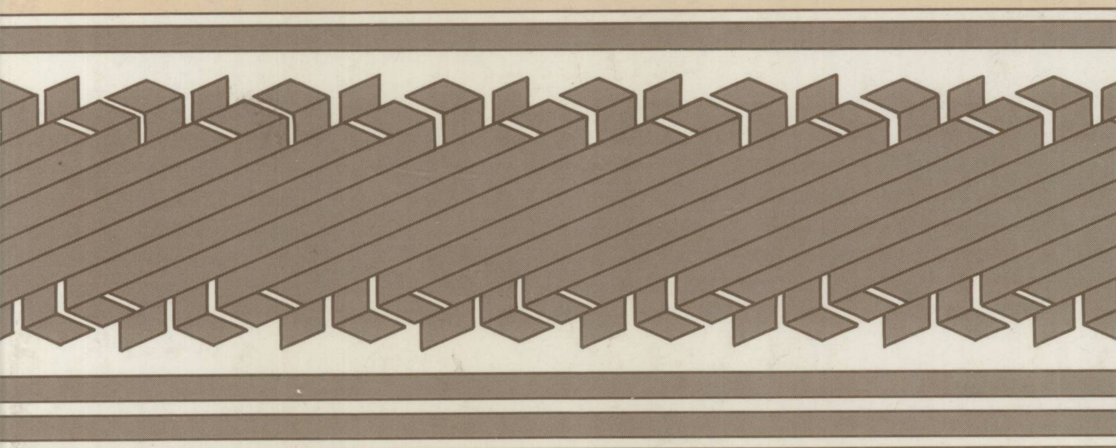
The Art of Digital Video

John Watkinson



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Preface

There would be very little to document in the subject of digital video were it not for the persistence of those who overcame countless obstacles in order to make it happen.

It is not so long ago that many of the devices described in these pages existed only in the imagination of those who dreamed of a better way of conveying and processing video. This new approach would not be some refinement of existing technology, offering modest gains, but a totally different approach, which would wipe away existing problems and introduce dramatic opportunities.

It was not enough simply to have the dream, because dreams don't pay bills. It was necessary to implement the dream, and this would require the adoption of technologies which had previously little or no relevance to television: computation, laser optics, mass storage, simulation, error correction. Most of these disciplines were described in their own idiomatic terminology, and this in itself is a major obstacle to progress.

As yet there is no documented process which teaches us how to balance conflicting requirements of numerous disparate technologies to achieve a reliable end product. It can only be described as an art, and it has inspired the title of this book. Because there are so many disciplines involved, digital video is a fascinating and stimulating subject. It is a source of some regret that the intellectual content of modern digital video equipment generally exceeds that of the program material which it handles.

Digital video continues to develop, but it has reached a point where a book of this kind becomes feasible. The basic principles are largely agreed, there are real products with which to earn a living, and we now have standards for recording and interconnection of digital video. The picture quality obtained with these machines is of a high standard, but techniques which are yet to be widely applied can result in a further improvement within the existing line standards.

This book describes all of the essential theory of digital video and a great deal of the practice, but the subject is too great to attempt to include any history. The current position in High Definition is too fluid to document at the present time and has been consciously omitted except where general principles apply.

The range of disciplines to be covered is so great that this cannot be a conventional book. The need for understanding is too great for a book to assume a high academic level in all these subjects.

This book adopts the same approach as that used in *The Art of Digital Audio*. Every concept begins with the basic mechanism involved and defines its terminology. Wherever possible, explanations are given in plain English, equations being used as a last resort.

There are few stated facts, since these are easily forgotten. Instead there are reasons, arguments and mechanisms from which facts can be deduced. The approach works equally well from basic levels to advanced concepts, so there is also plenty in this book for the expert, and there are references for those who wish to go further.

Words have been carefully chosen to reduce the chances of misunderstanding, and where a misnomer is in common use, it will be identified.

A lot of care went into *The Art of Digital Audio*, but I was not prepared for the overwhelming support of the approach. It would be unthinkable to do anything different in this book.

Acknowledgements

For Anne

I must first thank David Kirk, who invited me to write a series on digital video for 'Broadcast Systems Engineering', which he then edited, and Ron Godwyn, who succeeded him. The response to this series provided the impetus to turn it into a book.

