Picture Coding Symposium, Lisbon, Portugal, November 7-9, 2007.

DESIGN OF MUTIPLE DESCRIPTIONS WITH SYMBOL-BASED TURBO CODES OVER NOISY CHANNELS WITH PACKET LOSS

Mehrdad Valipour and Farshad Lahouti
Wireless Multimedia Communications Laboratory
School of Electrical and Computer Engineering, College of Engineering, University of Tehran
mvalipour@ece.ut.ac.ir and lahouti@ut.ac.ir

ABSTRACT

Multiple descriptions (MD) with symbol-based turbo (SBT) codes are proposed, where the decoder exploits both non-uniformity of descriptions and their dependencies. A distortion-power adaptive system is obtained by setting an entropy constraint for quantizer design, which together with the MD index assignment (IA), control the level of redundancy at the MD source coder output. This is in turn exploited by the source and channel decoders for robust transmission in presence of noise and packet loss (PL). At the source coder, the IA is designed for an M-description vector quantizer using an efficient simulated annealing algorithm. Through sensitivity analysis, it is shown that in contrast to noisy channels without PL, it is better that MD is designed for the operating channel SNR in the presence of PL. Numerical results indicate improved performance in comparison to the prior art.

Index Terms— *Joint source channel coding, Multiple description vector quantizer, symbol-based turbo code, index assignment, MIMO, noisy channels with packet loss.*

1. INTRODUCTION

Multiple descriptions (MD), a type of joint source channel coding, is an efficient way for transmitting multimedia over channels with packet loss (PL). In MD coding, source symbols are mapped into two or more descriptions and transmitted over different noisy or noiseless channels with PL. Even if some descriptions are lost, the receiver exploits residual redundancy of the descriptions and effectively reconstructs the source symbols at the receiver.

In MD based on index assignment (IA), e.g. [1]-[2], the source encoder (SE) consists of a quantizer whose cells are mapped into several descriptions using an IA table. In recent years transmitting multimedia over wireless channels have received noticeable attention; consequently, designing MD for noisy channels with PL has been considered [3]-[5]. In [3], the design of a multiple description scalar quantizer (MDSQ) with two descriptions over channels with noise and PL is considered, using a computational complex approach. In [4], an M-channel multiple description vector quantizer (MDVQ) is suggested using the generalized Lloyd algorithm and the Binary Switching Algorithm for the quantizer and the IA design, respectively. An IA is designed in [5] for an MDSQ system using a genetic algorithm, in a setting where only one of the descriptions is subject to noise.

For communication of multiple descriptions over noisy channels a channel encoder (CE) may be used, and the redundancy between the descriptions can be exploited during channel decoding, e.g. [6]-[7]. In [7], an MD scheme coded with binary turbo codes is suggested. To the best of our knowledge, in all reported MD schemes with channel coding and iterative decoding at the receiver, a binary channel code is used which requires a symbol-to-bit and a bit-to-symbol converter. This in turn does not allow us to effectively exploit the MD residual redundancy, or more specifically the non-uniformity of descriptions.

1.1. Contributions of this paper and the system model

In this paper, using a multiple description source coder and symbol-based turbo codes, a *power-distortion adaptive system* is designed. By employing an entropy constrained vector quantizer, and efficient design of IA, we control the redundancy of the descriptions at the output of SE. This redundancy is exploited in turn during the decoding, providing a lower distortion over a wide range of channel SNR. This is a good example of joint source channel coding for robust transmission of multimedia over channels subject to noise and packet loss.

The source coder considered here is an M-channel MDVQ along with an MMSE source decoder (SD). A fast scheme based on simulated annealing (SA) is proposed to effectively design IA for robust transmission over noisy channels with PL. Through sensitivity analysis, it is shown that in contrast to noisy channels without PL, it is better that MD is designed for the operating channel SNR in the presence of PL.

For exploiting memory between bits of a symbol, as shown in figure 1, we use symbol-based turbo (SBT) codes [8]. In the proposed system, both non-uniformity of the quantized symbols and the dependency between descriptions are exploited during channel decoding. Also, the proposed source and channel decoder is formulated based on a single structure to operate in presence of noise and all possible packet loss patterns.

This paper is organized as follows. In section 2, the SE and

This work has been supported in part by the Iran Telecommunications Research Center.

