Progressive Image Coding for Noisy Channels

P. Greg Sherwood and Kenneth Zeger, *Senior Member, IEEE*

***Abstract*—We cascade an existing image coder with carefully chosen error control coding, and thus produce a progressive image compression scheme whose performance on a noisy channel is significantly better than that of previously known techniques. The main idea is to trade off the available transmission rate between source coding and channel coding in an efficient manner. This coding system is easy to implement and has acceptably low complexity. Furthermore, effectively no degradation due to channel noise can be detected; instead, the penalty paid due to channel noise is a reduction in source coding resolution. Detailed numerical comparisons are given that can serve as benchmarks for comparisons with future encoding schemes. For example, for the 512 $\times$ 512 Lena image, at a transmission rate of 1 b/pixel, and for binary symmetric channels with bit error probabilities 10^{-3}, 10^{-2}, and 10^{-1}, the proposed system outperforms previously reported results by at least 2.6, 2.8, and 8.9 dB, respectively.**

I. Introduction

ONE OF THE most successful and practical image coders today for the noiseless channel was originally developed by Shapiro [1] and later refined by Said and Pearlman [2]. Their schemes achieve a "progressive" mode of transmission, namely that as more bits are transmitted, better quality reconstructed images can be produced at the receiver. The receiver need not wait for all of the bits to arrive before decoding the image; in fact, the decoder can use each additional received bit to improve somewhat upon the previously reconstructed image.

These wavelet-based encoders have been shown to perform better than almost any other existing compression scheme. In addition, they have the nice features of being progressive and computationally simple. However, to obtain the high-quality compression that they achieve, variable-length coding is used with significant amounts of "state" built into the coder. The result is that channel errors can cause a nonrecoverable loss of synchronization between the encoder and decoder. Total collapse of the reconstructed image often results from loss of synchronization. In fact, vast majority of images transmitted using this progressive wavelet algorithm will frequently collapse if even a single transmitted information bit is incorrectly decoded at the receiver.

One approach to circumventing loss of synchronization on noisy channels is to use fixed-rate image compression techniques, and those not based upon finite state algorithms. However, some of these techniques have the disadvantages of not being progressive, not performing as well for good quality channels, or having extremely high computational complexity. Two of the most competitive techniques for protecting images from channel noise are found in [3] and [4].

Another approach to protecting image coders from channel noise is to divide the transmitted bitstream into two classes, the "important" bits and the "unimportant" bits, based upon the effects of channel errors on these bits. The important bits can then be sent as header information using good error control codes and the remaining bits can be sent with weaker channel codes. This type of technique was used in [5] and [6].

A more traditional approach to protecting source coder information from the effects of a noisy channel is to cascade the source coder with a channel coder. Analytical results have recently been obtained in [7] as guidance in choosing the optimal trade-off between source coding and channel coding. In fact, these results roughly follow those that we use in the present system.

In this paper, we present a low-complexity technique that preserves the encoding power of the progressive wavelet schemes of Shapiro–Said–Pearlman, preserves the progressive transmission property, and is simple to implement in practice. We focus on binary symmetric channels with large bit error probabilities.

One nice feature of the proposed coding system is that its performance for a given image remains constant with probability near one over all possible received channel error patterns. Effectively, no degradation due to channel noise can be detected. In fact, the effect of channel noise is to force the transmitter to encode the image at a lower source coding resolution and devote more bits to channel coding. Thus, on very noisy channels, the reconstructed image quality will be that of the noiseless channel encoder, but at a lower source coding rate. The system does not have to be designed for any particular transmission rate, and in fact works quite well over a broad range of transmission rates. One goal of this letter is to present state-of-the-art numerical results for noisy channel image transmission systems that can be useful for future comparisons.

II. System Description

One powerful method of error control coding is to use a concatenated code consisting of a Reed–Solomon outer code followed by a convolutional inner code (e.g., [8]). This approach, for example, was used in [5] for transmitting Joint Photographers Expert Group (JPEG) images across noisy channels. It was also used in [9] and [10] for transmission across a Gaussian channel. We adopt a related concatenated coding scheme with somewhat more flexibility and lower complexity to protect the output of the Said–Pearlman coder.

