HIGH-REDUNDANCY EMBEDDED MULTIPLE-DESCRIPTION SCALAR QUANTIZERS FOR ROBUST COMMUNICATION OVER UNRELIABLE CHANNELS

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ABSTRACT

Robust communication over unreliable channels requires highly resilient bit-streams that, for Multiple Description Coding (MDC) systems, correspond to a high-redundancy level between descriptions. Additionally, MDC systems expanded over bandwidth-limited channels require source adaptation to the available bit-rate and user's needs, hence, a fine grain scalability of each description is required as well. In this paper we propose a new type of Embedded Multiple Description Scalar Quantizers (EMDSQ) targeting the desired features of high redundancy level and fine grain scalability of each description. In addition, the generalized form of the EMDSQ for an arbitrary number of channels is proposed, allowing for realistic codec design in practical multi-channel communication environments. Experimental results show the EMDSQ systematically yield better rate-distortion performance in comparison to the Multiple Description Uniform Scalar Quantizers (MDUSQ) previously proposed in the literature.

1. INTRODUCTION

Sending data over unreliable channels with high delay sensitivity or no feedback channels, such as packet networks and wireless links, may require data-reconstruction without the missing packets. In this context, Multiple Description Coding (MDC) has become the most appropriate approach providing an error resilient transmission over channels with diversity since it enables extracting the meaningful information from a subset of the received bit-streams. Additionally, at the decoder side, data-reconstruction improves as the number of received descriptions increases.

In order to produce multiple descriptions of the input data, several MDC techniques rely on quantization, as proposed in [1], [2]. In this context, the design of multiple description scalar quantizers (MDSQ) was pioneered in [1] under the assumption of fixed-length codes and fixed codebook sizes. Significant improvements are reported in [2], where the quantizers' design is made under a given entropy-constraint, and not on a given codebook size. Lately, a practical wavelet-based coding system employing the MDSQ of [1] was proposed in [3].

From a different perspective, image and video transmission over bandwidth-limited channels requires the source adaptation to the available bit-rate and to the user's needs (corresponding to different image or video reconstructed qualities, to terminals with different resolutions or computational power), hence, a fine-grain scalability of each description is required as well. This property enables progressive image and video reconstruction (in terms of quality or resolution) from the partially received multiple descriptions at the decoder side.

In addition, robust communication over unreliable channels requires highly resilient bit-streams that, for MDC systems, correspond to a high redundancy level between descriptions.

A practical system conceived to meet these constraints was previously proposed in literature in [4], in which the MDC algorithm is based on multiple description uniform scalar quantizers (MDUSQ). For a high level of redundancy and for low bit-rates, the approach proposed in [4] constitutes the state-of-the-art, outperforming embedded MDC based on polyphase transform proposed in [5].

In this paper, we propose a different type of Embedded Multiple Description Scalar Quantizers (EMDSQ) producing scalable descriptions and targeting a high redundancy level. In addition, the generalized form of the EMDSQ for an arbitrary number of channels is proposed, allowing for realistic codec design in practical multi-channel communication environments. The above-mentioned MDUSQ [4] and the EMDSQ are incorporated in a wavelet-based coding system that employs a customized version of the QuadTree (QT) coding algorithm of [6]. The results obtained on a common image dataset with both MDC systems demonstrate that the proposed EMDSQ achieve systematically better rate-distortion performance on a broad range of bit-rates.

The paper is structured as follows. In Section 2 the proposed EMDSQ are introduced. The MD-QT coding algorithm is described in Section 3, and comparative coding results are given in Section 4. Finally, Section 5 draws the conclusions of this work.

2. EMBEDDED MULTIPLE-DESCRIPTION SCALAR QUANTIZERS

The proposed EMDSQ are designed to meet the following features: (1) producing double-deadzone embedded central quantizers for each quantization level, and (2) enabling progressive transmission of each description using side-channel embedded quantizers. The first design constraint ensures optimal (at high rates), and nearly-optimal (at lower rates) rate-distortion performance [7]. The second design constraint, for an erasure channel model characterized by burst errors, enables (a) the rate control for transmissions over bandwidth-limited channels, and (b) the progressive refinement of the central-channel reconstruction by using the undamaged data from the partially-damaged received side-channels.