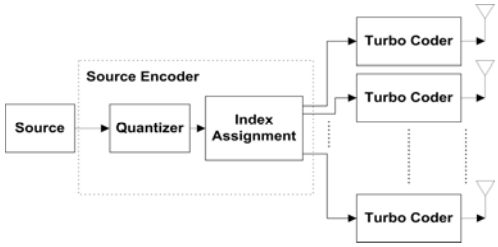

Figure 1. Structure of the transmitter of MD with symbol based turbo codes.

the SD is introduced, and an IA table is designed for MDVQ over noisy channels with PL. Joint channel decoding of descriptions is elaborated in section 3. Sections 4 and 5 include the numerical results, and conclusions.

2. SOURCE CODING

Consider a vector quantizer which maps a *k*-dimensional source vector $\mathbf{X}$ into one of *N* vector quantizer cells. Each cell is then mapped to M descriptions using an IA table. In other words:

$$\mathbf{X} \rightarrow \mathbf{I}(\mathbf{X}) = \left(I_1(\mathbf{X}),...,I_M(\mathbf{X})\right) \subset \Theta_{N_1} \times ... \times \Theta_{N_M}\ , \quad (1)$$

where $\Theta_N = \{1,...,N\}$. Let us denote the encoding cell (Voronoi region) and the codevector corresponding to $\mathbf{I}(\mathbf{X})$ by $\mathrm{V}(\mathbf{I})$ and $\mathbf{c}(\mathbf{I})$, respectively. The set of MD IA table cells with a valid $\mathbf{I}(\mathbf{X})$ is denoted by $\{\mathbf{I}\}$. The output of the SE $I_m(X)$, or for simplicity I_m, $m \in \Theta_M$, is converted to a R_m-bit binary sequence, and transmitted over a noisy channel with PL.

To investigate the effect of noise and packet loss, M equivalent independent binary symmetric channels (BSC) are considered between the output of SE and the input of SD, one for each description. The bit error rate (BER) and the packet loss probability of the m^{th} equivalent channel are denoted by P_m and μ_m, respectively. The sequence $\mathbf{J} = \left(J_1,...,J_M\right)$ is received at the SD, where J_m is the output of the m^{th} equivalent channel. The sequence $\mathbf{Q} = \{Q_1,...,Q_M\} \subset \{0,1\}^M$, indicates the status of descriptions at the decoder, i.e., $Q_m = 0$ specifies the loss of the m^{th} description.

The estimated symbol $\hat{\mathbf{X}}_{\mathbf{Q},\mathbf{J}}$ by a MMSE source decoder may be written as:

$$\hat{\mathbf{X}}_{\mathbf{Q},\mathbf{J}} = \sum_{\mathbf{i}\in\{\mathbf{I}\}} P(\mathbf{I}=\mathbf{i} \mid \mathbf{J},\mathbf{Q})\mathbf{c}(\mathbf{i}) = \frac{1}{P(\mathbf{J}\mid\mathbf{Q})} \sum_{\mathbf{i}\in\{\mathbf{I}\}} P(\mathbf{J}\mid\mathbf{i},\mathbf{Q})P(\mathbf{i})\mathbf{c}(\mathbf{i}) \quad (2)$$

where: $P(\mathbf{J}\mid\mathbf{Q}) = \sum_{\mathbf{i}\in\{\mathbf{I}\}} P(\mathbf{J}\mid\mathbf{i},\mathbf{Q})P(\mathbf{i})$.

Note that $\mathbf{I}$ is independent of $\mathbf{Q}$, so $P(\mathbf{I}\mid\mathbf{Q}) = P(\mathbf{I})$; and $P(\mathbf{I}) = \int_{\mathrm{V}(\mathbf{I})} f(\mathbf{x})d\mathbf{x}$ is computed using probability distribution function (pdf) of source symbols $f(\mathbf{x})$, parameters of the quantizer and the IA table. We have:

$$P(\mathbf{J}\mid\mathbf{I},\mathbf{Q}) = \prod_{m=1}^{M} P(J_m \mid I_m, Q_m)\ , \quad (3)$$

$$P(J_m \mid I_m, Q_m) = \begin{cases} P_m^{\,d_H(I_m,J_m)}\left(1-P_m\right)^{R_m - d_H(I_m,J_m)} & Q_m = 1 \\ 1/N_m & Q_m = 0 \end{cases} \quad (4)$$

Where $d_H\left(I_m, J_m\right)$ is hamming distance between J_m and I_m.

