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ORIGINAL PAPER

Multiple description wavelet coding with dual decomposition and cross packetization

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Abstract In this paper, a novel wavelet-based multiple description coding (MDC) is proposed with *dual decomposition* (DD) and *cross packetization* (CP). Through dual decomposition, each description has two parts, the *primary* and the *complementary*. The former contains the *structural* information, including the positions and signs of significant coefficients, whereas the latter contains the *residual* data, which are the absolute values of the significant coefficients' magnitude. The primary part is most crucial for source reconstruction; hence, their codes generated by the x-tree wavelet encoder are duplicated in both descriptions for heavy protection. On the other hand, the residual data are processed by the multiple description scalar quantizer to generate two indices for their respective descriptions as the complementary part. The proposed DD–MDC method effectively enhances error-resilience capability for robust transmission. For the packet-switching networks, the proposed CP, which produces the row packets and column packets for the two descriptions, respectively, is incorporated into the DD–MDC framework, leading to the DDCP–MDC scheme. Extensive simulation results have clearly shown that the proposed wavelet-based DD–MDC and DDCP–MDC methods are highly error resilient and consistently yield high coding gain; particularly, when only one description is available, the reconstructed image quality is superior to that obtained with other existing methods.

Keywords Multiple description coding · Error-resilient coding · X-tree · Decomposition · Packetization · Packet switching networks

1 Introduction

Most communication networks in use nowadays are the so-called "best-effort" networks without any guarantee of quality of service (QoS). When the data are moved from a higher capacity link to another link with a lower capacity, network congestion might be incurred due to the lack of channel capacity. As a result, some packets will be rejected and are lost. Moreover, noise and interference can also lead to transmission failure. One of the conventional means to handle these adverse situations is retransmission, but at the expense of causing more delays. In case of frequent packet loss, delays are quite often unacceptable in real-time applications [1]. To address this issue, *multiple description coding* (MDC) [2] was introduced as an effective approach and has received a considerable amount of attention in recent years.

The MDC was first advocated for speech communications, followed by its use in the image and video

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transmission over the packet-erasure networks [2–9]. The basic idea of MDC is to generate multiple substreams from the source data, called *descriptions*, which are then sent to the receiver through diverse channels. When all the descriptions are available at the receiver, the decoder can reconstruct the source with the highest fidelity. However, if some packets in one or more channels are lost, the goal is to ensure that the quality of the reconstructed signal is still acceptable. This is achievable due to the added redundancy available in both channels so that in the case of any channel erasure incurred in one description (channel), the decoder is still able to retrieve some lost information from another description (channel).

Vaishampayan [2] published the first popular MDC framework, called the *multiple description scalar quantizer* (MDSQ). Battlo et al. [3] introduced the *multiple description transform coding* (MDTC), along with some theoretic rate-distortion results for the sources with memory. Wang et al. [4] proposed another MDTC scheme by employing a *pairwise correlating transform* to introduce dependencies between the two descriptions. The combination of multiple description coding and wavelet coding yields better coding quality than that of their predecessors. Jiang and Ortega [5] suggested a simple and efficient wavelet-based MDC scheme, called the *polyphase transform and selective quantization* (PTSQ). In this method, wavelet coefficients are separated into multiple phases and coded by the *set partitioning in hierarchical trees* (SPIHT) [7] encoders, respectively. Codewords from one phase and the protection information from another phase form one description. Based on SPIHT, PTSQ yields a very high coding efficiency. Miguel et al. [7] developed another wavelet-based MDC scheme, called MD-SPIHT, in a similar way except that the protection for a description is spread in two or more descriptions. MD-SPIHT has demonstrated better error-resilient results than PTSQ did in 16 descriptions. Servetto [8] introduced a hybrid approach by incorporating the MDSQ into sub-band coders (MDSQSC). The performance of the MDSQSC is not as good as that of the PTSQ in 2-description coding. However, in the case of 16-description coding with heavy loss, it even outperforms MD-SPIHT. A JPEG2000 compatible MDC scheme, denoted as CWJ2000, was proposed in [9] to generate a set of rate-distortion optimized multiple descriptions with slightly better results than PTSQ does in two descriptions. In [10], Cai and Chen proposed the *structure unanimity-based multiple description coding* (SUMDC), which outperforms the PTSQ in two descriptions.

