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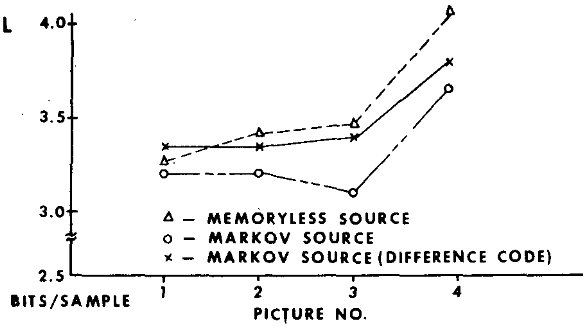

Fig. 3. Average code length $L$ for different systems.

C. A. Sjursen for operating the optical scanning system, and D. M. Henderson for building the 24-level quantizer.

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# The Effect of Channel Errors in the Differential Pulse-Code-Modulation Transmission of Sampled Imagery

ROGER J. ARGUELLO, MEMBER, IEEE, HARVEY R. SELLNER, AND JOHN A. STULLER

*Abstract*—**This paper presents an analysis, simulation, and discussion of the effects of communication errors on four-bit differential pulse-code modulation (DPCM) sampled imagery. Simulations are presented that describe the effects of inserting periodic "PCM updates" in order to correct communication errors in the DPCM transmission of photographic scenes that have been scanned and sampled at the Nyquist rate.**

## Introduction

THE ESTABLISHMENT of high-speed computer networks will become a reality in the seventies. When these networks augmented to provide image-processing and image-transmission capability between remotely located terminals, they will become, in the author's estimation, a major factor in uniting the image-processing community in the United States. In order to disseminate the large volume of imagery that is expected from many diverse users, efficient encoding methods must be developed in order to ameliorate computer-node data-link channel-capacity requirements. This paper presents an analysis, simulation, and discussion of the effects of communication errors on differential pulse-code modulation (DPCM) sampled imagery. DPCM encoding is considered as a candidate technique for the node-to-node transmission of image samples derived from a photographic scanner system.

Analytical modeling of a DPCM communication system subject to channel noise is difficult due to nonlinearities in the encoding system. In addition, assumptions found necessary to provide analytical tractibility sometimes conflict with accurate modeling of the subjective tradeoffs involved. The problem is compounded because the proper merit functions for picture quality are not as yet identified [1], [2].

In view of these difficulties, simulations are essential for the optimization of DPCM sampled-image systems. The approach taken in this paper is to generate sampled-image simulations using a facsimile-type scanner and computer DPCM model [3].

The performance of DPCM is highly dependent on sampling rate: oversampling provides a redundancy of

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information that portrays DPCM in an overly optimistic light, in the presence of channel errors. In this investigation a four-bit DPCM system was evaluated at the Nyquist rate. The Nyquist rate is affected by the electro-optical imaging elements of the photographic scanner as shown in Fig. 1, before sampling takes place. The electro-optical elements of the scanner constitute a low-pass spatial filter, thereby reducing the sampling rate required to prevent spectrum foldover. Spatial sampling is generally accomplished in a one-dimensional fashion as in conventional line-scan systems.

## I. Description of System Simulated

Simulations were performed of two- , three- , and four-bit DPCM sampled images of scenes having a dynamic range of a decade and sampled at the Nyquist rate. These simulations have shown that the application of a tapered four-bit DPCM results in imagery that is substantially free from slope overload and granularity artifacts. The two- and three-bit DPCM systems were not free from these artifacts.

All scenes shown in this paper are sampled images that have been blurred by a system-blur function whose modulation-transfer function is indicated in Fig. 1. In addition, all sampled images employ Nyquist sampling and have a format of 300 lines by 400 elements per line. Also, these sampled images contain computer-generated noise having a Gaussian probability density function to simulate the effect of scanner noise appearing in a real scanner/transmission system having a 44 dB peak-to-peak signal-to-rms noise ratio. These scenes, in the form of positive transparencies, were photographically prepared to provide a linear relationship between transmittance- and scene-intensity values.

While the absolute amplitude of thresholds and levels are governed by signal amplitude, it is recognized also that full advantage of the signal is not taken if the DPCM granularity noise is too high. The DPCM smallest level was therefore chosen to be equal to the rms scanner noise in order to provide the best compromise between low-signal response and minimum ratios between quantizer levels. The resulting granularity plus scanner noise is simply the root sum square of scanner and quantization noise, or 1.4 times the scanner noise. Refer to Table I for threshhold and level assignments for the four-bit DPCM system. Note that the value of the smallest level was chosen at the rms value of the additive noise. Threshold values of the quantizer are chosen midway between quantizer levels. In such a quantizer the error amplitude ranges between plus and minus half a quantum step [4].

