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An Efficient Progressive Bitstream Transmission System for Hybrid Channels With Memory

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***Abstract*—We consider progressive transmission over a hybrid channel introducing bit errors and packet erasures. The existing solutions are analyzed and extended to the case of a channel that exhibits memory on both bit errors and packet erasures. We then propose a simple, low-complexity coding scheme that transforms the hybrid channel into a channel with a single impairment for which various optimization techniques exist. Both rate-based and distortion-based optimization problems are investigated. It is shown that our proposed solution has lower channel coding and rate-distortion optimization complexities compared to the known solutions. Simulation results for channels with and without memory show the effectiveness of our proposed solution over a wide range of operating conditions. Numerical results also indicate that the rate-based solution of our proposed algorithm is very close to the corresponding distortion-based solution.**

***Index Terms*—Finite-state channels, joint source-channel coding, progressive transmission, packet erasures, unequal protection.**

I. Introduction

Embedded source coding enables the source decoder to progressively reconstruct its data at different bit rates from the prefixes of a single bitstream. Practical implementations of embedded source coders include EZW [1], SPIHT [2], and EBCOT (JPEG2000) [3] for still image coding, and three-dimensional (3-D) SPIHT [4] and MPEG-4 FGS [5] for video coding. The embedded capability of encoders, however, comes at the expense of high sensitivity to transmission noise and the possibility of error propagation. Therefore, progressive transmission of an embedded bitstream over a noisy channel has to be accompanied with appropriate channel coding or joint source-channel coding schemes. In this work, we consider embedded source coders and use the terms *embedded* and *progressive* interchangeably.

Joint source-channel coding of progressive bitstreams is usually formulated as an optimization problem. In a distortion-based framework, the goal is to minimize the expected distortion of the received bitstream for a given transmission rate. The rate-based approach tries to maximize the number of error-free source symbols under the same constraints. The rate-based solution is generally suboptimal in the distortion sense. However, the rate maximization problem is simpler and the solution is independent of the distortion-rate (D-R) curve of the source which makes it attractive in situations where such a curve is difficult to obtain. Another important aspect of progressive transmission is the unbalanced nature of the bitstream. Earlier bits of an embedded bitstream have to be decoded first before one can use the later bits. As a result, an embedded bitstream is usually unequally protected, with the earlier bits being given more protection against loss.

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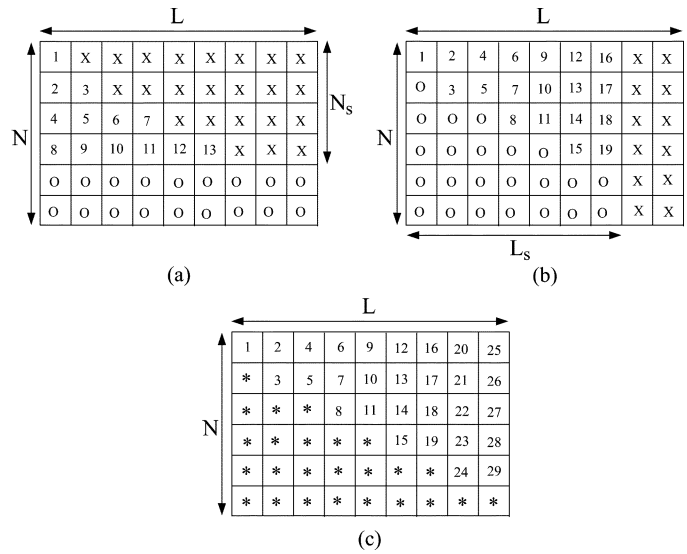

Fig. 1. Codes for the hybrid channel. The numbers represent the ordered symbols of the source. X, O and * symbols represent the parity symbols for error, erasure and error-erasure protection, respectively. (a) RS2Da. (b) RS2Db. (c) RS1D.

Progressive transmission over noisy and lossy channels has been extensively studied in the literature [6]–[26]. Efficient algorithms for finding optimal rate-based solutions exist [19] and optimal distortion-based solutions can be found in certain scenarios. In the case of a packet erasure channel, distortion-based solutions exist that are optimal for general sources [23] and for sources with convex D-R curves [24], and it has been shown that an optimal rate-based solution is essentially an equally protected system [15]. In the case of a random bit-error channel and a source with an exponential D-R curve, efficient and optimal distortion minimization is possible [21]. Numerous other techniques can be found in the above references that find locally-optimal or suboptimal solutions with varying degrees of complexity. Efficient search algorithms have also been introduced that perform very close to the optimal solution [15], [22]. Error resilient techniques based on independently decodable packets and estimation of lost source symbols have also been introduced and combined with forward error correction for robust transmission of embedded bitstreams [12], [13].

In this work, we consider the joint source-channel coding of progressive bitstreams over a hybrid channel that introduces bit errors, as well as packet loss. This channel models a wireline packet network whose data is transmitted over a wireless channel. Packet loss is caused by network impairments such as congestion, while bit errors are caused by the wireless transmission medium. In either case, a realistic channel model is one that captures the correlations between the errors or erasures. Packets are lost in bursts while the network is congested and similarly, a deep fade in the wireless channel causes a long burst of bit errors. As a result, in this work we are primarily interested in a channel model in which the packet erasure and bit-error mechanisms exhibit memory.