Manuscript received March 13, 1997. This work was supported in part by the National Science Foundation. The associate editor coordinating the review of this manuscript and approving it for publication was Prof. R. Mersereau.

The authors are with the Department of Electrical and Computer Engineering, University of California–San Diego, La Jolla, CA 92093 USA (e-mail: zeger@ucsd.edu).

Publisher Item Identifier S 1070-9908(97)05227-9.

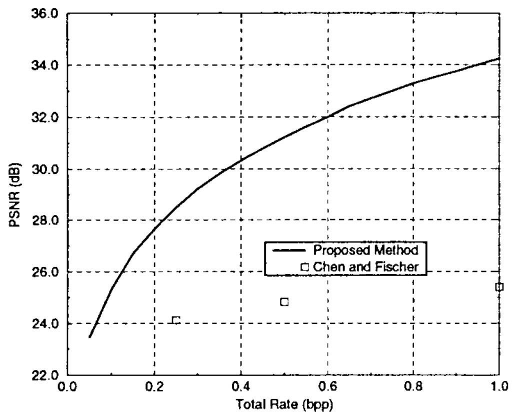

Fig. 1. Results for 512 × 512 Lena over a BSC with BER = 0.1.

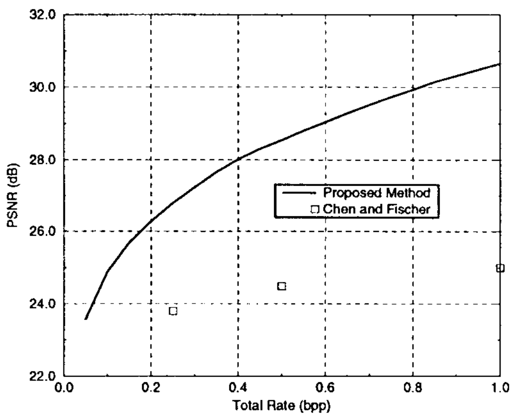

Fig. 2. Results for 512 × 512 Goldhill over a BSC with BER = 0.1.

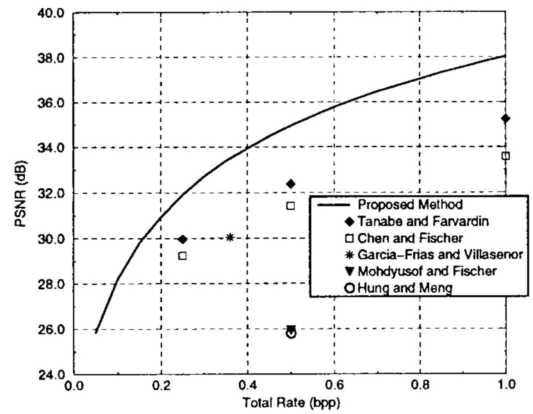

Fig. 3. Results for 512 × 512 Lena over a BSC with BER = 0.01.

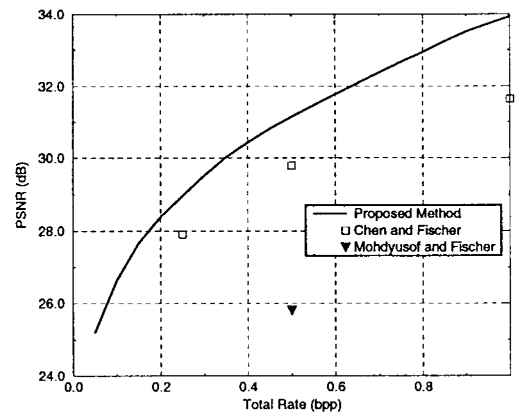

Fig. 4. Results for 512 × 512 Goldhill over a BSC with BER = 0.01.

The main idea is to partition the output bit stream from the Said–Pearlman image coder into consecutive blocks of length N (we used $N = 200$). Then a collection of c checksum bits are derived based only on these N bits (we use $c = 16$). Finally m zero bits, where m is the memory size of the convolutional coder, are added to the end to flush the memory and terminate the decoding trellis at the zero state. The resulting block of $N+c+m$ bits is then passed through a rate r rate-compatible punctured convolutional (RCPC) coder [11].

