Results of a Prototype Television Bandwidth Compression Scheme

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Abstract—The transmitter/receiver system for bandwidth or data-rate compression of television signals, described herein, is a prototype model of the experimental system of Cherry et al. [1]. The system is suitable for both black-and-white or half-tone pictures, in realistic noise conditions. The system parameters may be adjusted so that an optimum run-length encoding may be found; the great advantages of run-length quantizing are shown, especially with regard to practical instrumentation, leading to the use of buffer stores of modest capacity. One particular cheap form of receiver operates on a quantized-variable-velocity principle and, being much more simple and cheap than the transmitter, is suitable for use in situations requiring many receivers.

I. Introduction

THIS PAPER EXTENDS the experimental and theoretical work of the open-loop compression system proposed and partly described in an earlier paper (Cherry et al. [1]), leading to the description of a flexible prototype television bandwidth compression system for industrial and commercial purposes, or for long-distance links in broadcast systems, of full broadcast quality, for "on-line" trials. The system is basically that described by Cherry et al. [1], to which extensive reference will be made, though developments have led to differences of detail, and include an increase in flexibility by provision for variation of certain system parameters.

II. Description of System

The block diagram shown in Fig. 1 contains the essential details of the prototype transmitter encoder. The separate blocks of Fig. 1 have been outlined in [1], but a brief description will be given here for completeness.

The open-loop system combines attempts to exploit certain statistical and subjective redundancies in the television signal, with the aim of reducing the average rate of binary digits required to specify the picture information with given fidelity. Attempts are made to extract the essential signal data in a noise-combating fashion for subsequent statistical run coding. The resultant nonuniform data rate is then equalized by feeding into a buffer store (called an "elastic encoder") for uniform transmission through a suitable channel. Two sets of data must be transmitted, the brightness data and the run-length data.

Manuscript received December 1, 1966; revised January 27, 1967. This work was supported by the National Research and Development Corporation and the Science Research Council.

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III. Detail Detection

A band-limited television signal may be completely described by samples taken at the Nyquist rate. The "detail detector" is required to locate successive Nyquist samples of equal amplitude (i.e., which fall on a common "run") in order that run-length coding may be implemented. Inferential methods are exploited, aiming to discriminate against noise present in the signal. In this case the "runs" constitute successive samples of equal amplitude (within prescribed fidelity constraints), although "runs" of other signal features are feasible as possible alternatives.

The detail detector used in the work described here is an improved version of the one built by Kubba [2] and used by Cherry et al. [1]. The improved performance of the new detail detector is described by Vieri [3], who reports a reduction of approximately 20 percent in the number of samples needed, compared with the earlier version, with very little change in quality for typical half-tone pictures. He also notes that the improved version gives a run-length distribution which is more nearly exponential; such a result conforms with an exponential shape for the autocorrelation function as measured by Kretzmer [4]. An alternative analysis of the detail detector operation, proposed by Pearson [5], regards the problem as a significance test on a null

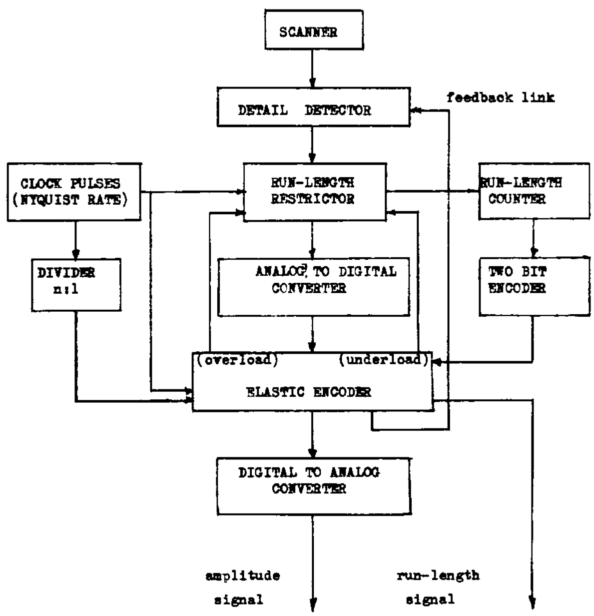


Fig. 1. Transmitter encoder.

hypothesis that two samples belong to the same population. The resultant strategy is the same as proposed by Kubba [2] except that the thresholds can only be optimized according to subjective tests performed on the resultant pictures.[1]

IV. Run-Length Restriction

The detail detector output corresponds to a train of amplitude-modulated samples obtained by removing those Nyquist samples which do not begin new runs. These runs may be of any length (but each an integral number of Nyquist intervals), and are suitable for Shannon-Fano coding, though the number of run lengths possible in practice is large, thereby creating formidable instrumentation problems. Measurements of the run-length probability distributions (Vieri [3] and others) indicate an exponential distribution with negative exponent, so that an upper limit on the maximum permissible run length would be desirable and reasonably efficient. An even more economical method of instrumenting run coding is to restrict the permissible run lengths to a small subset of the original distribution, all other run lengths being broken up into suitable combinations of these standard runs by insertion of additional samples. The process described by Cherry et al. [1] is called "run-length restriction." It is envisaged that the optimum restricted run-length probability distribution will be almost flat (in which case variable-length coding will be unnecessary), but this can only be experimentally determined.