Coding schemes for the hybrid channel have been proposed in [10], [11], [14] and efficient optimization techniques have been introduced in [13], [15], [16]. These solutions are based on product codes that

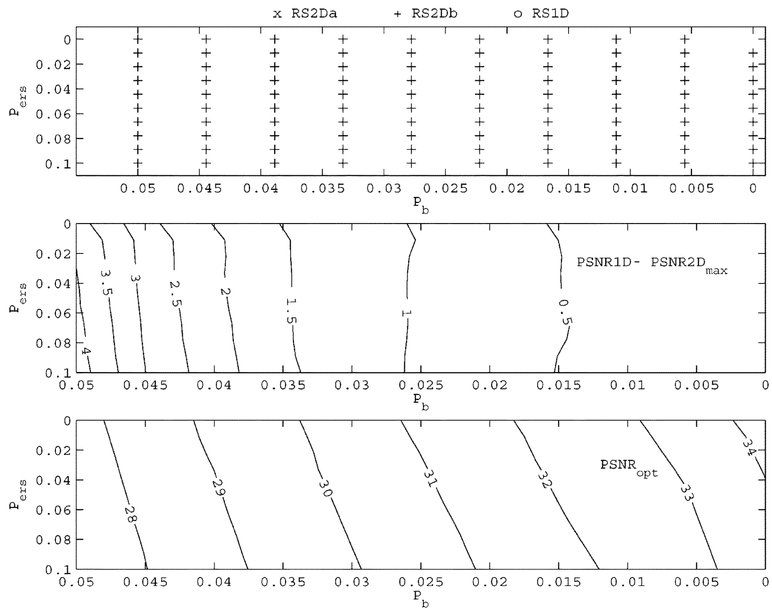

Fig. 2. Optimization results for a memoryless channel with $N = 100$ and $L = 100$.

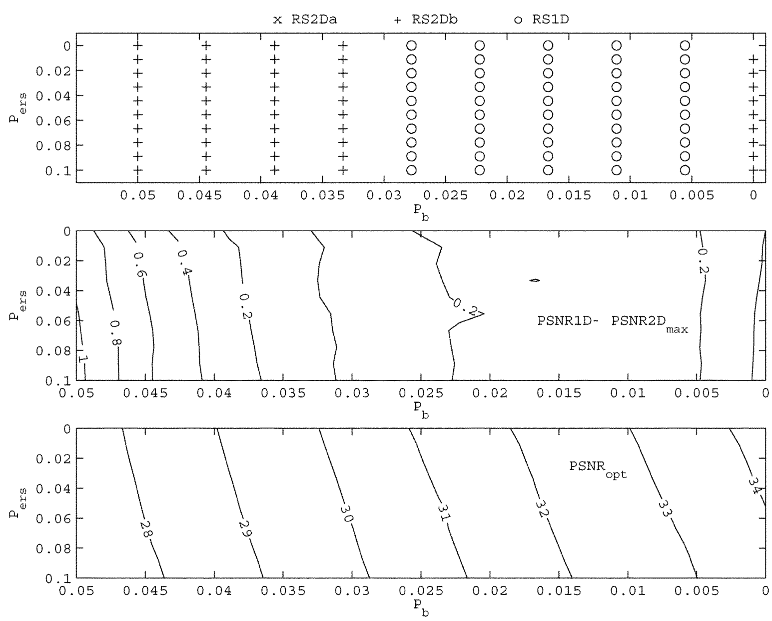

Fig. 3. Optimization results for a memoryless channel with $N = 200$ and $L = 50$.

are complex and introduce extra decoding delay. The existing systems transmit symbols of a codeword sequentially over a wireless channel and as a result, perform poorly when the errors caused by this channel are highly correlated. Moreover, they cannot unequally protect against both the bit errors and packet erasures. Finally, the existing rate-based solutions for the hybrid channels are far from being optimal.

More recently, a product coding scheme has been introduced for the transmission of JPEG2000 bitstreams over wireless channels that outperforms some of the known techniques of the literature [25]. One of the advantages of the latter scheme over previous product codes is its ability to provide unequal protection against both the errors and the erasures. However, the channel itself is not hybrid and the packet erasures are caused only by the decoding errors of the row code. Moreover, joint source channel optimization is done partially by exhaustive search.

The main contribution of this work is to challenge the accepted view that a hybrid channel has to be protected with a high-complexity product code. This goal is achieved by transforming the complex problem of the hybrid channel into a simpler problem of a single-impairment channel for which known solutions exist. We combine the bit errors and packet erasures into an equivalent channel, and use a single error-erasure correcting code to protect against both channel impairments. This allows us to apply the vast array of the known optimization techniques cited before, to the problem at hand. We show that this simple structure addresses all the issues associated with the existing solutions, and more importantly, it achieves performance gains over a wide range of operating conditions.