The end-to-end system distortion consists of the channel distortion and the source distortion, which are due to the noise and packet loss of the channels and the VQ noise at the SE, respectively. When the distortion criterion is the mean square error, for a multiple description system, the average distortion is shown to be given by:

$$\mathrm{D}_{\mathrm{av}} = \mathrm{D}^{\mathrm{SE}} + \mathrm{D}^{\mathrm{Channel}} \quad (5)$$

where D^{SE} is the quantization distortion and the channel distortion $\mathrm{D}^{\mathrm{Channel}}$ is:

$$\mathrm{D}^{\mathrm{Channel}} = \sum_{\mathbf{q}\in\{0,1\}^M} P(\mathbf{Q}=\mathbf{q})\mathrm{D}_{\mathbf{q}}^{\mathrm{Channel}} \quad (6)$$

$$\mathrm{D}_{\mathbf{q}}^{\mathrm{Channel}} = \sum_{\mathbf{j}\in\Theta_{N_1}\times...\times\Theta_{N_M}} \sum_{\mathbf{i}\in\{\mathbf{I}\}} P(\mathbf{i})P\left(\mathbf{j}\mid\mathbf{i},\mathbf{q}\right)\left\|\mathbf{c}(\mathbf{i}) - \hat{\mathbf{x}}_{\mathbf{q},\mathbf{j}}\right\|^2 \quad (7)$$

A similar relation to (5) is reported in [9] for vector quantization over a noisy channel, and (6) is a generalization of (3) in [3].

For controlling the level of redundancy at MD Source coder, an upper bound on the total entropy of quantized symbols, H_T, is proposed during SE design. Therefore, the SE design objective is:

$$\{\text{Encoding cells, codevectors and IA table}\} = \underset{\substack{\text{Encoding cells}\\ \text{Codevectors}\\ \textit{IA Table}}}{\arg\min}\ \underset{\textit{Subject to } H_T < h_0}{\mathrm{D}_{av}} \quad (8)$$

Since the optimal solution of (8) is very complex, a sub-optimal solution is used. First the encoding cells and codevectors of the vector quantizer are obtained by minimizing D^{SE} subject to $\mathrm{H}_T < h_0$. Then by fixing the VQ, an MD IA table is designed for minimizing the average distortion. For former optimization, an entropy constrained vector quantization is employed.

An exhaustive search for finding the optimal MD IA table requires $(N_1\times\cdots\times N_M)!/(N_1\times\cdots\times N_M - N)!$ tests. Here, a simulated annealing algorithm is used instead. Let a *search region* be defined as a region in the IA table where the SA algorithm operates, and a *neighborhood region* be defined as the neighboring cells of a certain cell within the search region. Note that $\{\mathbf{I}\}$ is a subset of the search region. In summary, we start with a random IA table. Then, each cell in the search region is substituted with a cell in its neighborhood region, and the average distortion is computed. If the distortion decreases, the change is accepted; else if the ratio of the computed distortion to the obtained distortion is lower than a specific value, the change is accepted only with a certain small probability. This probability is set based on the ratio of the obtained and computed distortions. The process is repeated until no substitution occurs during a certain number of iterations. As a result of defining the search and neighborhood regions, naturally the proposed SA method runs faster than the one suggested in [2], or the GA-based algorithm of [5]. Our experiments demonstrate the effectiveness of this scheme. The proposed method is referred as channel optimized MDVQ (CO-MDVQ) in the results section.

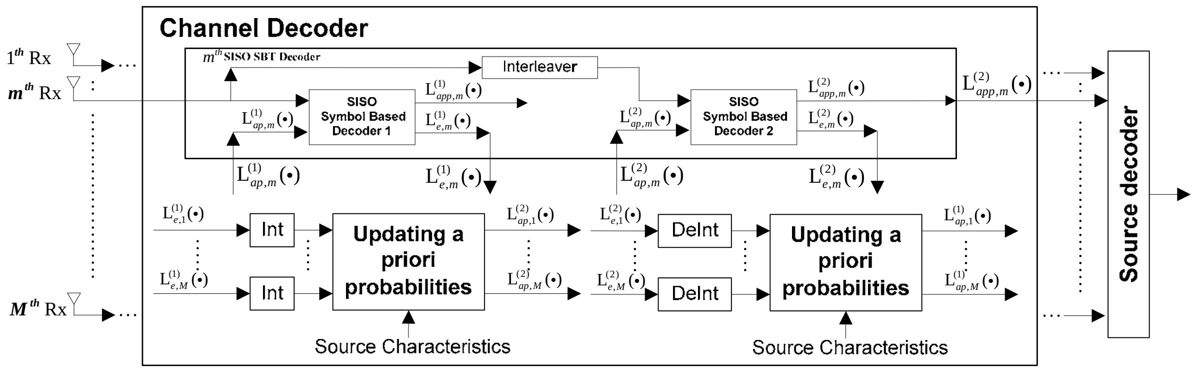

Figure 2. Structure of the receiver of MD with symbol based turbo codes.