2.1 Two channels EMDSQ

For the two-channel EMDSQ, we denote the set of embedded side-quantizers as $Q_S^{m,0}$, $Q_S^{m,1}, \dots$, $Q_S^{m,P}$ with $m=1,2$, and the set of embedded central-quantizers as Q_C^0, Q_C^1, …, Q_C^P, where $Q_C^{p-1}(q_k^1, q_k^2) = Q_S^{1,p-1}(q_k^1) \cap Q_S^{2,p-1}(q_k^2)$ for any quantization level p, $0 \le p \le P$. The partition cells of any quantizer $Q_S^{m,p}$ and Q_C^p are embedded in the partition cells of the quantizers $Q_S^{m,P}$, $Q_S^{m,P-1}, \dots$, $Q_S^{m,p+1}$ and Q_C^P, $Q_C^{P-1}, \dots$, Q_C^{p+1} respectively.
The example depicted in Fig. 1 illustrates an instantiation of the proposed two-channel EMDSQ. In view of simplification, we consider only two quantization levels $p=0,1$. We notice, for instance, that the partitions $S_{-,1}^{2,1}$ and $S_{+,1}^{2,1}$ of the second-channel embedded quantizer $Q_S^{2,1}$ are divided respectively into the three partitions $S_{\pm,1,0}^{2,0}$, $S_{\pm,1,1}^{2,0}$ and $S_{\pm,1,2}^{2,0}$ of the higher rate quantizer $Q_S^{2,0}$. Furthermore, it can be noticed that the central quantizer obtained from the side quantizers presented in Fig. 1 is indeed a double-deadzone embedded quantizer. Thus, from a rate-distortion perspective, it holds the abovementioned properties of optimality at high rates and near-optimality at lower rates [7].

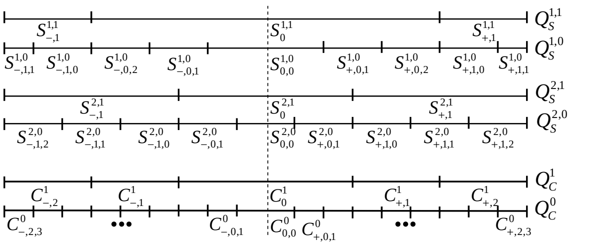

Fig. 1. Two-channel EMDSQ. The two side quantizers are $Q_S^{m,p}$, with $m=1,2$ and $p=0,1$. Q_C^p represents the central quantizer.

For two-channel EMDSQ, the analytical expression of the proposed embedded side-quantizers is:

$$Q_S^{m,p}(x) = \begin{cases} Q^{m,p}(x) & \dfrac{|x|}{2 \cdot 3^p \Delta} + \dfrac{\xi}{3^p} + \dfrac{m-1}{2} > 0 \\ 0 & otherwhise \end{cases} \tag{1}$$

with

$$Q^{m,p}(x) = sign(x) \left\lfloor \frac{|x|}{2 \cdot 3^p \Delta} + \frac{\xi}{3^p} + \frac{m-1}{2} \right\rfloor \tag{2}$$

where $\lfloor a \rfloor$ denotes the integer part of a, $\Delta > 0$ is the cell size for Q_C^0, and ξ (with $\xi < 1$) determines the width of the deadzone.
The central-channel's analytical expression is then given by:

$$Q_C^p(x) = \begin{cases} Q^p(x) & \dfrac{|x|}{3^p \Delta} + \dfrac{\xi}{3^p} > 0 \\ 0 & otherwhise \end{cases} \tag{3}$$

where

$$Q^p(x) = sign(x) \left\lfloor \frac{|x|}{3^p \Delta} + \frac{\xi}{3^p} \right\rfloor \tag{4}$$

By tuning the value of the parameter ξ we can control the width of the central deadzone. It should be noted that, when $\xi = 1/2$, the central quantizer is uniform, while when $\xi = 0$, the deadzone width is 2Δ (this case is exemplified in Fig. 1). Negative values of the parameter $\xi < -1/2$ are further widening the deadzone [7].