This correspondence is organized as follows. In Section II, the existing techniques for progressive transmission over hybrid channels are reviewed and an extension to the case of a channel that exhibits memory on both bit errors and packet erasures is presented. Our proposed coding scheme is then introduced together with the solution to the associated optimization problem. Numerical comparison of the al-

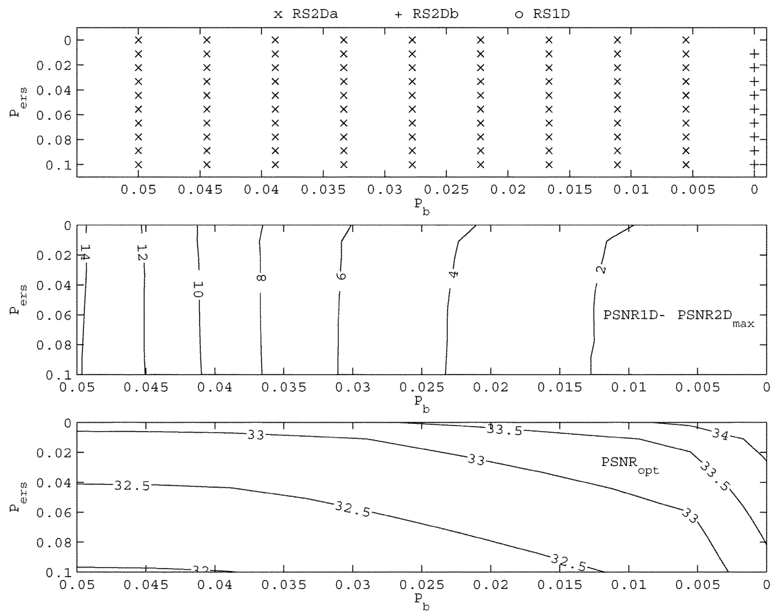

Fig. 4. Optimization results for a memoryless channel with $N = 50$ and $L = 200$.

gorithms is presented in Section III. Finally, Section IV concludes this work.

II. Coding Schemes

We use the following definitions throughout the text. For memoryless channels, P_b and P_{ers} represent the bit-error probability and the packet erasure rate, respectively. Channels with memory are characterized by $P_{\text{err}}(n, m)$ and $P_{\text{ers}}(n, m)$ which are defined as the probability of m bit errors out of n transmitted bits and the probability of m packet erasures out of n transmitted packets, respectively. In this case, P_{ers} refers to the average packet erasure rate. We assume that the total transmission budget is $B_T = NL$, where N is the number of packets and L is the packet size in symbols. We consider a symbol size of s bits and the symbol error probability is denoted by $P_{s\epsilon}$. For memoryless channels, $P_{s\epsilon} = 1 - (1 - P_b)^s$ and for channels with memory, $P_{s\epsilon} = 1 - P_{\text{err}}(s, 0)$.

In this work, channel coding for all the transmission schemes is done using rate compatible punctured Reed–Solomon (RS) codes over $GF(2^s)$ [29]. Because of their non-binary structure, RS codes have excellent burst error correcting capabilities. This makes them particularly useful in channels with correlated bit errors, which is the main focus of our work. The minimum distance of RS codes is known and that enables us to derive analytical expressions for decoding failure rates. RS codes provide a wide range of coding rates through puncturing and this flexibility can be exploited for optimization purposes. Another important feature of RS codes is their ability to correct errors and erasures simultaneously, a property that is crucial in the development of our low complexity solution. In the context of packetized transmission, another useful aspect of RS codes is the fact that for a bounded distance RS decoder, the probability of decoding error is much smaller than the probability of decoding failure. This means that the decoder either declares decoding failure, or decodes the codeword correctly. This eliminates the need for an additional error detection code, such as a cyclic redundancy check (CRC) code, that is usually used for packet error detection. Finally, we note that using the same code for all the transmission schemes forms a fair basis for comparing different techniques.

The following optimization techniques have been proposed for channels with bit errors only but they are also relevant to our work on the

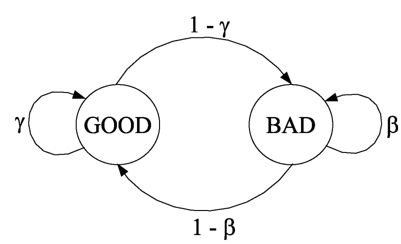

Fig. 5. Gilbert-Elliot channel.

hybrid channel transmission systems. A provably optimal technique for finding a rate-based solution has been proposed in [19]. We refer to this algorithm as ROPT. Similarly, an optimal solution for the distortion optimization problem exists when the source has an exponential D-R curve [21]. This algorithm is referred to as DOPT. For sources with arbitrary D-R curves, a fast local search (LS) algorithm has been proposed in [22] that performs very close to the optimal solution. All these algorithms have an optimization complexity of $\mathcal{O}(NL)$.

