CODING OF DIGITAL IMAGERY FOR TRANSMISSION OVER MULTIPLE NOISY CHANNELS

Sumohana S. Channappayya
Telecom. Research Center
Dept. of Electrical Engineering
Arizona State University
Tempe, AZ 85287-7206
sumohan@asu.edu

Glen P. Abousleman
Speech and Signal Processing Lab.
Motorola, IISG
8201 E. McDowell Rd.
Scottsdale, AZ 85257
glen1@kuma.geg.mot.com

Lina J. Karam
Telecom. Research Center
Dept. of Electrical Engineering
Arizona State University
Tempe, AZ 85287-7206
karam@asu.edu

ABSTRACT

This paper presents a multiple description image coding scheme that facilitates the transmission of digital imagery over multiple noisy channels. The proposed scheme divides the image into smaller parts that are transmitted over the individual channels of an inverse multiplexing system. The division or splitting is done in such a fashion that it facilitates the interpolation of lost coefficients in the case of one or more channel failures. At the receiver, the image is reconstructed by proper assembly of the data received from each channel. In case of channel failure, the missing coefficients are estimated from the available data with the use of a novel post-processing scheme. For operation over four noisy channels with various bit error probabilities, we investigate the quantitative and subjective performance of the proposed system for the case of multiple channel failures.

1 INTRODUCTION

Inverse multiplexing is the process of aggregating several low-rate channels to form an effective higher-rate channel. Transmission of digital imagery over these (possibly noisy) channels poses an interesting design problem. Although this problem is somewhat similar to transmission of imagery over packet-based networks [1], [2], there are certain differences between the two scenarios that facilitate improved interpolation of lost data in the multiple channel case.

Generally speaking, multiple description source coding addresses the problem of partial loss of a binary source description during transmission [3]. In the current context, multiple descriptions of the image are transmitted over multiple noisy channels, such that if one or more of the channels becomes non-functional, a useful representation of the image can be reconstructed at the decoder. Additionally, we require that if all channels are operational, the reconstructed image should be identical to the case where a single higher-rate channel is utilized. Accordingly, the original image is split or divided into smaller parts that form the multiple descriptions of the image. These parts are then coded and transmitted over the low-rate noisy channels. At the decoder, an inverse procedure is applied to reassemble the multiple image descriptions.

The problem of splitting the input image has a number of constraints. The image should be split in such a way so as to minimize the amount of redundant information that is sent on each of the channels comprising the inverse multiplexed system. In the case of channel failure, post processing must be performed at the decoder to improve the visual quality and the PSNR of the reconstructed image. Thus, the splitting scheme should facilitate the estimation of lost coefficients from available coefficients in the case of channel failure.

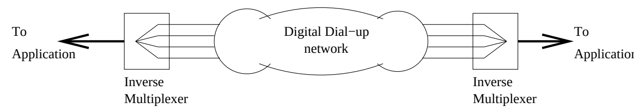


Figure 1. Inverse multiplexer.

This paper is organized as follows. Section 2 provides an overview of the inverse multiplexing system and the image coding topology that is employed. The proposed multiple description and post-processing schemes are described in Section 3. Coding examples are discussed in Section 4, and a conclusion is given in Section 5.

2 OVERALL SYSTEM CONFIGURATION

2.1 Inverse Multiplexing

An inverse multiplexer is a device that combines a number of low-bandwidth channels to form an effective high-bandwidth channel [4]. The goal of this device is to use existing resources more effectively, rather than the more expensive alternative of replacing the low-bandwidth channels with one or more channels of higher bandwidth. The inverse multiplexer is an ad-hoc solution, however. The number of channels that are combined is varied depending upon the bandwidth requirement. That is, channels are dropped and added depending on the instantaneous bandwidth requirement. For example, higher bandwidth may be required at the beginning of a video sequence, where intraframe encoding is employed, as opposed to the middle of the sequence where interframe prediction is used. More channels would be combined at the beginning of the transmission, and the channels that are not needed at a later time would be dropped. The device is illustrated in Figure 1. The channels that form the inverse multiplexer would have different delays and possibly different bit error probabilities (BEPs), in general. The protocols that run on the device have been designed to handle the varying delays and channel characterisitics. In the present work, we assume that all of the channels have identical delays and identical channel characteristics.