The "run-length restrictor" consists of a shift register of eleven stages and associated set-reset logic, and is capable of restricting an input train of runs, labelled by a Nyquist train of 1's (start of runs) and 0's (remaining members of runs), to a train of standard runs by the insertion of extra 1's into the run-length sequence as it passes down the shift register. The standard runs, labelled 1, p, q, and r, where $1 \le p \le q \le r$, are permitted to assume a range of values so that the experimental determination of an optimum set is possible. Measurements and calculations, Vieri [3], suggest that the following combinations of runs will include an optimum set.

Run	Length (Nyquist units)								
1									
p	2	3	4						
q		3	4	5	6	7			
r				5	6	7	8	9	10

We have considered it necessary to consider a wide range of standard run lengths, even though the overall compression for any particular set can be predetermined by numerical calculations on the run-length probability distribution, because the subjective effects of restriction needed assessment.

[1] An alternative theoretical approach to detail detection has also been reported by Sekey [6].

This run-length restrictor is further provided with a capability of modified restriction when commanded by the elastic encoder during "underload" and "overload" conditions; see Fig. 1.

V. The Elastic Encoder

The run-length restrictor output now corresponds to amplitude-modulated samples obtained by removing those Nyquist samples that do not begin any of the now standard runs. This irregular sample train is next converted into a regular one, having a reduced Nyquist rate, using a shift register technique (Fig. 2). This is done by stacking the samples in a storage device, as they occur, and emptying it at a uniform rate by the regular removal of samples at the head of the stack. The situation is one frequently encountered in queueing theory and it will be discussed in more detail in the Appendix.

A practical storage device, called an "elastic encoder," for equalizing the sample spacing has been described by Cherry et al. [1]. If the amplitude-modulated samples are first converted into binary PCM form, then the elastic encoder can be realized by a bank of shift registers operating in parallel (see Fig. 2). Each amplitude-modulated sample is converted into parallel binary PCM form and the digits inserted into the "stacking stage" of the "brightness shift registers" (see Fig. 2) so that one shift register is required for each digit of the PCM signal. Simultaneously, the corresponding standard run *length* is coded into a binary PCM signal and inserted in the same "stacking stage" of the "position registers." Each set of corresponding storage cells in the parallel arrangement of shift registers constitutes a stacking stage. In our present case, using 4 standard run lengths, 2 "position registers" are required.

An extra "control register" is necessary to operate the associated logic which moves the stacking stage up and down the registers in step with the input and output sequences. The input and output sequences must be arranged so that input and output pulses never occur at the same instant, and this can only happen when the Nyquist rate is a

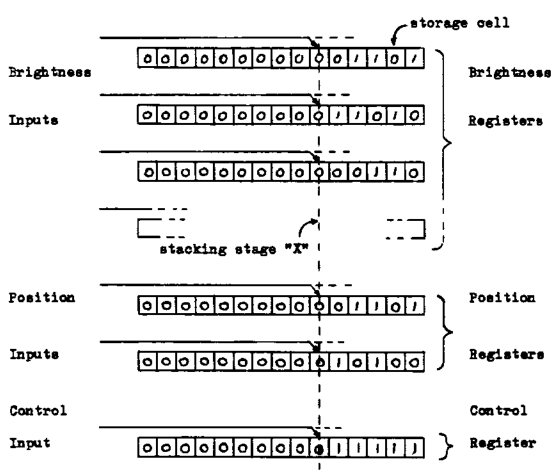


Fig. 2. Elastic encoder.

multiple of the output reduced Nyquist rate. (This is the sampling ratio n to 1, n an integer.)

The position "X" of the stacking stage is monitored at both ends of the control register so that "underload" and "overload" conditions can be detected and used to modify the operation of the run-length restrictor in an optimum fashion. The underload and overload facilities should not be confused with "elastic encoder feedback," described in Section VI, which considers the required elastic encoder capacity.

VI. Capacity Requirements

The equilibrium behavior of a finite-size elastic encoder with a stationary random input is considered in the Appendix, where it is suggested that a run-coded television signal can be usefully considered as a random sequence of samples having "short-term" stationarity ("short-term" meaning of the order of one line length). It is suggested that the mean rate of this random sequence exhibits "long-term" variations only.

The "long-term" variations of mean sampling rate can be minimized in the practical situation since the detail detector constitutes the sample source. It merely requires that the detail detector thresholds be adjusted by feedback from the elastic encoder.

It should be noted that a change in the detail detector thresholds, corresponding to a change in the detection fidelity constraints, results in a change in the proportion of Nyquist samples selected, but the resulting run-length distribution remains essentially exponential in "shape."

The detailed behavior of the elastic encoder, and in particular the required storage capacity, depends upon the actual form of feedback, the allowable proportion of time in the "overload" condition, i.e., with the elastic encoder completely full, and also upon the scanning standards employed.

The requirement of constant line-scan period is equivalent to restricting the elastic encoder to be in the same state at the end of each line, i.e., the same number of stages are filled at the end of each line. The basic effect of this form of feedback is to coarsely quantize the scanned lines containing excessive detail and to finely quantize lines containing little detail, and is thus broadly equivalent on a macroscopic scale to the coarse quantization of high-frequency components of the signal described by E. R. Kretzmer [10].

