Adaptive Rate Allocationfor Unequal Budget Images Transmissionover Time-Varying BSC Channels

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Abstract

An efficient rate allocation algorithm for the progressive transmission of multiple images with unequal budgets over time-varying BSC channels is proposed. The algorithm is linear-time in the number of transmitted packets per image and its rate allocation solution for each image can achieve a performance equal or very close to the distortion optimal solution for that image. Our simulations for the transmission of images, encoded by embedded source coders, over the binary symmetric channel (BSC) show that with very low complexity the proposed algorithm successfully adapts the channel code rates to the changes of the channel parameter

Key words:progressive transmission, Joint Source Channel Coding, time-varying channels

1. Introduction

Embedded bit streams are generated by many source coders to allow the progressive reconstruction of the source at different bit rates from the prefixes of a single bit stream. In a packet transmission system, such bit streams are packetized and transmitted over noisy channels. To protect the packets against channel errors, forward error correction (FEC) is often employed in a joint source-channel coding (JSCC) framework with unequal error protection (UEP) [1]-[10].

As an essential part of a JSCC scheme with FEC and UEP, one would have to solve the problem of assigning channel codes of different rates to different source packets under a constraint on the total bit budget B or the total transmission rate R. This problem is called *rate allocation*. Well-known cost functions for rate allocation are the average mean squared error (MSE) distortion, the average peak signal-to-noise-ratio (PSNR), and the average number of correctly received source bits [3]-[5]. We indiscriminately refer to the corresponding optimal solutions for the first two cost functions as *distortion optimal*, and to the optimal solution for the last cost function as *rateoptimal*. While the rate optimal solution has a lower complexity and enjoys other advantages such as independence from the source, e.g., the image, and from the source coder performance, it results in some performance loss compared to the distortion optimal solution [3], [4]. Distortion and rate optimal solutions for variable-length transmitted packets were proposed in [3] with $O(R^2)$ and $O(R)$ complexities, respectively. An efficient distortion optimal solution for fixed-length transmitted packets was recently derived in [1]. The complexity of obtaining this solution is $O(N^2)$, where N is the number of transmitted packets. Suboptimal approaches for finding the distortion optimal solution were also proposed in [2], [4], [6], [8].Hamzaoui *et al.* [4] proposed a method, called local search approach, for finding a local minimum solution for the distortion optimal FPP, starting from a rate optimal solution. Also a heuristic graph (*Beam*) search method was proposed by Fresia *et al.* [8], in which they considered only *q(=3)* best path-queue in each iteration of the search.

In this work, we consider the progressive transmission of multiple embedded bit streams over noisy channels. We assume that the channel conditions can change with time but are known at both the transmitter and the receiver. The time-varying model is a natural choice for wireless applications. We also assume that the bit streams are transmitted in sequence and that the channel conditions remain unchanged over the transmission period of each bit stream but may change from one bit stream to the next. The goal is to find the distortion optimal rate allocation solution for each bit stream in a fixed-length transmitted packet scenario with a complexity considerably lower than that of the algorithm of [1]. To achieve this, we propose to first find a distortion optimal solution for the first bit stream using the algorithm of [1], and then adaptively modify this solution for the subsequent streams using a linear-time algorithm.

We test our algorithm for the transmission of multiple embedded images over a time-varying binary symmetric channel (BSC) and observe that under a wide variety of channel conditions, the algorithm converges to the distortion optimal solution with very low complexity. Transmission of multiple images over the BSC has also been studied in [7], where the authors solve the JSCC problem jointly for all the images with a constraint on the total available bandwidth. The work in [7] however is based on a static channel model where the channel parameter is fixed during the whole transmission.