## II. Channel-Error Performance Prediction

In the node-to-node transmission of imagery, switching, thermal, and burst noise cause bit errors in the received data stream. When a channel error occurs in a conventional DPCM transmission system, the value of the incorrectly received signal increment is stored in the receiver predictor and affects each successive scene element on that line. The predictor is reset to zero at the start of each line to remove any bias errors that may have accumulated on the previous line. The extent of the error bias caused by a channel error can be reduced by the use of a finite time-constant integrator in both the transmitter and receiver feedback loops. However, the time constant required for adequate channel-error attenuation is not necessarily compatible with that needed for good quality scene reconstruction over those regions of the output scene that are error free.

### *A. PCM Updating for Error Correction*

An alternate approach to reducing the effects of channel errors is to periodically transmit PCM updates that set the receiver predictor voltage to that of the trans-

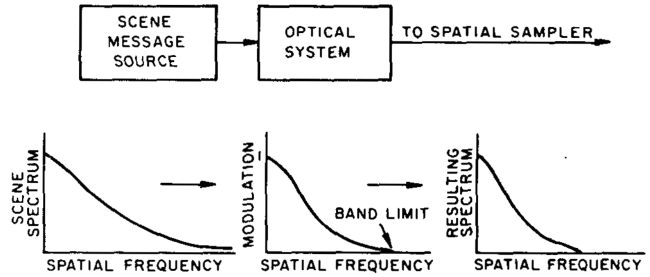


Fig. 1. Optical band-limiting of scene.

TABLE I
Quantizer Characteristics and Codeword Assignments for Four-Bit DPCM System

| Level Number | Level Value[a] | Threshold[a] | Codeword |
|---|---|---|---|
| 1 | −103 | | 0111 |
| | | −83 | |
| 2 | − 63 | | 0110 |
| | | −50 | |
| 3 | − 37 | | 0101 |
| | | −30 | |
| 4 | − 23 | | 0100 |
| | | −18 | |
| 5 | − 13 | | 0011 |
| | | −10 | |
| 6 | − 7 | | 0010 |
| | | − 5 | |
| 7 | − 3 | | 0001 |
| | | − 2 | |
| 8 | − 1 | | 0000 |
| | | 0 | |
| 9 | + 1 | | 1000 |
| | | + 2 | |
| 10 | + 3 | | 1001 |
| | | + 5 | |
| 11 | + 7 | | 1010 |
| | | +10 | |
| 12 | + 13 | | 1011 |
| | | +18 | |
| 13 | + 23 | | 1100 |
| | | +30 | |
| 14 | + 37 | | 1101 |
| | | +50 | |
| 15 | + 63 | | 1110 |
| | | +83 | |
| 16 | +103 | | 1111 |

[a] Level and threshold units are normalized so that a value of 1 corresponds to the rms noise level.

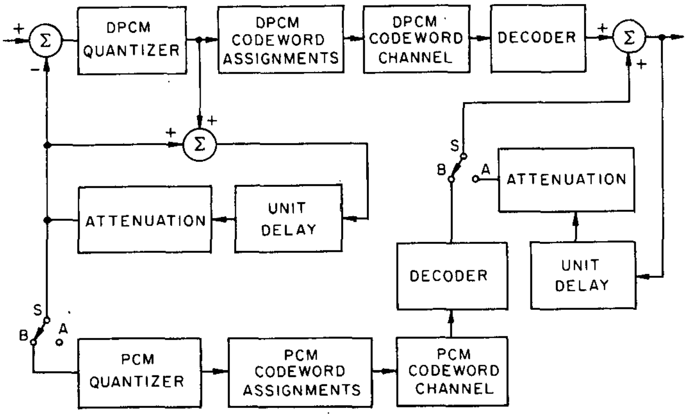


Fig. 2. DPCM with PCM update simulation block diagram.

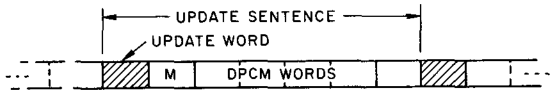


Fig. 3. Transmitted data sequence.

mitter, as illustrated in Fig. 2. The extent of a bias error at the receiver output may thereby be reduced from a fraction of the picture line to a fraction of the update period.

A simple analytical expression for the expected percent of incorrectly reconstructed scene elements for the system of Fig. 2 can be derived for the case that the probability of error in decoding does not depend upon the particular DPCM or PCM word transmitted. Consider the typical update "sentence" illustrated in Fig. 3. Let

$M$ ≡ the number of DPCM words in the sentence,
$N$ ≡ the number of scene elements that are correctly reconstructed by the receiver when processing the update sentence,
$q$ ≡ the probability that a DPCM word is correctly received,
$Q$ ≡ the probability that the PCM word is correctly received.