A less drastic form of feedback is possible if a variable line-scan period is permitted, as is the case in the results reported here. When the number of samples in a line is in excess of the average number per line, then, in one line period, the elastic encoder will fill a net amount equal to this excess. Conversely, when the number of samples in a line is less than the average, then, in one line period, the elastic encoder will empty a net amount equal to this deficiency. The probability of a large net increase or decrease in the number of filled stages in one line period can be controlled by the amount of feedback employed. In this case, the "slow" feedback should aim at keeping the traffic intensity (see Appendix) just less then unity. The actual movement of the stacking stage during one line-scan period can usefully be used to serve as the "slow" feedback signal by taking advantage of line-to-line correlation.

The limiting case of the "slow" feedback is that in which the feedback link is completely removed. The elastic encoder will then fill and empty according to the picture content, the sampling ratio n, and the setting of the detail detector thresholds. The maximum variation in line duration in this case is proportional to the elastic encoder capacity. The "long-term" variations in mean sampling rate in this limiting case determine the amount of "underload" and "overload" in any particular picture; an increase in the detail detector thresholds generally causes an increase in the amount of "underload" and a decrease in the amount of "overload." Generally "overload" reduces picture quality, while "underload" inserts redundant samples with little benefit; i.e., the latter process is wasteful.

The experimental results in Section IX, using an elastic encoder of 30-stage capacity and with the feedback link disconnected, together with further results (Robinson [8]) in which an infinite capacity store is simulated, again with no feedback, suggest that storage approximately equal to the average number of runs per line together with a small amount of "slow" feedback would be adequate. An indication of the variability of the line statistics (i.e., the probability distribution of the number of run-coded samples per television line) has been given by Vieri [3], who found that "only 5 percent of the measured lines used a number of runs more than 50 percent greater than the mean." This tends to support the estimate of the required storage capacity, given above.

Further benefit might accrue if a form of "fast" feedback is also used, in which the queue length exerts some continuous detail detector control.

It should be noted that if the run-coded sample train can be considered to have independent successive run lengths and a probability distribution other than exponential, then the variance of the number of samples arriving over a long period of time is smaller than that for the completely random situation. Note that run-length restriction changes the probability distribution; the limiting case is of course the distribution in which all run lengths are equal. It can be concluded that the assumption of a completely random distribution errs on the conservative side.

VII. Variable Velocity Receiver

The most obvious form of decoder consists essentially of an elastic decoder of equal capacity to the elastic encoder at the transmitter, in which case conventional receivers would be used. However, more economical and simple receivers are especially attractive wherever broadcast "many-receiver" situations exist. Accordingly, an experimental study using a *quantized*-variable-velocity principle is described (Robinson [8]) in which decoding and display are performed on a single CRT. A 536 Tektronix oscilloscope was used for convenience because it had a wide bandwidth deflection system, so that the displayed raster was limited to 3-by-4 inches in size.

The "quantized-variable-velocity receiver" is outlined in Fig. 3. The run-coded samples will be correctly positioned on the final display, provided the horizontal time base is controlled so that its velocity is switched between the three or four quantized velocities proportional to the restricted run lengths. The time-base is conventional, with switched velocity control obtained by feeding into the miller time base grid a time-switched current having the three or four values proportional to the quantized run lengths. The control circuit current sources are accurate to approximately 1 percent. Brightness compensation is considered in the next section.

It should perhaps be emphasized here that *continuous* beam velocity control is not required; only a number of distinct velocities are needed, corresponding to the three or four quantized (restricted) run lengths. Thus, the corresponding transmitted "position signal," having only one of three or four values, is highly resistant to channel noise.

VIII. Brightness Compensation

Brightness compensation (Robinson [8]), required to correct the variations in display brightness due to changes in horizontal scan velocity, is considered in Figs. 4 and 5.

The necessary dynamic range of a variable-velocity display tube is larger than that for a conventional receiver, so that nonlinear tube characteristics assume greater significance. Various practical approximations of typical CRT characteristics are considered and in each case the necessary compensation is described.

The brightness signal v is added to a pedestal v_0, the sum amplified in a linear amplifier, and connected to the grid of a display tube.

Thus, $V=Ke=K(v+v_0)$.

Assuming that screen brightness is proportional to beam current I, and that I_1 and I_2 correspond to black level and white level, respectively, at any one velocity, we require I_1 and I_2 to change in direct proportion to any change in velocity. This change is obtained by appropriate changes in the gain K of the linear amplifier. Consider the following CRT characteristics:

a) linear CRT characteristic—the whole system is linear and K is directly proportional to velocity
b) constant gamma CRT characteristic—if the time base velocity increases by a factor k, then correct compensation requires an increase in amplifier gain of $k^{1/\gamma}$
c) piecewise linear CRT characteristic—correct compensation requires changes in amplifier gain matched to the tube characteristic, and also requires a different pedestal v_0 for each velocity
d) a piecewise constant gamma CRT characteristic can be postulated in which the compensation method is as in c).

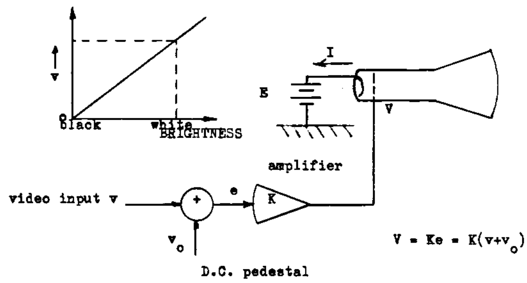


Fig. 4. Brightness compensation.

