ADVANTAGES OF DIGITAL TRANSMISSION IN CATV TRUNKS

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Seven advantages of using digital transmission in the CATV industry are given, and two of these advantages are discussed at length. A CATV system using digital signals can be significantly less expensive than a conventional system. The ratio of the cost of cables and amplifiers for a conventional system and a digital system is determined and bounded above and below. The economic advantage of the digital system increases as trunk lengths increase. This economic advantage can be further increased by using picture coding techniques to reduce the required bandwidth. The field of picture coding is reviewed and the most important results which have been obtained to date are referenced. The potential to transmit three digital, picture coded standard television signals in a conventional 6 MHz bandwidth is discussed.

Introduction

Digital transmission has long been considered a very useful modulation technique with several advantages over the more conventional analog transmission. Recent events and advancing technologies are making digital transmission feasible on very large scales. The major impetus to digital transmission has been the emergence of inexpensive and highly reliable integrated circuits, which means that sophisticated digital encoders and transmission schemes are now economically feasible. One result of this is that digital transmission figures strongly in the future of our two largest communication systems, the Bell system and the military communication system. In the 1980's, a large portion of the commercial telephone traffic between metropolitan areas will be by digital transmission with a data rate of hundreds of M bits/sec per channel, Bell Laboratories (1970). A major future transmission system for Bell System will be a buried millimeter waveguide carrying 230, 000 voice channels of 64 K bits/sec each, A. T. &T. (1972). The military plans to use digital transmission for most of their communications by a 1980's time frame. There is presently a large scale effort underway to change existing military analog systems over to digital systems.

This paper lists some of the advantages of digital transmission as applied to CATV systems and discusses two of these advantages in some detail. The economic advantage of digital transmission for CATV trunks is illustrated, and the applications and advantages of picture coding for television pictures are discussed.

Advantages of Digital Transmission

Digital transmission has a number of advantages over the modulation scheme presently used for transmission of signals in CATV systems. The list of seven advantages given below is perhaps not exhaustive, but does include the most significant advantages. Some advantages are:

1. Digital transmission provides an efficient trade-off between bandwidth and signal-to-noise ratio. This translates into an economic advantage for long-distance trunks. A system for transmitting digital signals can be less expensive than a conventional system, as discussed in section 3 below.
2. Digital encoding of two-dimensional signals (picture coding) can greatly reduce data rate and bandwidth requirements. This is also discussed in greater detail below.
3. Digital signalling allows flexibility in multiplexing and multiple access, which should prove very important in two-way operations.
4. Information can be encoded for error control and/or security. These are two of the major reasons why the military has decided to change to digital transmission.
5. Digital modulation generally requires less dynamic range than a conventional TV signal for the same picture dynamic

range, and thus, less intermodulation type interference is generated in practical amplifiers. This is important since, in a CATV system, conservation of dynamic range is as important as conservation of bandwidth.

6. A digital system can reduce the effects of outside interfering signals in a CATV system.
7. Since digital modulation is a non-linear modulation, the degradation in picture quality due to reflections in the transmission system can be eliminated.

Naturally, the advantages of digital transmission are not obtained without some disadvantages. Some important disadvantages are:

1. The terminal equipment of a digital system is more complex than the terminal equipment of an analog system. However, because of the widespread use of large-scale integrated circuits, this need not result in extremely expensive or unreliable equipment. Kwan (1973) states that terminal equipment for digital radio has a "comparatively low cost". The cost of terminal equipment is not considered in this paper.
2. Digital techniques generally use more bandwidth than analog techniques. However, cable systems enjoy the option of being able to provide more bandwidth by simply paralleling cables. The Bell System presently plans to use 22 coaxial structures in one cable for their T4 coaxial cable digital system.
3. Digital techniques are not widely understood by practicing CATV engineers. It is hoped that this paper and others like it will help alleviate this disadvantage.

In the next section, an economic advantage of digital transmission for long-distance CATV trunks is discussed.

Cost Comparison of Transmission Systems

Until just recently, digital signalling and encoding equipment was prohibitively expensive so that digital transmission was used only where high performance was essential and cost was of secondary importance, as in the space program. As pointed out above, large scale integrated circuits have drastically lowered the cost of digital equipment. However, even with these lower costs, digital transmission will be more expensive than analog transmission for the next few years since the development costs for a digital system must be recovered. Development costs for analog systems have been largely recovered and market forces have lowered prices. Thus, it would be unrealistic to compare the total cost of a digital system with the cost of an analog system. A more realistic comparison is to consider the transmission costs of digital and analog systems.