3. CHANNEL CODING

As shown in figures 1 and 2, the descriptions are independently channel encoded using a set of symbol-based turbo codes [8], and jointly channel decoded at the receiver. The encoder of a SBT code is the same as that of a binary turbo code, with the exception of a symbol level interleaver. The SBT decoder makes use of a merged trellis constructed by merging several stages of the encoder trellis. This allows us to exploit both non-uniformity of the quantized symbols and the dependency between descriptions more effectively.

As shown in figure 2, the channel decoder consists of M SBT decoders. The a priori probability of a constituent decoder related to one description is updated using the extrinsic probabilities of the constituent decoders corresponding to all descriptions and the dependencies between descriptions. Let $L_{app,m}(i) \triangleq L_{app,m}(I^l_m = i)$ be defined as the logarithm of the a posteriori probability at the output of the m^{th} SBT decoder, where l is index of a symbol in the frame, i.e.:

$$L_{app,m}(i) = \log\left(P\left(I^l_m = i \,|\, \mathbf{Y}\right)\right), i \in \Theta_{N_m}, m \in \Theta_M, l \in \Theta_L \qquad (9)$$

where $\mathbf{Y}$ is the received sequence from the channels and L is the frame length. Following the turbo decoding principle, we have:

$$L_{app,m}(i) = L_{ap,m}(i) + L_{ch,m}(i) + L_{e,m}(i)\,, \qquad (10)$$

where $L_{ap,m}(i)$, $L_{ch,m}(i)$ and $L_{e,m}(i)$ are a priori probability, the channel probability and the extrinsic probability of $I^i_m = i$, respectively. $L_{ch,m}(i)$ is computed using binary sequences and the channel transition probability, and when the m^{th} description is lost in the channel, $L_{ch,m}(i)$ is set to $\mathrm{Log}(1/N_m)$. In each iteration, the a priori probability of a SISO decoder is updated as follows:

$$L^{next}_{ap,m}(i) = L^{last}_{e,m}(i) + \log\Big\{0.5\Big(P_m(i) + \qquad (11)$$
$$\sum_{\substack{i_1 \in \Theta_{2^{R_1}} \\ i_m = i}} \cdots \sum_{i_M \in \Theta_{2^{R_M}}} \Big[P\left(i_m \,|\, i_1,...,i_{m-1},i_{m+1},...,i_M\right) \prod_{\substack{k=1 \\ k \neq m}}^{M} \mathrm{Exp}\left(L^{last}_{e,k}(i_k)\right)\Big]\Big)\Big\}$$

where $P_m(i)$ and $P\left(i_m \,|\, i_1,...,i_{m-1},i_{m+1},...,i_M\right)$ are computed, considering the source encoder structure and the pdf of the source. Also, $\mathrm{P}\left(J_m \,|\, I_m = i\right)$ in (3) is given by

$$\mathrm{P}\left(J_m \,|\, I_m = i\right) = \mathrm{Exp}\left(L_{app,m}(i)\right), m \in \Theta_M\,, i \in \Theta_{N_m} \qquad (12)$$

4. PERFORMANCE EVALUATION

For performance analysis, SBT codes with $G_1 = G_2 = \left[1 \quad \left(1+D+D^2+D^3\right)/\left(1+D^2+D^3\right)\right]$ and an interleaver of length 4096 are used. The number of iterations for decoding is 10. The source is one-dimensional, Gaussian with unit variance. The signal constellation is BPSK, and channels have additive white Gaussian noise.

In figure 3, the performance of systems with different source encoders designed with different entropy constraints are compared. The end-to-end reconstructed signal to noise ratio (SNR) is plotted as a function of channel SNR. The parameters M, N, $\boldsymbol{\mu} = [\mu_1, \mu_2, \mu_3]$ and $\mathbf{R} = [R_1, R_2, R_3]$ are set to 3, 33, $[0.05, 0.05, 0.05]$ and $[2, 2, 2]$. It is observed, that by managing the level of redundancy at the source encoder, and effectively exploiting it at the source and channel decoders, the overall distortion decreases dramatically for a certain range of channel SNR. In other words, the system adapts the encoder parameters for optimized performance, indicated by the dashed line in figure 3, at different channel SNRs. Also, testing the performance of the proposed system with other packet loss rates, a similar behavior is observed. This result demonstrates the effectiveness of joint source and channel coding.

