PB 151384

NBS

Technical Note No. 25

Boulder Laboratories

COMMUNICATION THEORY ASPECTS OF TELEVISION BANDWIDTH CONSERVATION

BY WILLIAM C. COOMBS

U. S. DEPARTMENT OF COMMERCE
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ABSTRACT

New concepts of communication bandwidth utilization and conservation are in prospect through difference signal modulation systems in which only relative changes information is transmitted in lieu of absolute amplitudes. By these systems, the changes data function is made one of time as well as of amplitude, so that better advantage can be taken of redundancies in the video signal.

Advantageous conversions of information rate are made feasible by reason of a tremendous disparity existing between the extremely high information capacity of conventional television systems and the relatively very low perception capability of a human observer channel. Information conversions more consistent with perception capabilities of the human channel are achieved in difference signal modulation without usual great expansion of bandwidth that would be required to reproduce every possible absolute amplitude of each datum in the whole video picture mosaic directly.

Conversion to binary digital form accrues the further advantages of binary systems, including greater immunity to noise, greater adaptability to discrete data storage media, greater ease of scrambling for security, and greater amenability of encoding to optimum parametric controls for most advantageous transmission.

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1. Introduction

In the interval since adoption of N. T. S. C. monochrome television standards in 1946, important advances have been made in the joint fields of information and communication theory. Some of these advances are indicative of the fact that the time may not be far off when Industry and the Government will want to re-evaluate the standards chosen at an earlier date. Such re-evaluation might well lead to new concepts of frequency assignment and bandwidth utilization.

In the following summary discussion of some new advances in the art, an endeavor will be made carefully to distinguish between purely theoretical possibilities and those which experiments have demonstrated to be immediately practical. Suggested courses of action will be tempered with observations of what in the past has been most readily accepted by the industry, and what can be counted on for adequate engineering compliance with theoretical design requirements in the future.

One of the factors in the early sensing of congestion in the VHF band, which led to the television "freeze" and long interval of re-examination of frequency allocation policy, was undoubtedly the incomplete engineering of broadcast-to-receiver systems in mass communication installations. For example, in principle, a receiver antenna system demands equal attention with a broadcast antenna system to complete a communication link (according to the Reciprocity Theorem). However, the public and the marketing industry have demonstrated a reluctance to accept optimum engineered antenna systems as a requirement for television receiver installations.

Thus, the marketing tendency has been to ignore the signal enhancement that could be had through engineered antenna systems, and receiver system designs have been directed more and more toward portability and minimal dependence on antenna type, orientation, and location.

This tendency has left the public and the industry in a poor condition to accept mass re-direction of television broadcasting from the VHF to the UHF spectrum, where antenna directivity, engineering for permanent installations, and more restricted concepts based on beamed energy must be used for optimum performance.

In recognition of a general impasse which seems to have characterized television spectrum utilization and assignment problems for many years, some independent attention has been given to what might be gained through new concepts of television modulation and encoding methods, so as to minimize requirements for bandwidth in the first place, and to permit more ready accommodation to less favorable areas of the spectrum which might become available.

According to these concepts, VHF and UHF spectra utilizations are viewed as two different problems of most immediate major concern:

(1) In the VHF band, where the channels reserved for television use are most limited in number, yet most in demand, the problem is almost entirely one of bandwidth. If the required bandwidth could be made smaller, space might be found for many more channels.

(2) In the UHF band, where many more channels are available, the problem has in part been one of reliability and area coverage

relative to the VHF band*. If greater reliability of reception could be had for given transmitter-to-receiver antenna relationships, there would be a much greater inclination for prospective users to accept UHF assignments, without the force of law.

Eventually, these two problems may be expected to resolve together since anything that might be done to enhance one frequency band could be applied to enhance the other band also. Since very few of the television receiver sets in mass use in the United States are equipped to receive UHF, and any thought of mass movement to that band or any other band would entail major equipment conversion in any case, this is an opportune time to consider recent advances in theory which point to use of considerably revised systems as being possibly desirable in all bands.

Because of the new circuit concepts involved, the following discussion should perhaps be thought of in terms of what might first be arranged for military and other Government systems, the Government being more readily able to make mass conversions of equipment without becoming involved with manifold problems of private or commercial use.