The expected number of correctly reconstructed scene elements that result when the update sentence is processed is

$$E(N) = \sum_{i=0}^{M+1} i \Pr (N = i). \tag{1}$$

The probability that all $M + 1$ elements are correctly reconstructed is the probability that all $M + 1$ words of the update sentence are correctly received:

$$\Pr (N = M + 1) = Qq^{M} \tag{2}$$

The probability that exactly $i$ scene elements ($1 \leq i \leq M$) are correctly reconstructed is the probability that the first $i$ words of the sentence are received correctly but the $(i + 1)$th word is received incorrectly:

$$\Pr (N = i) = Qq^{i-1}p, \qquad 1 \leq i \leq M, \tag{3}$$

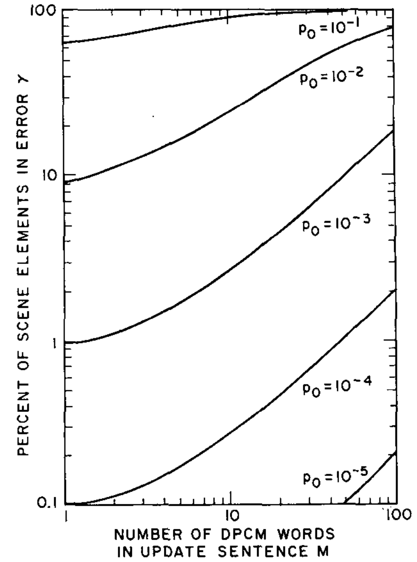


Fig. 4. Plot of percentage of scene elements in error $\gamma$ versus number of DPCM words in update sentence $M$.

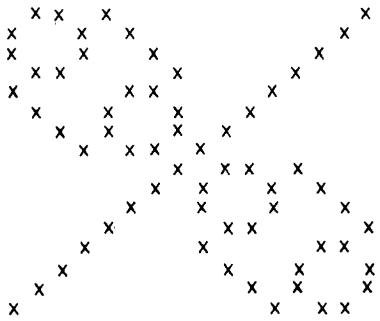
TRANSMITTED LEVEL NUMBER

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 1 | 2 | 1 | 2 | 2 | 3 | 4 | 3 | 3 | 2 | 3 | 2 | 2 | 1 | 1 |
| | 0 | 2 | 1 | 2 | 1 | 3 | 2 | 3 | 4 | 2 | 3 | 2 | 3 | 1 | 2 | 2 |
| | | 0 | 1 | 2 | 3 | 1 | 2 | 3 | 2 | 4 | 3 | 2 | 1 | 3 | 2 | 3 |
| | | | 0 | 3 | 2 | 2 | 1 | 2 | 3 | 3 | 4 | 1 | 2 | 2 | 3 | 4 |
| | | | | 0 | 1 | 1 | 2 | 3 | 2 | 2 | 1 | 4 | 3 | 3 | 2 | 5 |
| | | | | | 0 | 2 | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 2 | 3 | 6 |
| | | | | | | 0 | 1 | 2 | 1 | 3 | 2 | 3 | 2 | 4 | 3 | 7 |
| | | | | | | | 0 | 1 | 2 | 2 | 3 | 2 | 3 | 3 | 4 | 8 |
| | | | | | | | | 0 | 1 | 1 | 2 | 1 | 2 | 2 | 3 | 9 |
| | | | | | | | | | 0 | 2 | 1 | 2 | 1 | 3 | 2 | 10 |
| | | | | | | | | | | 0 | 1 | 2 | 3 | 1 | 2 | 11 |
| | | | | | | | | | | | 0 | 3 | 2 | 2 | 1 | 12 |
| | | | | | | | | | | | | 0 | 1 | 1 | 2 | 13 |
| | | | | | | | | | | | | | 0 | 2 | 1 | 14 |
| | | | | | | | | | | | | | | 0 | 1 | 15 |
| | | | | | | | | | | | | | | | 0 | 16 |