2. System Description

We consider the transmission of multiple compressed embedded bit streams over a noisy channel with constraint on the total bit budgets of bit streams. Each source bit stream S_j is identified by its distortion-rate function $D_j(i)$, which provides the distortion associated with the first *i* bits of the stream. A set of channel codes with rates $\boldsymbol{r} = \{r_1, r_2, \cdots, r_M\}$is used to protect the source packets. All channel codes have the same coded block length *n* and different information block lengths $k_1 < k_2 < \cdots < k_M$, where $k_i = n \times r_i$ for $i = 1, \cdots, M$. Each information block consists of L overhead bits which would include a cyclic redundancy check code (CRC) and the information about the channel coding rates. The size of the source packet is then equal to $k_i - L$. We use the notation $P_e^j(r_i)$ to denote the probability that a source packet of the bit stream S_j protected by the channel code of rate r_i is decoded erroneously at the receiver. The packet error rates are functions of channel conditions and can change for the transmission period of different bit streams. This dependency is emphasized through the index j in $P_e^j(r_i)$. The side information about the channel conditions is estimated at the start of the transmission of each bit stream at the receiver and is fed back to the transmitter. It is assumed that the channel variations through the transmission of one bit stream are negligible. Given the available total bit budget for each bit stream, B_j,the total number of transmitted packets is determined by $N_j = \left\lfloor {}^{B_j}/_{n} \right\rfloor$ ($\lfloor x \rfloor$ denotes the largest integer less than or equal to *x*). The rate allocation algorithm at the transmitter is responsible for finding the distortion optimal solution for each bit stream S_j by assigning optimal rates $R_{j1}, \cdots, R_{jN_j}$, $R_{ji} \in \boldsymbol{r}, \forall i$, to the transmitted packets to minimize the average distortion for S_j. At the receiver, the packets for each bit stream are received and decoded and the source is reconstructed with increasing accuracy as more packets arrive. We assume that the system is able to detect errors with probability one and that we discard the first erroneous packet and all subsequent packets for each bit stream. The cost function (average distortion) for the rate allocation algorithm of S_j is given by

$$D^j\left(R_{j1},\cdots,R_{jN_j}\right) = D_0^j P_1^j + \sum_{k=1}^{N_j-1} D_k^j P_{k+1}^j \prod_{i=1}^{k}\left(1-P_i^j\right) + D_{N_j}^j \prod_{i=1}^{N_j}\left(1-P_i^j\right) \quad (1)$$

Where $D_k^j = D_j\left(\sum_{i=1}^{k}\left(R_{ji}n - L\right)\right)$, $1 \le k \le N_j$, is the distortion associated with the erroneous ($k+1$)th packet (assuming all the previous packets have been decoded correctly), D_0^j is the source variance, and $P_i^j = P_e^j\left(R_{ji}\right)$is the error probability of the i th packet of S_j, which is a function of both the rate R_{ji} and the channel conditions during the transmission of S_j.

3 Proposed Rate Allocation Algorithm

Consider the sequence of rates $\vec{R} = (R_1,\cdots,R_N) \in \boldsymbol{r}^N$. To describe the proposed rate allocation algorithm, we need the following definitions:

Definition 1: A sequence $\vec{R'} \in \boldsymbol{r}^N$is called a *neighborof* $\vec{R}$*at position i*, $1 \le i \le N$, if $R'_j = R_j$ for every $1 \le j \le N, j \ne i$, and$R'_i \ne R_i$.

Definition 2: A sequence $\vec{R'}$is called an *adjacent neighbor of* $\vec{R}$ *at position i* if it is a neighbor of $\vec{R}$at position *i*, and if $R'_i = r_{k_i \pm 1}$, where $r_{k_i} = R_i$. If $R'_i = r_{k_i+1}$, we call $\vec{R'}$the *adjacent upper neighbor of*$\vec{R}$ *at position i,* and denote it by $N^{i+}\left(\vec{R}\right)$. Otherwise, we call it the *adjacent lower neighbor of*$\vec{R}$ *at position i*, and denote it by $N^{i-}\left(\vec{R}\right)$.

For the transmission of multiple images, we assume that the distortion optimal rates for the first image are obtained, for example by using the algorithm of [1]. We then propose the following algorithm to derive the rates for the subsequent images. Initially, we assume fixed budget *B* (and transmitted packets *N*) for all images, similar to previous work in [11] and then extend it to unequal budgets case.