The cyclic redundancy outer code (CRC) used for error detection has the advantages of extremely low computational complexity and great flexibility in selecting block lengths (block lengths are unconstrained, in contrast to Reed–Solomon block lengths). The resulting bitstream is transmitted across a binary symmetric channel with bit error probability ϵ and then is decoded.

The decoder consists of a Viterbi decoder with the added feature that the "best path" chosen is the path with the lowest path metric that also satisfies the checksum equations. This additional constraint eliminates certain paths from consideration. In fact, whenever an undetected error would occur in the ordinary Viterbi decoder without the checksum bits, the correct path through the trellis was usually the one with the second lowest path metric. When the check bits indicate an error in the block, the decoder usually fixes it by finding the path with the next lowest metric. Systems of this type were analyzed in [12].

The proposed channel decoder requires little computation beyond that of the usual Viterbi decoding algorithm for the convolutional code. In addition, since punctured convolutional codes are used in this system, the trellis decoding is simplified because the trellis is that of a $1/N$ rate code for all the punctured rates. For a code of rate K/N, this translates into a computation savings by a factor of $2^{K-1}/K$ per decoded bit. In order to easily search for other likely trellis paths if necessary, some additional storage is required over the normal Viterbi algorithm.

Each candidate trellis path is checked by computing a 16-b CRC. The CRC polynomial was selected from those listed in [13] and [14] based on the number of information bits in a packet. For example, with 200 information bits in a packet, the selected CRC polynomial was $X^{16}+X^{14}+X^{12}+X^{11}+X^8+X^5+X^4+X^2+1$.

III. Experimental Results

The system was tested on two 512 × 512 images, the standard Lena and Goldhill images from the University of Southern California data base, in order to allow comparison with existing techniques. Each image was coded at bit error probabilities of $\epsilon = 10^{-1}$, $\epsilon = 10^{-2}$, and $\epsilon = 10^{-3}$, and at transmission rates ranging from 0 b/pixel up to 1 b/pixel, in increments of 0.05 b/pixel. All the RCPC codes used in testing were selected from tables in [11] or based

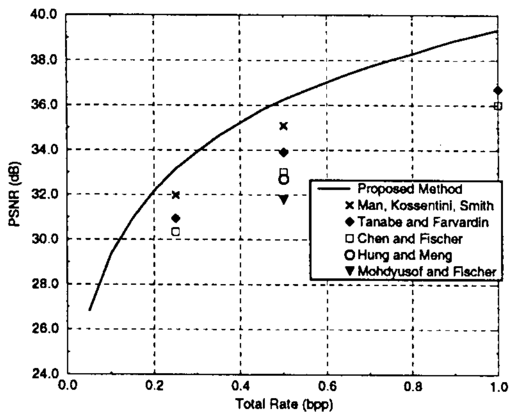

Fig. 5. Results for 512 $\times$ 512 Lena over a BSC with BER = 0.001.

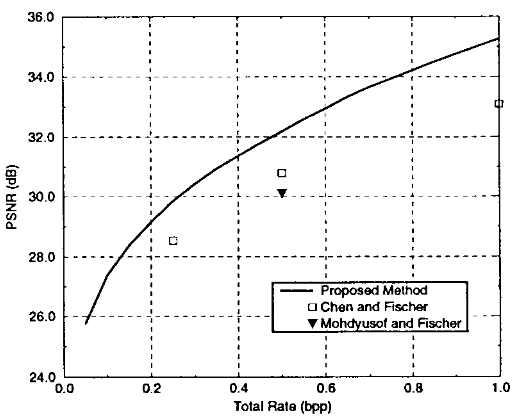

Fig. 6. Results for 512 $\times$ 512 Goldhill over a BSC with BER = 0.001.

on convolutional codes listed in [8]. In particular, a rate 2/7 memory 6 (punctured rate 1/4) code was used on the $\epsilon = 10^{-1}$ channel, a rate 2/3 memory 6 (punctured rate 1/3) code was used on the $\epsilon = 10^{-2}$ channel, and a rate 8/9 memory 6 (punctured rate 1/3) code was used on the $\epsilon = 10^{-3}$ channel.