RECEIVED LEVEL NUMBER

$ij^{th}$ ENTRY = NUMBER OF POSITIONS THAT CODEWORDS ASSIGNED TO LEVELS $i$ AND $j$ DIFFER

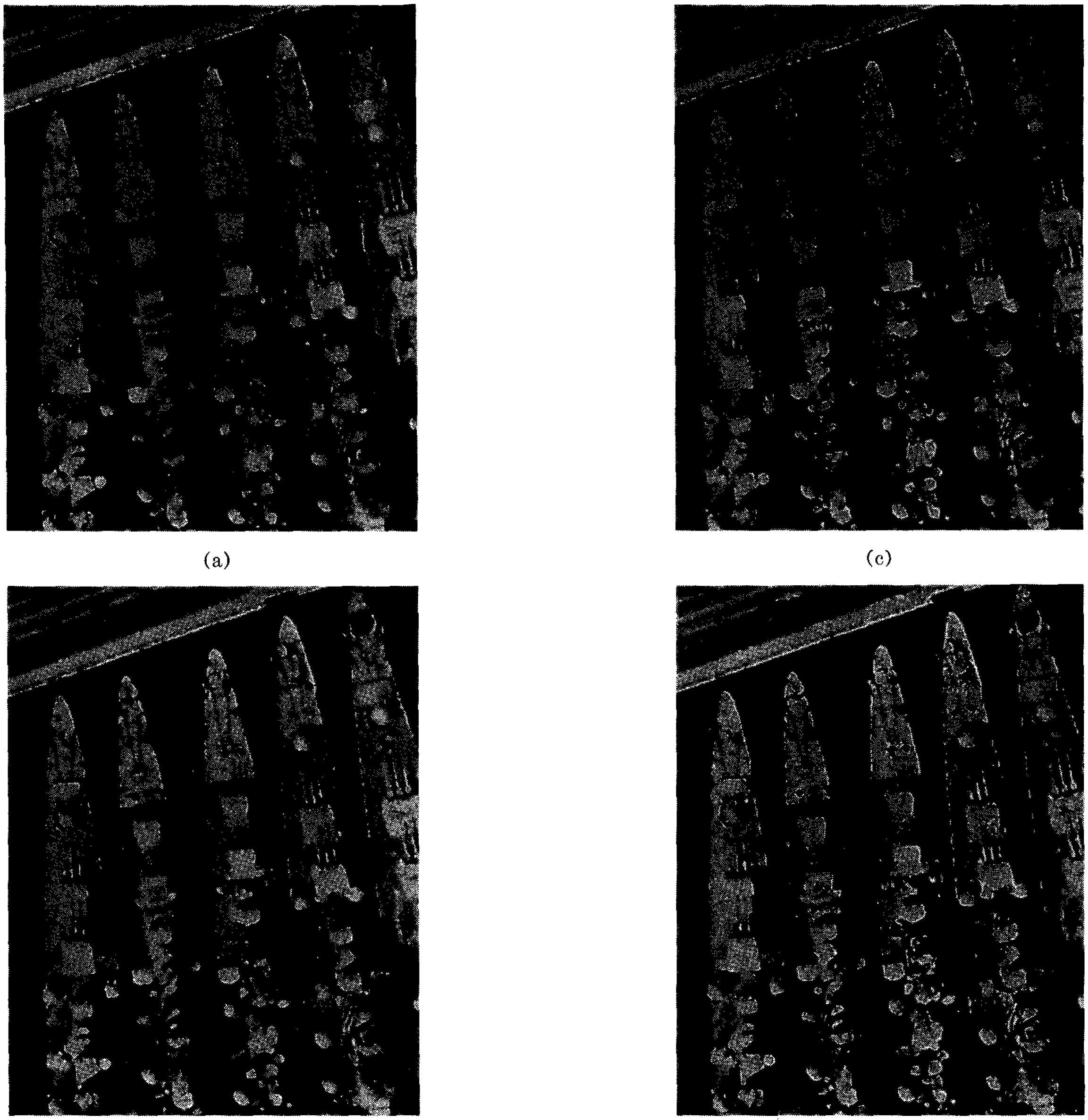
(a)



LOCATIONS OF UNITY ELEMENTS OF HAMMING ARRAY

(b)

Fig. 5. Hamming-distance matrix of DPCM codewords.



(a) (c) (b) (d)

Fig. 6. Four-bit DPCM sampled images with PCM updates; bit-error rate (BER) = $10^{-4}$. (a) PCM update every 26 elements. (b) PCM update every 52 elements. (c) PCM update every 104 elements.

where $p \equiv 1 - q$ is the probability that a DPCM word is incorrectly received. Equation (3) ignores outcomes for which a second error within the update sentence accidentally "corrects" a previous error. Substitution of (2) and (3) into (1) gives

$$E(N) = Qq \sum_{i=0}^{M} iq^{i-1} + (M+1)Qq^{m}$$
$$= Q\frac{1 - q^{M+1}}{1 - q}. \tag{4}$$

