DISTORTION OPTIMIZED MULTIPLE CHANNEL IMAGE TRANSMISSION UNDER DELAY CONSTRAINTS

Wen Xu, Sheila S. Hemami

Cornell University, School of Electrical and Computer Engineering, Ithaca, NY 14853
email: {wxu, hemami}@ece.cornell.edu

ABSTRACT

When multiple channels are aggregated into a higher bandwidth logical channel, strategic product codes can be used to protect data against both channel losses and failures. Previous work in [1] has considered a delay-optimal partitioning scheme given pre-determined error correction codes (ECCs). In order to achieve an improved distortion performance, image bit streams can be partitioned together with an appropriate selection of ECCs based on channel conditions. This paper addresses the problem of jointly partitioning image data over multiple channels and selecting product coding rates from a finite set to minimize the decoding distortion under delay constraints. Experimental results show that the image quality degrades very slightly when the delay constraint decreases over a wide range, with a gain up to 4.5 dB achieved over that using a sequential optimization method.

1. INTRODUCTION

Using multiple parallel channels to transmit delay-sensitive images can provide a higher bandwidth logical channel [2] and thus more timely delivery than that using a single low-bandwidth channel. An example application is to transmit a large number of compressed images using parallel network paths for real-time viewing. Strategic forward error correction (FEC), such as product codes, can be applied to increase the robustness to channel losses and failures [3] [4] [5]. This paper considers the problem of jointly partitioning the image data and selecting ECC rates for multiple channels in order to achieve the minimum decoding distortion, when the channels have nonhomogeneous characteristics (bandwidth, packet loss rates, delays, probability of channel failures).

The FEC is applied both within and across the channels, following a similar structure proposed in [1]. The difference between the product codes used in [1] and those in [4] or [5] is that the former approach results in a "non-rectangular" product code, which assigns an unequal amount of FEC-encoded data to each channel taking into account different channel delays and bandwidth capabilities. The rectangular product code structure in the latter approaches, however, always allocates an equal amount of FEC-encoded data in each channel, which results in unbalanced delays in receiving the data due to unequal channel conditions. Another difference lies in the source and channel models assumed, where the former approach works with any compression methods under both channel packet losses and channel failures. The latter approaches assume progressive source coding and a channel failure model.

In this paper an optimization scheme is proposed for robust image transmission over multiple channels. This scheme jointly partitions a pre-encoded image bit stream into multiple substreams for multi-channel transmission and selects FEC coding rates in the product code structure from a finite set. Both the partitions and coding rates are optimized to achieve the minimum decoding distortion under delay constraints to receive the images. Since a joint optimization procedure is applied, the distortion performance can be improved compared to a sequential procedure [1], at the expense of increased computational complexity.

It is assumed that the image bit stream is transmitted over non-time-varying channels (portions of the bit stream can be similarly dealt with when the channel conditions vary). The channel characteristics are available to the optimization procedure, including bandwidths, delays, packet loss rates (PLRs), and probabilities of channel failure (PCFs).

This paper is organized as follows. Section 2 outlines the product coding structure. In Section 3, the joint optimization problem is formulated, with algorithms provided in Section 4. Experimental results are presented in Section 5.

2. CODING SCHEME

As shown in Figure 1, the source data is partitioned into k channels (denoted as S-channels). Additional $(N - k)$ failure-protection channels (denoted as FP-channels) carry cross-channel FEC coding redundancy. Data in each channel is further FEC-protected to combat packet losses within the channels. When fewer than $(N - k)$ channels fail, lost data in the failed channels can be recovered through cross-channel decoding. For notation simplicity, the S-channels are labelled $1 \ldots k$ and the FP-channels are labelled $(k+1) \ldots N$. More details of the coding scheme can be found in [1].

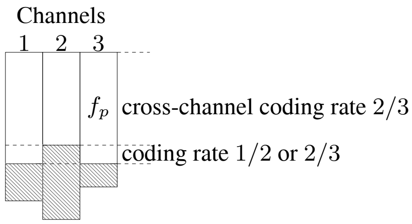

Fig. 1. Proposed product coding structure. $N = 3$. $k = 2$. Channels 1 and 2 are S-channels. Channel 3 is an FP-channel. f_p is the amount of cross-coding redundancy. The gray area indicates the column-FEC redundancy.

It is assumed that the decoding distortion of the images is monotonically decreasing when the amount of residual data loss decreases after product code decoding. This assumption requires that any data loss in the FEC-encoded data has the same contribution in the final distortion regardless of its location in the bit stream. It can be achieved when the image bit stream is randomly shuffled and interleaving is applied when using FEC.