In the SUMDC, a significant wavelet coefficient x, which is a wavelet coefficient lager than the given threshold T (i.e., $|x| \geq T$), is sub-sampled bit-wise to produce an odd-position coefficient x_o and an even-position coefficient x_e. For instance, a five-bit coefficient $x = +1\mathrm{b}_3\mathrm{b}_2\mathrm{b}_1\mathrm{b}_0$ will produce an odd-position coefficient $x_\mathrm{o} = +\mathrm{b}_3\mathrm{b}_1$, and an even-position coefficient $x_\mathrm{e} = +\mathrm{b}_2\mathrm{b}_0$. Those odd-position coefficients and even-position coefficients are coded separately, forming the two descriptions. If an odd-position coefficient x_o is significant (i.e., $|x_\mathrm{o}| > 0$), then the related even-position coefficient x_e is also significant (i.e., $|x_\mathrm{e}| > 0$), and vice versa. Furthermore, since both the odd- and even-position coefficients provide the same structural information consisting of the locations and signs of significant coefficients, it means that such important information is already present in both descriptions. Therefore, at the decoding stage, it provides more flexibility in the construction of descriptions and yields higher coding performance. To exploit the advantages of both SUMDC and MDSQ, a new approach for producing two descriptions, called the *dual decomposition* (DD), is proposed in this paper. To further enhance the error-resilience ability for the packet-switching networks, a new data packetization scheme, called the *cross packetization* (CP), is also proposed and incorporated with the DD. For the ease of referring to these two MDC schemes, they are denoted as DD–MDC and DDCP–MDC, respectively.

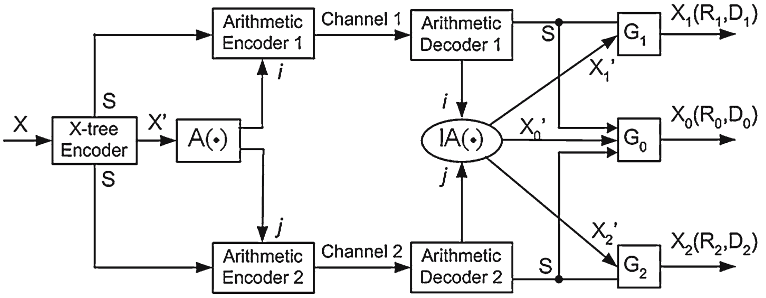
The structure of the remaining sections of this paper is as follows. Section 2 discusses the basic idea and framework of the proposed dual decomposition multiple description wavelet coding system. Section 3 shows how to conduct the cross packetization on the re-organized wavelet-coefficient blocks in both the horizontal and the vertical directions using MDSQ to generate two indices as the complementary part of their respective descriptions so as to strengthen the error-resilience capability over packet-switching networks. Simulation results are included in Sect. 4 and compared with that of the state-of-the-art MDC methods. Conclusions are drawn in the final section.

2 Dual decomposition multiple description wavelet coding

2.1 The framework of the DD–MDC codec system

The framework of the proposed *dual decomposition* (DD) MDC codec system is shown in Fig. 1, where symbol X indicates the wavelet coefficients resulting from a *discrete wavelet transform* (DWT) (not explicitly shown in the figure); symbol S denotes the structural

Fig. 1 The framework of the proposed DD–MDC codec system



information of wavelet coefficients, including the positions and signs of the significant coefficients. These critical data are duplicated in both arithmetic encoders for entropy coding. Symbol X' represent the *residual* data, which are the magnitude differences between the current significant coefficients (not smaller than a threshold) and the significant coefficients with smallest magnitude in the given threshold, which are fed into the multiple description scalar quantizer $A(\bullet)$ to generate the indices *i* and *j* for the residuals of the significant coefficients. Both arithmetic encoders separately encode the structural data first, forming the primary part for each description, followed by the encoding of respective index *i* or *j* to form the complementary information. These descriptions are transmitted to the receiver over diverse channels.

At the receiver side, together with the multiple description scalar dequantizer $IA(\bullet)$, both arithmetic decoders independently decode their received descriptions to recover the primary part and the complementary part to rebuild the structural data and indices, respectively. The central decoder G_0 receives the information from both channels; while the side decoders, G_1 and G_2 receive information only from their respective channels. If both descriptions are received correctly, wavelet coefficients can be reconstructed through G_0 based on the structural data and indices (i, j) decoded from both channels. On the other hand, if one channel is erased, the primary information can still be recovered because of the structural data that are available in both descriptions.

