EFFICIENT IMAGE AND CHANNEL CODING FOR WIRELESS PACKET NETWORKS

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ABSTRACT

We combine multiple description (MD) quantization, entropy coding, and data partitioning to improve the error resiliency of images over varying packet loss channels. Our proposed scheme degrades gracefully as channel conditions worsen. A multidimensional extension of the two-channel multiple description scalar quantizer (MDSQ) improves robustness. A high performance wavelet image coder is designed for MDSQ, using the Set-Partitioning-In-Hierarchical-Trees (SPIHT) algorithm for entropy coding. Experimentally, with 4 descriptions, the new coder outperforms previous reports at any loss rate.

1. INTRODUCTION

As multimedia communications are used for harsh environments such as low power wireless devices, error resilient source coding becomes more important. Wireless devices are especially challenging because they operate in difficult environments (e.g., multipath fading channels), with relatively severe bandwidth processor, and memory constraints. The goal is to perform well under noisy conditions and degrade gracefully as channel conditions worsen.

Typically, multimedia applications operate at a level in the network protocol stack that is conceptually disjoint from the physical layer. Therefore the channel appears as a packet erasure channel to the application (i.e., packets arrive error-free or else are lost). This contrasts other scenarios, where the packet erasure model is handled by adding cyclic redundancy check (CRC) codes at the application layer. Therefore we focus on a packet erasure channel with possibly unknown or varying erasure rates. This channel is an n-channel generalization of the 2-channel model typically assumed in multiple description (MD) coding (e.g. [1]). Due to the similarity, previous work on both multiple descriptions and coding for packet erasure channels is relevant.

Previous work on MD coding includes methods which allow a wide range of redundancy levels to be introduced across a small set of descriptions (usually two descriptions). The MD scalar quantizer in [1] uses an index assignment to map a regular quantizer index to a pair of indices with a selectable amount of redundant coding between them. Application of MD scalar quantizers to image coding was considered in [2], including discussion of extensions to more than two descriptions. Correlating transforms are used to introduce redundancy between pairs of values in [3, 4]. In [5] quantized overcomplete frame expansions are used to produce a small set of descriptions with some redundancy.

Data partitioning is another technique used to add error resiliency to a source coder (e.g. [6, 7, 8, 9]). High performance compression algorithms, such as the SPIHT image coder [10], often require the source coder bits to be decoded in a sequential and uninterrupted fashion for correct interpretation. Carefully partitioning the data into separate streams prior to coding can improve the error resilience. The idea is that the source decoder can use more of the correctly received information because independent pieces of the transmission can be correctly interpreted despite losing other portions. Data partitioning often also facilitates the application of unequal error protection channel coding. This method is an attractive technique for situations where the decoder complexity and graceful degradation under varying channel conditions are important. The cost is a loss of compression performance because the dependencies among the partition elements cannot be fully exploited.

If the number of packets is large, Forward Error Control (FEC) channel codes at the output of the source coder work well. When the codes' block lengths are long, a large number of rates are possible and thus the code rate can be accurately matched to the channel. Also the FEC can be applied in an unequal fashion based on the importance of the information to provide improved efficiency and some graceful degradation (e.g. [11, 12]). The major costs of this method include decoding complexity, decoding delay (i.e., loss of progressivity), and sensitivity to channel mismatch.

The best choice among known methods depends on the number of packets (or descriptions) to be transmitted. Often the network imposes constraints by limiting the maximum packet size (i.e., the path maximum transmission unit (MTU)) or by distributing the information into a set of naturally separate descriptions as in a multichannel transmission

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system. In this paper, we assume the number of packets is fairly small (i.e., fewer than 10), and investigate extensions of the two-channel multiple description mappings to create efficient and error resilient image coders.

2. IMAGE CODING STRUCTURE

Many high performance image coding algorithms entropy code the scalar quantized coefficients of a linear transform (e.g. wavelet). We consider a similar structure where the scalar quantizer is replaced by an MDSQ, and each of the M descriptions is coded by an independent entropy coder. Each description is coded separately using the SPIHT algorithm with arithmetic coding (see Figure 1). This method (called MDSQ-SPIHT hereinafter) works well for MDSQ's with high redundancy, since each description image is roughly a coarsely quantized version of the original image.

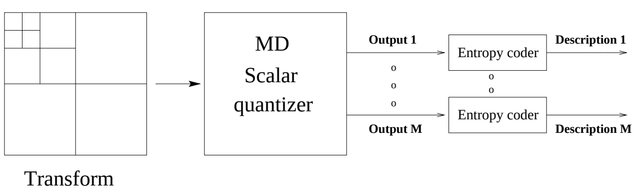


Fig. 1. Block diagram of an image coder for packet loss channels.

