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PRODUCT CODE ERROR PROTECTION OF PACKETIZED MULTIMEDIA BITSTREAMS

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ABSTRACT

Sherwood and Zeger proposed a source-channel coding system where the source code is an embedded bitstream and the channel code is a product code such that each row code is a concatenation of a cyclic redundancy check (CRC) and rate-compatible punctured convolutional codes (RCPC) and the column codes are Reed-Solomon (RS) codes. We improve this system for wireless applications by efficiently reorganizing the source code into a set of independently decodable packets, which makes it more robust in varying channels. We also give a linear-time algorithm for finding an optimal equal error protection for the resulting system. Experimental results show that the performance of our system significantly outperforms that of the current state-of-the-art in fading channels with varying statistics.

1. INTRODUCTION

The embedded wavelet coders [1, 2, 3] have competitive rate-distortion performance, low complexity, and progressive ability. However, these coders are very sensitive to channel noise because a single transmission failure can lead to an irreversible loss of synchronization between the encoder and the decoder. In one-way communication systems, two different approaches can be used to deal with this problem. The first one is based on forward error correction (FEC). The most powerful FEC-based transmission systems for embedded codes are due to Sherwood and Zeger [4] and Sachs, Anand, and Ramchandran [5]. Both systems protect the embedded bitstream with a product channel code whose row code is a concatenated CRC/RCPC code, and column code is a systematic RS code. The second approach consists of reorganizing the output bitstream of a zero-tree embedded wavelet coder into packets that correspond to independent sets of wavelet coefficients [6, 7, 8]. Since the packets are independently decodable, error propagation is limited to the packets where errors occur.

One important limitation of the above systems is that they are not efficient when the channel conditions are unknown or variable, which is the typical situation for a real-world channel. In particular, for wireless communication, channel statistics rapidly change in time; thus, very often, a system designed for one channel state is used at another. To overcome this problem, Cosman, Rogers, Sherwood, and Zeger [9] proposed a hybrid coder which combines the packetization technique of [7] with the FEC method of [10]. In this way, the output bitstream of an embedded wavelet coder is packetized into independently decodable packets, which are then protected by a concatenated CRC/RCPC coder. For pure Rayleigh flat-fading channels and those including packet erasure, the performance of the scheme outperforms that of [7] and [10] for channels with varying statistical conditions. In [11], we provide a real-time algorithm to find an appropriate RCPC code rate for the hybrid system of [9] and show that the performance of this system can be significantly improved by replacing the packetized zerotree wavelet coder of [7] with the optimal packetization scheme of [8].

In this paper, we improve the hybrid system of [11] by combining it with the product code system of [4]. Thus, we packetize the bitstream of a zero-tree wavelet coder and protect the packets with the product channel code of [4]. In [4], the RCPC code rate and the RS protection were selected *ad-hoc* without optimization. In contrast, we provide an algorithm that quickly finds an optimal equal error protection (EEP) solution for a packetized bitstream. Experimental results show that our system outperforms the system of [4], the system of [11], and the state-of-the-art system of [5] for Rayleigh fading channels with unknown or varying conditions.

The rest of the paper is organized as follows. In Section 2, we propose our EEP optimization algorithm for product code protection of a packetized bitstream. In Section 3, we compare the performance of our system to that of [4], [11], and [5].

2. PRODUCT CODE SYSTEM

Let $\mathcal{R} = \{r_1, \ldots, r_m\}$ be the set of RCPC code rates. For a given code rate $r \in \mathcal{R}$, the source bitstream is packetized into packets of $L(r)$ symbols (for example, bytes) each. Then, these packets are subdivided into q groups of k_i packets each, $1 \leq i \leq q$. Each of the $L(r)$ columns of k_i source symbols from the same group i of source packets is encoded with an (n_i, k_i) RS code. Next, CRC bits are appended to each row, and each row is independently encoded with the RCPC code of rate r, yielding N RCPC codewords of L symbols each. Suppose now that the channel codewords are sent through a noisy wireless channel. At the receiver side, the RCPC decoder is used to correct the bit errors in the received packets. However, if the CRC detects a residual error in the packet, the packet is considered to be lost. Finally, RS decoding is used to recover the lost packets.

A product code error protection scheme is a pair (r, π) where $r \in \mathcal{R}$ and $\pi = \{(n_1, k_1), \ldots, (n_q, k_q)\}$ is such that (n_i, k_i) is an RS code used to protect the ith group of k_i source packets. Thus, $\sum_{i=1}^{q} n_i = N$, and $\sum_{i=1}^{q} k_i = M(\pi)$ is the number of source packets (see Table 1).