With the structural data and either index *i* or *j*, side decoder G_1 or G_2 can rebuild the source image with acceptable fidelity. The outputs of the decoders are $X_i(R_i, D_i)$, for $i = 0$, 1, and 2. For $i = 0, X_0(R_0, D_0)$ is the image reconstructed by the central decoder G_0 with the *base rate* R_0 and the *central distortion* D_0. Note that R_0 is the desired bit rate to be met by a traditional (single description) codec with distortion D_0. If $i = 1$ or $i = 2$, $X_i(R_i, D_i)$ is the image reconstructed by the side decoder G_i with the *side rate* R_i and the *side distortion* D_i.

2.2 Dual decomposition (DD) algorithm

For the proposed DD–MDC system, the wavelet coefficients are decomposed *twice* through a hierarchical way and with a special arrangement of the generated data (thus, called the *dual decomposition*) as follows. First, the wavelet coefficients are separated into the *primary* part and the *complementary* part, followed by a further decomposition of the latter. The primary part contains the *structural* information regarding the locations and signs of the significant coefficients, forming the so-called *significance map*. Note that this information is equally available in both descriptions as the most crucial data for image reconstruction at the decoder. On the other hand, the residual data (complementary part) are less critical as compared with the structural information. So they are further processed with an MDSQ to generate pairs of quantization indices that are sent to two separate descriptions.

An x-tree encoder [11] is employed to implement the *dual decomposition*. An x-tree is a hierarchical inter-band quadtree (Fig. 2). Similar to the zero-tree [12], the offspring of the x-tree root must be a *zero*. However,

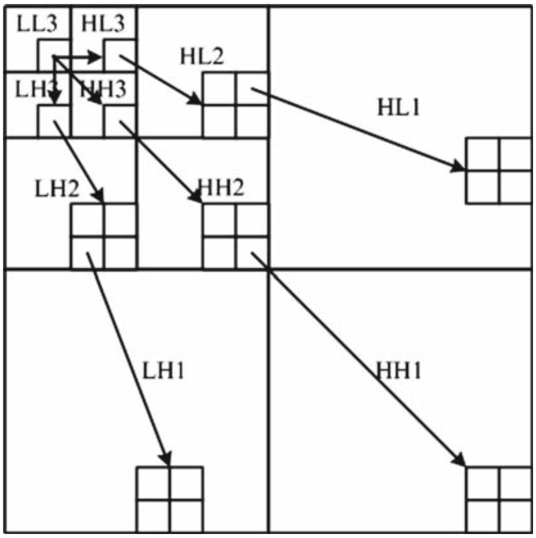


Fig. 2 Hierarchical inter-band quadtree

to extend its representation ability, its value can be a positive number, a negative number, or even a zero. From [11], one can see that the coding efficiency of the x-tree encoder is similar to that of the SPIHT [7].

To create the primary part and residual data, a group of thresholds, denoted as $T_0, \ldots, T_N$, which satisfy $T_{i+1} = T_i/2$ (for $0 \leq i \leq N-1$) and $\max|x| < T_0$, is used to quantize the wavelet coefficients $\{x\}$. For each threshold T_i, the corresponding primary information (i.e., the x-tree-based significance map of wavelet coefficients) is generated, and the codewords of the map are fed into both arithmetic encoders. Meanwhile, each magnitude difference between the current significant coefficient and the minimum magnitude significant coefficient in the given threshold is send to the MDSQ $A(\bullet)$ to generate the indices i and j and fed into their respective arithmetic encoders.

