Robust Image Compression for Transmission over Time-Varying Channels

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Abstract

We propose a rate-distortion (RD) approach to the optimization of image coding for transmission over time-varying channels. The information available about the channel error rate, is used to adapt the joint source-channel coding (JSCC) scheme. We focus on structured JSCC schemes to obtain realizations with feasible complexity. The image is hierarchically quantized, followed by unequal channel error protection matched to the importance of the bits. We allow the use of variable length codes in the source coder which provides adaptation to image statistics and higher compression performance. At the same time, we maintain error resilience by sending the synchronization information error free (through heavy protection). We show that efficient rate-distortion performance can be achieved by optimizing the overall system for the target rate and channel conditions. We present simulation results obtained on coding images for time-varying channels, which show that RD optimized JSCC schemes substantially outperforms conventional fixed length JSCC and can gain more than 6 dB in PSNR of reconstructed frames..

1 Introduction

The design of multimedia compression systems for transmission over band-limited wireless channels is becoming increasingly important due to applications such as personal communication systems. Wireless links have time-varying channel error rates, ranging from error free transmission to deep fades where the error rates can be as high as 10^{-1}. One of the important challenges in the design of these systems is to achieve efficient performance over such widely time-varying channel noise conditions. A straightforward approach to this problem is to design the system for worst case channel conditions, using powerful error correction codes to clean up the channel in conjunction with the source coder for the reduced rate. However, this approach is too conservative and substantially undermines performance under low channel noise conditions. An alternative approach is to use extremely long interleavers to redistribute channel errors more uniformly and design the compression scheme for the resulting artificially stationary noise statistics. However, for many, if not most, multimedia applications, the required delay is intolerable. Further, the interleaving approach compromises the ability to exploit the correlations which naturally occur in channel errors.

Depending on the application, some information about the channel error condition may be available at the encoder or the decoder or both. Thus, a superior design paradigm would exploit such information to adapt the source channel coders to the channel condition, in order to minimize the total distortion. This joint source-channel coding (JSCC) approach can provide superior rate-distortion performance while incurring low delay.

However, conventional methods for JSCC image coding have been mostly restricted to fixed length codes [2]. Although this approach guarantees adequate error resilience, it implies significant loss of compression efficiency. A multimode framework was proposed in [1] to optimally trade-off compression efficiency of variable length codes with error robustness of fixed length codes. Multimode image coders can be designed to minimize the overall rate-distortion cost. An alternative approach was proposed in [5] where variable length code words are packetized and transmitted. An analytic expression for the channel distortion and was used to optimize the rate-distortion performance of the image coder. We note, however, that all these approaches explicitly assume a given fixed channel error conditions, and do not carry over to the time-varying case. Additional JSCC frameworks for image compression over time-varying channels have

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been presented in [3]. However, these approaches do not aim to optimize the overall rate-distortion performance. The main purpose of this work is to present a *rate-distortion approach* to the design of JSCC-based image coders for *time-varying channels.*

A major concern in JSCC-based image coding is complexity. Since a JSCC scheme is optimized jointly for both the source and the channel statistics, it involves greater complexity than separate source and channel coding. In the case of time-varying channels, the complexity may become prohibitive due to the adaptation of the coder to the channel conditions, which may result in a new encoder/decoder pair for each state of the channel. Thus, we restrict our focus to coders of feasible complexity, which are designed to optimize the rate-distortion performance.

The organization of this paper is as follows: The general formulation of the problem is presented in section 2. We discuss the use of channel state information (CSI) in optimizing the encoder/decoder and the resultant complexity trade-offs. In section 3 , we propose a structured JSCC image coding system. The system consists of an hierarchical source encoder optimized for the image statistics, whose output bits are of unequal importance. The channel encoder can use CSI to provide unequal error protection, matched to the importance of the bits. The system can be easily readjusted for a different channel condition by varying the error protection provided to the different bits, resulting in an efficient low complexity implementation. Section 4 proposes a design algorithm for the system which optimizes the overall rate-distortion performance. We present simulation results for compression and transmission of real images over time-varying channels in section 5. RD optimized JSCC image compression is shown to outperform conventional approaches. Conclusions and areas for future work are discussed in section 6.

2 Problem Formulation

A sketch of a transmitter/receiver pair communicating over a time-varying channel is given in Figure 1.