Suppose that error protection scheme (r, π) is used. Let $Q = \{1, 2, \ldots, M(\pi)\}$ be the set of source packet indices (packet 1 is sent first, packet 2 is sent next, etc). Consider all possible subsets of n elements of Q and let Q_n^j, $n = 1, \ldots, M(\pi)$, $j =$

							+	+	o	o
							+	+	o	o
X	X	X	X	X	X	X	+	+	o	o
X	X	X	X	X	X	X	+	+	o	o
							+	+	o	o
Y	Y	Y	Y	Y	Y	Y	+	+	o	o

Table 1. A general product code structure. There are $N = 6$ packets, $M(\pi) = 3$ source packets, and $q = 2$ groups of source packets that are encoded with different RS codes. X denotes an RS redundant symbol of a $(4, 2)$ RS code, Y is an RS redundant symbol of a $(2, 1)$ RS code, + is a CRC redundant symbol, and o is an RCPC redundant symbol. Empty cells contain information symbols. The RCPC code need not be systematic.

							+	+	o	o
							+	+	o	o
							+	+	o	o
X	X	X	X	X	X	X	+	+	o	o
X	X	X	X	X	X	X	+	+	o	o
X	X	X	X	X	X	X	+	+	o	o

Table 2. Product code structure with EEP.

$1, \ldots, \binom{M(\pi)}{n}$, denote the jth such subset. For example, if $Q = \{1, 2, 3\}$, then $Q_1^1 = \{1\}$, $Q_1^2 = \{2\}$, $Q_1^3 = \{3\}$, $Q_2^1 = \{1, 2\}$, $Q_2^2 = \{1, 3\}$, $Q_2^3 = \{2, 3\}$, and $Q_3^1 = \{1, 2, 3\}$. Let $P^{(r,\pi)}(Q_n^j)$ denote the probability that all source packets in Q_n^j are not correctly decoded by the product code (r, π), while all other source packets are correctly decoded and $d^{(r,\pi)}(Q_n^j)$ denote the corresponding distortion (we use the squared-error $||.||_2^2$). Then one can show that the expected distortion is

$$E_N(r,\pi) = P_0^{(r,\pi)} d_0^{(r,\pi)} + \sum_{n=1}^{M(\pi)} \sum_{j=1}^{\binom{M(\pi)}{n}} P^{(r,\pi)}(Q_n^j) d^{(r,\pi)}(Q_n^j), \tag{1}$$

where $P_0^{(r,\pi)}$ and $d_0^{(r,\pi)}$ are the probability that all source packets are correctly decoded and the corresponding distortion, respectively. For $Q_n^j = \{l_1, \ldots, l_n\}$, $n \le M(\pi)$, $l_1 < \cdots < l_n$, we assume that

$$d^{(r,\pi)}(Q_n^j) = d^{(r,\pi)}(Q_1^{l_1}) + \cdots + d^{(r,\pi)}(Q_1^{l_n}) - (n-1) d_0^{(r,\pi)}, \tag{2}$$

which is satisfied if all lost wavelet coefficients are set to zero and only an approximation if a more sophisticated interpolation technique is used. Let $\Delta d_j^{(r,\pi)} = d^{(r,\pi)}(Q_1^j) - d_0^{(r,\pi)}$, $j \in Q$. Then from (1) and (2), we have

$$E_N(r,\pi) = d_0^{(r,\pi)} + \sum_{j=1}^{M(\pi)} \Delta d_j^{(r,\pi)} P_j^{(r,\pi)}, \tag{3}$$

where

$$P_j^{(r,\pi)} = \sum_{n=1}^{M(\pi)} \sum_{i=1, j \in Q_n^i}^{\binom{M(\pi)}{n}} P^{(r,\pi)}(Q_n^i)$$

is the probability that the jth source packet is not correctly decoded by the product code.

If the symbols from the jth source packet are protected with an (n_j^*, k_j^*) RS code, then

$$E_N(r,\pi) = d_0^{(r,\pi)} + \sum_{j=1}^{M(\pi)} \Delta d_j^{(r,\pi)} \sum_{i=n_j^*-k_j^*+1}^{n_j^*} p^{(r,n_j^*)}(j;i) \tag{4}$$

where $p^{(r,n_j^*)}(j;i)$ is the probability that the jth source packet is not correctly reconstructed by the CRC/RCPC decoder and the total number of packets that are not correctly reconstructed by the CRC/RCPC decoder from the group of n_j^* packets is i.