Therefore, the expected number of correctly reconstructed scene elements per transmitted word is

$$\xi = \frac{E(N)}{M+1} = Q\frac{1 - q^{M+1}}{1 - q}\frac{1}{M+1}. \tag{5}$$

Since each transmitted word corresponds to exactly one scene element, $\xi$ is the expected fraction of the scene that is correctly reconstructed. The expected percent of incorrectly reconstructed scene elements is then

$$\gamma = 100\,(1 - \xi) \text{ percent.} \tag{6}$$

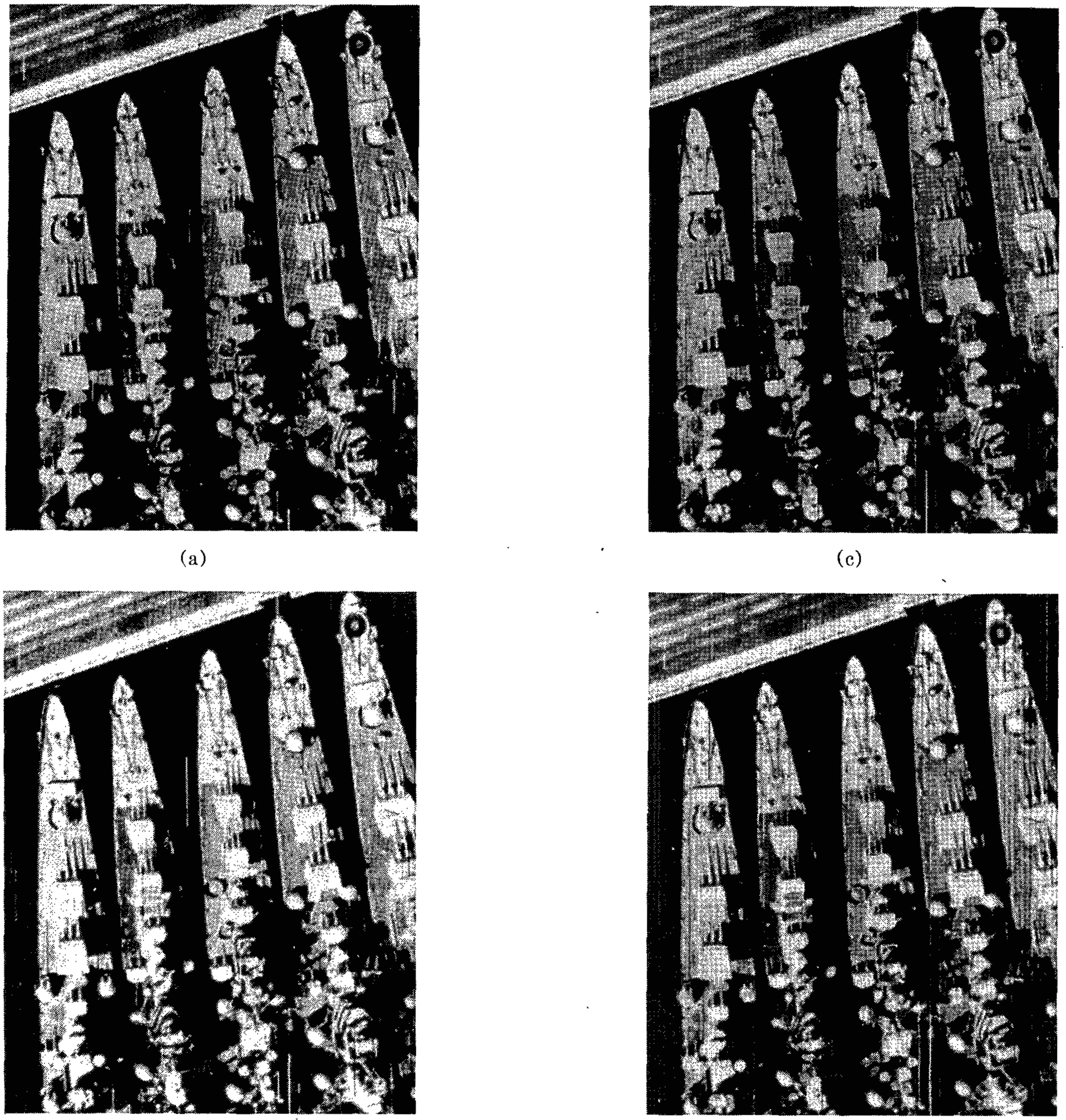
Equation (6) is plotted in Fig. 4 as a function of the channel-bit-error probability $P_0$. For this plot, the PCM and DPCM codewords were assumed to consist of 8 and 4 binary digits, respectively (such that a unique codeword is assigned to each quantizer level). Thus,

$$Q = (1 - p_o)^8 \tag{7}$$

and

$$q = (1 - p_o)^4. \tag{8}$$

Note that $\gamma$ increases monotonically with $M$ from a minimum at $M = 0$ (not shown on plot). The price paid