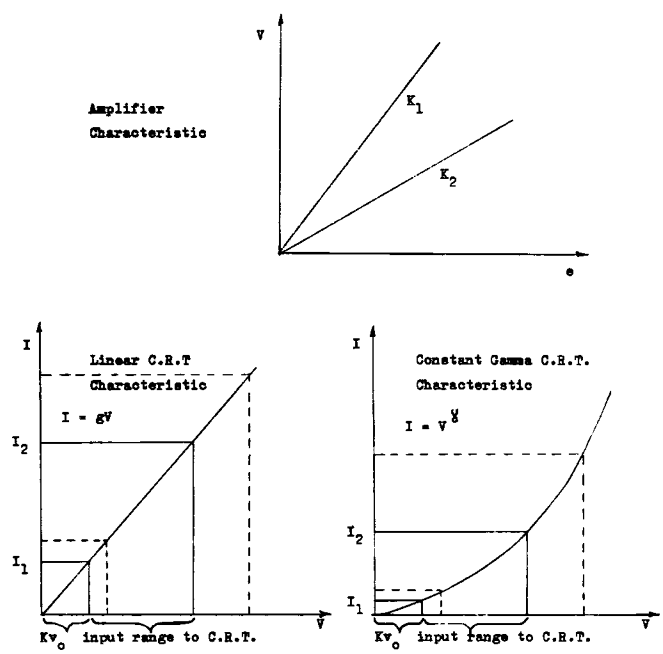


Fig. 5. Amplifier and CRT characteristics.

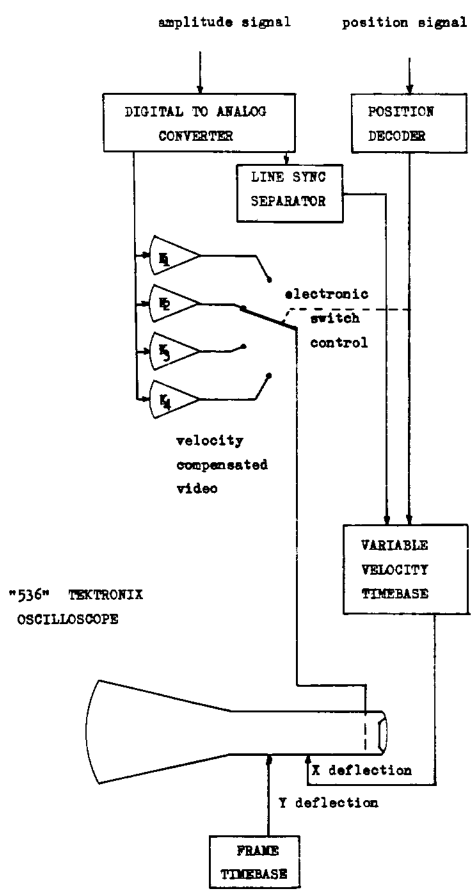


Fig. 3. Prototype variable-velocity receiver.

IX. Experimental Results

The transmitter performance can be assessed without building an elastic decoder system, by reconstructing the pictures from the samples at the run-length restrictor output, though actual pictures taken from an experimental quantized-variable-velocity receiver are also illustrated.

The reconstruction uses a "box-car generator" as a simple form of interpolation (Fig. 6). Although the samples were taken from the run-length restrictor output, they were also fed into the elastic encoder so that the "underload" and "overload" effects were observed.

The feedback link was not connected in these experiments, although of course the "underload" and "overload" facilities were maintained; the detail detector thresholds were set manually to optimize the results by reducing the average sampling rate until overload effects largely disappeared.

The system signal-to-noise ratio was approximately 40 dB, and the elastic encoder had a 30-stage capacity, i.e., it had storage for 30 run-coded samples.

Typical quantized-variable-velocity pictures are shown in Fig. 7; run lengths are labelled $l(l, p, q, r)$ and relative amplifier gains are labelled $g(K_1, K_2, K_3, K_4)$.

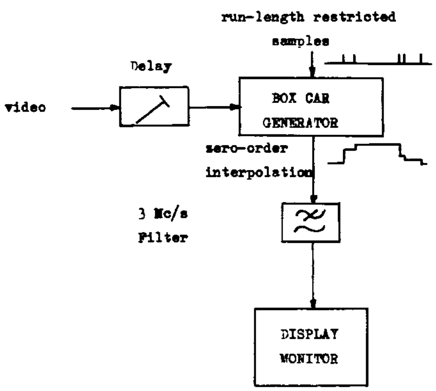


Fig. 6. Simulation system.

Initially the CRT was assumed to be linear; however, better results were obtained with a gamma of 1.3 (using a gamma corrector at the transmitter), and the brightness compensations were adjusted to be more in accord with the values indicated in b). The actual values selected were obtained experimentally, since the possible values had been preset according to a).

The bandwidth of the horizontal deflection circuits was 10 MHz.

X. Discussion of Results

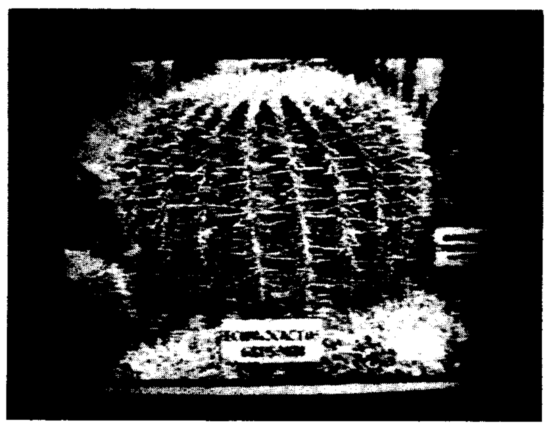
The simulation results in Fig. 8, in which the sampling ratio $n=3$, and the detail detector was set to minimize the effects of "overload," are all single-frame pictures; consequently, a certain amount of noise in these photographs is in excess of that obtained by direct viewing on a television monitor. The experimental elastic encoder had been made of only a 30-sample capacity; the expected overload distortion could then be studied subjectively. Full use of the detail detector capability therefore was not possible because the traffic intensity (see Appendix) was set at an artificially low level in order to minimize "overload," producing an excess of samples inserted during "underload." This effect can clearly be seen in Fig. 8(c). The effect of restriction can also be seen in Fig. 8(c) as spurious contours in the "detail function."