Minimizing (4) over all m RCPC code rates and all RS protection schemes is a difficult combinatorial optimization problem in the general case. However, the problem can be efficiently solved when equal error protection is used. This is the case when $q = 1$ (Table 2). Thus, $n_1 = N$ and $k_1 = M(\pi)$. Let $p_i^{(r)}$ be the probability that i packets of N cannot be correctly reconstructed by the CRC/RCPC decoder. Then equality (3) can be expressed as

$$E_N(r,\pi) = d_0^{(r,\pi)} + \frac{1}{N} \sum_{j=1}^{M(\pi)} \Delta d_j^{(r,\pi)} \sum_{i=N-M(\pi)+1}^{N} i p_i^{(r)}. \tag{5}$$

A straightforward $O(mN)$ algorithm can be used to minimize (5).

3. RESULTS

In all experiments, we used the SPIHT bitstream of the 8 bits per pixel (bpp) 512 × 512 standard Lenna image as a source code. We first compare our product code system to the one of Sherwood and Zeger [4] for a flat-fading Rayleigh channel. This channel is characterized by the average signal-to-noise ratio (SNR) and the normalized Doppler spread f_D. We simulated the channel with Jakes' method [12]. For the channel coder of the two systems, we used a 16-bit CRC with generator polynomial 0x15935 and an RCPC code with generator polynomials $(0117, 0127, 0155, 0171)$, mother code rate $1/4$, and puncturing rate 8 [13]. Thus, the set of RCPC code rates was $\{8/9, 8/10, \ldots, 8/32\}$. The decoding of the RCPC code was done with a list Viterbi algorithm where the maximum number of candidate paths was 100. The channel codeword size L was set to 48 bytes. For our system, we packetized the source bitstream with the optimal technique of [8] and optimized the product code with the EEP algorithm of Section 2. Sherwood and Zeger do not provide an optimization algorithm for their product code. Therefore, we used the product code settings of their best experimental results, which were obtained with unequal error protection [4]. Figure 1 shows the results when the product codes were designed for SNR = 10 dB and $f_D = 10^{-5}$ and tested for the same Doppler spread but at various SNRs. The reported results were obtained with 5000 independent simulations. The figure shows that our system significantly outperformed the system of [4] when the channel conditions varied.

We now compare our product code system to our hybrid system [11] and to the multiple description product code system of [5]. For all systems, we used the same CRC/RCPC coder described

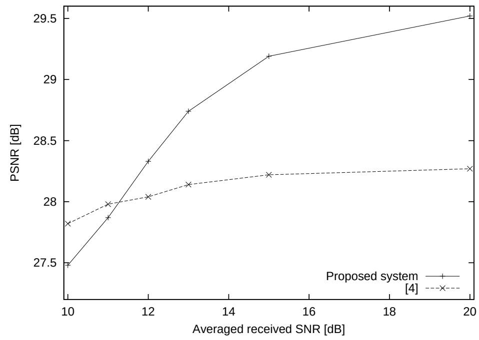

Fig. 1. PSNR in dB of the average mean squared error (MSE) as a function of the average received SNR for the Lenna image. The systems were designed for a Rayleigh channel with $f_D = 10^{-5}$ and SNR $= 10$ dB, and tested over Rayleigh channels with $f_D = 10^{-5}$. The transmission rate is 0.25 bpp.

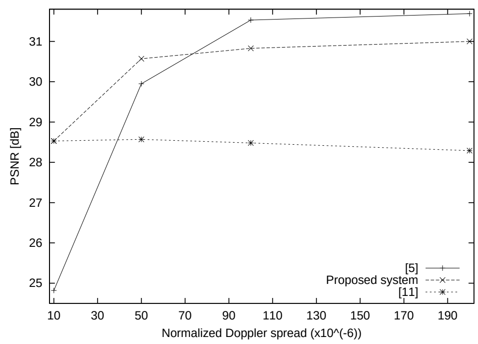

Fig. 2. PSNR in dB of the average MSE as a function of the average normalized Doppler spread f_D for the Lenna image. The systems were optimized for a Rayleigh channel with $f_D = 10^{-4}$ and SNR $= 13$ dB, and tested over Rayleigh channels with SNR $= 13$ dB. The transmission rate is 0.25 bpp.

above. Figure 2 shows the performance of the schemes when they were optimized for one pair of channel parameters and tested when the SNR was fixed while f_D was varied.

Figures 3 and 4 show the performance of the schemes when they were optimized for one pair of parameters and tested when both channel parameters were varied. When the optimization was done for the exact channel conditions, the system of [5] had a better performance than our systems. However, the situation changed when the channel conditions varied. In particular, the system of [5] collapsed when long bursts (low f_D) were present, while our systems remained robust. Also note how our new system outperformed our previous scheme [11].