(a) (c)

(b) (d)

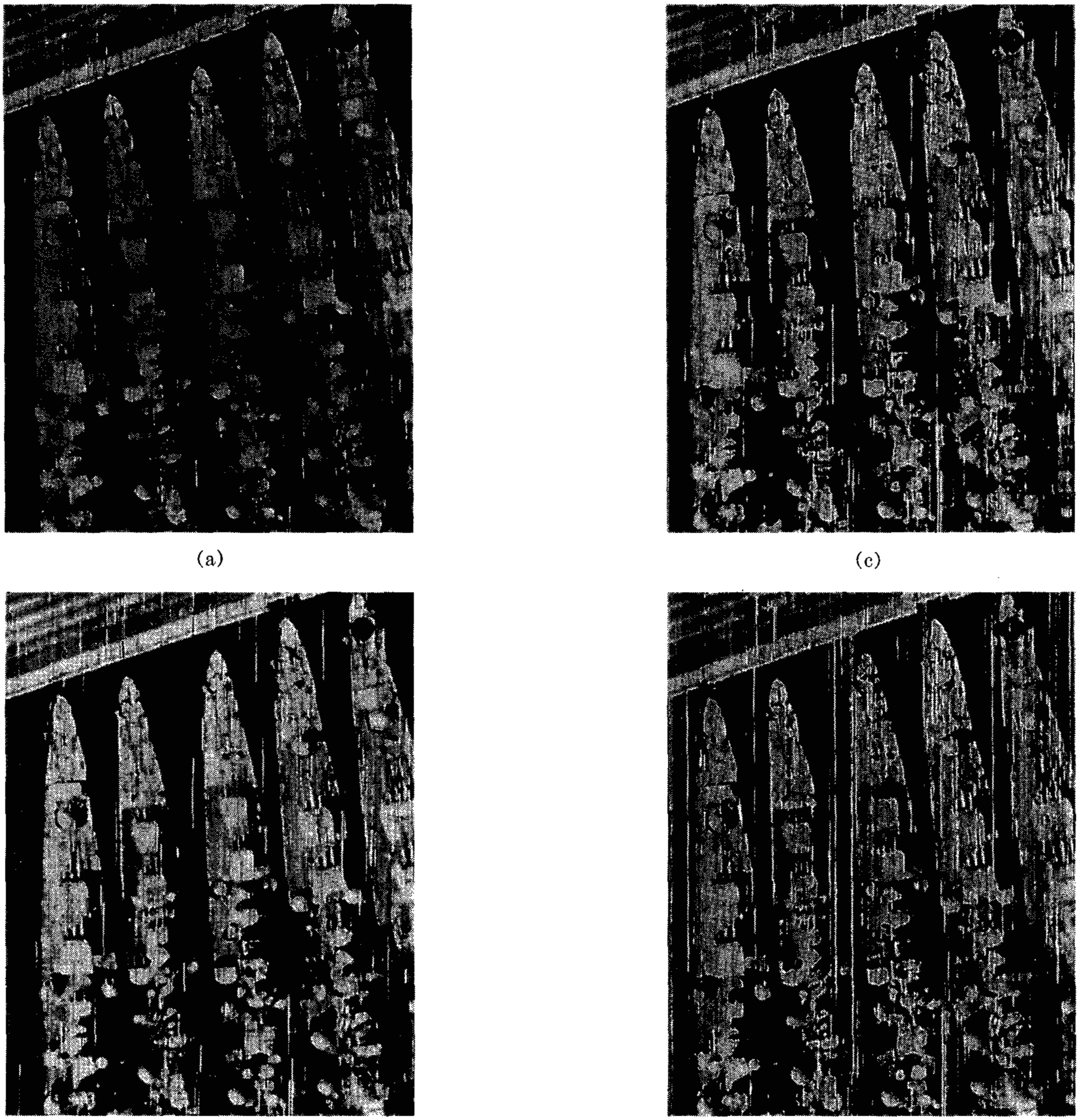
Fig. 7. Four-bit DPCM sampled image with PCM updates; BER $= 10^{-3}$. (a) PCM update every 26 elements. (b) PCM update every 52 elements. (c) PCM update every 104 elements.

for correcting more and more errors is, of course, an increase in the total number of channel bits used in transmitting a photograph.

### *B. Codeword Assignments*

Although the percent of image elements incorrectly reconstructed does not depend upon the particular codeword-to-quantizer level mapping assumed for the above class of codes, certain mappings are nevertheless superior to others. The reason is that some mappings tend to produce smaller output-signal bias errors than others. These mappings produce output images that appear less degraded by channel errors, even though the number of incorrect scene elements is actually the same as that produced by an inferior mapping.