The publications of the Society of Motion Picture and Television Engineers and of the European Broadcasting Union have been extremely useful.

I am indebted to the many people who have found time to discuss complex subjects and to suggest reference works. Particular thanks go to David Lyon and Roderick Snell of Snell and Wilcox, Takeo Eguchi, Jim Wilkinson, David Huckfield and John Ive of Sony, Luigi Gallo of Accom, Graham Roe of Pro-Bel, Dave Trytko, Joe Attard, John Watney, Fraser Morrison and Ab Weber of Ampex, John Mallinson of CMRR San Diego, Roger Wood of IBM and John Baldwin.

Last but not least thanks to Margaret Riley of Focal Press for helping it along.

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Chapter 1

Why Digital?

1.1 The advantages of digital video

The first methods used in television transmission and recording were understandably analog, and the signal formats were essentially determined by the requirements of the cathode ray tube as a display, so that the receiver might be as simple as possible and be constructed with a minimum number of vacuum tubes. Following the development of magnetic audio recording during the Second World War, a need for television recording was perceived. This was due to the number of time zones across the United States. Without recording, popular television programmes had to be performed live several times so they could be seen at peak viewing time in each time zone. Ampex eventually succeeded in recording monochrome video in the 1950s, and the fundamentals of the Quadruplex machine were so soundly based that to this day analog video recorders still use rotating heads and frequency modulation.[1] Study of every shortcoming in the analog process has led to the development of some measure to reduce it, and current machines are capable of excellent performance. The point to appreciate, however, is that analog recording has become a mature technology and has almost reached limits determined by the laws of physics. The process of refinement produces increasingly small returns.

As there is now another video technology, and known as digital, the previous technology has to be referred to as analog. It is appropriate to begin with a comparison of the fundamental differences between these technologies.

In an analog system, information is conveyed by the infinite variation of some continuous parameter, such as the voltage on a wire or the strength of flux. When it comes to recording, the distance along the medium is a further analog of time. However much the signal is magnified, more and more detail will be revealed until a point is reached where the actual value is uncertain because of noise. A parameter can only be a true analog of the original if the conversion process is linear, otherwise harmonic distortion is introduced. If the speed of the medium is not constant there will not be a true analog of time and the result is known as timebase error.

It is a characteristic of an analog system that the degradations at the output are the sum of all the degradations introduced in each stage through which the signal has passed. This sets a limit to the number of stages a signal can pass through before it becomes too impaired to be worth watching. Down at signal level, all impairments can be reduced to the addition of some unwanted signal such as noise or distortion, and timing instability such as group-delay effects and chroma phase errors. In an analog system, such effects can never be separated from the original signal; in the digital domain they can be eliminated.

Although it is possible to convey signals which have an arbitrary number of states, in most digital video systems, the information is in binary form. The signals sent have only two states, and change at predetermined times according to a stable clock. If the binary signal is degraded by noise, this will be rejected at the receiver, as the signal is judged solely on whether it is above or below some threshold. However, the signal will be conveyed with finite bandwidth, and this will restrict the rate at which the voltage changes. Superimposed noise can move the point at which the receiver judges that there has been a change of state. Time instability has this effect too. This instability is also rejected because, on receipt, the signal is reclocked by the stable clock, and all changes in the system will take place at the edges of that clock. Fig. 1.1 shows that, however many stages a binary signal passes through, it still comes out the same, only later. It is