As noted in [4, 9], in addition to the average decoded distortion, one should also consider the cumulative distribution function of the decoded distortion to measure the performance of a source-channel coding system in a noisy channel. Figure 5 indicates that for varying channels our systems are less likely to generate poor reconstructions than the system of [5]. However, since the performance of the SPIHT bitstream decreases after packetization, the system of [5] had a higher probability of generating the lowest MSEs. For example, the lowest MSEs produced by our systems

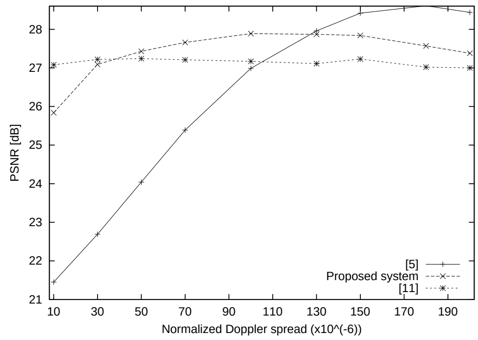

Fig. 3. PSNR in dB of the average MSE as a function of the average normalized Doppler spread f_D for the Lenna image. The systems were optimized for a Rayleigh channel with $f_D = 10^{-4}$ and SNR $= 13$ dB, and tested over Rayleigh channels with SNR $= 10$ dB. The transmission rate is 0.25 bpp.

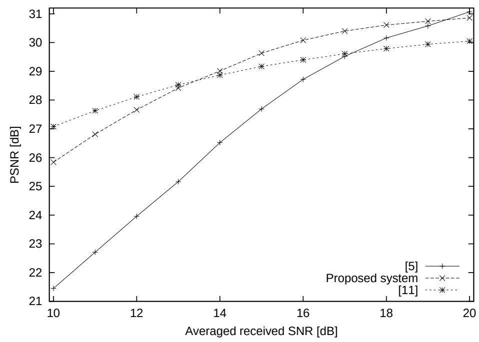

Fig. 4. PSNR in dB of the average MSE as a function of the average received SNR for the Lenna image. The systems were optimized for a Rayleigh channel with $f_D = 10^{-4}$ and SNR $= 13$ dB, and tested over Rayleigh channels with $f_D = 10^{-5}$. The transmission rate is 0.25 bpp.

were 57.4 in 40.8 % and 50.81 in 66.1 % for the system of [11] and the product code system, respectively, whereas the system of [5] yielded an MSE of 43.7 in 63 % of the cases.

Finally, Figure 6 shows visual results. It confirms the observation made in [9] that reconstruction errors in schemes using packetization are localized in space.

4. CONCLUSION

We proposed a transmission system for multimedia data based on packetization of an embedded source bitstream and error protection with a product code. We also provided a linear-time algorithm for equal error protection. The algorithm finds an optimal solution under assumption (2). Our system outperformed the system of [4], which uses a product channel code without packetization, and our previous scheme [11], which exploits packetization but uses only RCPC codes for error correction. On the other hand, our system had a worse end-to-end performance than the state-of-the-art product code scheme of [5] in fading channels with known statistics. This is due to the fact that the system of [5] is advantaged because it includes adaptive arithmetic coding of the source bitstream, which is not possible with packetization since packet loss

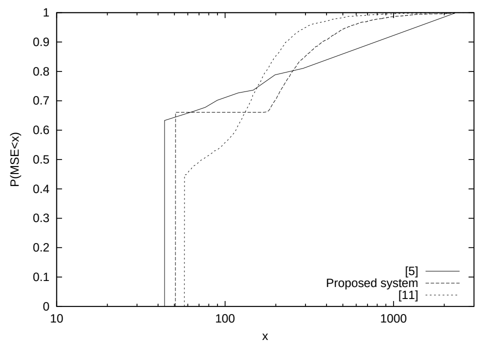

Fig. 5. Cumulative distributions of the distortion for the Lenna image. The systems were optimized for a Rayleigh channel ($f_D = 10^{-4}$, SNR $= 13$ dB). Results are shown for a Rayleigh channel with SNR $= 10$ dB and $f_D = 10^{-5}$. The transmission rate is 0.25 bpp.

destroys context adaptation. However, our system was more robust to varying channel conditions, which makes it attractive for wireless applications. Note that the product code of [5] is not appropriate for packetized bitstreams.

We provided experimental results for images, but our system can also be used with tree-based wavelet video codes [3, 8].

One interesting open question is to see if unequal error protection (equation (4)) can improve the results obtained with EEP.

Fig. 6. Median quality of Lenna with the product code system of [5] (26.99 dB) (top) and our product code system (27.92 dB) (bottom) at transmission rate 0.25 bpp for a Rayleigh channel with $f_D = 10^{-4}$ and SNR $= 10$ dB. The two systems were optimized for a Rayleigh channel with $f_D = 10^{-4}$ and SNR $= 13$ dB.

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