Insight into the suitability of a given codeword mapping for the transmission of the quantizer-level information may be obtained from its associated Hamming-distance matrix [5]. The $ij$th entry of the Hamming-distance matrix equals the Hamming distance between the codewords assigned to quantizer levels $i$ and $j$ (hence Hamming-distance matrices are symmetrical). When an error occurs in the transmission of quantizer-level information, the probability is highest that the error will be in only one bit of the received word (assuming $p_o < 0.5$). Most channel errors will therefore cause level transitions to codewords separated by a Hamming distance equal to one. It is desirable that the "ones" of the Hamming matrix be clustered as near to the principal diagonal of this matrix as possible, in order that most channel



(a) (c)

(b) (d)

Fig. 8. Four-bit DPCM sampled image with PCM updates; BER $= 10^{-2}$. (a) PCM update every 26 elements. (b) PCM update every 52 elements. (c) PCM update every 104 elements.

errors result in the smallest possible receiver bias error, thereby minimizing their subjective effect. This argument clearly extends to two-, three-, and four-bit errors per codeword. Distance-two entries should be closer to the principal diagnoal than distance-three entries, etc.

The particular codeword assignments used for the simulations are given in Table I. A natural eight-bit binary code assignment was employed for the PCM transmissions. Fig. 5(a) and 5(b) gives the Hamming matrix for the DPCM code and illustrate the locations of the unity-distance elements. Note that certain unity elements of this Hamming matrix are far removed from the principal diagonal. However, the clustering of unity-distance elements near the center of the matrix is particularly favorable with regard to the preponderance of low-signal difference values in agreement with the quantizer-input histogram [6].

## III. Results of Simulation

Figs. 6–8 show the results of the four-bit DPCM simulations for channel-bit-error rates ranging from $10^{-4}$ to $10^{-2}$. The update sentence length for these simulations ranged from $M + 1 = 26$ to $M + 1 = 104$ scene elements. In these figures, artifacting due to the four-bit DPCM system is scarcely observable. Channel-bit errors, however, appear as biases in the signal. These are manifested as streaks running in the scan direction. These streaks do not run the full length of the scene because periodic PCM updates are inserted to limit their extent.

TABLE II
DPCM TRANSMISSION ERRORS

| Figure | Bit-Error Probability | Number of Errors | Expectation |
|---|---|---|---|
| 2(a) | $1 \times 10^{-4}$ | 104 | 81 |
| (b) | | 104 | |
| (c) | | 104 | |
| 3(a) | $1 \times 10^{-3}$ | 782 | 808 |
| (b) | | 782 | |
| (c) | | 782 | |
| 4(a) | $1 \times 10^{-2}$ | 8075 | 8080 |
| (b) | | 8075 | |
| (c) | | 8075 | |

TABLE III
PCM TRANSMISSION ERRORS

| Figure | Bit-Error Probability | Number of Errors | Expectation |
|---|---|---|---|
| 2(a) | $1 \times 10^{-4}$ | 14 | 6 |
| (b) | | 9 | 3 |
| (c) | | 4 | 2 |
| 3(a) | $1 \times 10^{-3}$ | 66 | 63 |
| (b) | | 31 | 32 |
| (c) | | 15 | 16 |
| 4(a) | $1 \times 10^{-2}$ | 614 | 630 |
| (b) | | 309 | 315 |
| (c) | | 152 | 158 |

Since their starting point is random, streak lengths can vary from one element to the sentence length. The PCM update words are also subject to channel errors; consequently, in some cases, a PCM word introduces a new bias error at the end of a DPCM error string, thus extending the streak length to nearly two sentences. Notice that the relative frequency of streaks increases as the bit-error probability is increased from $1 \times 10^{-4}$ to $1 \times 10^{-2}$.

Figs. 6(a) and (b) each show a white streak in the water area in the same starting location and extending the entire update sentence length. This channel error occurred during a PCM update word that was common to the 26- and 52-element sentence lengths but not to the 104-element case. This example illustrates the additional probability for error in a scene introduced as a result of increasing the update frequency; i.e., the PCM updates become somewhat more susceptible to channel errors.

The positions of PCM update words were advanced on consecutive lines. The resulting skewed update pattern is particularly evident in the high-bit-error-rate cases, e.g., bit-error-rate $10^{-2}$.

Table II lists the total number of DPCM errors occurring in Figs. 6–8 and the theoretically expected numbers of DPCM errors. Table III provides a similar list of PCM update errors.