As described in [1], an MDSQ is a cascade of a scalar quantizer followed by an index assignment which maps 1 index to M indices. We consider uniform quantization for the central quantizers with a fixed image-wide stepsize. If the amount of redundancy is fixed for all subbands, then the stepsizes for side quantizers are the same for all wavelet coefficients. The redundancy is tuned by selecting the number of central quantizer cells relative to the number of bits in the description indices. An example of two index assignments is shown in Figure 2 for the two-description case.

Each of the numbered cells in the mappings represents a cell of the central quantizer, and each quantized coefficient is mapped into a pair of coordinates which specify its position in the grid. In these examples, the central quantizer indices are placed along diagonals of the grid, and the redundancy is controlled by selecting the number of diagonals. When only one of the two descriptions is received, all the central cells along the given row or column are possible, so it is important to minimize the spread (i.e., the difference between the minimum and maximum indices in the row or column) for good error resilience.

The same concept can be extended to more than two descriptions by using higher dimensional mappings. Cells from the central quantizer are placed along diagonals of an M-dimensional hypercube. Figure 3 illustrates the concept with a three-dimensional mapping which includes only the

1	2						
3	4	5					
	6	7	9				
		8	10	11			
			12	13	15		
				14	16	17	
					18	19	21
						20	22

(a) Index assignment with high redundancy

1	3	5	7				
2	8	10	12	14			
4	9	15	17	19	21		
6	11	16	22	23	25	27	
	13	18	24	29	30	32	34
		20	26	31	36	37	39
			28	33	38	41	43
				35	40	42	44

(b) Index assignment with less redundancy

Fig. 2. Example MD index assignment mappings for two descriptions.

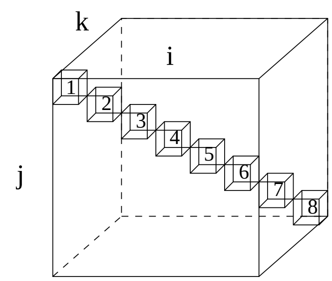


Fig. 3. Example of a three-dimensional MD mapping.

main diagonal resulting in a (3,1,3) repetition code of the central quantizer indices. Adding other diagonals around the main diagonal reduces the redundancy and allows the channel coding rate to be adjusted. The algorithm used to generate the multi-dimensional mappings adds elements successively along each of the diagonals beginning at the upper corner and proceeding to the lower corner. At each step, the diagonals are sorted according to the minimum value along each dimension and the central quantizers cells are assigned in that order to reduce the spread.

The redundancy of the mapping is directly related to the the number of hypercube cells *not* assigned a central quantizer index. With Q central quantizer cells, S indices for each description, and M descriptions, the channel code rate of the mapping is

$$r_c = \frac{\log_2(Q)}{M \log_2(S)}. \tag{1}$$

Thus it is difficult to create maps which provide high channel code rates with few central quantizer cells and many descriptions. These situations occur in the context of image coding when coding the coefficients in the higher frequency subbands. In such situations, data partitioning can be applied so that information about a specific high frequency coefficient is only sent in a subset of the packets. A similar type of data partitioning was used in the context of image coding for packet erasures in [8, 9].

The choice of mapping also has an impact on the individual entropy coders for each description. Low redundancy mappings result in high-entropy descriptions, reducing the effectiveness of the entropy coders. Also, the individual descriptions may not be matched very well in terms of rate and error resilience. It is important to match the descriptions so the loss of any description is approximately equivalent, thus improving error resilience.

Even though the MD mapping is designed to have approximately equal spread among all descriptions, it may not result in well-matched description rates since they will not be equally compressible. One method of balancing the descriptions is to use different permutations of the index M-tuple throughout the image. Therefore the MD mapping used for a particular coefficient is a composition of a multi-dimensional MD mapping and a coefficient-dependent permutation (e.g., the permutation may depend on the location or sign of the coefficient). For two descriptions, the sign of the coefficient can be used to select the permutation. For example, if the central quantizer index 1 is mapped into indices $(1, 0)$ for side quantizers, then the central quantizer index -1 is mapped into $(0, -1)$.

We propose two permutation schemes for an arbitrary number of descriptions in order to balance the bit-rates among descriptions. The first one, a local permutation scheme applicable to any coders, rotates the M-tuple component order for a coefficient positioned at (x, y) according to the value of $(x + y)$ mod M. The second scheme is suitable for zero-tree type wavelet coders. It uses the first scheme only on the root coefficients (lowest subband), and all the descendents of a root coefficient will have the same index order as their ancestor. Both schemes can equalize the bit-rates among descriptions, but experiments show that the second scheme is slightly better than the first scheme when the SPIHT coder is used.