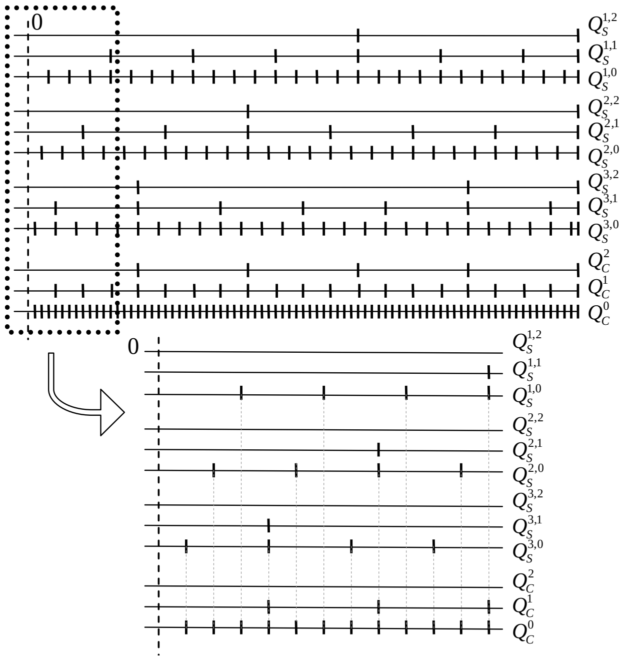

Fig. 2 Three-channel EMDSQ. The three side quantizers are $Q_S^{m,p}$, with $m=1..3$ and $p=0..2$. Q_C^p represents the central quantizer. The negative side is a mirrored version of the positive one shown above.

2.2 Generalization to M-channel EMDSQ

Taking as a starting point equation (1) that describes the side-channel quantizers corresponding to the two-channel EMDSQ, it is possible to generalize the analytical formula for M-channels, as shown below:

$$Q_S^{m,p}(x) = \begin{cases} Q^{m,p}(x) & \dfrac{|x|}{M \cdot (M+1)^p \Delta} + \dfrac{\xi}{M \cdot (M+1)^p} + \dfrac{m-1}{M} > 0 \\ 0 & otherwhise \end{cases} \tag{5}$$

with

$$Q^{m,p}(x) = sign(x) \left\lfloor \frac{|x|}{M \cdot (M+1)^p \Delta} + \frac{\xi}{M \cdot (M+1)^p} + \frac{m-1}{M} \right\rfloor \tag{6}$$

where $m, 1 \le m \le M$ denotes the channel index.
In addition, similar to (3), one derives from (5) the central-channel quantizer for M-channels, as:

$$Q_C^p(x) = \begin{cases} Q^p(x) & \dfrac{|x|}{(M+1)^p \Delta} + \dfrac{\xi}{(M+1)^p} > 0 \\ 0 & otherwhise \end{cases} \tag{7}$$

where

$$Q^p(x) = sign(x)\left\lfloor \frac{|x|}{(M+1)^p\Delta} + \frac{\xi}{(M+1)^p} \right\rfloor \tag{8}$$

Notice that the two-channel case of side quantizer (1) and central quantizer (3) follows from (5) and (7) respectively, for $M = 2$.

Based on the generalized side-quantizer expression (5) one deduces that the cell-size $\Delta_S^{(p)}$ for the side-quantizer $Q_S^{m,p}$ depends on the number of channels M by $\Delta_S^{(p)} = (M+1)^p \Delta_S$, where Δ_S is the cell size for the highest-rate side-quantizer $Q_S^{m,0}$. Similarly, from (7) one obtains the cell-size for the central quantizer Q_C^p as $\Delta^{(p)} = (M+1)^p \Delta$, where Δ is the cell size for the highest-rate central-quantizer Q_C^0. Moreover, one obtains $\Delta_S = M \cdot \Delta$.

Fig. 2 depicts the case of three channels ($M = 3$) and three quantization levels ($0 \le p \le 2$). Notice from this example that the side quantizers are indeed embedded – e.g. the partitions of the side quantizers $Q_S^{m,0}$ are embedded in the partitions of the side quantizers $Q_S^{m,1}$ and $Q_S^{m,2}$ respectively. Moreover, notice that for each quantization level p, the central quantizer Q_C^p is a double-deadzone embedded quantizer with cell size $\Delta^{(p)} = 4^p \Delta$. Furthermore, for the side quantizers, one has $\Delta_S^{(p)} = 4^p \Delta_S$, where $\Delta_S = 3 \cdot \Delta$ is the cell size of $Q_S^{m,0}$.

3. WAVELET-BASED QUADTREE MULTIPLE DESCRIPTION CODING SCHEME

In this section, we illustrate the use of the proposed EMDSQ in an embedded intraband wavelet-based coding scheme, for the particular case of $M = 2$ and $\xi = 0$. The coding algorithm relies on the quadtree (QT) coding of the significance maps proposed in [6], and is referred to as Multiple Description-QT (MD-QT) coding.