Chang and Freeny (1968) have made a detailed study of digital transmission over a coaxial cable system with cascaded amplifiers. They concluded that "in many practical systems it is not only economical, but also optimum to use identical analog repeaters", rather than all digital repeaters when transmitting digital information over the system. This means that much of what is known today about cascaded systems is directly applicable for digital transmission.

It appears that the most reasonable comparison is to compare the costs of the transmission system for digital and analog signals carrying the same number of channels over the same distance and delivering the same output signal-to-noise ratio. Since the construction and right-of-way costs will be the same, it suffices to compare the cost of the cable and analog amplifiers for the system using digital signals with the similar cost of a conventional system. The main difference between the two systems is that the digital system generally will be a multi-cable system having parallel trunk cables, as discussed in Kirk and Paolini (1970). For the specific example here, there are three parallel trunk cables.

This comparison neglects the cost of digital terminal equipment since, as discussed above, development costs would be associated with the digital equipment and not with the analog equipment. Also, as trunk lengths increase, the terminal costs become less of a factor and can be neglected.

It is convenient to consider two different systems and to subscript variables with a 1 if they are for system one (conventional) and with a 2 if for system two (digital). Thus, let C_1 represent the total cable cost for system one and A_1 represent the total amplifier cost for system one. Define the transmission cost, T_1, as the sum of the cable cost and the amplifier cost, so that the ratio T_1/T_2 is the transmission cost of system one divided by the same cost for system two and is referred to here as the cost factor. If T_1/T_2 is greater than unity, the cost comparison is favorable to system two, while if the ratio is less than unity, the comparison favors system one. It is easily shown that

$$\frac{T_1}{T_2} = (k_1 + 1)\left(\frac{k_1}{R_c} + \frac{1}{R_A}\right)^{-1}$$

where $R_c = C_1 / C_2$, $R_A = A_1 / A_2$, and $k_1 = C_1 / A_1$. Each of these three terms is briefly discussed below.

Assume that system one (the conventional system) has 25 cascaded amplifiers, each with 20 dB gain, and carries 40 channels. Then, assuming typical values for amplifier and cable cost, it can be shown that k_1 (cable cost over amplifier cost for system one) is given by

$$k_1 = 2.4 \left(\frac{L}{10}\right)^3 ,$$

where L is the trunk length in miles. As L increases, the cable diameter must increase, so that attenuation will decrease to keep the same number of amplifiers. The larger diameter cable costs more and the amplifier cost stays the same, so the ratio of cable cost to amplifier cost must increase. However, it is surprising that it increases with the third power of the trunk length.

The ratio of cable costs, R_c, and the ratio of amplifier costs, R_A, can also be found and related to system parameters. The usual assumptions that the cost per unit length of the cable is proportional to the cross-sectional area of the cable and that there is no dielectric loss in the cable lead to

$$R_c = \frac{B_1}{B_2} \left(\frac{SNR_1}{SNR_2}\right)^2 ,$$

where B_1 is bandwidth per channel for system one and SNR_1 is the signal-to-noise ratio which system one must deliver to the receiver. For a conventional system, B_1 is 6 MHz and SNR_1 might be 40 dB. Since a digital system trades bandwidth for signal-to-noise ratio, B_2 can be several times larger than B_1, and SNR_2 will be much less than SNR_1. For the example which follows, B_2 is 20 MHz and SNR_2 is nearly 10 dB less than SNR_1, yet the second system delivers the same performance as the first system.

The ratio of amplifier costs, R_A, is found in a similar manner and has a form similar to R_c:

$$R_A = \frac{B_1}{B_2} \left(\frac{SNR_1}{SNR_2}\right)^{-1} \frac{U_1}{U_2} ,$$

where U_1 is the cost of an individual amplifier for system one and, since we have assumed 25 amplifiers for the conventional system, $A_1 = 25\, U_1$.

When the three terms, k_1, R_c, and R_A, are substituted into the cost ratio (or cost factor) equation and the resulting expression maximized with respect to the signal-to-noise ratio for the second system, the maximum value of T_1 / T_2 is

$$\left(\frac{T_1}{T_2}\right)_{max} = \frac{3.95}{L} \frac{B_1}{B_2} \left[2.4\left(\frac{L}{10}\right)^3 + 1\right]\left(\frac{U_1}{U_2}\right)^{2/3} .$$

When T_1 / T_2 is maximized, the optimum design value of signal-to-noise ratio for system two is obtained. Next, it is necessary to get some bounds on U_1 / U_2; then a graph of the above equation can be presented.