The results shown in Fig. 8 are those one would expect from an ideal receiver, provided there are no errors in the transmission channel, except that here the "box-car" form of interpolation is employed, which can only produce a poorer picture than a full decoder; it cannot give a better one.

Further results (Robinson [8]) indicate that with a store of larger capacity (simulated by disconnecting the "underload" and "overload" links to the run-length restrictor), sampling ratios of about six can be achieved with results similar to those illustrated in this paper.

(a)

(a) Variable-velocity reconstruction. $l(1, 2, 4, 10)$, $g(1, 2, 4, 8)$. The transmitted signal had an artificially low signal-to-noise ratio of 30 dB; $n=4$.



(b)

(b) Variable-velocity reconstruction. $l(1, 2, 4, 10)$, $g(1, 2, 4, 9)$, $n=3$.

Note: Quantized-variable-velocity reconstructions, 32-level amplitude quantization only (see text), and 30-stage elastic encoder used at transmitter (photographic exposure 1/5 second). In each of these photographs, the received signal, including synchronization, was of 5-bit quality only.

Fig. 7.

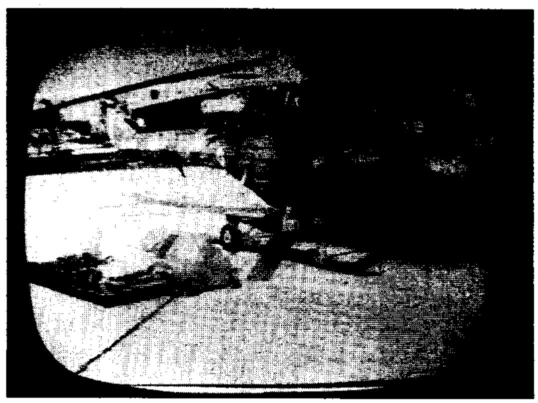
The most surprising result of this investigation has been the effect of run-length restriction on the quality of the final picture. The calculations on the number of extra samples inserted by this process (Vieri [3]) were confirmed, but their subjective effect has been one of improved quality and not the reverse as might have been anticipated. Indeed, the contrary is the case; *the extra samples appear to give even better results than would a similar number inserted by first removing the run-length restrictor and then increasing the detail detector sampling rate to compensate.* The slight contouring effect due to run-length restriction is less noticeable than the streaky nature of the pictures without restriction. The slight flicker effect, due to the difference between successive fields, also disappears. These results suggest that the detail detector has greatest difficulty in handling long runs (confirmed by a band-splitting system suggested by Vieri [3]).

Typical variable-velocity pictures are shown in Fig. 7. The noisy structure in these photographs is due to two limitations, both unconnected with the variable-velocity principle.

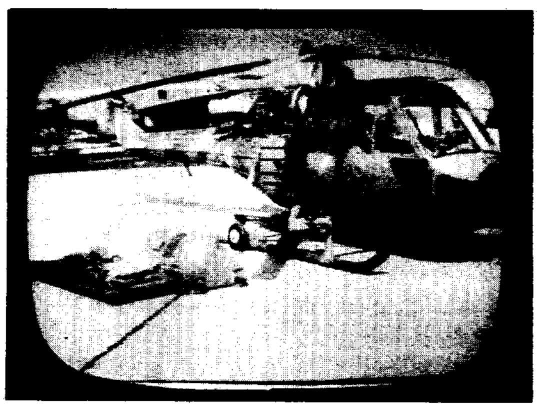
(a) Original picture.

(b) Reconstruction. $l(1, 2, 4, 10)$.

(c) Detail function. $l(1, 2, 4, 10)$.



(d) Reconstruction. $l(1, 2, 4, 10)$.



(e) Original picture.

Note: All these photographs are single-frame (1/25 second); $n=3$ in all reconstructions. In all cases, the encoder store was restricted to a capacity of 30 samples.

Fig. 8.

The analog-to-digital converter at the transmitter was only capable of handling five bits, so that 32 level signals were used in this prototype system (including synchronization); however, a seven-bit analog-to-digital converter is a modest requirement by present-day standards. Also, the phosphor structure of the display CRT was the limiting resolution factor in the small variable-velocity display.

XI. Conclusions

The results generally confirm the proposals for a basic bandwidth compression system made by Cherry et al. [1].

The analysis in Section VI together with the experimental results using our very limited elastic encoder store of 30 samples, suggests that an elastic encoder with 100–150-stage capacity would be adequate for most purposes. It is essential to minimize "overload," even at the expense of an average deterioration in picture quality over large regions, if necessary. It is suggested that the best use is made of the elastic encoder if a variable line-scan period is allowed. If the elastic encoder is made unnecessarily large, then the corresponding possible line-period variations will require the use of a ratchet time base.