A. Product Code RS2Da

The coding scheme of [16] is shown in Fig. 1(a). We refer to this system as RS2Da. The first N_s packets contain source symbols that are unequally protected against bit errors. Erasure coding is applied across the packets and equally protects the source packets against packet loss. Whenever N_s or more packets are received, erasure decoding recovers the first N_s packets which are subsequently decoded for bit errors. The cost function for the distortion-based problem is given by

$$\mathcal{E}_D = P_R(N_s)\mathcal{E}_D^{N_s} + (1 - P_R(N_s))\, D_0 \tag{1}$$

where $\mathcal{E}_D$ is the expected distortion, $P_R(N_s) = \sum_{n=0}^{N-N_s} P_{\text{ers}}(N, n)$ is the probability of recovering N_s or more packets, and $D_0 = \sigma^2$ represents the source variance. $\mathcal{E}_D^{N_s}$ is the expected distortion given that the first N_s packets have been recovered and is given by

$$\mathcal{E}_D^{N_s} = \sum_{i=1}^{N_s+1} D_{i-1}\Phi_{C_i} \prod_{j=1}^{i-1} \left(1 - \Phi_{C_j}\right) \tag{2}$$

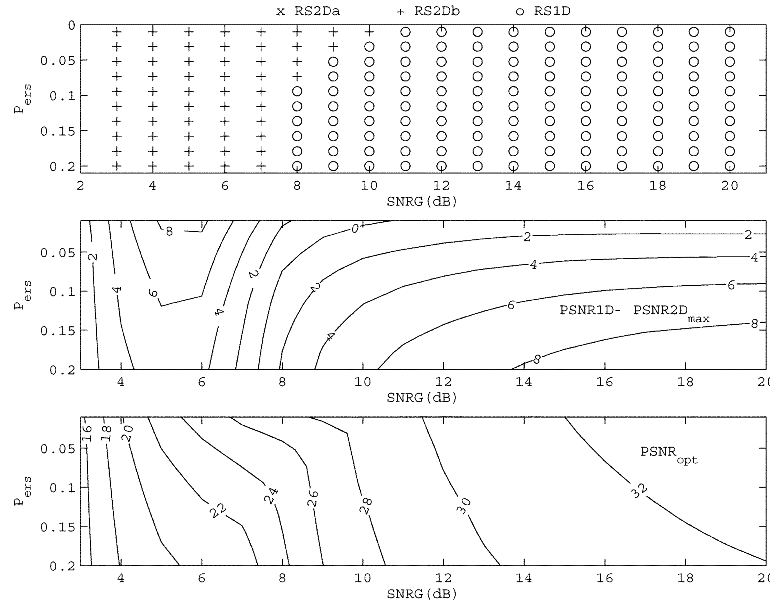

Fig. 6. Optimization results for a channel with memory for $N = 100$ and $L = 100$.

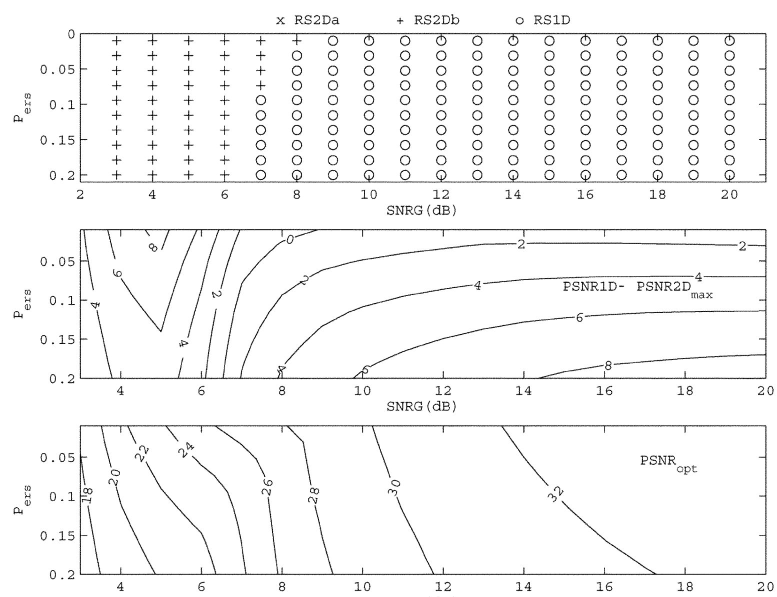

Fig. 7. Optimization results for a channel with memory for $N = 200$ and $L = 50$.

In the above equation, C_i is the number of parity symbols of the i^{th} packet, Φ_{C_i} is the corresponding probability of decoding failure, and $\Phi_{C_{N_s+1}} = 1$. D_i is the distortion associated with the data in the first i packets. The goal is to minimize $\mathcal{E}_D$ with respect to the variables $C_i (1 \leq i \leq N_s)$ and N_s. Similarly, the rate-based cost function is defined by

$$\mathcal{E}_R = P_R(N_s)\mathcal{E}_R^{N_s} \tag{3}$$

where $\mathcal{E}_R$ is the expected number of error-free progressive symbols. $\mathcal{E}_R^{N_s}$ is the expected number of error-free progressive symbols, given that the first N_s packets have been recovered and is given by

$$\mathcal{E}_R^{N_s} = \sum_{i=1}^{N_s+1} R_{i-1}\Phi_{C_i}\prod_{j=1}^{i-1}\left(1-\Phi_{C_j}\right) \tag{4}$$

where $R_i = \sum_{n=1}^{i}(L - C_n)$ and $R_0 = 0$. The goal is now to maximize $\mathcal{E}_R$ with respect to the variables $C_i (1 \leq i \leq N_s)$ and N_s.