2.2 COTCQ-Based Image Coder

The image coding topology utilized in the present work is a modified version of the image coder presented in [5]. The block diagram is shown in Figure 2. In this coder, the input image is decomposed into 22 subbands using a modified Mallat tree configuration as shown in Figure 3. Each subband is partitioned into four classes

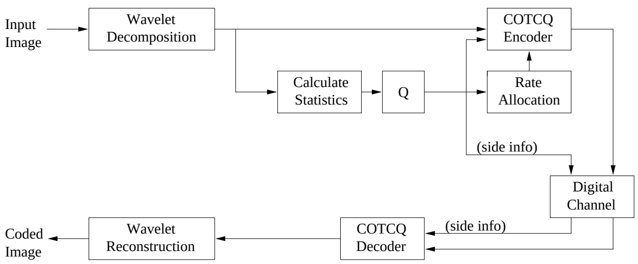


Figure 2. Block diagram of the COTCQ-based image coder.

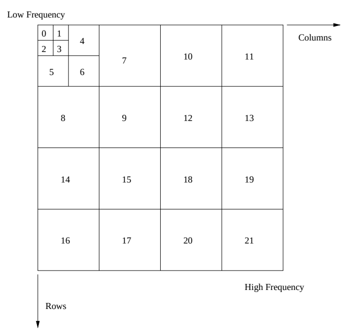


Figure 3. 22-subband image decomposition.

as discussed in Section 3. All resulting sequences are then quantized using fixed-rate channel-optimized trellis-coded quantization (COTCQ) [5]. Rate allocation is performed in an optimal fashion by an iterative technique that uses the rate-distortion performance of the various designed channel-optimized trellis-based quantizers. Note that this coder configuration enables the transmission of compressed data over noisy channels without the use of channel coding.

For the proposed image codec, the COTCQ stage was designed for use with the binary symmetric channel (BSC), characterized by bit error probability, P_b. For the considered image coding application, we derived a general expression of the transition probability matrix in terms of the encoding bit rate, R.

The COTCQ design was performed to support the following bit error probabilities:

$$\begin{aligned} P_b \quad = \quad & 0.0,\ 0.0001,\ 0.0005,\ 0.001,\ 0.005,\ 0.01,\ 0.05, \\ & 0.1,\ 0.15,\ 0.2,\ 0.25,\ 0.3,\ 0.35,\ 0.4,\ 0.45,\ 0.5. \end{aligned}$$

For each P_b, fixed-rate COTCQ codebooks were designed in one-bit increments from $R = 1$ to $R = 10$ bits per sample. COTCQ codebooks were designed using zero-mean, unit-variance, sample sequences derived from a Laplacian pseudo-random number generator. In [5], we present a fast COTCQ encoding algorithm that reduces the computational complexity by a factor of $C/2$, where $C = 2^{R+1}$ is the total number of codewords in the COTCQ codebook, and R is the encoding rate.

3 MULTIPLE DESCRIPTION AND POST PROCESSING SCHEMES

In the present work, we address the four-channel inverse multiplexer case. A four-channel inverse multiplexer refers to the case

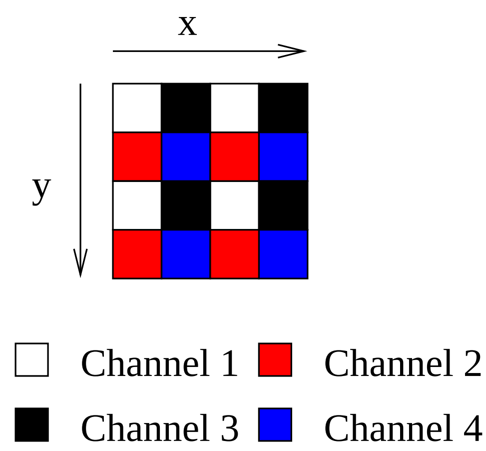


Figure 4. Splitting scheme used for the four-channel inverse-multiplexed case.

where four channels are combined to form a channel with an effective bandwidth of four-times that of an individual channel.

3.1 Splitting scheme

Consider the subband splitting scheme illustrated in Figure 4. In this scheme, four coefficients are combined to form a group as shown. Each of the four coefficients in the group is sent on a different channel as indicated by the shade of the coefficient. All coefficients of the same shade are grouped together to form a smaller subband that is one-fourth the size of the original subband. Referring to the 22-band decomposition illustrated in Figure 3, consider the LL subband, which is labeled as subband 0. Let $X_{LL}(i,j)$ represent a coefficient at position (i,j), and let the size of the subband be 32×32. Referring to Figure 4, with the top left corner as the origin, and $1 \leq x \leq 16$, $1 \leq y \leq 16$, four LL subbands, each of dimensions 16×16, are created by sampling the LL subband as follows:

$$X_{LL1}(x,y) = X_{LL}(2x-1, 2y-1) \tag{1}$$

$$X_{LL2}(x,y) = X_{LL}(2x-1, 2y) \tag{2}$$

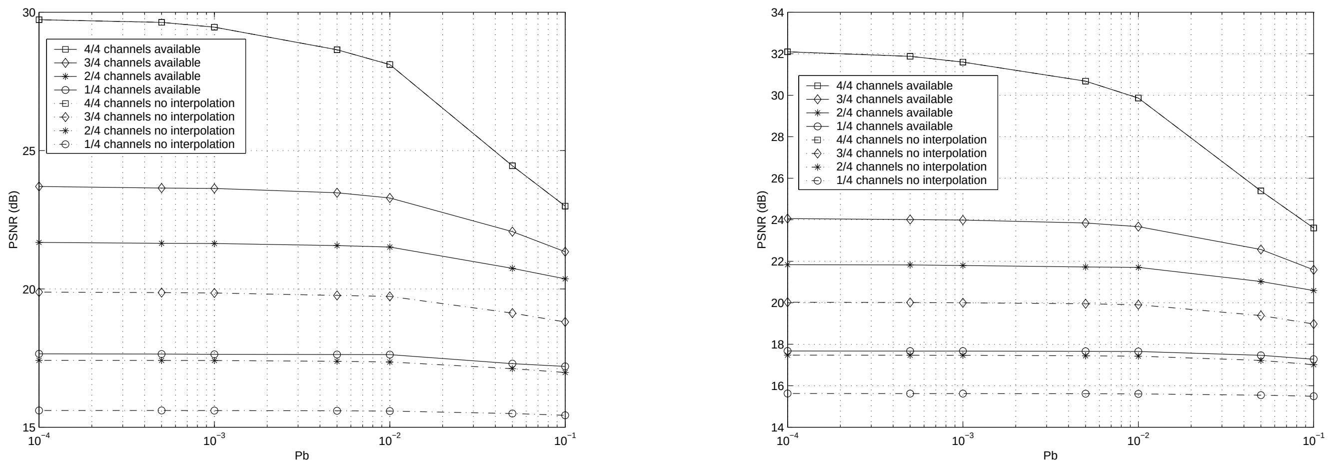
$$X_{LL3}(x,y) = X_{LL}(2x, 2y-1) \tag{3}$$

$$X_{LL4}(x,y) = X_{LL}(2x, 2y). \tag{4}$$

This rule is applied to all 22 subbands in the wavelet-transformed image to obtain four subimages, X_1, X_2, X_3, and X_4, each of which is one-fourth the size of the original image, X. Each of the smaller images is coded at the specified bit rate to obtain four coded bit streams. The statistics of each of the four subimages are different from each other, and from the original image. The subbands in each subimage are normalized by subtracting their respective mean, and dividing by their respective standard deviation. These statistics are sent to the decoder as side information. A combination of repetition and channel coding is utilized to ensure that the side information is received without error. Each of the coded bit streams is then transmitted on its assigned channel.

At the receiver, each of the four bit streams is decoded to provide four subimages. An inverse operation is performed to reassemble the subimages. Using the same convention as above, this operation is expressed as:

$$X_{LL}(2x-1, 2y-1) = X_{LL1}(x,y) \tag{5}$$



(a) Lena image coded at 0.25 bpp

(b) Lena image coded at 0.5 bpp

Figure 5. 512×512 Lena image encoded at various Pbs, with various channels operational.

$$X_{LL}(2x-1,2y) = X_{LL2}(x,y) \tag{6}$$

$$X_{LL}(2x,2y-1) = X_{LL3}(x,y) \tag{7}$$

$$X_{LL}(2x,2y) = X_{LL4}(x,y). \tag{8}$$

This operation is applied to all 22 subbands. One important difference at the decoder is that all channels may not be available. In the case of channel loss, only the available coefficients are used in the above equations. After this process, the inverse wavelet transform is applied to recover the full-size coded image.

It is evident from Figure 4 that all the neighbors of a lost coefficient are available in the case of a single channel failure. When two channels fail, the availability of the closest neighbors cannot be guaranteed. Thus, the availability of neighboring coefficients depends on the relative location of the failed channels.

3.2 Post processing scheme

Post processing schemes are typically used to remove visually annoying artifacts and to provide error concealment in the received image in the case of channel errors. In the current context, post processing is used to improve the quality of the image that is received in the case of channel failure. A number of schemes address the problem of image restoration in the context of packet loss in packet-based networks [2, 1, 6]. The scheme developed in the present work addresses the problem of image restoration in the case of channel failure. It differs from the packet loss case in that the coefficient loss pattern is known, unlike the random nature of packet loss. The knowledge of the coefficient loss pattern can be exploited to develop efficient restoration schemes. Further, the splitting scheme was developed to specifically facilitate restoration.