Algorithm 1:Rate Allocation Algorithm

1. Initialization:
   $\vec{R}_j = \vec{R}_{j-1}$, where $\vec{R}_{j-1}$is the rate assignment for the previous image; $I_u = N$; $Q = 0$.
2. Let $r = R_{jI_u}$ and use I_l to denote the smallest index *i* for which $R_{ji} = r$.
3. Set $I = I_u$.
4. If $D^j\left(N^{I+}\left(\vec{R}_j\right)\right) < D^j\left(\vec{R}_j\right)$, then
   $\vec{R}_j = N^{I+}\left(\vec{R}_j\right)$ and $I = I - 1$,
   If $I < I_l$, go to Step 9; else repeat Step 4.
   Else, go to Step 9.
5. If $K_l \le N$, then
   Let $r = R_{jK_l}$ and use K_u to denote the largest index *i* for which $R_{ji} = r$.
   Else, go to Step 8.
6. Set $I = K_l$.
7. If $D^j\left(N^{I-}\left(\vec{R}_j\right)\right) < D^j\left(\vec{R}_j\right)$, then
   $\vec{R}_j = N^{I-}\left(\vec{R}_j\right)$ and $I = I + 1$,
   If $I > K_u$, then $K_l = K_u + 1$ and go to Step 5; else repeat Step 7.
   Else,
   If $K_u < N$, then $K_l = K_u + 1$ and go to Step 5; else go to Step 8.

8. If $Q = 1$, stop.
9. If $I_l > 1$, then
$I_u = I_l - 1$, and go to Step 2;
Else,
$K_l = I_l$, $Q = 1$, and go to Step 5**.**

At steps 4 and 7, the proposed algorithm searches for the distortion optimal rate assignment in the adjacent upper and lower neighborhoods of the current rate assignment, respectively. The search of the adjacent upper neighborhoods is performed first and is based on decreasing order of the position index. This is followed by the search of the adjacent lower neighborhoods in an increasing order of the position index. This backward-forward search has a linear complexity in N and can be repeated multiple times if needed.

In order to extend the proposed rate allocation algorithm to the unequal budgets case, only the initial step of $\vec{R}_j$ approximation is modified:

1.1) Set $\vec{R}_j = null$; $N_j = N$;$I_u = N_j$; $Q = 0$.
1.2) If $N_j = N_{j-1}$, then
Set $\vec{R}_j = \vec{R}_{j-1}$
1.3) If $N_j < N_{j-1}$, then
a) Set $= \left\lfloor \frac{N_{j-1}}{N_j} \right\rfloor$.
b) For $(1 \le i \le N_j)$& $(C(i-1) < N_{j-1})$,
Set $\vec{R}_j(i) = \vec{R}_{j-1}(C(i-1)+1)$.
1.4) If $N_j > N_{j-1}$, then
a) Set $C = \left\lfloor \frac{N_j}{N_{j-1}} \right\rfloor$.
b) For $(1 \le i \le N_j)$& $((i-1) < CN_{j-1})$,
Set $\vec{R}_j(i) = \vec{R}_{j-1}\left(\left\lfloor \frac{i-1}{C} \right\rfloor + 1\right)$
1.5) If $length(\vec{R}_j) < N_j$, then
Repeat last item of $\vec{R}_j$, $(N_j - length(\vec{R}_j))$ times.
1.6) if $length(\vec{R}_j) > N_j$, then
Discard last $(length(\vec{R}_j) - N_j)$ items from $\vec{R}_j$.
1.7) Apply steps of algorithm 1 from second step.

The proposed modifications indeed re-scale$\vec{R}_{j-1}$ in order to make a suitable initial approximation for $\vec{R}_j$ by puncturing or extending of $\vec{R}_{j-1}$ on the basis of image transmission budget decreasing or increasing, respectively. We show the capability of this simple algorithm through simulation in the next section

4. Simulation Results and Discussions

To study the performance of the proposed rate allocation algorithm, we consider the transmission of multiple gray scale images with size 512×512 and 8 bits per pixel (bpp) over a time-varying BSC. The images are “Barbara”, “Goldhill”, “Lena”, “Boat”, “Mandrill”, “Peppers”, “Washsat”, and “Zelda”. For the rest of the paper, these images are numbered from one to eight, respectively. Each source image is compressed by the set partitioning in hierarchical trees (SPIHT) coder of [12]. For the error protection, we arbitrarily choose the sequence of seven irregular repeat-accumulate (IRA) codes designed

in [6]. We assume that the probability of error detection is one and consider the exact same packetization strategy, including CRC, as in [6]. In our simulations, we also ignore the bandwidth required for channel estimation. For each image, knowing the channel parameter ε and the total bit budget *B*, the rate allocation algorithm assigns the channel coding rates. The end-to-end peak signal-to-noise ratio is then calculated as the measure of performance by $PSNR = 10log_{10}\frac{255^2}{D}$,
where *D* is the average distortion given by (1).