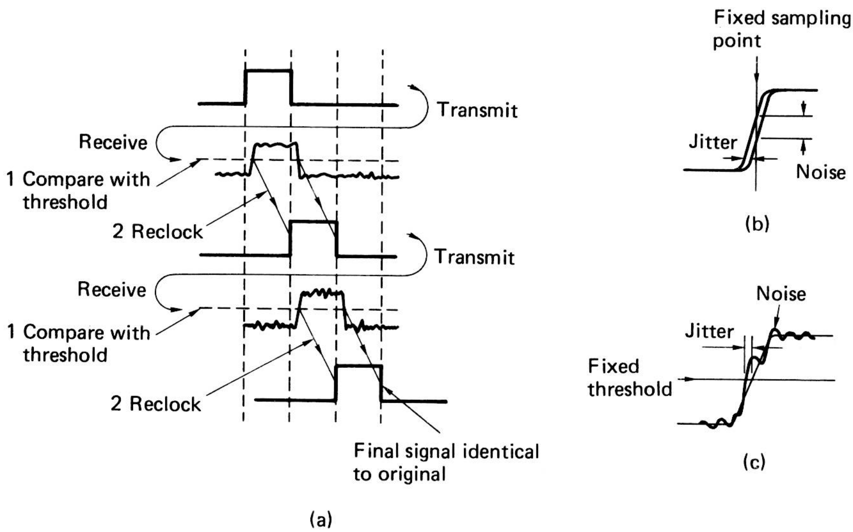

Figure 1.1 (a) A binary signal is compared with a threshold and reclocked on receipt, thus the meaning will be unchanged. (b) Jitter on a signal can appear as noise with respect to fixed timing. (c) Noise on a signal can appear as jitter when compared with a fixed threshold

possible to convey an analog waveform down such a signal path. That analog waveform has to be broken into evenly spaced time elements (a process known as sampling) and then each sample is expressed as a whole number, or integer, which can be carried by binary digits (bits for short). Fig. 1.2 shows that the signal path may convey sample values either in parallel on several wires, where each wire carries a binary signal representing a different power of two, or serially in one channel, at higher

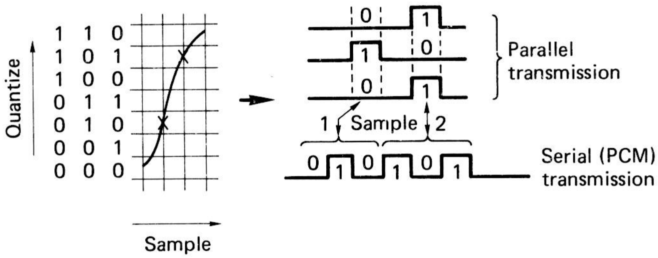

Figure 1.2 When a signal is carried in numerical form, either parallel or serial, the mechanisms of Figure 1.1 ensure that the only degradation is in the conversion processes

speed, a process called pulse code modulation (PCM). The only drawback of this scheme is that a single high-quality video channel requires about 200 million bits per second. Digital video only became viable when advances in high-density recording made such a data rate available at reasonable cost.

In simple terms, the signal waveform is conveyed in a digital recorder as if someone had measured the voltage at regular intervals with a digital voltmeter and written the readings in binary on a roll of paper. The rate at which these measurements are made and the accuracy of the meter now wholly determine the quality of the system, because once a parameter is expressed as discrete numbers, those numbers can be conveyed unchanged through a recording process. This dependence on the quality of conversion is the price paid to make quality independent of the signal path. As it is so critical to picture quality, a whole chapter of this book is dedicated to sampling and conversion. Since a digital system faithfully conveys the original analog waveform, it is equally feasible to digitize component or composite video signals. In the case of composite digital, there is complete freedom from differential gain error.

A magnetic head cannot know the meaning of signals which are passed through it, so there is no distinction at the head/medium interface between analog and digital recording. Thus a digital signal will suffer all the degradations that beset an analog signal: particulate noise, distortion, dropout, modulation noise, print-through, crosstalk and so on. However, there is a difference in the effect of these degradations on the meaning of the signals. As stated, digital recording uses a binary code, and the presence or absence of a flux change is the only item of interest. Provided that flux change can generate a playback pulse which is sensibly bigger than the noise, the numerical meaning will be unchanged by reasonable distortions of the waveform. In other words, a bit is still a bit, whatever its shape. This implies that the bits on the medium can be very small indeed and can be packed very close together; hence the required data rate is achievable. If the trivial example of the paper tape recording is pursued further, suppose that the tape upon which the voltages were written became crumpled up. If it were smoothed out, the numbers would still be legible and could be copied without error to a new piece of paper. By comparison, if a photograph is crumpled up, it will look like a crumpled-up photograph for evermore.

Large disturbances of the recording, such as dropout or severe interference, may cause flux changes to be missed, or simulate ones which did not exist. The result is that some of the numbers recorded will be incorrect. In numerical systems, provision of an error-correction system is feasible; in analog systems it is not. In PCM systems, corruption of high order bits can cause severe disturbance of the video waveform, and at the recording densities necessary to give economy of tape usage, a properly engineered error-correction system is absolutely essential to return the corrupted numbers to their original value. It is probably true to say that, without error-correction systems, digital video recording would not be economically feasible.