The effect of different parts of the system on the performance is investigated in figure 4. The reconstructed SNR is plotted as a function of the channel SNR. The parameters M, N, H_t, $\boldsymbol{\mu} = [\mu_1, \mu_2]$ and $\mathbf{R} = [R_1, R_2]$ are set to 2, 33, 4.77, $[0.05\ 0.05]$ and $[3, 3]$. For MD with binary turbo codes, the a priori probabilities are updated as in [10]; for MD with SBT codes equation (11) is used instead. The work of [7], which uses MD with binary turbo codes and a MAP source decoder, is used as a baseline for comparisons. As seen in this figure, using channel optimized MDVQ improves the average distortion in a wide range of channel SNR. The MMSE SD outperforms the MAP SD, especially in presence of packet loss at high channel SNR. Using SBT codes, the redundancy at the MD source coder output is exploited more effectively, and the average distortion is dramatically decreased over a wide range of channel SNR.

The sensitivity of the IA design algorithm to BER of the equivalent channels is investigated in figure 5. An IA table is designed for a specific value of channels BER $\mathbf{P}=[P_1, P_2]$, and used for channels with different, but symmetric, $\mathbf{P}$. The parameters M, N, H_T, $\mathbf{R}=[R_1, R_2]$ and $\boldsymbol{\mu}=[\mu_1, \mu_2]$ are set to 2, 21, 4.14, $[3,3]$ and $[0.05\ 0.05]$, respectively. The following results are observed from this figure:

- If the noisy channels do not suffer from PL, in comparison with an IA table designed at a low channel BER, an IA table designed at a high channel BER provides a smaller average distortion in a wide range of channel BER. A similar result for a vector quantization is reported in [11].
- If the equivalent channels have noise and packet loss, the former observation is no longer valid, and it is better that the IA table is designed for a channel BER closer to the true operating point.

5. CONCLUSIONS

In this paper, a joint source channel coding system is proposed using MDVQ with symbol-based turbo codes. The joint design involves controlling the dependency between the descriptions and efficiently exploiting this redundancy at the source and channel decoders. Also, an M-description VQ over noisy channels with PL is designed. It is shown that in contrast to noisy channels without PL for noisy channels with PL, it is better that MD is designed for a channel SNR close to the true operating point.

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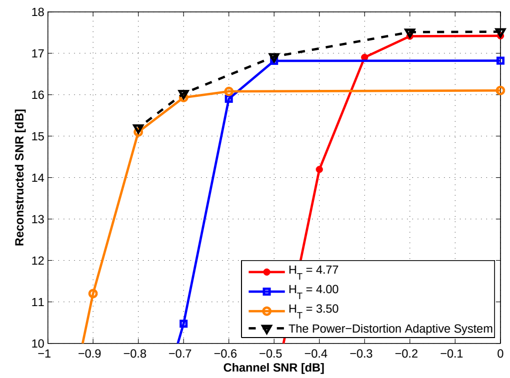

Figure 3. Performance of the JSCC system using MD with SBT codes. Three descriptions are used.

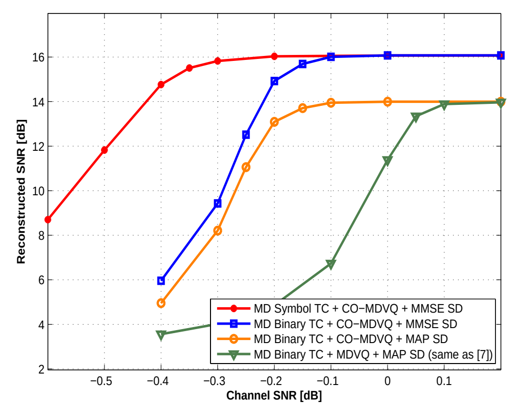

Figure 4. Performance comparison between different MD systems with channel codes.

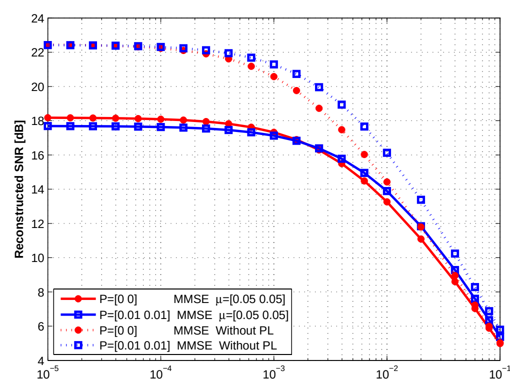

Figure 5. Performance of a MD system designed at a specific value of the equivalent channels BER, and used over channels with different BER.