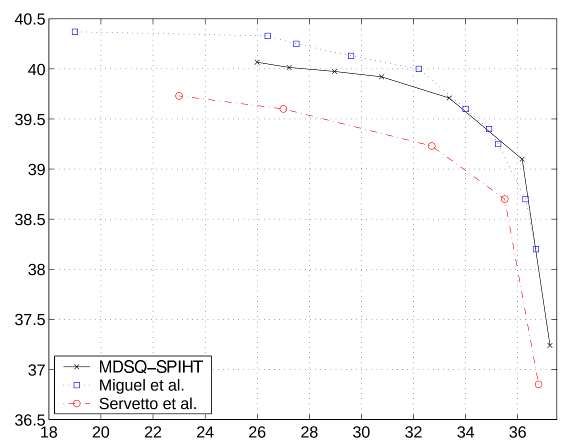
3. EXPERIMENT RESULTS

The 9/7 Daubechies wavelet and a 5-level wavelet decomposition was used for the 512x512 Lena image, and a 4-level decomposition was used for the 256x256 Lena image. The total bit rate in the experiments ranges from 1.0 bpp to 1.25 bpp. An MDSQ is used to generate the M descriptions, and they are supplied to the SPIHT entropy coder. The stepsize for the central quantizer is determined by a bisection search algorithm to meet the total bit budget.

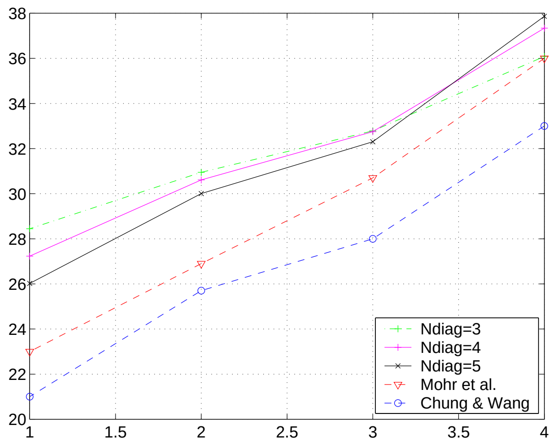
First we compare different index permutation schemes when SPIHT is used as the entropy coder for each description. For the 512x512 Lena image coded at a total rate of 1 bpp in 2 descriptions, the zero-tree based permutation scheme is about 0.2 dB better than the local permutation scheme in terms of reconstruction PSNR for both the central quantizer and the side quantizers, and is about 0.3 dB better than the sign-based permutation scheme. Therefore the zero-tree based permutation scheme is used for the remaining results in this section.

Figure 4 compares the proposed method and that of Miguel *et al.* [9] and Servetto *et al.* [2] for the case of 2 descriptions. The results are comparable to those of [9] in the high redundancy region (i.e., low central PSNR region) but are slightly worse in the low redundancy region where the data partitioning used in [9] is able to achieve very low redundancy. The improvement over [2] can be attributed to the improved entropy coder provided by the SPIHT algorithm as well as the better index permutation scheme based on zero-trees over that based on signs.

The results in Figure 5 show the performance of a 4-description coder for a number of different redundancy levels. As more diagonals are added to the mapping (reducing the redundancy), the performance with no description loss improves but the performance with heavy description loss degrades. Compared to the method of Mohr *et al.* based on unequal loss protection (ULP) [13], the proposed method with 5 diagonals outperforms ULP by $1.6 \sim 3.0$ dB depending the number of descriptions received.



8, and we compare MDSQ-SPIHT with the scheme of Miguel *et al.* [9], and with the ULP scheme of Mohr *et al.* [11]. Using 5 diagonals, our coder performs close to their schemes when there is no description loss, but is about 3 to 5 dB worse than that of [11] when there is a loss of 1 to 2 descriptions; on the other hand, MDSQ-SPIHT performs better than [11] when at least 4 descriptions are lost, and the gain is as high as 10 dB when only 1 description is received.



8 descriptions, high frequency bands are only coded with 4 descriptions, which are alternated into one of the two groups – each having 4 descriptions – in a predetermined order. This reduces the total bit rate given the stepsize, thus achieving finer quantization given the total bit budget. In Figure 6, the PSNR for the cases with no description loss or just 1 description loss improves by about 1 dB, but the PSNR with only 1 description received drops by about 4 dB.