For each image and each bit error probability, many thousands of independent trials were simulated on a computer for the various transmission rates, which translates into millions of packets. In these tests, the path search depth was limited to 100 candidate paths, and if none of these 100 paths satisfied the CRC check, then decoding for that image was stopped at that packet giving incomplete decoding. The inner RCPC codes were selected so that the probability of incomplete image decoding was below 0.01 for the highest transmission rate of interest (1.0 b/pixel) for each channel bit error rate (BER).

The curves in Figs. 1–6 show the resulting peak signal-to-noise ratio (PSNR) of the cascaded source coding and channel coding system as a function of the overall transmission rate across a binary symmetric channel (BSC). The other points in the plots include those of Tanabe and Farvardin [3], Chen and Fischer [4], as well as those in [15]–[18]. Numerous other results exist in the literature, but all of them appear to be inferior to the results reported in [3], [4], and [18] or else do not provide results for the test images we considered.

REFERENCES

[1] J. M. Shapiro, "Embedded image coding using zerotrees of wavelet coefficients," *IEEE Trans. Signal Processing,* vol. 41, pp. 3445–3462, Dec. 1993.
[2] A. Said and W. A. Pearlman, "A new, fast, and efficient image codec based on set partitioning in hierarchical trees," *IEEE Trans. Circuits Syst. Video Technol.,* vol. 6, pp. 243–250, June 1996.
[3] N. Tanabe and N. Farvardin, "Subband image coding using entropy-coded quantization over noisy channels," *IEEE J. Select. Areas. Commun.,* vol. 10, pp. 926–943, June 1992.
[4] Q. Chen and T. R. Fischer, "Robust quantization for image coding and noisy digital transmission," in *Proc. DCC'96,* pp. 3–12.
[5] T. P. O'Rourke, R. L. Stevenson, Y.-F. Huang, and D. J. Costello, Jr., "Improved decoding of compressed images received over noisy channels," in *Proc. ICIP-95,* pp. 65–68.
[6] D. W. Redmill and N. G. Kingsbury, "Still image coding for noisy channels," in *ICIP-94,* pp. 95–99.
[7] B. Hochwald and K. Zeger, "Tradeoff between source and channel coding," *IEEE Trans. Inform. Theory,* Sept. 1997, to be published.
[8] S. Lin and D. J. Costello, Jr., *Error Control Coding: Fundamentals and Applications.* Englewood Cliffs, NJ: Prentice-Hall, 1983.
[9] M. J. Ruf, "A high performance fixed rate compression scheme for still image transmission," in *Proc. DCC'94,* pp. 294–303.
[10] ——, "Source and channel coding of images using the operational rate-distortion function," in *Proc. ISITA'96,* Victoria, B.C., Canada, pp. 751–754.
[11] J. Hagenauer, "Rate-compatible punctured convolutional codes (RCPC codes) and their applications," *IEEE Trans. Commun.,* vol. 36, pp. 389–400, Apr. 1988.
[12] N. Seshadri and C.-E. W. Sundberg, "List Viterbi decoding algorithms with applications," *IEEE Trans. Commun.,* vol. 42, pp. 313–323, 1994.
[13] T. V. Ramabadran and S. S. Gaitonde, "A tutorial on CRC computations," *IEEE Microelectromech. Syst.,* vol. 8, pp. 62–75, Aug. 1988.
[14] G. Castagnoli, J. Ganz, and P. Graber, "Optimum cyclic redundancy-check codes with 16-bit redundancy," *IEEE Trans. Commun.,* vol. 38, pp. 111–114, Jan. 1990.
[15] J. Garcia-Frias and J. D. Villasenor, "An analytical treatment of channel-induced distortion in entropy coded image subbands," in *Proc. DCC'97.*
[16] A. C. Hung and T. H.-Y. Meng, "Error resilient pyramid vector quantization for image compression," in *Proc. ICIP-94,* pp. 583–586.
[17] Z. Mohdyusof and T. R. Fischer, "Subband image coding using a fixed-rate lattice vector quantizer," in *Proc. ICIP-95,* pp. 101–104.
[18] H. Man, F. Kossentini, and M. J. Smith, "A channel error robust EZW image coding technique," in *Proc. 2nd Erlagen Symp. Advances in Digital Image Communications,* Apr. 1997.