We model the channel as a discrete memoryless channel whose bit error rate, ϵ, may be time-varying. More specifically , ϵ can take one of N values, $\{\epsilon_i | i = 1, 2, ...N\}$ with probability $p(\epsilon)$. The channel is assumed to be varying slowly enough, so that the error rate, ϵ, can be estimated accurately at the receiver. This is the channel state information (CSI). The receiver quantizes the CSI and sends it to the transmitter through a reliable side channel. The transmitter does not have access to the exact current bit error rate, ϵ, both due the quantization and the delay in transmission of CSI. We denote the approximate CSI available at the transmitter as s, where s can take one of M ($M <= N$) values $\{s_j | j = 1, 2...M\}$. Let the conditional probability of true bit error rate given the transmitter CSI, be denoted $p(\epsilon|s)$.

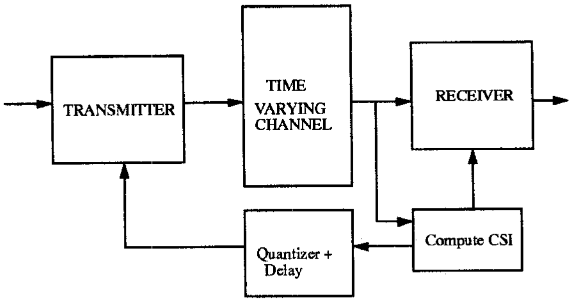

Figure 1: *JSCC scheme communicating over a time varying channel. Channel is estimated at receiver, quantized and sent reliably to transmitter. Channel state estimation shown outside receiver for clarity.*

The encoder design consists, in effect, of the design of a set of M JSCC coding schemes, one for each state, or CSI value, s. The JSCC coders are therefore optimized for the conditional statistics given by $p(\epsilon|s_j)$, $j = 1, 2, ..M$, and the image statistics.

Note that the decoder also has access to s and thus is always synchronized to the JSCC scheme used by the encoder. Moreover, it knows the exact channel error rate ϵ, which it can exploit further. Thus, we can have two types of decoding rules depending on the allowed complexity:

1. "Hard Decision" Decoding: The receiver has M decoders, one per channel state s.

2. "Soft Decision" Decoding: Use a JSCC decoder which takes into account both the current JSCC encoder and the current bit error rate ϵ. There are MN decoders at the receiver.

Obviously, soft decoding can give better performance than hard decoding, but is of greater complexity. This basic system can be designed to minimize the overall rate-distortion cost as explained in section 4. However, it is important to first address the question of complexity. Even the simpler hard decoding system requires M encoders and M decoders. Moreover, a different rate constraint and/or different channel conditions require a complete redesign of the system. Therefore, such a system seems impractical in a real environment with multiple rate constraints and channel conditions as in multicast applications. Motivated by these observations, we present a *structured* JSCC coder in the next section, which can be easily reoptimized for different rate constraints and channel conditions while maintaining feasible complexity.

3 System Description

The system we propose builds on the work presented in [2].

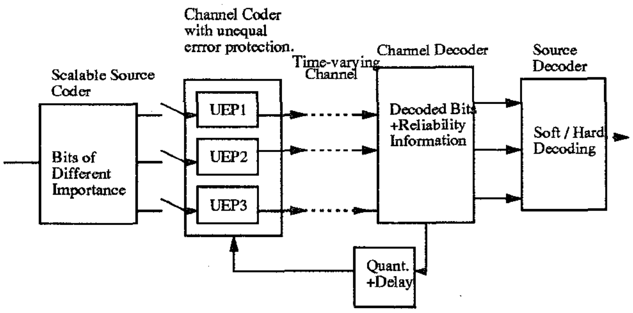

Figure 2: *Structured JSCC: Source is hierarchically quantized followed by error protection matched to importance. CSI is used to adapt channel encoder. Reliability information can be used for soft decoding.*

Refer figure 2 for a simple sketch of the system. The image is encoded by a hierarchical source coder, whose output is a bit stream of varying importance. The channel encoder chooses a subset stream of the bit stream for transmission, to which it offers unequal error protection. The choice is made depending on the target rate constraint, the importance of the individual bit, and the current channel state condition available to the channel encoder. Thus the source encoder can be optimized for hierarchical image compression and does not need to have access to the channel statistics. At the same time, the channel encoder needs only the relative importance of the bits from the source encoder and no knowledge of source statistics is required. The channel coder minimizes the actual distortion, for the given rate constraint and the statistics of the channel.