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* For example, the Television Allocations Study Organization, sponsored by the National Association of Broadcasters, the Electronic Industries Association, the Association of Maximum Service Telecasters, the Committee for Competitive Television, the Joint Committee on Educational Television, and others, reported in March 1959 on a two-and-a-half year technical survey of television channels used in commercial broadcasting. On the basis of thousands of field tests and home observation tests, it was indicated that the VHF channels averaged approximately 1.3 to 2.17 greater transmission range to point of rapid picture deterioration, or roughly 1.7 to 4.7 times the area coverage of UHF, the smaller figures corresponding to high band VHF vs. low band UHF and the larger figures to low band VHF vs. high band UHF.

At the outset, recognition is, of course, given to the bandwidth saving possible in single sideband systems. Actually, because of the practical problems of cutting off spectra near zero frequency, it is more practical to compute minimum required bandwidth in terms of vestigial sideband requirements, as compared with double-sideband systems of nearly twice the overall frequency span.

Similarly, immediate recognition is given to the fact that typical television systems actually only realize a video information transcription of one completely independent picture datum per cycle of highest frequency of bandwidth at most; whereas, communication theory indicates that two such data can be resolved for distinctive transmission in each cycle of bandwidth. Development along the lines of applying pulses capable of receiver response in $\frac{\sin \omega t}{\omega t}$ functions allows theoretical independence of two data pulses per cycle and therefore doubling of information in the same transmission bandwidth.

In what follows, it will be assumed that full attention will have been given to achieving all such full potentials of transmission according to the developmental status of the art. The concerns of this paper will henceforth be directed toward what further might be accomplished through revision of communication parameters and the modulation or encoding processes.

2. <u>The Shannon Law.</u>

The basis for believing that modulation and encoding system revisions might alone help resolve the problems of available bandwidth in the VHF band, and of reliability in the UHF band, is found in information theory developments of the past twelve years.

One aspect of theory portending of this potentiality for improved systems comes directly from the Shannon law for communication information rate in the presence of noise:

$$C = B \log_2 \frac{P + N}{N}$$

where C = bit rate of communication in bits per second

B = bandwidth in cycles per second

P = signal power

N = noise power

This law relates information rate, bandwidth, signal-to-noise ratio, and time of transmission. Total information, of course, would be the above rate multiplied by time T in seconds.

As applied to the VHF problem of limited bandwidth availability, the law suggests that by arranging the picture information so as to lower the information rate, through more efficient selection of data and re-distribution in time, the signal may be encoded to a lower bandwidth without reducing the signal-to-noise ratio.

As applied to the UHF problem of insufficient reliability or coverage in a region of presently incompletely used channel space, the same law may be interpreted in the sense: For a given communication rate, a properly encoded expansion of useful bandwidth will reduce the signal-to-noise ratio required to complete a successful transmission.

As channel space would become increasingly non-available in the UHF band, the problem would, of course, eventually merge with that of the VHF band, in seeking bandwidth reduction through more efficient picture information transmission.

An interchange may also be made between bandwidth and time. For example, with further development of storage kinescopes, it is realistic to believe that it may soon be possible to drop the scanning frame rate from the present 30 frames per second rate, down to perhaps 10 frames per second, for a majority of common applications. This would allow a bandwidth reduction from 4 Mc down to 1.33 Mc per second, by changing the information rate.

Since the enunciation of Shannon's communication theorems about twelve years ago, major theoretical efforts have been made to evolve more efficient codes for discrete information transmission, by Fano, Elias, Laemmel, Shannon, and many others. However, results obtained in this particular line of approach have not been of such a nature as to find their way to immediate significant practical application, having longer range potentialities.

3. Bandwidth Interchange.

Before advancing to some approaches to signal encoding having more immediately practical prospects for pay-off, two examples of bandwidth interchange problems will serve to emphasize practical limitations to what can be achieved in a beneficial way by application of communication theory.