To derive some upper and lower bounds on T_1 / T_2, the cost of an individual amplifier must be considered in more detail. The cost of an individual amplifier for system one, U_1, is

$$U_1 = K_1 + E_1 ,$$

where K_1 is the cost of the case, power supply, and any regulating circuitry, while E_1 is the cost of the electronics and the equalizer. An upper bound is attained when the cost of the case is the dominating item; i.e., $K_1 \gg E_1$ and $K_2 \gg E_2$. A lower bound is attained when the cost of the electronics is the dominating item; i.e., $E_1 \gg K_1$ and $E_2 \gg K_2$.

An example of the upper and lower bounds on the cost factor is given in figure 1. The specific digital system in this example has three parallel trunk cables and uses an eight level amplitude shift keyed signal. The channel signal-to-noise ratio for the digital system is 9 dB below that of the conventional system, but as pointed out previously, the signal-to-noise ratio at the output of the receiver is the same for both systems and is 40 dB in this example. It is planned that the complete derivation and other examples with graphs similar to figure 1 will be given in a forthcoming report by the first author.

The major conclusion is that digital transmission has an increasing economic advantage as trunk length increases. This is shown for a specific digital scheme as compared with a conventional system, but the same conclusion holds for other digital systems. Also, the comparison here was between a digital system and a conventional single-cable trunk carrying 40 channels, but if a digital system is compared with a sub-band long distance trunking system carrying 40 channels the same conclusion holds; i.e., the digital system has an increasing economic advantage as trunk length increases.

The economic advantage alluded to above can be even greater if more sophisticated encoding is used. It is impractical to use encoding techniques for analog transmission, but source

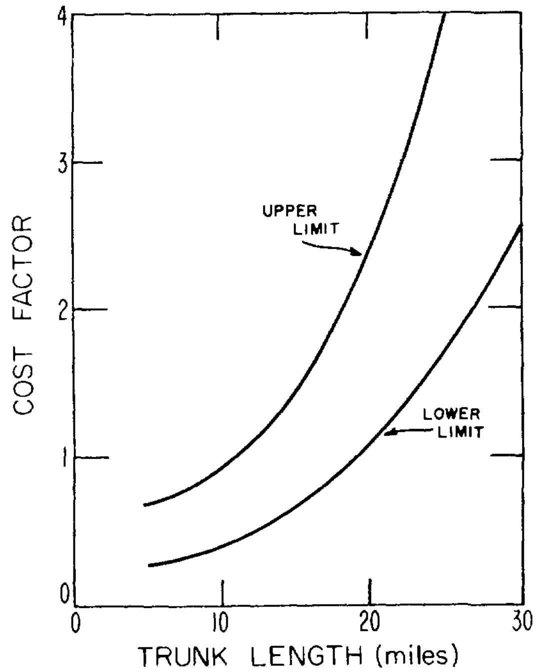

Figure 1. Cost factor vs. trunk length

encoding (picture coding) techniques can be easily realized when the picture is in digital form. The advantages of picture coding are discussed in the following section.

Picture Coding

U.S. broadcast quality television has 525 lines per frame, a four-to-three aspect ratio, and requires 30 frames per second for a conservative margin above the eye-sensitive flicker rate for studio light levels (Fink, 1957). Equivalent vertical resolution varies from 72 horizontal lines per inch for a 5 inch high display screen to 20 lines per inch for an 18 inch high monitor screen (Fink, 1957). The number of active lines per frame may vary from 483 to 499.

The picture can be visualized as a matrix of picture elements. The broadcast television picture has 2.7×10^5 picture elements per frame. For 30 frames per second, the rate becomes 8.1×10^6 picture elements per second.

For analog to digital encoding, eight bits per sample or picture element is considered sufficient for high quality television, with nine bits often specified for long distance relay. Television data rates would be greater than 64 M bits/sec. Each estimate excludes the housekeeping bits required for bit, word, line, and frame synchronization.

The broadcast television video bandwidth is about 4.2 MHz. Sampled at the Nyquist rate with PCM encoding of 8 bits/sample, the corresponding data rate is 67 M bits/sec, which includes all synchronization signals. None of these data rates include allowance for reduction possible through data compression techniques.