It can be seen, by comparison with Cherry et al. [1], that run-length restriction has a beneficial subjective effect when used in conjunction with the present detail detector. The variable-velocity receiver results suggest that a larger display and a seven-bit quality amplitude signal could give broadcast quality pictures. In particular, the positional accuracy of the display should be quite acceptable.

The final data reduction ratio is obtained by multiplying the sampling ratio by 7/9 in the case of seven-bit brightness and two-bit run-length information. The compression ratio is the same as the data ratio in the case of binary PCM systems, but otherwise depends upon the proposed form of modulation.

The major problems associated with a complete system have been examined in this paper, except for the effect of channel noise on the run-coded signal. The latter has been investigated in relation to this system by Pearson [9], using a quantitative assessment of the subjective effects of position errors due to noisy channels in run-coded television signals. Further, the restriction of run lengths to three or four quantized values renders the position signal very noise-resistant. It appears that the development of variable-velocity receivers will possibly result in cheaper systems than could be obtained with elastic decoders. The variable-velocity time base, control, and brightness compensation circuits are relatively cheap and simple, although wide bandwidth deflection circuits, or some alternative, must be provided for large display systems. Improved variable-velocity receivers should result from the use of more accurate brightness compensation as outlined in Section VIII, together with better forms of interpolation. (Note that "box-car" interpolation is used in this system, whereas linear interpolation obtained by joining up the tops of the received amplitude-modulated samples with straight lines is particularly simple at the receiver, because here the samples arrive at a regular rate.)

Future work on detail detection is indicated by the effect of run-length restriction. In particular, a simple improvement might be achieved if the average picture brightness of each run is used as the run-coded sample, instead of the first sample as in this system. Further work on systems employing detail detection in the vertical as well as horizontal direction is proceeding, and should yield further compressions. A combination of the noise-combating procedure used here, together with the tapered quantization suggested by Graham [11], would appear to form a useful extension of detail detection.

The choice of the specific values of restricted run lengths is not critical and similar quality and compression values are obtained for a range of run lengths. However, it is obvious that once a particular run-length set has been chosen, the maximum possible compression is immediately bounded to a value somewhat below the maximum permitted run length, regardless of the setting of the detail detector thresholds. Thus, for the permitted set used here, reasonable quality pictures are possible but compression ratios above five or six are unrealistic.

Further work could include an extension of the restricted run-length values, especially for use with black-and-white picture material where larger compressions are practical.

The authors regard the implementation and perhaps extension of the feedback proposals made here to be essential for efficient usage of elastic encoders.

Appendix

Queue Storage (Robinson [8])

Budrikis [7] and others have shown that run-coded signals have exponential probability distributions and that successive run lengths along a television line are independent. In other words, the run-length samples occur randomly in time. It is useful to consider a run-coded television signal as a random sequence exhibiting "short-term" stationarity, i.e., as a random sequence in which the mean rate undergoes "long-term" variations. Here, the equilibrium behavior of a finite capacity storage device which takes account of necessary "underload" and "overload" facilities is considered.

Consider a queue of maximum size M, its input a train of independent pulses occurring at the Nyquist rate $1/T$, each with a probability of occurrence p, $0<p<1$ (i.e., a random sequence). Let the queue empty by one pulse at every nth Nyquist interval, giving a uniform output rate of $1/nT$. (Note that n, the sampling ratio, is an integer.) In practical stores it is necessary to stagger the possible input and output instants.

The queue can best be analyzed by considering the instants of time just prior to each output pulse.

An "underload" situation occurs whenever the queue is empty just prior to an output pulse. If no action is taken, then the scheme of run-length coding will break down. This is prevented by inserting an extra pulse into the queue whenever "underload" occurs.

An "overload" situation arises whenever the queue is of length M, in which case any input pulses which occur at this time are not accepted, but are lost to the system.

We define:

queue input data rate $= p/T$.
queue output data rate $= 1/nT$
queue data rejection rate (due to overload) $= L/nT$
queue data insertion rate (due to underload) $= I/nT$.

Also we define (by normalizing with respect to the output data rate):

$$\text{proportional overdrive rate} = \frac{p/T - 1/nT}{1/nT} = (np-1)$$

$$\text{traffic intensity (from telephone theory)} = np$$

$$\text{proportional rejection rate} = \frac{L/nT}{1/nT} = L$$

$$\text{proportional insertion rate} = \frac{I/nT}{1/nT} = I.$$

Let P_x be the probability that the queue is of length x, called the *queue state*, and consider

$$B(x) \equiv B(x; p, n) = \frac{n!}{x!(n-x)!} p^x \cdot (1-p)^{n-x}.$$

Then the equilibrium conditions are obtained as solutions to the following difference equations:

$$B(0) \cdot P_2 = [1 - \{B(0) + B(1)\}]P_1$$

$$B(0)P_{x+1} = [1 - B(1)]P_x - B(2)P_{x-1} - \cdots - B(x-1)P_2 - B(x)P_1$$

for $x = 2, 3, \cdots, n$.

$$B(0)P_{x+1} = [1 - B(1)]P_x - B(2)P_{x-1} - \cdots - B(n)P_{x-n+1}$$

for $x = (n+1), \cdots, (M-1)$,

and

$$\sum_{x=1}^{M} P_x = 1.$$

Also

$$L = \sum_{a=1}^{n-1} a\{P_M B(a+1) + P_{M-1}B(a+2) + \cdots + P_{M+a+1-n} \cdot B(n)\}$$

and

$$I = P_1 B(0).$$

The solutions to these equations are plotted for typical parameters of interest in Figs. 9 and 10.