First, let a re-coding of information from one set (C) of parametric design conditions to a second set (C') of transmission conditions having unchanged communication information rate be represented by

$$C = B \log_2 \left(1 + \frac{P}{N}\right) = C' = B' \log_2 \left(1 + \frac{P'}{N'}\right)$$

Starting with a very low assumed satisfactory signal-to-noise ratio of $\frac{P}{N} = \frac{10}{1}$ for a coded signal, and noting that for determining interchange ratios one can as well use $\log_e$ as $\log_2$,

$$\log_e \left(1 + \frac{P}{N}\right) = \log_e \left(1 + 10\right) = \log_e 11 = 2.3979.$$

Substituting in the above relationship:

$$C = B \log \left(1 + \frac{P}{N}\right) = B' \log \left(1 + \frac{P'}{N'}\right)$$

$$2.3979 = \frac{B'}{B} \log \left(1 + \frac{P'}{N'}\right)$$

From the assumed initial signal-to-noise ratio of $\frac{P}{N} = \frac{10}{1}$, let us now see what new signal-to-noise ratio would be required to preserve the same communication rate when the bandwidth B is cut in half, such that $B' = \frac{1}{2} B$; or $\frac{B'}{B} = \frac{1}{2}$:

$$\text{Log} \left(1 + \frac{P'}{N'}\right) = 2\left(2.3979\right) = 4.7958$$

$$\text{anti-log } 4.7958 = 121 = 1 + \frac{P'}{N'}$$

Whence, $\frac{P'}{N'} = 120$ - new signal-to-noise ratio required, with an ideal transmission system.

Remembering that this transition is predicated on Shannon's ideal encoding, and that one of the most efficient transmission systems yet achieved in practice, namely pulse code modulation, requires the order of 7 times as much power as ideal encoding, or a signal-to-noise ratio of about 14 times ideal in this case, it is apparent that a truly tremendous increase of power would be required to compensate for the reduction of bandwidth, if the communication information rate is to remain unchanged.

This example illustrates the practical futility of seeking bandwidth reduction on a signal re-coding basis if full video channel information capacity is maintained through the transmission channel. If full channel information capacity is provided throughout the system, but not utilized, the efficiency of the system will, of course, be lower than it need be.

On the other hand, the above example also serves to show that the converse procedure of increasing the encoded bandwidth from B' back to higher bandwidth B results in an equally remarkable reduction of power requirements to sustain a given information rate. The effective exponential increase of signal-to-noise benefit with only linear increase of bandwidth is only possible in coded systems. While such an exponential benefit in signal-to-noise ratio may not loom large when compared with the already relatively high signal-to-noise ratios commonly deemed to be necessary for acceptable broadcast television, the difference becomes very significant at the very low signal-to-noise ratios at which binary digital transmission remains possible.

It is suggestive from this example to seek improved transmitter to receiver relationships in the UHF band by utilizing modest increases of bandwidth in that region. Let us therefore proceed with a second example, in order to better perceive the order of bandwidth expansion required to encode a television signal in one of the more efficient codes, again taken as pulse code modulation.

If a 4 Mc video analog signal is assumed, the sampling theorem requires not less than 2 samples per cycle of highest frequency in video bandwidth measured from zero frequency, or 8 megabits. If the gray scale of the picture is arbitrarily quantized into 32 distinguishable levels from black to white, corresponding to association of 5 binary digits of variation for each video datum or sample, a binary code of 2^5 is required. This means that a communication channel space must be provided to send (8 megabits) X 5 = 40 megabits of information. Even under theoretically ideal conditions, this would require a four-fold addition to the original bandwidth existing before digital conversion. This is much too great an order of bandwidth increase to be considered practical for purposes of achieving less discriminate transmitter-to-receiver conditions, even in the UHF band.

It is clear from these examples that interchanges of parametric bandwidth and the other parameters in the basic communications formula do not lead to satisfactory solutions of the VHF and UHF television frequency allocation problems, despite the diligent pursuit of more efficient codes, <u>when bound by conventional standards of sustaining a given video information rate</u>.

These comparisons, based on ideal encoding or translation to the comparatively efficient pulse code modulation system, more than confirm the futility of attempting similar bandwidth transitions in non-coded systems. Schemes may be devised which will truly reduce the bandwidth of transmission, but in a non-encoded system, it must always be at a greater price in communication rate or communication range than in the encoded systems required by Shannon's ideal.