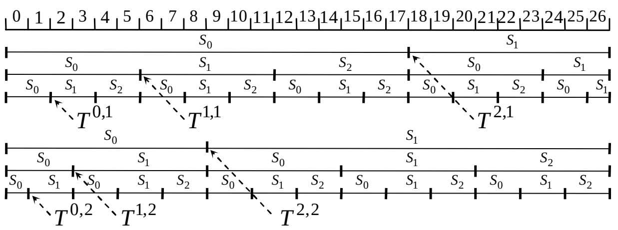

Fig. 3. Three-level representation of $Q_S^{m,p}$ for two-channel EMDSQ ($M = 2$, $0 \le p \le 2$) for an example with granular region ranging from 0 to 26. The significance-map coding is performed with respect to the set of thresholds $T^{p,m}$ with the rate of decay given by (10).

The coding passes performed by the proposed MD-QT coding system are the significance pass, employing the significance thresholds $T^{p,m}$, $0 \le p \le P$ followed by the refinement pass, utilizing the refinement thresholds $T_r^{p,m}$, with m, $1 \le m \le 2$ denoting the channel index.

For the lowest quantization rate P, the starting thresholds corresponding to each channel are $T^{P,1} = 2T$ and $T^{P,2} = T$ respectively. Since it is not desirable that the quantizer is characterized by an overload region, the T value is related to the highest absolute magnitude $w_{\max}$ of the wavelet coefficients as:

$$T = 3^{\lfloor \log_3(w_{\max}/3) \rfloor + 1} \tag{9}$$

Hence, the maximum number of quantization levels is $P = \lfloor \log_3(w_{\max}/3) \rfloor + 1$. In general, the significance thresholds used for each channel m, $1 \le m \le 2$ are given by:

$$T^{p,m} = \frac{T^{P,m}}{3^{P-p}} \tag{10}$$

Fig. 3 depicts a three-level representation of $Q_S^{m,p}$ for two-channel EMDSQ ($M = 2$, $0 \le p \le 2$) for an example with granular region ranging from 0 to 26.

It is noticeable that each quantization partition is divided at a lower quantization level into three partitions. Thus, the output provided by the index allocation operator is one of the following three symbols: S_0, S_1 or S_2 (see Fig. 3).

The purpose of the refinement pass is to perform the index allocation for coefficients that have already been coded as significant at the previous significance passes. In order to apply the index allocation, the coefficient that must be refined has to be rescaled with respect to the refinement-pass threshold $T_r^{p,m} = T^{p+1,m}$.

In order to improve the compression results, the output stream of symbols provided by the MD-QT coder (significance symbols, sign symbols, quantizer index symbols) are further entropy coded with an adaptive arithmetic coder [8].

4. EXPERIMENTAL RESULTS

To perform the comparison between the proposed EMDSQ and MDUSQ [7], both quantizers are applied on a memoryless Laplacian source of random generated numbers with zero mean and $\sigma = 27.2$, simulating a wavelet subband. The EMDSQ and MDUSQ are targeting the same high redundancy level (2 diagonals in the index assignment matrix). Fig. 4 shows that similar results are obtained for the side channels and the EMDSQ outperforms the MDUSQ for the central channel. Moreover, in comparison with the EMDSQ described in [9] (corresponding to a higher redundancy level, i.e. 1.5 diagonals in the index assignment matrix), the side-channel rate distortion characteristic is linear. In Fig. 4 the central channels rates correspond to the cumulated side-channel rate, respectively.

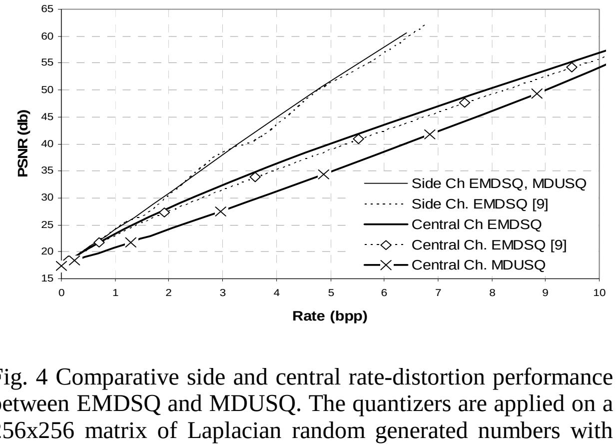

Fig. 4 Comparative side and central rate-distortion performance between EMDSQ and MDUSQ. The quantizers are applied on a 256x256 matrix of Laplacian random generated numbers with zero mean and $\sigma = 27.2$.