In the first set of experiments, we consider the transmission of the 8 images with the same budget, *B*, in random order, assuming that the channel parameter ε can only change by ±0.01 randomly for the transmission of adjacent images. In these experiments, we allow ε to vary in the range [0.01,0.1], starting from a random value in the interval for the transmission of the first image in the sequence. Different values of *B*, i.e., 0.252 bpp, 0.505 bpp and 0.994 bpp are also examined. Our experiments show that in every scenario, just a single application of our proposed algorithm converges to the distortion optimal solution for every image.

In the second set of experiments, we allow ε to vary faster by step sizes as large as 0.09. Simulation results for two different image and channel parameter sequences, and for *B* = 0.252 bpp, 0.505 bpp and 0.994 bbp are given in Tables 1 to 3, respectively. These results show that while a single application of the proposed algorithm may not always be able to properly adapt the rates for large variations in the channel parameter, the algorithm is still capable of tracking the optimal solution if the channel variations subside. In other words, the algorithm is robust against error propagation. Moreover, for fast channel variations, where a single application of the algorithm is incapable of achieving the distortion optimal solution, our experiments show that multiple applications of the algorithm, each starting from the rate assignment of the previous round, always converge to the distortion optimal solution. Our empirical results show that roughly $\left\lfloor\frac{|\varepsilon_c-\varepsilon_p|}{0.05}\right\rfloor$recalls of the algorithm is required, where$\varepsilon_c$and$\varepsilon_p$are the current and the previous values of the channel parameter, respectively.

a)First Experiment										
Image Sequence	1	2	3	4	5	6	7	8	6	3
Channel Parameter	0.04	0.08	0.1	0.08	0.04	0.07	0.05	0.03	0.02	0.01
Distortion Optimal PSNR(dB)	25.62	28.50	30.23	27.29	21.72	29.73	32.62	35.06	31.38	33.39
Proposed Algorithm PSNR (dB)	-	28.50	30.23	27.29	21.72	29.73	32.62	35.06	31.38	33.39
ΔPSNR (dB)	-	0	0	0	0	0	0	0	0	0
b) Second Experiment										
Image Sequence	6	2	4	5	8	3	2	1	7	8
Channel Parameter	0.01	0.1	0.01	0.07	0.03	0.04	0.01	0.03	0.04	0.05
Distortion Optimal PSNR(dB)	31.88	27.95	29.34	21.40	35.06	31.98	30.06	25.99	32.77	34.57
Proposed Algorithm PSNR (dB)	-	27.95	29.34	20.31	35.06	31.98	30.06	25.99	32.77	34.57
ΔPSNR (dB)	-	0	0	1.09	0	0	0	0	0	0

Table 1. PSNR comparison of values for the distortion optimal rate assignment and the solution of the proposed algorithm for two different random sequences of images and channel parameters (*B* = 0.252 bpp, and fast varying channel)

a)First Experiment										
Image Sequence	1	2	3	4	5	6	7	8	6	3
Channel Parameter	0.04	0.08	0.1	0.08	0.04	0.07	0.05	0.03	0.02	0.01
Distortion Optimal PSNR(dB)	28.85	30.44	33.30	29.88	23.41	32.75	34.05	37.80	34.21	36.73
Proposed Algorithm PSNR (dB)	-	30.44	33.30	29.88	23.41	32.75	34.05	37.80	34.21	36.73
ΔPSNR (dB)	-	0	0	0	0	0	0	0	0	0
b) Second Experiment										
Image Sequence	6	2	4	5	8	3	2	1	7	8
Channel Parameter	0.01	0.1	0.01	0.07	0.03	0.04	0.01	0.03	0.04	0.05
Distortion Optimal PSNR(dB)	34.60	30.00	32.60	22.78	37.80	35.14	32.51	29.30	34.20	37.34
Proposed Algorithm PSNR (dB)	-	30.00	32.60	22.61	37.80	35.14	32.51	29.30	34.20	37.34
ΔPSNR (dB)	-	0	0	0.17	0	0	0	0	0	0