Yet, there is no paradox in applying communication information theory to seek useful television bandwidth reduction or signal enhancement in accordance with the promise of Shannon's law. The above examples showed futility of practical application only because each example was predicated on maintenance of a fixed video communication rate throughout the system, irrespective of digital conversion of an arbitrary standard of 4 megacycles per second of video information.

4. Disparity Between the Information Capability of a TV System and the Perception Capability of a Human Channel.

Let us test the validity of accepted standards of required video bandwidth and information rate by citing some vivid comparisons of the information content of a television scanning system, on the one hand, and the information perception capability of the human observation channel, on the other hand:

Filipowsky [1] has noted the example of taking an average number of black and white television characters (picture-elements) per picture for good resolution as 500,000, and taking the number of distinguishable gray levels that can be consistently interpreted on a cathode ray screen as 10. The number of possible picture messages, when taking one picture interval as the message interval is then $10^{500,000}$, a completely incomprehensible number*.

Expressed in terms of an ideal transmission system following Shannon's law, a television channel bandwidth of 4 megacycles per

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* The incomprehensibility of this number is made vivid by Filipowsky's example [1] that "the whole universe, taken as a sphere ranging to the furthest nebulae could never accommodate more than 10^{100} tiny film pictures, when every available space would be closely packed with films of the thinest variety, each containing another of the possible messages which every standard television system can transmit."

second and signal-to-noise power ratio of 10,000 is capable of transmitting approximately 54 million bits of information per second.

Now, let us cite the apparent maximum rate of information perception by a human being, according to the best estimates of special study observations in the field. It is an amazingly low figure generally agreed to be no more than 50 bits per second [2,3,4].

This is a disparity between theoretical television rendition capability and human perception capability of more than a million times, for high signal-to-noise ratio. A disparity of many hundred thousands of times would continue to apply for practical systems. Most attempts to reconcile this disparity have been directed along the lines that the screen must be prepared to present the full information data at each point of the screen, irrespective of where the eye may be looking. This is not a very satisfying justification for providing so large a system information capability in a practical television system, particularly in the light of the previous citation, wherein Filipowsky has further noted that if each possible picture were framed in succession it would require a film projector to run continuously for $10^{499,991}$ years to pass all the system capability pictures without repetition -- remembering that this is the capability of a single picture interval.

Recognizing this tremendous disparity between information rate provided in a television system and the information perception rate of a human channel, we have abundant justification to depart from the conventional concepts provided by present television standards and re-approach the problem. The practical limitations of bandwidth adjustment previously computed need no longer apply, provided that simultaneously with bandwidth transitions there are also provided appropriate conversions from the original video input capability to the usable information rate that can be comprehended at the receiver.

How the human channel tracks or selects the comparatively low quantity of information it actually perceives, out of all the information made available, would be the subject of an obviously very important study. Unquestionably, such a study should be pursued under high priority. The above comparisons commend such action because there are potential pay-offs in bandwidth savings amounting to many times the savings in prospect by any other measure.

5. An Information Correlation Basis for Bandwidth Reduction.

The above comparison presents an entirely new tack to follow in considering reduced bandwidth or less noise disturbed television systems. Instead of seeking encoding methods in a system that faithfully retains all the information in a picture mosaic having an information capability hundreds of thousands times beyond human capability to receive it, let us seek more nearly to send information according to apparent time patterns of human capability to track the information that is received.

In considering how to go about bringing the television and human channels closer together, a first approach is to note that, whereas television is fundamentally thought of as a changing picture system, the human being is only capable of perceiving small details of change out of a total picture, on a 1/25th or 1/30th second basis. It is known [1] from motion picture experience that it takes the human being a few seconds to comprehend the content of any actually new scene. The human channel accepts little less when such a complete subject transition is accomplished through dissolves than when complete information is carried through, and the comprehension is considerably clearer when the transition is narrowed down in information content.

Since we do not know precisely how the human being references his information, we can remove one obstacle of indeterminacy of unknown human references by choosing a system of modulation in which only changes information will be sent. Considering the human channel's extremely low information rate, it is reasonable to believe that human perception also relates successions of information relatively, rather than on an absolute scale.