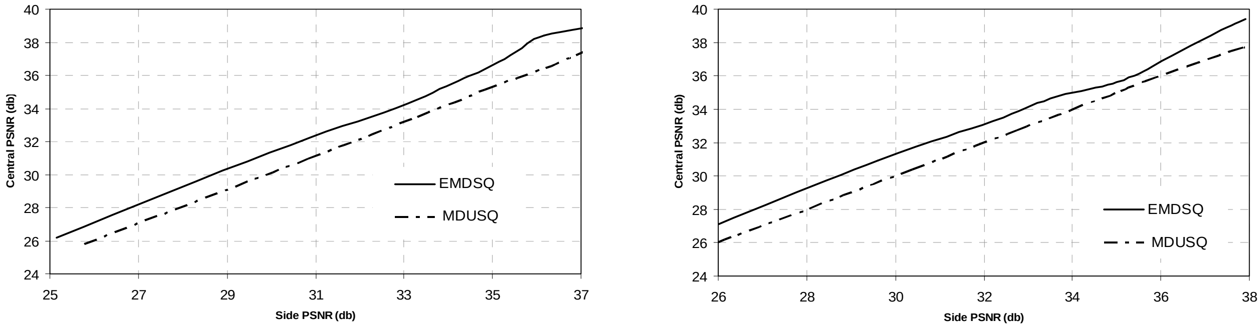

Fig. 5 Comparative central and side PSNR performance obtained with a wavelet based QT entropy codec employing EMDSQ and MDUSQ respectively. The results are reported on Lena 512x512 (left) and Peppers 512x512 (right) images for a rate ranging between 0.03 bpp and 1.13 bpp.

Similar to EMDSQ, the MDUSQ was integrated in the embedded MD-QT coding scheme, resulting in a common entropy-coding system for both types of quantizers. The results depicted in Fig. 5 obtained on Lena and Peppers images reveal that the for the same side-channel distortion, EMDSQ systematically yield better central-channel PSNR results compared to MDUSQ.

Image	Quant.	0.125	0.25	0.5	1	2	4
barbara	EMDSQ	23.85	25.86	28.75	33.07	37.90	44.88
	MDUSQ	23.69	25.17	27.62	31.83	37.23	44.17
goldhill	EMDSQ	26.92	28.72	30.61	33.47	36.82	42.82
	MDUSQ	26.59	28.30	30.47	32.91	36.40	42.38
boat	EMDSQ	25.93	28.28	30.91	34.89	39.57	46.21
	MDUSQ	25.63	27.93	30.67	34.15	39.27	44.99
cameraman	EMDSQ	23.05	25.21	28.08	31.75	36.63	44.80
	MDUSQ	22.77	24.75	27.49	31.09	36.37	44.73
mandrill	EMDSQ	20.73	21.87	23.40	25.63	29.79	35.39
	MDUSQ	20.65	21.57	23.13	25.21	28.77	34.68
average mean diff.		0.23	0.45	0.48	0.72	0.53	0.63

Table 1 Performance (PSNR) of the central reconstruction of the MD-QT codec employing EMDSQ and MDUSQ. The bit rates are ranging from 0.125 to 4 bpp.

In addition, the results given in Table 1 demonstrate that the proposed EMDSQ systematically outperforms the state-of-the-art MDUSQ of [4] on a broad set of images and target bit-rates.

5. CONCLUSIONS

The paper presents a new type of embedded multiple-description scalar quantizers, herein called EMDSQ, as well as a comparison with the MDUSQ of [4]. The EMDSQ fulfill the requirement of a high level of redundancy and enable progressive image (and video) transmission over unreliable channels. The experimental results show that the EMDSQ outperform the MDUSQ for the central channel. Thus, one may conclude that for an erasure channel model, coding techniques based on EMDSQ will provide systematically better rate-distortion performance.

For the particular case when an entire channel is lost, the experiments show comparable results for the side-channel reconstructions. Finally, the generalization of the EMDSQ for an arbitrary number of channels leads to the possibility of designing realistic codecs for practical multi-channel communication systems.

6. ACKNOWLEDGEMENTS

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