3. PROBLEM FORMULATION

Assume that the FEC coding rates (defined as the ratio between the number of source symbols and that of code symbols) are selected from a finite set $\mathcal{R}$ of size m, i.e., $\mathcal{R} = \{r_1, r_2, \ldots, r_m\}$ with $r_1 > r_2 > \ldots > r_m$. An image bit stream or a portion of an image bit stream of size f_{total} is to be partitioned into fractions $\{\alpha_1, \ldots, \alpha_k\}$ ($\sum_{i=1}^{k} \alpha_i = 1$) to transmit in each of the S-channels. Image data and cross-channel coding redundancy (f_p as in Figure 1) are protected by coding rates $\bar{r}_s = \{r_{s1}, r_{s2}, \ldots, r_{sN}\}$ where $r_{si} \in \mathcal{R}$ for $i = 1, \ldots N$.

An end-to-end delay T_{limit}, defined as the sum of transmission delay (data bits/bandwidth) and propagation delay (including intermediate routing, relay, congestion, etc.), is given as a constraint due to application requirements or limited resources. This constraint can be further translated into N transmission delay constraints, i.e.,

$$T_i = T_{limit} - T_{prop,i}, \;\; 1 \le i \le N, \tag{1}$$

where $T_{prop,i}$ is the known propagation delay in channel i. Therefore, each channel is associated with a bandwidth-delay product constraint $L_i = BW_i \cdot T_i$ ($i = 1, \ldots, N$) on the maximum amount of data to assign to channel i, with BW_i denoting the bandwidth of channel i.

Image distortion can be measured according to different metrics, such as MSE or a subjective measure. Regardless of specific distortion metrics, the optimization problem can be formulated as

$$\min_{\alpha_i, r_{si}} \text{Distortion}(\alpha_i, \bar{r}_s) \tag{2}$$

$$\text{subject to } f_{total} \frac{\alpha_i}{r_{si}} \le L_i, \;\; 1 \le i \le N,$$

where α_i ($i > k$) is equal to the maximum partition fraction in the k S-channels, i.e.

$$\alpha_i = \max_{1 \le j \le k} \alpha_j, \;\; k < i \le N. \tag{3}$$

As mentioned above, the relation between the image distortion and the residual loss rate after FEC decoding is monotonic. The formulation can thus be simplified to minimize the residual loss rate. Denote the residual loss rate in each of the S-channels after product decoding as $p_{res,i}(\bar{r}_s)$. The overall residual loss rate is

$$p_{res}(\bar{r}_s) = \sum_{i=1}^{k} \alpha_i \cdot p_{res,i}(\bar{r}_s), \;\; 1 \le i \le k. \tag{4}$$

Note that calculating or estimating $p_{res,i}$ for a certain coding rate assignment $\bar{r}_s$ depends on the specific ECCs used in the application. An illustrating example using Reed-Solomon codes is given in Section 4.

4. ALGORITHMS

In this section algorithms are provided to find the optimal partitions and channel coding rates as well as fast approximate solutions to the above formulation.

It can be shown that in order to minimize (4) subject to constraints in (2), the following results hold (*): *Given $p_{res,i}(\bar{r}_s)$, the minimum loss rate is achieved when data is allocated starting from the channel with the smallest $p_{res,i}$.*

Without loss of generality, assume the S-channels are sorted in order of increasing $p_{res,i}$ and only channel 1 to l ($1 \le l \le k$) have source data allocated. It is straightforward to obtain the partitions as determined by (*)

$$\alpha_i = \begin{cases} \dfrac{L_i r_{si}}{f_{total}} & i = 1, \ldots, l-1 \\ 1 - \dfrac{\sum_{i=1}^{l} L_i r_{si}}{f_{total}} & i = l. \end{cases}$$

Therefore the optimal algorithms involve a search within possible coding rates, their resulting $p_{res,i}$ and the corresponding partitions for the minimum overall loss rate. In the following, approximate algorithms are presented for two classes of channel conditions.

4.1. Without Channel Failure Protection ($k = N$)

When there is no failure protection because of reliable connections, all N channels are used to transmit the image data. The optimal algorithm has a worst-case complexity of $O(Nm^N)$ by searching within all possible coding rates for each channel and partitioning accordingly. The residual loss rate for each channel $p_{res,i}$ is directly determined by its channel's original loss rate $p_{loss,i}$ and its coding rate assignment. Using Reed-Solomon codes (n, l), for example, results in

$$p_{res,i} = \sum_{j=n-l+1}^{n} \frac{j}{n} \binom{n}{j} p_{loss,i}^{j} (1 - p_{loss,i}^{n-j}). \qquad (5)$$

where packet losses are considered as erasures.

An approximate greedy algorithm is designed to reduce the computation complexity. The algorithm starts with the channels' original loss rates. It increases the coding rate for one channel at a time if the increase reduces the overall residual loss rate. Then the data is partitioned following (*). The algorithm is summarized as follows. Initialize the minimum overall loss rate $p_{res,min} = 1$.