There are many other pertinent characteristics of cathode ray screen and human perception channels which have been confirmed in subjective observation tests. These also provide valid bases of support for conserving the bandwidth needed for satisfactory picture rendition. Without going into detail some of these are cited:

The eye is much more sensitive to gray scale changes in the broad low video frequencies areas of only slightly changing picture information than in the high frequencies or edge information areas. Thus, in recording a picture for minimum overall bandwidth transmission, a proportionately greater bandwidth may advantageously be reserved for conveying higher degrees of gray-level amplitude distinguishability in the low frequency areas. Filters provide a ready means of accomplishing this inner-system bandwidth allocation.

Whereas, skilled observers may claim to be able to detect as many as 30 to 100 distinguishable gray levels in a high quality full tone commercial photograph, it has been demonstrated that when reproduced on a cathode ray screen after being subjected to the camera tube and circuit tolerances of a good quality television system, the number of consistently distinguishable gray levels falls to 10 or 12. This does not mean to say that a gray scale video wedge cannot be made to register more than approximately 12 amplitude separation bands on a cathode ray screen. As a matter of fact, even 16 or 32 levels may prove insufficient to alleviate disturbing contouring effects when a picture is quantized by the pulse code modulation method, this method establishing amplitudes by fixed absolute reference to zero amplitude, instead of as relative changes information. But, if account is taken of the uniformity of the amplitude level across the screen and controllability in relation to other bands of gray level reproduction, less than a dozen levels remain consistently depicted in proper relation to the video signal, on the cathode ray screen.

For reproduction of a half-tone print, such as has received common acceptance of quality in newspaper photographs, the distinguishable levels on a cathode ray screen falls to half the number of the full-tone photograph. There is, therefore, no point in wasting channel space by assigning bandwidth specifically to provide capability for a greater number of gray scale levels than the system can itself reproduce with fidelity or make distinguishable to the eye.

Whereas, a typical high quality television system using 525 lines per frame and 30 frames per second is commonly construed to have a capability of about 658 independent picture elements per line (most systems do not really make good on this!), subjective observations made by many different experimenters in the field show that rarely does a video waveform show more than 40 significant transitions per line. For wide varieties of subjects, the number is much less than this. Since there is a high probability that anything missed on one scan would be at least partially interpreted on successive scans, this represents another area for consideration of bandwidth conservation*.

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* Whereas, in theory, this type of bandwidth reduction could be accomplished by dot interlace schemes over a period of time, psychological picture "crawl" effects have not allowed this approach to become practical. As with the contouring defect of pulse code modulation, however, this defect can be largely overcome by departing from conventional practice of depicting individual point amplitudes as absolute values measured from zero, and substituting diversity changes information interpreted on successive scans.

It can be demonstrated that the best commercial television camera tubes do not actually have a high frequency transient response consistent with the highest frequency inflections of a 4 megacycles video bandwidth signal. There is little point in providing transmission bandwidth for something that already fails to be reproduced with fidelity ahead of the modulation or encoding system.

Subjective observations have demonstrated vast amounts of redundancy in television pictures of all subjects, commonly averaging not less than an estimated 95% redundancy of information even in the most complex subjects. A complex subject might, for example, be a sea of thousands of moving faces, bodies, and arms in a football stadium. There is thus an important area for recoverable bandwidth through removal of redundancy in the video signal information. To recover bandwidth, this information must be redistributed in time.

In respect to time, major portions of acceptable television pictures remain still for seconds at a time. Very few details change at one time. Correspondingly, the low information rate of the human channel indicates that the eye must rely on many successive scans to derive its information interpretation. The human perception channel does not itself interpret new information in discrete or ideal step transitions but, as in much of nature, tends to follow exponential or similar response characteristics. At the very low information rate credited to the human channel, it would not be reasonable to expect immediate response to sharp transients of video change. Rather, such impressions are more likely to be simulated through a succession of scans, in the same way that motion pictures simulate action through a succession of steady state impressions.

There is here quoted an exerpt from a discussion by J. R. Pierce [5] which effectively sums up the substance of many of the above items:

"......by and large, successive pictures are much the same. The actual information needed to tell what the next picture will be is less than the system is capable of transmitting, and so the system is in this respect inefficient. Likewise, as the electron beam of the pick-up tube scans from one picture element to the next, the change of brightness is apt to be small, and on the average not much information is needed to specify the difference in brightness between one picture element and the next. Yet the television system is capable of transmitting a picture in which each picture element is wildly different from that preceding it. This capability is never called on in transmitting actual pictures, and so the television system is inefficient in providing more capabilities, more channel capacity, than is needed to transmit actual pictures."