The overload performance of the queue in equilibrium suggests that the most significant parameter is the traffic intensity np. When the traffic intensity is greater than unity the overload is largely independent of queue capacity M and of the sampling ratio n. When the traffic intensity is less than unity, the overload is generally less than 1 percent (at least for $M > 30$). The *queue state*, i.e., the P_x distribution, is plotted in Fig. 10 for a capacity of $M = 30$.

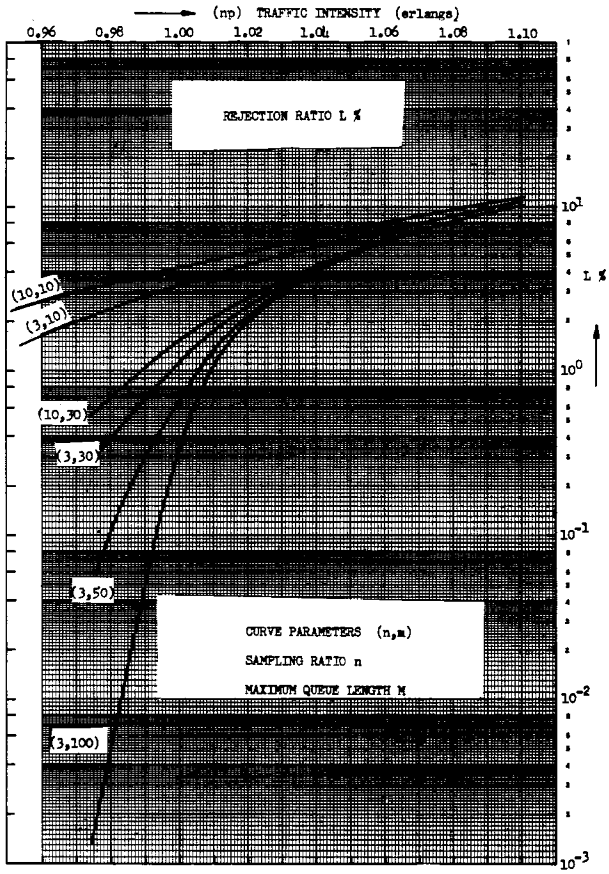


Fig. 9.

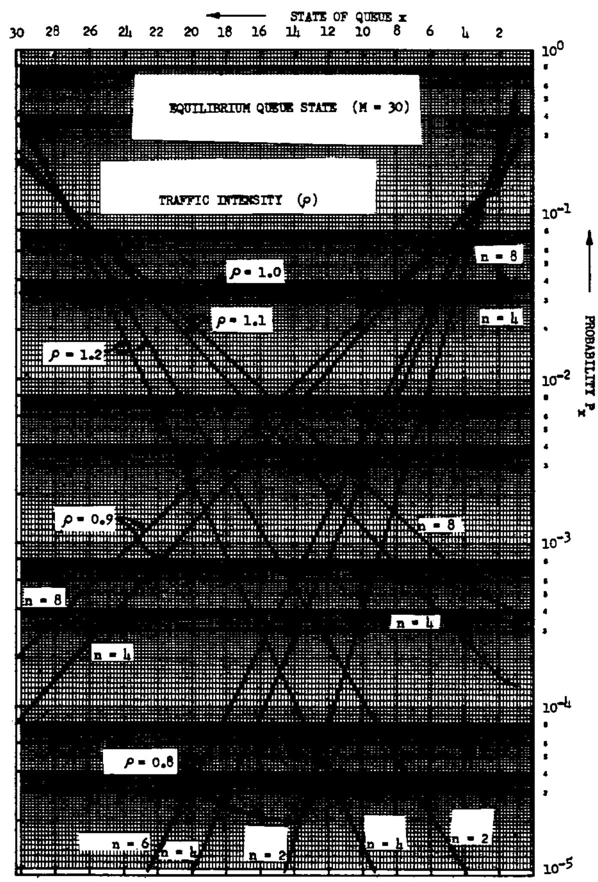


Fig. 10.

ACKNOWLEDGMENT

The authors wish to thank W. A. Gurnhill for his patient and skillful construction of much of the equipment.

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Source-Receiver Encoding of Television Signals

J. O. LIMB

Abstract—**The first stage of efficiently coding television signals—the nonreversible process of obtaining a discrete signal—is investigated. The process depends on the properties of the source and the receiver which in this case is the human sense of vision. Emphasis is given to the examination of the properties of the receiver and the selection of an appropriate criterion of performance. The criterion adopted is the probabilistic measure of viewer preference in a direct comparative judgment between the original and the coded-decoded version. For this criterion the precision with which picture components need be reproduced will depend primarily on the visual thresholds associated with the picture components. The "Optimum Decision" model of threshold vision is investigated using the criterion.**

As an example a practical encoder is discussed which is designed around the loss of sensitivity of the visual system adjacent to a change in luminance. High-quality pictures have been encoded having first-order entropies in the range 0.8 to 2.0 bits per picture element.

I. A Formulation of the Television Coding Problem

A. Introduction

RELATIVE TO speech signals, visual signals (television or facsimile) require a large amount of channel capacity for their transmission. There is considerable expense associated with providing wideband communication links, and any method which can transmit the same information more efficiently in terms of the required channel capacity will reduce this expense. Since the amount of information transmitted by a channel depends on time, bandwidth, and signal-to-noise ratio, an increase in efficiency could result in a reduction in the requirements in any one (or any combination) of these quantities.