Referring to Figure 4, a loss of one channel results in the loss of coefficients corresponding to one shade. Note that those coefficients corresponding to the other shades are available. The lost coefficients need to be estimated to improve the visual quality and PSNR of the reconstructed image. The estimation techniques vary across subbands, as each subband carries different information, and the relationship among the coefficients is different. The LL subband contains most of the energy in the image, and hence the lost coefficients in this subband must be estimated as accurately as possible to achieve good restoration. The LH and HL subbands (i.e., subbands 1 and 2 in Figure 3, respectively) contain edge information. The restoration of lost coefficients in these subbands helps in obtaining sharp edges in the reconstructed image. The other subbands are relatively less important in terms of the improvement they provide to PSNR and visual quality.

A number of techniques were employed to process the LL subband. These techniques included mean filtering, median filtering, and Weiner filtering. The PSNR and visual quality of the reconstructed image were used as metrics to measure the effectiveness of these techniques. It was found that median filtering gives the best results in terms of PSNR and visual quality. In median filtering, the lost coefficient is replaced by the median value of its neighbors that are sorted in ascending order. In the case of a single channel failure, every lost coefficient has all eight of its neighbors available. If the lost coefficient is represented by X_{lost}, and if its neighbors are $X_1 \ldots X_8$, then

$$X_{lost} = \text{median}(X_1 \ldots X_8). \tag{9}$$

Mean filtering was applied to the LH and HL subbands in the direction of the low-pass filtering. Mean filtering is used since the coefficients corresponding to edges have similar values. If the lost coefficient is represented as X_k, and its neighbors are X_{k-1} and X_{k+1}, then

$$X_k = \frac{X_{k-1} + X_{k+1}}{2}. \tag{10}$$

Filtering in the LL, LH, and HL subbands is performed after a symmetric extension of the subband on all four sides. Post processing was not performed on the remaining subbands since PSNR and visual quality were not improved.

4 CODING EXAMPLE AND RESULTS

The proposed system was used to process the 512×512 8-bit Lena image, coded at total rates of 0.25 bits/pixel (bpp) and 0.5 bpp, using the COTCQ-based image coder. The image coder produces four coded bit streams, each corresponding to one of the four channels. Each bit stream is sent over a BSC, characterized by bit error probability, P_b. It is assumed that all channels have identical statistics. The BEP of each channel is allowed to vary from

(a) (Left-Right, Top-Bottom) Three, two, one, and zero channel failures; no post processing

(b) (Left-Right, Top-Bottom) Three, two, one, and zero channel failures; post processing

Figure 6. 512×512 Lena image encoded at 0.5 bpp and Pb=0.01, with various numbers of channels operational.

0.0001 to 0.1. The receiver reconstructs the image by decoding the received bit streams, and reassembling the coefficients.

The reconstructed image was evaluated for the cases of no channel failure, one channel failure, two channel failures, and three channel failures. The experiments were conducted with and without the use of post processing. Both quantitative and subjective measures were observed. For the case where post processing is not used, the missing coefficients in the LL subband are replaced by the average of the means of the available LL subbands. The results are shown in Figures 5 (a) and (b), with overall encoding rates of 0.25 bpp and 0.5 bpp, respectively. Each point in Figure 5 corresponds to the average of ten independent experiments. From the figures, it can be seen that when one channel fails, the post processing improves the PSNR by about 4 dB at almost all BEPs. Also note the significant improvement with the use of post processing when two and three channels are non-functional.

Figures 6 (a) and (b) show the subjective performance of the proposed system for an overall encoding rate of 0.5 bpp, and a bit error probability of $P_b = 0.01$, with various numbers of channels operational. For the system with post processing, remarkable image fidelity is obtained even with three out of four channels non-functional. Also, the subjective and quantitative performance of the system when all four channels are operational is equivalent to that obtained if only one channel with four-times the bandwidth is used. Thus, no performance penalty is imposed by the splitting scheme.

5 CONCLUSIONS

A novel multiple description coding scheme for transmitting digital imagery over multiple noisy channels has been presented. The developed splitting scheme facilitates an interpolation process in the case of channel failure(s). Also, the developed post-processing scheme exploits the knowledge of the pattern of lost coefficients. When all channels are operational, the splitting scheme does not degrade the quality of the reconstructed image. Additionally, the scheme provides significant improvement in the visual quality and PSNR of the reconstructed imagery in the case of channel failures. The proposed system addresses the problems of channel failures in multichannel inverse-multiplexed systems, as well as bit errors in the compressed bit streams. Quantitative and subjective performance evaluations verify that the proposed system provides outstanding results in the presence of channel errors, and in the case of multiple channel failures.

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