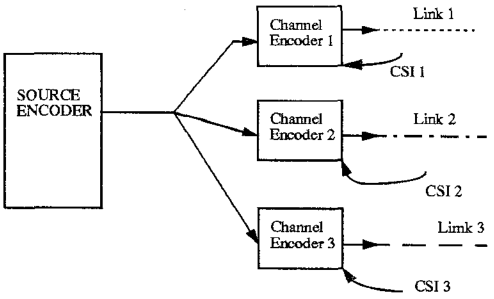

Figure 3: *Practical JSCC scheme in a Multicast Environment. Channel encoders located at intermediate points in the network; optimized for individual channel conditions.*

In practice as shown in Fig. 3, there can be multiple channel encoders for a given source encoder corresponding to different links with individual rate constraints and differing channel conditions. A multicasting application can have the channel encoders located at intermediate points (gateways) in the network, where they can drop less important bits, change error protection etc. This modularity enables practical realizations of low complexity, while still achieving efficient performance over each individual link. We next describe each of the individual components in greater detail.

3.1 Source Encoder

The image is compressed by a hierarchical source coder. Hierarchical fixed length compression schemes have been proposed [2] due to their robustness to channel errors. However, fixed length codes are very inefficient in compression and thus lead to poor overall performance. While most image coders use conventional variable length codes to achieve adaptation and compression efficiency, they suffer from channel error propagation. The error propagation makes it difficult to compute, and subsequently minimize, the channel distortion. One approach is to packetize the variable length codewords and subsequently evaluate the effect of error propagation (see for e.g. [5]).

An alternative multimode coding approach was proposed in [1]. Here quasi-fixed length codes are used for adaptation to statistics, while the synchronization information is sent error free to the receiver via heavy protection. This prevents error propagation and thus allows for direct optimization of the rate-distortion performance. We adopt a similar approach, with the notable distinction that hierarchical quantizers are incorporated to achieve scalability.

We first provide a short summary of multimode image coding. The image is divided into blocks and transformed by DCT. The coder provides a set of fixed length coding modes. Each mode consists of a bit allocation map for quantizing the DCT block and a corresponding set of hierarchical quantizers. The DCT block is encoded by the most suitable mode. (i.e the mode that minimizes the rate-distortion cost of encoding that block). Since the different modes are optimized for different source statistics, the encoder can adapt to varying statistics by switching modes. The mode index is sent as side information with the quantized DCT coefficients.

The following is a design algorithm for the multimode image coder. Define an initial partition of the training set of DCT blocks among the modes. Iterate the following steps:

1. For each mode, optimize the bit allocation and quantizers to minimize the rate-distortion cost for its training subset.

2. Entropy code the mode information to minimize side information.
3. Encode the training set using newly designed modes to form a new partition.

The algorithm produces a locally optimal multimode image coder. Note that the above multimode design is similar to the approach proposed in [4] [8], in the context of universal source coding for noiseless channels. Our main objective is to optimize the overall source-channel rate-distortion cost, subject to the constraints of feasible complexity.

3.2 Channel Encoder

The channel encoder consists of a set of rate compatible punctured convolutional codes (RCPC), which can provide unequal error protection. Rate compatible puncturing allows using the same encoder/decoder structure for the entire set of codes, thus reducing complexity.

The objective of the channel encoder is to adapt the modes used by the encoder, for the given rate constraint and channel state s, so as to minimize the overall distortion. The adaptation is very simple and consists of:

1. *effectively readjust the bit allocation map for each mode; performed by omitting to send of the individual quantizers.*
2. *provide unequal error protection matched to the importance of bits that are bing transmitted.*

The actual system optimization is described in section 4 Note that any error in the mode indices will lead to loss of synchronization and "error propagation". Therefore, the mode information is protected very heavily by the channel, to ensure that the probability of such error is negligible. There will only be a minimal loss of compression performance due to this heavy protection, since mode information is a small part of the total rate. Further, we confirmed through simulation that this loss is overwhelmingly offset by the gains in compression efficiency achieved through adaptation (via the different modes) to varying statistics.

3.3 Channel Decoder

The channel decoder also has access to the encoder state, s. Thus, it can compute the bit allocation and unequal error protection used by the channel encoder. The different RCPC codes are decoded and the individual bits of the received codewords are sent to the source decoder. Further, a reliability metric is computed for each bit and sent to the decoder. The reliability metric is simply the probability of channel error for each bit given the RCPC code used for protection, and the current channel error rate, ϵ, as estimated by the receiver.

