work still has to be done before we can know whether a digital TV service to the home would be feasible and economic, but the rewards would be so great that it certainly seems worth continuing with the research.

One key question as to whether such ideas can be turned into reality will centre around the ability of receiver manufacturers to provide low-cost digital receivers which can process Fourier transforms. Initial discussions suggest that it will be the late 1990s before such receivers could be available at realistic prices. It is interesting to compare these ideas with those of the engineers at the US Zenith corporation, who are looking at similar techniques in order to develop Advanced Television systems, as described in Chapter 10.


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