1. Initialize $j = 1$.
2. Try to decrease channel j's coding rate to the next one within the finite set $\mathcal{R}$, while maintaining the coding rate assignments for the other channels. Denote this trial of coding rate assignment as $\bar{r}_s^{(j)}$.
3. Calculate and record the total residual loss rate $p_{res}(\bar{r}_s^{(j)})$ (see (4)) by partitioning the source date according to (*). If the partition violates the delay constraints, delete this trial record. Restore the coding rate for channel j to its previous value. If $j < N$, set $j = j + 1$, go to step 2.
4. Sort $p_{res}(\bar{r}_s^{(j)})$ ($j = 1, \ldots, N$) in ascending order. Accept the first coding rate assignment (assume channel j^*) if it is no greater than the current $p_{res,min}$. Otherwise, stop.
5. Update the coding rate assignment for channel j^* and the minimum residual loss rate $p_{res,min} = p_{res}(\bar{r}_s^{(j)})$. Go to step 1.

This algorithm has a worst-case complexity of $O(mN^2)$.

4.2. With Channel Failure Protection ($k < N$)

When there are failure protection channels, the calculation of the residual loss rate becomes more complicated. $p_{res,i}$ depends on all the channels' loss rates and coding rate assignments. Similar algorithms, though, can be applied to find the optimal solution taking into account (3). The algorithms (optimal or greedy) have an additional search of the S-channels out of N channels, which results in a complexity factor of $O(\binom{N}{k})$.

In the following $p_{res,i}$ in terms of the channel loss and failure rates is expressed using RS-codes with $N = 3$, $k = 2$ due to space. Since the probability that two or more channels fail is negligible (otherwise more than one failure protection channel would have been selected), the overall probability of residual losses[1] after cross-channel decoding (denoted as RL) can be approximated as

$$\begin{aligned} Pr(\text{RL}) &= Pr(\text{RL}|\text{no S-chan.fail})Pr(\text{no S-channel fail}) \\ &+ \sum_{c=1}^{2} Pr(\text{RL}|c\text{-th chan. fails})Pr(c\text{-th channel fails}). \end{aligned}$$

Assuming that the residual lost packets after column decoding in the received channels are uniformly distributed, the $Pr(\text{RL})$ given that the c-th ($1 \leq c \leq k = 2$) channel has failed can be approximated as

$$\begin{aligned} Pr(\text{RL}|c\text{-th channel fails}) &= (p_{\bar{c}} + (1 - p_{\bar{c}})p_3)\alpha_c \\ &\quad + p_{\bar{c}}\alpha_{\bar{c}}, \end{aligned} \qquad (6)$$

where $\bar{c}$ is the complement of c in the S-channel set, p_i denotes the residual loss rate in channel i before cross-channel decoding (calculated according to (5)). By combining the multiplying factors for α's, the following can be obtained:

$$\begin{aligned} p_{res,c} &= q_{f,c} * (1 - p_{f,\bar{c}} * p_{f,3}) * p_c \\ &\quad + p_{f,c} * p_{f,\bar{c}} * q_{f,3} * q_3 * p_{\bar{c}} \\ &\quad + p_{f,c} * q_{f,3} * p_3 - p_{f,c} * p_{f,\bar{c}} * q_{f,3} * p_3 \end{aligned} \qquad (7)$$

where p_f is the channel failure probability, $q_f = 1 - p_f$. This derivation can be easily extended to different values of N and k. Note that the mapping from the original loss rates and channel failure rates to the residual loss rates at different coding rate assignments can be pre-computed and saved in a look-up table, whether there is any failure protection or not.

5. EXPERIMENTAL RESULTS

5.1. Comparison of Algorithms

A number of experiments have been performed to compare the performances between the optimal complete search algorithm and the approximate greedy algorithm under randomly generated channel conditions and constraints. Three channels are used to transmit a 0.1 Mbit stream. The channel parameters are randomly selected for each run as follows: without failure protection, bandwidth-delay constraints L's vary within [50, 100] kbits, and packet loss rates (PLRs) vary within [10%, 20%]; when there is failure protection

[1] The loss rates are assumed equivalent to probability of losses.

Table 1. The estimated parameters and required redundancy factors for the channels using one channel failure protection.

Channel i	BW_i(kbps)	$\tau_{prop,i}$(msec)
$i = 1$	99	50
$i = 2$	150	40
$i = 3$	210	80

using one channel, L's vary within [50, 120] kbits, PLRs within [10%, 20%] and channel failure probability within [0, 0.1].