Manuscript received December 17, 1966; revised January 17, 1967. This paper is published by permission of the Australian Post Office Research Laboratories. This paper was supported by financial assitance provided by the University of Western Australia in the form of a Gledden Research Fellowship.

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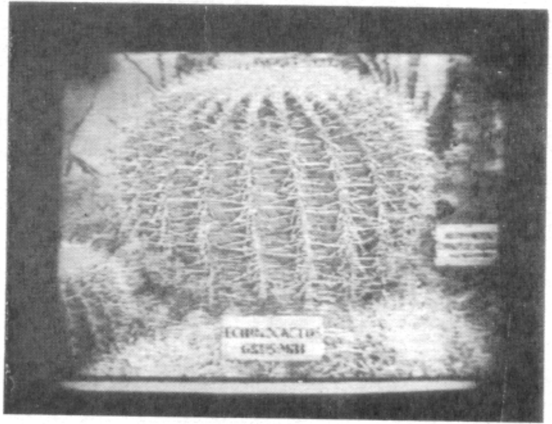
Consider the ideal communication channel shown in Fig. 1 as suggested by Graham [1] (see also [2], p. 2). The signal source may be, for example, a video camera, a microphone, or a scientific sensing device such as a thermocouple. The function of the source-receiver encoder (SR encoder) is to represent efficiently the input signal as a random signal of a standard form (say, binary) and will therefore be independent of the properties of the channel but will depend on the properties of the source and receiver. The channel encoder design, on the other hand, depends only on the properties of the channel. Any particular channel will be characterized by such defects as noise, fading, error bursts, and crosstalk and will therefore require an individually designed channel encoder and decoder. The channel decoder and SR decoder system perform the reverse operations to the encoders where such operations are reversible, so that the signal out of the channel decoder will be a random signal similar to the signal applied to the input of the channel encoder, and the signal out of the SR decoder will be similar to the continuous signal produced by the source.

In a communication system designed to provide an extension of the normal sensory facilities of a person (such as television and telephone) the properties of the signal source and particularly the receiver are very difficult to specify. In contrast, for example, the receiver in a digital or analog data link may be characterized quite easily—it may be a memoryless threshold device or some recording mechanism with

(a)

(a) Variable-velocity reconstruction. $l(1, 2, 4, 10)$, $g(1, 2, 4, 8)$. The transmitted signal had an artificially low signal-to-noise ratio of 30 dB; $n=4$.

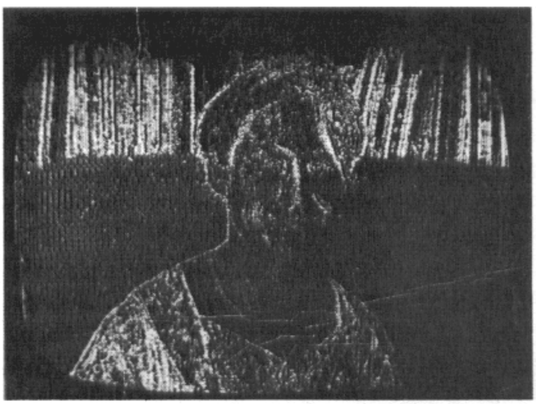


(b)

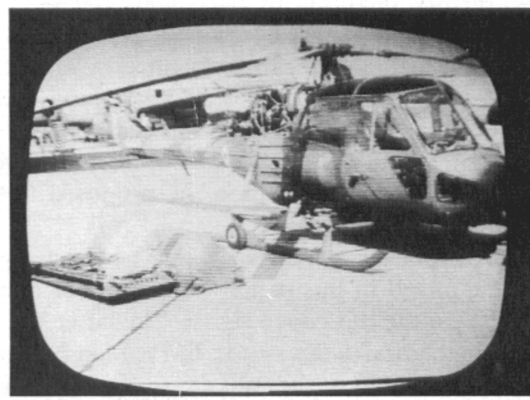
(b) Variable-velocity reconstruction. $l(1, 2, 4, 10)$, $g(1, 2, 4, 9)$, $n=3$.

(a) Original picture.

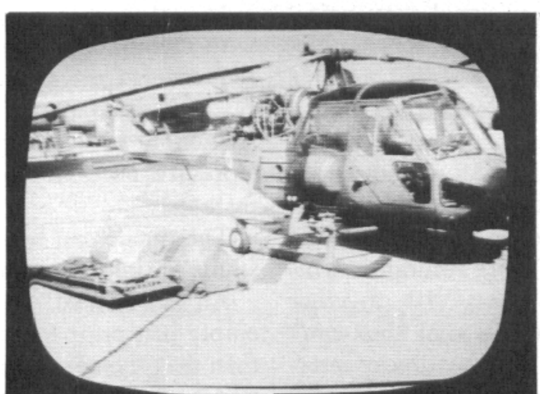
(b) Reconstruction. $l(1, 2, 4, 10)$.



(c) Detail function. $l(1, 2, 4, 10)$.



(d) Reconstruction. $l(1, 2, 4, 10)$.



(e) Original picture.

Note: All these photographs are single-frame (1/25 second); $n = 3$ in all reconstructions. In all cases, the encoder store was restricted to a capacity of 30 samples.

Fig. 8.