Table 2. PSNR comparison of the distortion optimal rate assignment and the solution of the proposed algorithm for two different random sequences of images and channel parameters (*B* = 0.505 bpp, and fast varying channel)

a)First Experiment										
Image Sequence	1	2	3	4	5	6	7	8	6	3
Channel Parameter	0.04	0.08	0.1	0.08	0.04	0.07	0.05	0.03	0.02	0.01
Distortion Optimal PSNR(dB)	32.45	32.80	36.30	32.92	25.75	35.33	36.10	40.37	36.61	39.90
Proposed Algorithm PSNR (dB)	-	32.80	36.30	32.92	25.75	35.33	36.10	40.37	36.61	39.90
ΔPSNR (dB)	-	0	0	0	0	0	0	0	0	0
b) Second Experiment										
Image Sequence		2	4	5	8	3	2	1	7	8
Channel Parameter	0.01	0.1	0.01	0.07	0.03	0.04	0.01	0.03	0.04	0.05
Distortion Optimal PSNR(dB)	37.01	32.40	37.00	24.93	40.37	38.40	35.76	33.12	36.22	39.63
Proposed Algorithm PSNR (dB)	-	32.40	37.00	24.80	40.37	38.40	35.76	33.12	36.22	39.63
ΔPSNR (dB)	-	0	0	0.13	0	0	0	0	0	0

Table 3. PSNR comparison of the distortion optimal rate assignment and the solution of the proposed algorithm for two different random sequences of images and channel parameters (B = 0.994 bpp, and fast varying channel)

In the third set of experiments, transmission budgets of the images are allowed to vary in the range [0.125bpp, 1bpp]. Table 4 shows the results. It shows that the proposed algorithm works equally well in the variable, as well as, fixed budgets cases.

In order to compare the performance of the proposed rate allocation algorithm with those of local search(LS)[4] and Beam search(BS)[8], their PSNR differences and CPU time ratios with respect to the proposed method are shown in Table 5. It is observed that the PSNR values of LS are the same as those of the proposed method. However, since local search algorithm needs an extra time for rate optimal solution, its CPU time is greater than the proposed algorithm. On the other hand, the CPU times of BS and the proposed algorithm are almost similar, but since the three saved path-queue may not be sufficient in general, it is observed that PSNR performances are poorer than the proposed algorithm in some cases.

The complexity of the proposed algorithm can be reduced to roughly half by performing only the backward or the forward search if $\varepsilon_c < \varepsilon_p$ or $\varepsilon_c > \varepsilon_p$, respectively. This can however result in some performance degradation for fast channel variations.

Image Sequence	6	2	4	5	8	3	2	1	7	8
Image Budget(bpp)	0.253	0.505	0.632	0.158	1.01	0.947	0.411	0.758	0.789	0.632
Channel Parameter	0.01	0.1	0.01	0.07	0.03	0.04	0.01	0.03	0.04	0.05
Distortion Optimal PSNR(dB)	31.88	29.12	33.79	20.77	40.47	37.06	30.92	31.43	35.53	38.07
Proposed Algorithm PSNR (dB)	-	29.12	33.79	20.77	40.47	37.06	30.92	31.43	35.53	38.07

Table 4. PSNR comparison of the distortion optimal rate assignment and the solution of the proposed algorithmfor a random sequence of images (with different budgets) and channel parameters

Image sequence	6	2	4	5	8	3	2	1	7	8
Image Budget(bpp)	0.253	0.505	0.632	0.158	1.01	0.947	0.411	0.758	0.789	0.632
Channel Parameter	0.01	0.1	0.01	0.07	0.03	0.04	0.01	0.03	0.04	0.05
ΔPSNR (dB) of LS*	-	0	0	0	0	0	0	0	0	0
ΔPSNR (dB) of BS*	-	0	0	0.04	0	1.26	0	0	0.19	0
Relative CPU time of LS*	-	1.23	1.52	1.10	1.76	1.67	1.31	1.54	1.58	1.51
Relative CPU time of BS*	-	1.15	1.08	1.17	0.91	0.93	1.12	0.99	0.98	1.05

* Difference with the proposed rate allocation algorithm is reported

Table 5.PSNR and CPU times Comparison of the [4] and the [8] with the proposed algorithm for random sequence of images of Table 4.

5. Conclusions

A low-complexity rate allocation algorithm for the transmission of multiple embedded bit streams over time-varying BSC channels is proposed. The algorithm was tested for the transmission of images encoded by SPIHT. It was demonstrated through simulations that for both slow and fast variations of the channel parameter, the proposed algorithm can perfectly track the distortion optimal rate assignment. While for slow variations of the channel, an iteration of the algorithm is often enough, for faster variations, multiple iterations may be required to achieve the distortion optimal solution. It is worth noting that while the fastest distortion optimal rate allocation algorithm has quadratic complexity in the number of transmitted packets, *N*, the complexity of the proposed algorithm is linear in *N*.

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