The approximation algorithm achieves a reasonable fidelity to the optimal solutions. Among 100 random runs without failure protection ($k = N$), the greedy algorithm finds the exact optimal solution in 99 runs. The ratio between the residual loss rate of the approximation and that of the optimal algorithm is 1.20 for the single non-optimal solution. When there is failure protection ($k = 2, N = 3$), the greedy algorithm finds the optimal in 59 runs with an average residual loss rate ratio of 2.89 to that of the optimal for the 41 non-optimal results.

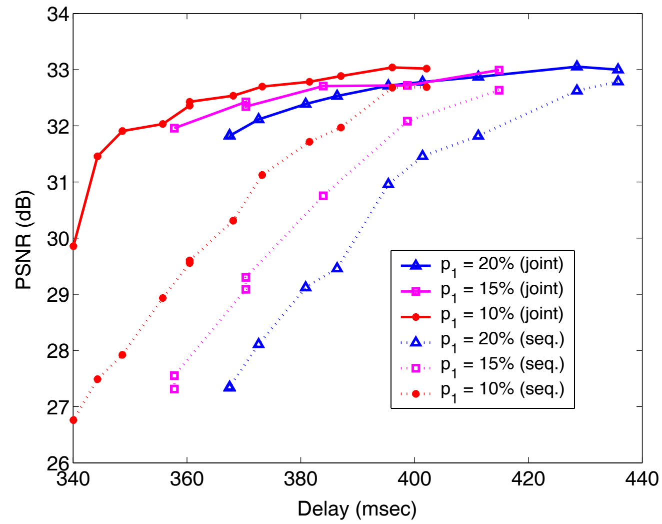

Fig. 2. Average decoding PSNR (over 1500 runs) of the Lena image encoded in JPEG-2000 at 0.25bpp vs. the delay constraint using the proposed coding scheme (BW = [99 kbps, 150 kbps, 210 kbps], PLR =[{10%, 15%, 20%}, 15%, 13%], τ_{prop} = [50 msec, 40 msec, 80 msec], $p_{fail} = 0.05$ for all the channels), the code length $n = 31$.

5.2. Comparison with Sequential Optimization under Different Delay Constraints

Experiments have been performed to optimize image qualities for varying delay constraints. For a comparison with previous results in [1] when the selection of coding rates is pre-determined, the experiments are performed under the same channel conditions as in Table 1. Figure 2 shows the average PSNR of the decoded image versus the delay constraints achieved by the fast approximate algorithm given in Section 4 over 1500 independent runs. The image (lena) is encoded in JPEG-2000 at 0.25bpp using JasPer [2] software. Reed-Solomon codes with a length of 31 are used. Three PLRs for channel 1 are considered, 20%, 15%, and 10%. The results in [1] are repeated in Figure 2.

Under these conditions, a maximum gain of 4.5 dB can be obtained at a low delay constraint of 367 msec, while a gain of 0.2 dB is achieved at a high delay constraint of 436 msec. Additionally, the selection of redundancy factors adapts to the variation in channel PLRs. Under the same delay constraints, a higher image quality is achieved when channel 1 has a smaller PLR because smaller redundancy factors have been selected. The differences in PSNR are below 1 dB, though, when PLR of channel 1 varies from 10% to 20%.

An investigation of the redundancy factors (defined as $(n - l)/l$ for a (n, l) RS-code) selected at the varying delay constraints under the above channel conditions is also performed using both the optimal and the fast algorithms. The fast algorithm is able to achieve the optimal solutions, except at two delay values (340.0 msec, 344.3 msec). The selected redundancy factors demonstrate a general increasing trend when the delay constraint is increased except channel 1 , which has a slight decrease from 0.41 to 0.35 at a delay constraint of 402.1 msec. Higher protections are therefore provided when resources become more abundant.

[2] http://www.ece.uvic.ca/~mdadams/jasper/

6. REFERENCES

[1] W. Xu and S. Hemami, "Delay-optimized robust transmission of images over multiple channels," in *Proc. ICME*, Baltimore, MD, Jul. 2003, vol. 1, pp. 285–8.

[2] P. H. Fredette, "The past, present, and future of inverse multiplexing," *IEEE Commun. Magazine*, vol. 32, no. 4, pp. 42–6, Apr. 1994.

[3] Y. Wang and Q. Zhu, "Error control and concealment for video communication: a review," *Proc. IEEE*, vol. 86, no. 5, pp. 974–97, May 1998.

[4] R. Puri and K. Ramchandran, "Multiple Description Source Coding Using Forward Error Correction Codes," in *Proc. 33rd ACSSC*, Pacific Grove, CA, Oct. 1999, pp. 342–6.

[5] A. E. Mohr, E. A. Riskin, and R. E. Ladner, "Generalized Multiple Description Coding through Unequal Loss Protection," in *Proc. ICIP*, Kobe, Japan, Oct. 1999, vol. 1, pp. 411–5.