In the digital domain, signals can be easily conveyed and stored in electronic circuitry. Unavoidable speed variations in recorders cause the numbers to appear at a fluctuating rate. The use of a temporary store allows those numbers to be read out at constant rate, a process known as timebase correction. In this way, timebase errors and chroma phase errors can be eliminated. The rock-solid vector display of a composite digital recorder is uncanny at first. The C-format timebase corrector, which made professional helical scan recording possible without field segmentation, was one of the first major applications of digital video. Chapter 4 treats this subject in some detail. The ease with which delay is provided also allows phase-linear filters and interpolators to be created in a straightforward manner, because the group-delay problems of analog filters cannot occur. Filters can be constructed which work with mathematical precision and freedom from component drift and with a response that can be easily changed.

The main advantages of digital video can be summarized as follows (they are not in order of importance because this will change with the application):

* The quality of a digital video link is independent of the characteristics of the channel in a properly engineered system. Frequency response, linearity and noise are determined only by the quality of the conversion processes. In recorders there is complete freedom from moiré and other analog recording artifacts. The independence of the quality from the medium also means that a recorder will not display different picture or audio quality if different brands of tape are used, provided that they all have acceptable error rates.

* A digital recording is no more than a series of numbers, and hence can be copied through an indefinite number of generations without degradation. This implies that the life of a recording can be truly indefinite, because even if the medium begins to decay physically the sample values can be copied to a new medium with no loss of information.

* The use of error-correction techniques eliminates the effects of dropout. In consumer products, error correction can be used to advantage to ease the handling requirements.

* The use of timebase correction on replay eliminates timebase error and can be further used to synchronize more than one machine to sample accuracy, eliminating the need for lengthy timing-in processes.

* The use of digital recording and error correction allows the signal-to-noise ratio of the recorded tracks to be relatively poor. The tracks

can be narrow and hence achieve a saving in tape consumption despite the greater bandwidth. Professional analog recorders must use wide tape tracks to give extremely good first-generation quality which then allows several generations of dubbing.

* The advantages listed also apply to the audio channels of video recorders. It is natural to digitize both audio and video, so that much common circuitry can be used. The audio quality possible in a digital DVTR then exceeds that of a professional analog audio recorder, which could not be said for analog VTRs. The rigid timebase control prevents phase errors between channels, which is particularly important with the advent of stereo audio in television.

* It is possible to construct extremely precise and stable digital filters and equalizers with inherent phase linearity. Such devices need no adjustment, and so the cost of manufacture can be less than the analog equivalent. The adoption of digital filtering makes possible such devices as picture manipulators and other effects devices which, though complex, are extremely reliable.

1.2 The opportunities

Digital video does far more than merely compare favourably with analog. Its most exciting aspects are the tremendous possibilities which are denied to analog technology. Once in the digital domain, the original picture is just a series of numbers, and these can be stored, conveyed and processed in many and varied ways. The computer industry has spent decades perfecting machines to store, convey and process streams of numbers at high speed and at a cost which continues to fall. Computers can generate artificial images for computer-aided design systems and simulators. Work has been done on the improvement of resolution and the elimination of flicker and other artifacts for computer displays, and broadcast digital video can take full advantage of such techniques. Recordings can be stored on computer disk drives, magnetic or optical, whose radially moving heads allow rapid random access to the information. For animation or editing of video, this is far superior to waiting for tape recorders to shuttle and preroll, although the sheer data rate of digital video prevents current disk-based machines from making lengthy recordings. An edit can be effected by reading samples from two sources and fading or switching between them in digital circuitry. The edit can be simulated, so that the outcome can be assessed, and the edit points can be moved around at will until the result is satisfactory. The final edited version can be recorded on a different medium if necessary, leaving the source material intact.

The cable and satellite communications networks around the world are increasingly being used for digital transmission, and a packet of digital video information can pass through as easily as a telex message or a bank transaction. Provided the original numbers are fed in the correct order at the correct rate to the final destination, for conversion to a picture, it does not matter how they have been conveyed.

The worlds of digital video, digital audio, communication and computation are closely related, and that is where the real potential lies.