## IV. CONCLUSION

There is a lack of noticeable image-quality degradation due to channel-bit errors for images having bit-error probabilities as high as $1 \times 10^{-4}$. Due to the codeword mapping chosen, most of the approximately 100 errors occuring in the $1 \times 10^{-4}$ bit-error-rate pictures at any of the three update periods are not observable in the final images. Of those that are observable, only about 5 percent are of sufficient difference to surrounding areas to be disturbing.

If usage requires operating at bit-error probabilities approaching $1 \times 10^{-3}$, it is seen that four-bit DPCM having periodic updates every 26 elements can be employed to provide good quality imagery. The time or bandwidth penalty paid for this update period over an update period of 52 elements is slight (4) percent. For these bit-error rates, an update period greater than 52 elements is not recommended without the use of some form of channel-error correction.

## ACKNOWLEDGMENT

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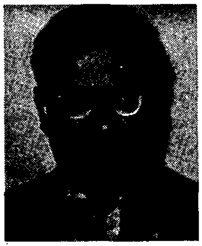

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**Harvey R. Sellner** was born in Detroit, Mich., on August 8, 1940. He received the B.S. degree in electrical engineering from Michigan State University, East Lansing, Mich., in 1962.

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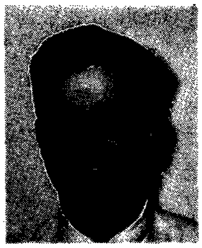

**John Stuller** was born in Norwalk, Conn., on January 16, 1941. He received the B.S. degree in electrical engineering from the Massachusetts Institute of Technology, Cambridge, in 1963; the M.S. degree in electrical engineering from the University of Southern California, Los Angeles; and the Ph.D. degree in electrical engineering from the University of Connecticut, Storrs, in 1971.

In 1963 he joined the Inertial Guidance Design Section of Northrop Nortronics Corporation, Palos Verdes, Calif., where he developed a communication system between computer and inertial platform and was responsible for systems analysis in the areas of digital logic, timing, amplitude modulation and demodulation, filtering, and transmission through a time-varying channel. In 1965 he joined TRW Corporation, Redondo Beach, Calif., As a member of the technical staff, he was responsible for determining requirements and performance of pulse compression, frequency angle, and other state-of-the-art radar systems. In the TRW Electro-Optics Department, he was responsible for design of electronic circuits used in OGO, AOGO satellites. At the University of Connecticut he worked as a doctoral fellow and taught senior courses in electronics and communication theory. In 1970, he joined the Perkin-Elmer Corporation, Norwalk, Conn. He performed several simulation studies in the areas of digital-image restoration and image communication. He has recently joined the Department of Electrical Engineering, University of New Brunswick, Fredericton, N. B., Canada, where he is Assistant Professor of Electrical Engineering. His research interests include statistical communication theory and digital image processing.

Dr. Stuller is a member of Sigma Xi.

# An Adaptive Dual-Mode Coder/Decoder for Television Signals

ARMIN H. FREI, MEMBER, IEEE, H. R. SCHINDLER, MEMBER, IEEE, AND PETER VETTIGER

*Abstract*—**An adaptive dual-mode coding system for television signals is described. Its main features are a low bit rate (1.5 bits per sample), the high quality of the reproduced picture, and its moderate hardware. The system is based on the statistical properties of video signals. Specifically, it makes use of the nonuniform spectrum of video signals in the form of a differential scheme containing linear prediction. Furthermore, areas of small amplitude changes between consecutive samples whose probability of occurrence is high are encoded with a reduced coding alphabet. Transients representing sharp edges in the picture are encoded and reproduced with little slope overload and busyness. A method for the buffering of the asynchronous data stream produced by the coder to match a synchronous channel is given.**

## I. INTRODUCTION

WHILE WATCHING a moving television picture a human observer accepts information at a rate much lower than the one required for the transmission of gray-level encoded raster-scanned video signals. This means that a large amount of redundancy and/or irrelevant information is present in today's video transmission procedures. At the same time, there is a need for the reduction in bit rate in future video communication systems for economic reasons. From the literature it can be seen that during the last twenty years many excellent contributions have been made aiming at the same goal: reduction of bit rate at preserved quality of the pictures transmitted (or stored) or, correspondingly, improvement of picture quality at a given bit rate. The methods and techniques used may be grouped into the following three categories [1].

1) Methods that make use of the statistical properties of the source (e.g., run-length coding, Huffman's coding procedure, point-to-point, line-to-line, and frame-to-frame correlation techniques, etc.) [2]–[20].

2) Methods that make use of the limitations of visual perception (e.g., flicker versus spatial frequency, gray-level resolution as a function of spatial frequency, etc.) [21]–[27].

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