For comparison, the Bell System PicturePhone* video telephone station set (Cagle et al., 1971) is currently designed to have 267 lines per frame with transmission at 30 frames per second. The aspect ratio is 11 to 10 on the basis of a standard design viewing distance of 35 inches. Broadcast designs use a standard viewing distance of 63 inches. The PicturePhone* signal bandwidth is nominally 1.0 MHz. For digital transmission, a 6.312 M bits/sec data rate is used with differential pulse code modulation (DPCM) and sample-to-sample redundancy removal (Millard and Maunsell, 1971).

At this point it is appropriate to review some important aspects of digitally encoding television video signals. The first important concept is that the video signal or picture has three dimensions -- two refer to location in a two dimensional field and the third gives the brightness (varies from black to white) of the picture at that point. Color video adds a fourth dimension.

The video signal power spectrum typically has an envelope that is relatively flat out to about twice the line rate or about 30 kHz for broadcast rates. Then the spectral envelope begins to drop at about 6 dB per octave. Hence, at 5 MHz (the nominal bandwidth), the spectral power is about 50 dB below the level at 10 kHz. The high frequencies are essential to maintain sharp edges. The low frequency power corresponds to large area brightness levels.

Conversion of the analog video signal to a digital signal and encoding for data compression to reduce the bit rate can be decomposed into two stages: irreversible encoding and reversible encoding. As an example, generation of a difference signal for encoding is a reversible process. With perfect transmission, the receiver can ideally reconstruct the picture exactly. In order to generate a digital signal from the analog video signal, quantization must take place. Quantization is an irreversible process because signals between decision levels are all assigned to the same representative level. The picture cannot be reconstructed exactly.

The simplest type of quantization to explain involves PCM encoding. The analog video signal

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is sampled at some rate equal to or greater than twice the highest frequency in the video signal power spectrum (Nyquist criterion). For discussion purposes, consider the highest frequency as 4.2 MHz. Then 8.4 M samples/sec are obtained as a sequence of PAM (pulse amplitude modulated) sampling pulses. This sequence drives the PCM encoder, which divides the black to white voltage range into 2^n discrete intervals. In uniform PCM encoding, all the intervals are equal. For each sample, an n-bit binary PCM word is generated to represent the quantized amplitude. The data or bit rate is then an $8.4n \times 10^6$ bits/sec PCM digital video sequence. For excellent broadcast quality pictures, n = 8 is generally agreed as sufficient except for long distance relay for which n = 9 may be required.

The PCM digital video sequence is the input signal to a reversible data compression encoder. For n = 8, the input data rate is 67.2 M bits/sec. If the encoder achieves a 10 to 1 compression, the transmitted signal bit rate (baseband signal) would be 6.72 M bits/sec. Conventionally, picture coding compression ratios are expressed in a different way, as explained later in the paper, although the concepts are similar. Further, in many techniques, the quantizing, encoding, and compression are performed simultaneously so that the signal processing explained in terms of PCM is not actually present. The digitally encoded and compressed data sequence has no resemblence to a picture structure unless the decompression-decoding algorithm is used.

Finally, it is noted that each method of quantizing an analog signal has a certain usable dynamic range for the input signal. Uniformly quantized PCM, for example, for n = 8 does not have sufficient dynamic range to digitize voice or video signals. Non-linear quantized PCM (referred to as companded PCM) is usually employed to obtain an adequate dynamic range to match the input signal dynamic range. Companding techniques have also been developed for delta modulation.

The state-of-the-art in reducing the data rate or bandwidth is reflected in Bell Laboratories publications (Mounts, 1970); special IEEE issues (IEEE Transactions on Communication Technology, Part I, December 1971, IEEE Proceedings, 1967 and 1972, IEEE Spectrum, 1972, and IEEE Transactions on Computers, 1972); and numerous survey papers such as Schwartz (1969), Huang et al. (1971), and Wilkins and Wintz (1971). A relatively up-to-date bibliography is available from the Image Processing Laboratory at the University of Southern California (Andrews, 1972). This bibliography contains approximately 1000 references on the subject of image processing, coding, and transmission. Some textbooks are also available (Rosenfeld, 1971; Lawrence, 1967; and Berger, 1971). The consensus at the present time indicates data rates of 1 M bits/sec for 30 frames per second can give good quality gray scale video transmission for Bell System PicturePhone* television signals. Recent developments presented at the 1973 Picture Coding Conference** indicate Bell System plans for a 1.544 M bits/sec PicturePhone* digital transmission data rate for network applications including T1 carrier. The single video channel encoder uses frame-to-frame redundancy encoding with Shannon-Fano variable code word lengths. A 345,000 bit frame memory and a 12,000 bit coder buffer are included.