When a maximum distance separable (MDS) code (e.g., RS code) is used, a packet with C parity symbols fails to decode if the number of symbol errors exceeds $\lfloor C/2 \rfloor$ [29]. For short burst lengths, Φ_C can be approximated by ignoring the inter-symbol correlation of the bit errors. In this case, $\Phi_C = 1 - \sum_{i=0}^{\lfloor C/2 \rfloor}\binom{L}{i}P_{se}^i(1-P_{se})^{L-i}$. For long burst lengths, the symbol errors are correlated and the above expression for Φ_C is not valid. In this case, Φ_C can be obtained using simulations.

The ROPT algorithm can be used to maximize the cost function $\mathcal{E}_R^N$ with an $\mathcal{O}(NL)$ complexity and this solution yields the optimal rate-based solution for n packets where $1 \leq n \leq N-1$ [19]. As a result, a single optimization of complexity $\mathcal{O}(NL)$ suffices to evaluate the optimal value of $\mathcal{E}_R^{N_s}$ for all possible values of N_s. The optimal values of $\mathcal{E}_R^{N_s}$ can then be substituted in (3) to find the corresponding $\mathcal{E}_R$. Consequently, $\mathcal{E}_R$ can be maximized with an overall complexity of

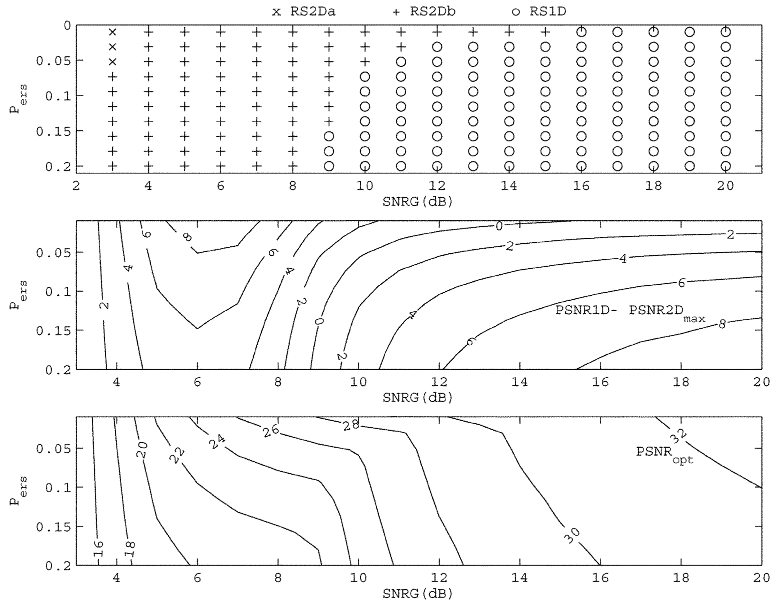

Fig. 8. Optimization results for a channel with memory for $N = 50$ and $L = 200$.

$\mathcal{O}(NL)$. In the case of distortion optimization, the same property holds for the DOPT algorithm when the source has an exponential D-R curve [16]. For arbitrary sources, one can minimize $\mathcal{E}_D^n$ with an $\mathcal{O}(nL)$ complexity using the LS algorithm for $1 \leq n \leq N$, resulting in an overall complexity of $\mathcal{O}(N^2L)$ for minimizing $\mathcal{E}_D$. We note that the variable N_s explicitly defines the budget allocation between the error and erasure protection components of the system.

B. Product Code RS2Db

The coding scheme of [15] is shown in Fig. 1(b). We refer to this system as RS2Db. The first L_s columns contain source symbols that are equally protected against errors using $C = L - L_s$ parity symbols, and the encoding across the packets provides unequal protection against packet loss. Received packets at the receiver are first decoded for bit errors. If a packet fails decoding at this stage, all its symbols are marked as erased. Erasure decoding then tries to recover the symbols that have been erased in the channel, as well as the symbols that have been marked as erasures due to the error decoding failure. Let C_i denote the number of parity symbols of the i^{th} column code. The distortion-based cost function for this system is

$$\mathcal{E}_D = \sum_{i=0}^{L} P_i D_i \tag{5}$$

and the rate-based cost function $\mathcal{E}_R$ is obtained by replacing D_i with R_i where R_i is the number of source symbols in the first i columns, and D_i is the associated distortion. By definition, $R_0 = 0$, $P_0 = \mathrm{Prob}(X > C_1)$ and $P_L = \mathrm{Prob}(X \leq C_L)$ where X is the number of erased packets. For $i = 1, 2, \cdots, L-1$, $P_i = 0$ if $C_i = C_{i+1}$ and $P_i = \sum_{n=C_{i+1}+1}^{C_i} P_N(n, C)$ otherwise. $P_N(n, C)$ is the probability of n packets being erased out of N transmitted packets, when the number of parity symbols of the row code is C. The number C determines the decoding failure probability of the row code. This latter failure probability, in turn, affects the number of the packet erasures, since a failed packet is considered as erased in the erasure decoding stage. Consequently, $P_N(n, C)$ is treated as a function of C.