There is, therefore, great consistency of purpose, embracing many aspects of television and human perception systems, in seeking television bandwidth conservation by encoding to transmit only significant changes information, correlated to human perception capabilities, instead of in absolute amplitudes such as would be required to specify totally non-related pictures from one instant to the next.

This is the logic that supports the modulation system design approaches discussed in the next paragraph.

6. Difference Signal Modulation.

Reference to the Shannon communication formula shows that, contrary to the previously cited examples for full conventional video information maintained throughout the system, bandwidth interchange through adjustment of communication law parameters becomes very attractive when accompanied by appropriate conversions from the initial video information capacity. For an ideal encoding exchange, bandwidth may, in theory, be reduced in direct proportion to the information capacity reduction. Similarly, signal-plus-noise to noise power ratio demands could be exponentially reduced in proportion to such information reduction.

An apparent feasible way of accomplishing an advantageous form of information conversion, without seriously impairing the message interpreted by the eye, is to convert absolute amplitude discrete data contained in the video picture mosaic to relative changes information. This makes the data function become one of time as well as amplitude and therefore allows better advantage to be taken of redundancies of the video signal by enabling function amplitude diversifications to be interpreted over successive time scans.

This stretchout of the information gleaning process is consistent with the much slower information rate of the human observer, relative to the initial video mosaic information capacity. Additionally, the changes amplitude diversification of repeated scans, not being referred to zero or other absolute reference, offers a solution for overcoming the psychological "crawl" effects that characterize horizontal-dot-interlace attempts to reduce the bandwidth of conventional amplitude modulation. Thus, utilization of bandwidth to satisfy only changes requirements does not impose any apparent new conditions that might be expected to produce visible deterioration of picture quality, but rather, portends improved scanning action.

Before citing experimental evidence considered to verify advantages of changes information suggested above, it is pertinent to note that competent observers have adjudged surprisingly high-quality picture responses, without important degradation of any pictures but critical test patterns, when standard television signals have been passed through well-designed low-pass filters of as low as 2 Mc bandwidth [6]. Accordingly, in order not to confuse attributes of subjective quality benefit within margins of personal subjective interpretation differences, comparisons of conventional and digital modulation methods were made on filter-controlled video nominally set below 4 Mc video equivalence, and more significant reductions of digital bit rate were explored than would be accountable by a 2 to 1 difference in human observer interpretation.

A practical test of the feasibility of a modulation system embodying changes information principles exists in the digital Difference Signal Modulation System reported to the U.S. Army Signal Research and Development Laboratory under Contract DA-36-039-SC74928 [7]. In order to grasp the full significance of the experiments discussed in this report, one must appreciate the fact that the digital conversion of an analog waveform, without infinite inspection and ideal encoding, is nominally considered to require at least 5 to 6 binary digits of information to be associated with each cycle of analog information bandwidth, to statistically match the code and convey the full potential of analog information.

In estimating the bit rate required for a difference signal modulation system having the same 4 Mc per second discrete video data response capability of the pulse code modulation digital television system considered in a previous example in this paper, presuming no correlation of video information, one arrives at a theoretical bandwidth requirement 50% greater than for the PCM system. The pulse code modulation system, it will be recalled, was found to require not less than a 40 megabits per second transmission rate to convert a 4 Mc video bandwidth to a 5-digit quality picture. Hence, even with the benefit of minimum (Nyquist interval) sampling, a digital difference signal modulation system conforming to conventional concepts of required information capability would be expected to require a transmission rate of not less than 60 megabits per second. This is 7.5 times the 8-megabit rate ideally needed to depict a 4 Mc/sec. bandwidth of discrete video information.

Yet, when a digital difference signal modulation system was constructed and allowed to make its own "changes" information selection on successive scans, within a given modulation bandwidth capability, it was found to completely digitize a picture into binary pulse form, and to reassemble the picture elements at the receiver, using no more bit rate than a comfortable 2.5 ratio of pulse repetition frequency to highest frequency in the video bandwidth.