3.4 Source Decoder

The source decoder uses the mode index (received error free due to its heavy protection) and the received codewords of the quantizers to estimate the DCT coefficients. Again, the estimation can be done in two ways: (i) "Hard Decision": The source decoder disregards the reliability metric and maps back each received codeword to a source value which is fixed for the channel state s. (ii) "Soft Decision": The source decoder uses the reliability information and the received bits to form a best estimate of the coefficient.

Finally, inverse DCT is performed to recover the block.

4 RD Optimization

The design of the system consists of adjusting the effective bit allocation maps of the modes, and the RCPC assignment to the bits, for each value of s. The objective is to minimize the total distortion, D, while satisfying the rate constraint, $R \leq R_{max}$. Equivalently, the problem is formulated as an unconstrained minimization of the Lagrangian $D + \lambda R$. Note that this Lagrangian is separable and allows us to optimize the bit allocation and RCPC assignment of the DCT coefficients in the various modes independently. Further, we can perform independent design of the system for each value of s.

We now describe a simple optimization method to minimize the Lagrangian.

1. *Given channel encoder state s, compute $p(\epsilon|s)$ the conditional channel error rate.*
2. *For each mode;*

   For each DCT coefficient;

   (a) *Go over the possible bit allocations $r = 0, 1, 2, ..r_{max}$.*
   (b) *Find the best RCPC assignment to minimize RD cost for $p(\epsilon|s)$.*
   (c) *Select bit allocation r and RCPC for the coefficient.*

Note that gradient descent algorithms can be used instead of exhaustive search to reduce the complexity associated with optimizing the bit allocation.

5 Results

In this section, we present simulation results to demonstrate the performance of RD optimized JSCC. We

$\epsilon ->$	0.0	10^{-4}	10^{-3}	$5 * 10^{-3}$	10^{-2}
$s1$	1/3	1/3	1/3	0	0
$s2$	0	0	0	1/2	1/2

Table 1: *Conditional probability of channel error, $p(\epsilon|s)$, for different channel conditions.* $p(s1) = p(s2) = 1/2$.

Rate in bpp	Fixed Length JSCC	RD Optimized JSCC
0.4	24.43	28.78
0.5	24.92	29.87
0.6	25.25	30.73
0.75	26.07	31.99
1.0	27.37	33.49

Table 2: *Performance of fixed length coding and RD optimized coding, at various target rates. Avg. PSNR (in dB) of reconstructed image is shown.*

compare the performance of RD optimized coders with fixed length JSCC for compression and transmission of images over time-varying channels. The source coder was designed for a rate of 1bpp. The image *BARBARA* was used for the design the coder.

We used a BSC in our simulations, whose bit error rate can take the values, $\{\epsilon = 0.0, 10^{-4}, 10^{-3}, 5 * 10^{-3}, 10^{-2}\}$ as in [6]. The CSI available at the encoder can take values $s1$ and $s2$. We assumed $p(s1) = p(s2) = 1/2$. The conditional probability of the current bit error rate, $p(\epsilon|s)$, is summarized in table 2.

We used the RCPC codes described in [7] for error protection. The mode information was protected using a 1/3 code, which guaranteed an error rate less than 10^{-14} for even the highest bit error rate of the channel. The proposed design algorithm was used to optimize the channel encoder for the given channel conditions and the target rate constraint. The performance of the compression scheme was tested on the image *LENA* The results are summarized in table 2. Note, that the rates include all side information and channel protection. The results illustrate the gains achievable by RD optimized JSCC over fixed length JSCC for time-varying channel conditions. In particular, gains in the order of 6 dB were achieved in these preliminary simulations.

Though we have demonstrated the performance with simple channel models, it is straight-forward to extend this framework for application in more involved channel models.

6 Conclusion and Future work

A rate-distortion framework was proposed for designing image coding schemes for transmission over time-varying channels. The JSCC scheme is adapted using the channel state information to minimize the total distortion. To obtain an implementation of feasible complexity, we focus on structured JSCC where the image is hierarchical quantized followed by unequal error protection matched to importance of bits. The image is compressed using multimode codes which can adapt to image statistics, and thus achieve good compression performance. Adequate error resilience is maintained by providing heavy protection to the synchronization information. We show that the overall system can be optimized to achieve efficient rate-distortion performance. Simulation results demonstrate that RD optimized image coding can outperform fixed length systems for transmission over time-varying channels and achieve gains of up to 6dB in PSNR of reconstructed images .

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