The optimization algorithm of the RS2Db system was originally proposed for packet erasure channels without memory [15]. In what follows, we extend this algorithm to the case of correlated packet loss by finding an analytical expression for $P_N(n, C)$. A non-overlapping packet decoding failure is defined as the one that occurs to a packet that is not erased in the channel. It is clear that an overlapping decoding failure should be treated as an erasure. It follows that

$$P_N(n, C) = \sum_{m=0}^{n} p(N_f = n - m | N_{\mathrm{ers}} = m) P_{\mathrm{ers}}(N, m) \tag{6}$$

where N_f and N_{ers} represent the number of non-overlapping decoding failures and the number of packet erasures in the channel, respectively. When the packet length is sufficiently large, packet decoding failures can be considered independent and

$$p(N_f = n - m | N_{\mathrm{ers}} = m) = \binom{N-m}{n-m} \Phi_C^{n-m} (1 - \Phi_C)^{N-n} \tag{7}$$

where Φ_C is the probability of decoding failure of the row code which was derived in Section II-A. The algorithms of [15] can now be applied to the RS2Db system to obtain an optimal rate-based solution with a complexity of $\mathcal{O}(NL)$, or a distortion-based solution with an $O(NL^2)$ complexity. The budget allocation between the error and erasure protection in this system is explicitly defined by the variable L_s.

C. Proposed Solution

Our proposed transmission system is shown in Fig. 1(c). We refer to this system as RS1D. The i^{th} column forms an RS codeword with C_i parity symbols. The cost function of the distortion-based problem is

$$\mathcal{E}_D = \sum_{i=1}^{L+1} D_{i-1} \Psi_{C_i} \prod_{j=1}^{i-1} \left(1 - \Psi_{C_j}\right) \tag{8}$$

and the rate-based cost function $\mathcal{E}_R$ is obtained by replacing D_i with R_i, where R_i is the number of data symbols in the first i columns and D_i is the associated distortion. Ψ_{C_i} is the failure probability of the i^{th} codeword and $\Psi_{C_{L+1}} = 1$.

The RS2Da and RS2Db schemes perform a search for the optimal values of N_s and L_s, respectively, that explicitly define the budget allocation between the error protection and the erasure protection components. This search manifests itself in the quadratic complexities of

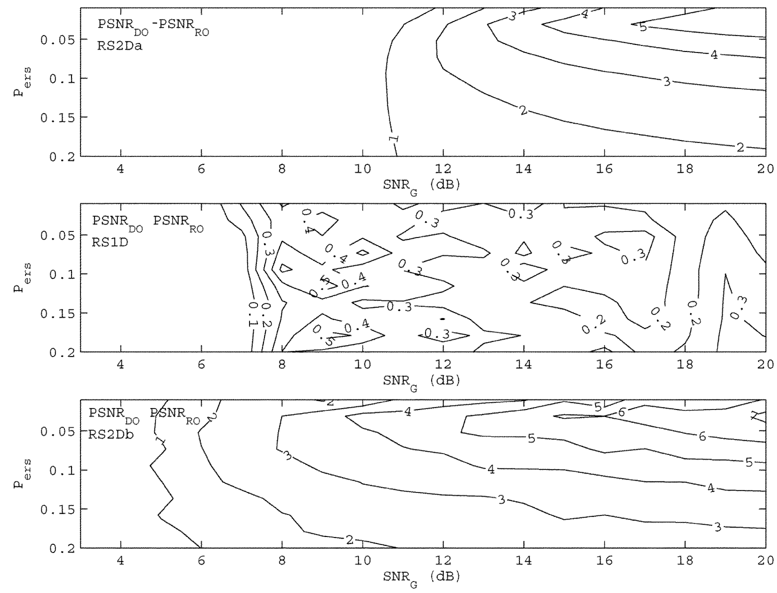

Fig. 9. Difference between the distortion-based and rate-based solutions for $N = 100$ and $L = 100$.

the corresponding optimizations. In the RS1D system, the probabilities Ψ_{C_i} incorporate the effects of both channel impairments into a single quantity. This facilitates an implicit budget allocation without the need for a search along the N or L coordinates. As a result, one can expect a linear complexity in N and L for the RS1D system. A close examination of (8) reveals that this is indeed the case. This cost function is identical to the cost function (2), that can be optimized with an $\mathcal{O}(NL)$ complexity using the ROPT, DOPT, or LS algorithms for the rate or distortion-based problems.

We note that the RS1D system unequally protects the source against both the errors and the erasures, whereas the RS2Da and RS2Db systems use equal protection for one of the components. Moreover, the RS coding across the packets interleaves the symbol errors of the RS1D system. Not only does this property improve the system performance for burst errors, but it also simplifies the failure rate calculations.

In what follows we derive an analytical expression for Ψ_C. An RS code with C parity symbols can correct up to $N_{\rm err}$ symbol errors and $N_{\rm ers}$ symbol erasures as long as $2N_{\rm err} + N_{\rm ers} \leq C$ [29]. As a result

$$\Psi_C = 1 - \sum_{i=0}^{N} p\left(N_{\rm err} \leq \left\lfloor \frac{C-i}{2} \right\rfloor | N_{\rm ers} = i\right) P_{\rm ers}(N, i). \quad (9)$$

In the above expression, $N_{\rm err}$ represents the number of non-overlapping symbol errors. It follows that

$$p\left(N_{\rm err} \leq \left\lfloor \frac{C-i}{2} \right\rfloor | N_{\rm ers} = i\right) = \sum_{j=0}^{\lfloor \frac{C-i}{2} \rfloor} p(N_{\rm err} = j | N_{\rm ers} = i). \quad (10)$$