Side-by-side comparison of analog and digital system monitors using a wide range of still and rapidly moving camera subjects revealed no perceivable reduction of information in the difference signal digitizing process. Indeed, the fidelity of rendition of moving subjects, without the presence of expected smear or granular degradation under circumstances of highly reduced bit rate, is believed in part explanable only by the increased coincidence and coherence of the television system with human channel response capabilities, when reduced information progresses as relative changes information instead of as discrete amplitude values requiring individual correlation to a myriad of indeterminate human reference points.

Several advantageous factors are to be noted as entering into determination of minimum required digital bit rate for producing acceptable pictures in difference signal modulation processes. For wide ranges of typical television signals the autocorrelation function for small displacements of picture information approaches exponential shape [8]. Ready advantage can be taken of this fact in difference signal modulation, because each previous comparison sample used in determining the change signal is all that is needed for providing natural or in-built prediction, presuming exponential step change response control. When the probability distribution of the change signal is thus approximated by an exponential function, the statistics of the television signal tend to be matched closely in the resultant code. This does not mean that for a low sampling rate all of the information will be transmitted, but for such information as is selected, matching to the code will be efficient.

Prediction utilizing correlation between successive picture elements provides savings of channel capacity that can be translated to benefits in bandwidth, time, or average power. Translated to a 6-bit channel, it has been noted [9], that a predictive redundancy of 3 bits in the television message avails a potential halving of the bandwidth. Previous-frame prediction also holds a potential for removing slightly more than one bit of redundancy per sample.

From another point of view, it has been determined [10] that a power reduction of the order of 10.5 to 22 db (depending on complexity detail of the picture) can alternatively be availed by previous value prediction. In this connection, it is noted that in the particular difference signal modulation system referred to above [7], the previous value comparison loop constitutes an effective inverse feedback loop, and noise cleaning advantage is effected in much the same manner as in other inverse feedback loops.

In respect to correlation of changing picture information, it has long been established from both motion picture and television theory that successive pictures are not only required to be enough alike that satisfactory illusions of continuous motion can be produced, but also, the brightness illuminations across a picture must be related if a meaningful picture is to be produced. Hence, it is pertinent to seek correlations not only for purposes of channel capacity conservation but for enhancement of picture information itself.

It is in the failure to provide for more substantial correlation of information in the television signal, and correlation with the human channel, as above described, that present television practices appear to be most deficient in providing efficient channel capacity utilization.

The principal significance of the cited difference signal modulation research is that, without having to know what the eye's own particular scanning methods are, the information in the overall picture mosaic can be reduced within margins needed to depict only perceptible transitions of change. In effect, it was confirmed that the same picture as depicted in a conventional scanning system having a given analog video bandwidth capability without correlation, could be essentially reproduced in a digital difference signal modulation system in which the bit rate needed for digital conversion had been reduced below that computed for full channel independent data conversion by a factor of not less than 6 to 1. The circuits required to accomplish this were practicably simple, having only a small fraction of the complexity and overall system control problems of a PCM system.

The achievement of this picture digitizing goal without great expected expansion of bandwidth, but rather, more effective video bandwidth utilization, provides a new concept of the television transmission problem. As pointed out previously, such digitizing without great bandwidth increase is only made possible by taking advantage of margins of excess provided in conventional system standards over the perception capabilities of the human observer. If the compromised bit rate difference signal system were tested for direct transient response to each possible independent information element amplitude in the analog video picture mosaic, it would never meet the test. Yet, neglecting expected slight sampling structure at very close viewing distances, the human observer senses no loss of information relative to the conventional amplitude modulation system, despite the digital conversion.

It is possible to arrange the difference signal modulation change characteristic so that the system automatically allows progressively more steps of brightness level in the low frequency change areas. This, plus random sampling, overcomes the disturbing contouring effects that characterize pulse code modulation picture quantizations. This also brings about a desirable distribution of transmission energy in the direction of low frequency transitions, which are most significant in overall structure of the picture. Moreover, the dynamic characteristic governing the changes function can be arranged to provide steepest change transitions capability at the points of reversal from the extremes of brightness or darkness amplitudes. This makes the change function characteristic directionally consistent with greatest probabilities of change, and at the same time creates self-stabilization against cumulative error or excitation from large uni-polarity noise pulses.