The 525 line broadcast television picture, as noted previously, has 270,000 picture elements per frame. This is not 525 squared because of the 4:3 picture aspect ratio and other resolution factors. At a 30 frames per second rate, about 8.1×10^6 picture elements per second are obtained. Connor et al. (1972) summarize intraframe coding techniques and the number of transmitted bits per picture elements as:

fixed length code with predicted algorithm	3-4 bits per picture element (24.3 - 32.4 M bits/sec)
Variable length code with predictive algorithm	2-3 bits per picture element (16.2 - 24.3 M bits/sec)
Adaptive techniques	1.2-2.2 bits per picture element (9.72 - 17.8 M bits/sec)
Transform techniques (2 dimensional, adaptive) Wintz (1972)	1-2 bits per picture element (8.1 - 16.2 M bits/sec

It is important to note that the statement 1-2 bits per picture element is the result of dividing the 8.1 - 16.2 M bits/sec data rate by 270,000 picture elements. It is an average and does not mean that each picture element requires 1-2 bits. Some picture elements need more and some less.

Inter-frame coding described by Haskell et al. (1972) simulated a 1 bit per picture element average rate with a 67,000 bit buffer required for overflow. Ignoring the forced updating of picture information due to buffer overflow, the long-term average data rate is about

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**Image Processing Laboratory, University of Southern California, Los Angeles, Calif. (see Andrews, 1972).

0.35 bits per picture element. Buffer size and delay make it difficult to achieve this rate with a single channel. If data from several (12-15) conditional-replenishment coders are combined prior to buffering and transmission, the required channel rate appears to be about 0.5 bits per picture element. This would involve a data rate of about 4.1 M bits/sec for each video picture signal using black and white rather than color techniques. For color transmission, the data rate would be around 10 M bits/sec. These rates actually apply only to the head-and-shoulders picture of the PicturePhone* application.

The CATV system will be assumed to use 5 MHz bandwidth for the television video signal. Also, a signal-to-noise ratio of 42 dB to 48 dB at a conventional television receiver is assumed as well as excellent phase stability because of color transmission. This type of communications channel can support an 8 level coherent PSK modulation (3 bits per signal element) for transmission on the cable or for interconnection. Assuming a required bit error rate of 1×10^{-6} (4 bit errors per second) for good picture quality, a signal-to-noise ratio of 19 to 20 dB is needed. The signal bandwidth for the 4.1 M bits/sec rate is needed. The signal bandwidth for the 4.1 M bits/sec rate would be between 1.4 MHz and 2.8 MHz (Hill, 1972). One could then ideally transmit two or three digital television black and white video channels for every analog television video signal as long as the PicturePhone* picture statistics are applied. For color, larger bandwidths would be needed. This would represent the current research and development state-of-the-art for digital PicturePhone* television. A key unanswered question in this area concerns the memory size for commercial television pictures because the rate of change of picture elements from frame to frame would be expected to be greater than in the PicturePhone* application. The numbers presented above are based only on a head-and-shoulders type picture. The savings in signal-to-noise ratio is substantial and represents an area for trade off with the required digital equipment and buffers for data compression.

Analog transmission is characterized by an accumulation of noise which gradually degrades the signal-to-noise ratio irreversibly. Operation of IF amplified microwave links with diversity and 80 dB signal-to-noise ratios does permit coast-to-coast video transmissions. Digital transmission accumulates errors during regeneration because of noise exhibited partly as clock jitter, but the degradation is reversible with error correction coding. Monitoring and fault location are easier with digital transmission, but degradation exhibits a threshold effect. If time division multiplex transmission is used, timing and synchronization requirements impose added costs and error sources.

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From the point of view of CATV interconnection and to some extent within the larger CATV systems, digital transmission may be a feasible alternative in the future. An 80 video channel interconnection loop may be able to operate at less than a 400 bits/sec data rate in a bandwidth less than 200 MHz for black and white transmission. This bandwidth is within the capabilities of coaxial cable, microwave radio, and satellite relay. A digital loop network configuration would provide point-to-point CATV system interconnection with far less interconnecting links than other network configurations and also would give 24-hour full channel service without central office switching. It appears that investigation of the application of this technology to CATV systems would be desirable at the present time.

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