If the packets are sufficiently long, the symbol errors can be considered independent, and as a result

$$p(N_{\rm err} = j | N_{\rm ers} = i) = \binom{N-i}{j} P_{\rm se}^{j} (1 - P_{\rm se})^{N-i-j}. \quad (11)$$

III. Numerical Results

In this section, we present the numerical results of the different coding schemes. We use the 512 × 512 gray-scale Lena image encoded progressively using the SPIHT encoder [2]. For the RS2Da and RS1D systems, we have used the ROPT and LS algorithms to find the rate and distortion-based solutions, respectively. The RS2Db system is optimized using the techniques of [15]. The peak signal-to-noise ratio (PSNR) is defined as $\mathrm{PSNR} = 10 \log_{10}(255^2/D)$, where D is the expected distortion. The total transmission budget is $B_T = LN = 10^4$ bytes, which translates into a transmission rate of 0.3 bits per pixel.

A. Memoryless Channels

For memoryless channels, the error and erasure rates P_b and $P_{\rm ers}$ define the operating conditions of the channel. Distortion optimization results for this channel are shown in Figs. 2–4 for different values of N and L. The top figure shows the optimality region of each algorithm. The symbol X represents the region in which the RS2Da algorithm outperforms the RS2Db and RS1D algorithms. The symbols + and O represent similar regions for the algorithms RS2Db and RS1D, respectively. The middle curve is a contour plot that shows the difference between the PSNR of the RS1D system and the PSNR of the best product code. The bottom curve is the contour plot of the best PSNR. The first observation from the above figures is that the optimality region is mainly determined by P_b. When N is small, both the RS2Db and RS1D schemes perform poorly. This can be explained by the fact that these two algorithms rely on the column code to correct both the errors and the erasures, while the RS2Da system uses the column code only for erasure protection. A small value for N means a weaker column code and a poor performance for the RS2Db and RS1D systems. The RS2Da system loses this advantage for a sufficiently large N. Fig. 3 shows that when N is large and L is small, the RS1D system outperforms the product codes for moderate channel conditions. In this case, the row codes of the product codes are weak and do not help much. Finally, we can see that the RS1D system is never optimal under severe channel conditions. In this case, the channel puts too much burden on a code that should correct both channel impairments.

From the above experiments, we conclude that the RS1D system provides a good performance for memoryless channels under moderate channel conditions if the number of packets is sufficiently high. Performance gains (if any) of the RS1D system are small (around 0.2 dB), but the optimization and encoding/decoding complexity is much lower.

B. Channels With Memory

The time-varying bit-error rate of a fading channel can be modeled using the two-state Gilbert-Elliott channel shown in Fig. 5. In our ex-

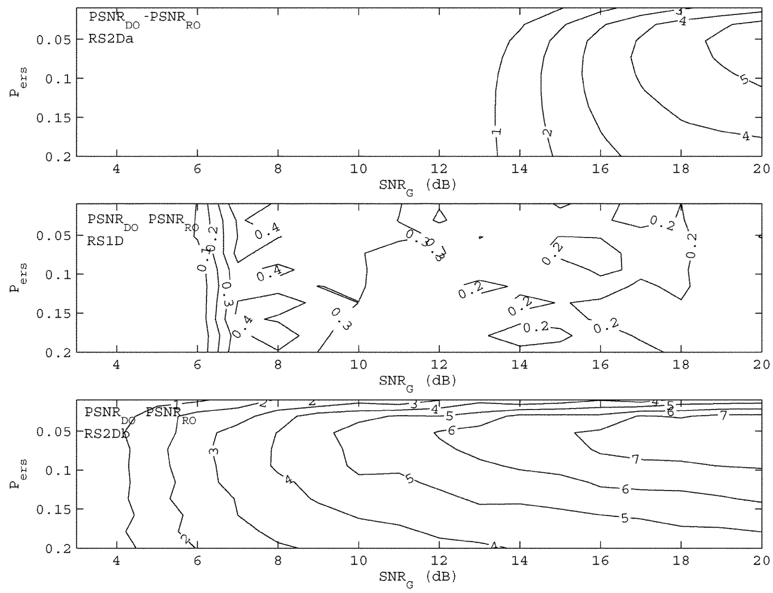

Fig. 10. Difference between the distortion-based and rate-based solutions for $N = 200$ and $L = 50$.

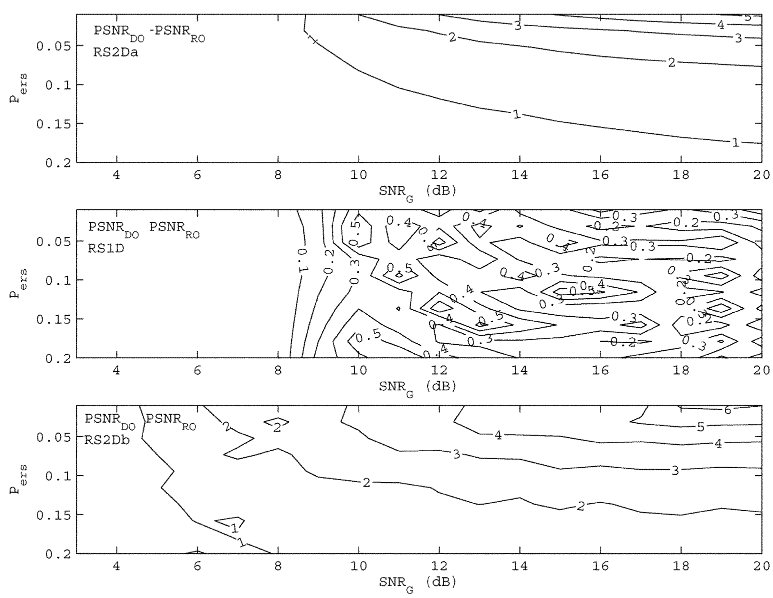

Fig. 11. Difference between the distortion-based and rate-based solutions for $N = 50$ and $L = 200$.