In capitalizing on redundancies in the video information bandwidth, bandwidth reduction, as previously noted, can only be practicably achieved to the extent that there is a reduction in the information transmitted. Accordingly, some of the video information will never be sent. But, that which is sent can be enhanced in the sense that it is intelligently selected and efficiently matched to the coding system.

7. Further Advantages of Digital Systems.

Conversion to a binary television system avails all the advantages of any noise penetrating binary system. Instead of having to maintain fidelity of many analog gray scale brightness levels in a modulation wave form, the receiver detector is only required to detect presence or absence of signal. In this regard, the binary television signal has a noise penetration benefit similar to that of telegraphic message transmission relative to voice communication.

Within the threshold of receivability and on-off detection relative to noise, the received signal can be clipped, sliced, cleansed of noise, and be made to activate locally regenerated pulses of desired waveform at the receiver, to reconstruct a noise-free picture. Being in digital form, the binary train of data can be readily scrambled and unscrambled, to preserve military security over a transmission link. Since the signal can be regenerated at a receiving point, it can be reinserted over a large number of communication links and repeater stations in tandem, without accumulation of noise through repeated amplification.

Certain new concepts of application would, of course, be required in general practice. Since a binary system is amenable to noise - cleaning, the limit of range transmission would be a very positive one, namely, at such distance where presence or absence of signal cannot be detected above noise.

This tends to approach an "either-or" condition, the same as in all binary systems, which have greatest possible immunity to noise in the designed range. Propagation-wise, this means a much sharper threshold of maximum coverage which, however, can be expected at considerably greater range. Within the range of binary discrimination there will be a good picture, and not far outside this threshold of range there will be virtually no picture. This is in distinction from the less abrupt threshold or progressively worsening picture that characterizes a conventional amplitude modulation system as distance is increased beyond a relatively high signal-to-noise ratio range needed for good reception.

There are other considerations involved than what produces an acceptable picture, in deciding optimum transmission systems for all applications. For example, an optimum number of digits can generally be determined as statistically best-matching the signal against noise. This design determination may not necessarily coincide with the minimum bandwidth needed for acceptable picture construction. These and other aspects of the conservation problem remain to be further investigated for digital television systems.

Most of all, achievement of a practical digital television system opens up innumerable possibilities for transmission flexibility and bandwidth conservation. Once converted to digital form, many different forms of storage can be applied to binary data. Reference to Shannon's communication formula cited earlier in this paper shows that individual or combination interchanges of information rate and bandwidth can be made in linear proportion to time exchange.

Thus, in addition to such bandwidth reduction as may be achieved through information capacity reduction, spreading the time of transmission by a factor of two would allow further reduction of bandwidth by a factor of two, for transmission. By accepting delay in transmission, digital storage devices would permit playback at the receiver in the same full video time scale as the picture introduced at the transmitter.

This flexibility and amenability of digital television systems to new vistas of bandwidth conservation particularly commends digital television systems for consideration in Space Systems applications. A great many of the satellite and other Space communication plans already announced are predicated on delayed transmission of data in digital form.

8. Conclusions and Recommendations.

Progress of the United States in outer space and satellite communications demands up-to-date standards of television and data transmission, taking full advantage of progress in the art. A system which occupies an information space in excess of what can be interpreted at the receiver by a factor of many hundred thousands of times is not consistent with solution of either the signal energy or the bandwidth requirement problems of space and worldwide communications.

Clearly, the manifold advances in communication information theory and in the theory of human perception characteristics, mainly in the period since N.T.S.C. television standards were adopted, calls for a complete review of the whole concept of television transmission as now practiced.

In the interest of advancing radio propagation and standards missions, it is consistent with the functions of the Bureau to study and evaluate new advances in the art. In the case of television, there is indicated an immediate need for further study and evaluation in the field of human perception as related to television system standards. There is also an urgent need to investigate completely the transmission aspects of digital television.

With the assistance and endorsement of Industry and the other Government civilian and military service agencies, it is believed that continuing investigations in the areas discussed by this paper will evolve recommendations for vastly improved television systems. Work in this direction should be directed jointly toward the goals of enabling the Government to deal more effectively with the ever-enlarging bandwidth allocation problem, and bringing into play new advances of the art which inevitably must accompany progress in the Space Age.

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