periments, we have used the transition probabilities of $\gamma = 0.99873$ and $\beta = 0.99$. These values represent an average burst length of 100 bits. Per-state bit-error rates are derived from the per state signal-to-noise ratios (SNRs) using [28], as follows:

$$\varepsilon_G = 0.5\left[1 - \sqrt{\mathrm{SNR}_G/(1+\mathrm{SNR}_G)}\right] \quad (12)$$

$$\varepsilon_B = 0.5\left[1 - \sqrt{\mathrm{SNR}_B/(1+\mathrm{SNR}_B)}\right] \quad (13)$$

where SNR_G and SNR_B represent the signal-to-noise ratios of the GOOD and BAD states, respectively. We have assumed that $\mathrm{SNR}_G = 10\mathrm{SNR}_B$. Packet erasures are modeled using a Gilbert channel. The Gilbert channel is essentially the same as the Gilbert-Elliot channel with constant values of $\varepsilon_G = 0$ and $\varepsilon_B = 1$. For this channel, $\gamma = 0.99873$ and β is used as a parameter to vary the average probability of packet erasures, P_{ers}. We have used the analytical expressions for $P_{\mathrm{err}}(n,m)$ and $P_{\mathrm{ers}}(n,m)$ from [27].

Distortion optimization results are shown in Figs. 6–8. The curves in the figures represent the same quantities as the ones in Section III-A. From these figures we see that the RS1D algorithm outperforms the product codes for moderate and high values of SNR_G, and the gain can be quite significant (up to 8 dB). This excellent performance can be attributed to fact that the row codes of both product codes suffer from bursts of errors. The situation is less severe for the RS2Db system, however, since a symbol that cannot be decoded (as a result of an error burst on its packet) gets a second chance of decoding by the erasure code, for which the error burst is interleaved. The redundancy of the row code, however, is wasted since this code cannot handle long error bursts. The RS1D system, on the other hand, never experiences an error burst because of the interleaving, and there is no loss associated with a row code. The interleaving gain was not realized in Section III-A because the channel was memoryless. Similar to the case of the memoryless channel, the RS1D system performs poorly when the channel conditions are severe. We also note from the figures that the RS2Da system is almost never optimal for channels with memory.

We now evaluate the rate-based performance of the three systems. In Figs. 9–11, we have shown the performance loss of the rate-based solution compared to the distortion-based solution. The top, middle and bottom curves show the loss for the RS2Da, RS1D, and RS2Db systems, respectively. We see from the figures that the performance loss for the RS1D scheme never exceeds 0.5 dB over the entire range. The loss in performance for the RS2Da and RS2Db systems, however, is quite significant and can be as large as 7 dB. This is true even when the product code is operating in its optimality region. As an example, consider Figs. 6 and 9. It can be seen that at $\mathrm{SNR}_G = 7\ \mathrm{dB}$, the RS2Db system provides the best distortion-based performance, while its rate-based solution is about 2 dB worse than the corresponding distortion-based solution.

From the above experiments, it can be concluded that the RS1D system provides an excellent solution for channels with memory when the channel conditions are moderate or good. Moreover, the RS1D scheme is robust against the source modeling errors, since it can achieve a source-independent, optimal rate-based solution that is very close to the distortion-based solution. Neither of the above statements apply to the product code schemes. Finally, we note that the RS2Db system includes an RS encoder/decoder which can be also used in the RS1D mode of operation. One can then implement the RS2Db system and adaptively switch to the RS1D mode of operation based on the channel conditions. This hybrid RS1D-RS2Db scheme achieves excellent results over the entire region of operation.

IV. Conclusion

We considered progressive bitstream transmission over hybrid channels that introduce bit errors as well as packet erasures. The existing transmission schemes were analyzed and extended to the case of a channel with correlated bit errors and correlated packet loss. A novel, low-complexity transmission system was then introduced and the associated rate and distortion-based optimization problems were formulated. We derived the analytical expressions for the decoding failure rates of the system and showed that the proposed optimization problem can be efficiently solved with the well-known techniques in the literature. Our numerical results showed that not only does the proposed technique achieve reductions in the complexities of the rate-distortion optimization and channel coding, but it also outperforms the existing solutions over a wide range of operating conditions. We also showed that our proposed technique yields a high-quality, optimal rate-based solution that is particularly useful when the source statistics are not known. It was numerically shown that the rate-based solution of our proposed scheme is within 0.5 dB of the corresponding distortion-based solution, while the existing product coding schemes lose up to 7 dB when optimizing the source coding rate instead of the distortion.

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