The proposed DD algorithm is summarized as follows:

1. Choose a group of thresholds, denoted as $T_0, \ldots, T_N$, which satisfy $T_{i+1} = T_i/2$ (for $0 \leq i \leq N-1$) and $\max|x| < T_0$.
2. For each threshold T_i (iterating from $i = 1$ to $i = N$),
   - 2.1. Find the minimum magnitude among those significant coefficients whose magnitudes are above the current threshold T_i.
   - 2.2. For each coefficient x, if x is not marked as a *coded-node*, then
     - 2.2.1. Encode its structural information using the x-tree encoder and send the codewords to both arithmetic encoders.
     - 2.2.2. If x is significant ($|x| \geq T_i$), then
       - Send the magnitude difference between the current coefficient and the minimum magnitude found in 2.1. to MDSQ A($\bullet$) to generate two indices i and j, and
       - Send indices i and j to their corresponding arithmetic encoders and mark the coefficient as a *coded-node*, which denotes that the coefficient has been coded and needs not be re-coded.
3. The outputs of both arithmetic encoders separately form Description 1 and Description 2.

3 Dual decomposition and cross packetization multiple description wavelet coding

3.1 Motivation

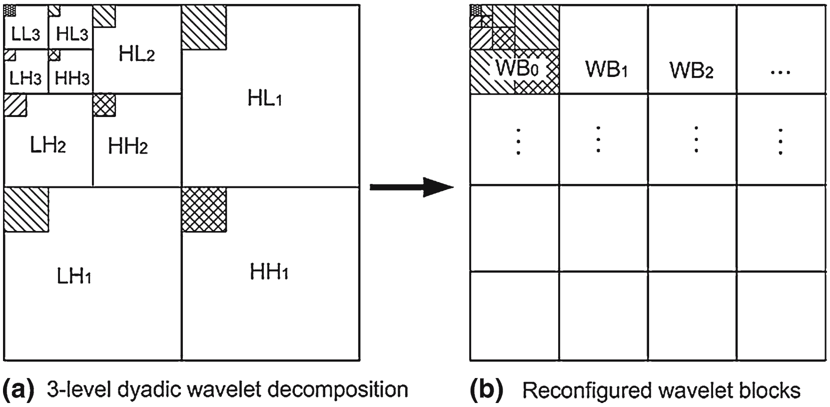
Up to this point, the proposed DD–MDC scheme works quite well in a typical erasure (i.e., completely failed or unavailable) channel. However, since most modern communication networks consist of packet-switching channels, the descriptions need to be divided into packets for their transmission through different channels. As a result, packets from both descriptions are subject to packet loss whenever the networks get congested.

Furthermore, to provide the best quality of the reconstructed image, all the packets that arrive at the receiver intact should be used in the image reconstruction. Therefore, the entire image transmission framework boils down to two essential issues: (1) how to packetize the descriptions into packets at the transmitter side in order to fit for the various packet-loss circumstances, and (2) how to make the best use of all correctly received packets at the receiver side to reconstruct the image.

An intuitive approach is to divide the transformed image into N sub-images and then directly apply the DD–MDC scheme to each sub-image to generate its description packets. However, since the N sub-images are independent from each other, if both descriptions of a specific sub-image are totally lost, the reconstructed image will be severely degraded. To avoid such catastrophic circumstance, a new data packetization scheme, called the *cross packetization* (CP), is proposed and incorporated into the DD–MDC to greatly enhance the error-resilience capability and reduce the degradation due to packet loss.

3.2 Encoding

First, a three-level dyadic wavelet decomposition is performed on the source image, resulting in 10 sub-bands, LL_3, HL_i, LH_i, and HH_i, for i = 1, 2, and 3. Then, the wavelet coefficients are separately rearranged to form the wavelet blocks as shown in Fig. 3a, b. The collection of shaded blocks presented in Fig. 3a demonstrates the hierarchical quadtree, rooted in the baseband LL_3. Figure 3b shows how the wavelet coefficients from the same quadtree are rearranged to form their wavelet blocks. The wavelet blocks are then grouped row by row to generate 8 row slices (Fig. 4a) and column by column to produce 8 column slices (Fig. 4b). All row pictures (slices) and column pictures (slices) are separately coded in the way similar to the aforementioned DD–MDC. However, only one description is generated for each case (say, Description 1 for the row picture, and Description 2 for the column picture). Note that when any two slices contain loss packets (for instance, H_4 and V_4 as graphically illustrated in Fig. 4c), only the intersected slice area are possible to have no packet data at all in the worst case. Thus, the proposed CP is inherited with strong error-resilience capability, especially when a large number of packets get loss.



(a) 3-level dyadic wavelet decomposition **(b)** Reconfigured wavelet blocks

Fig. 3 Rearrange the wavelet coefficients of an image to form wavelet blocks

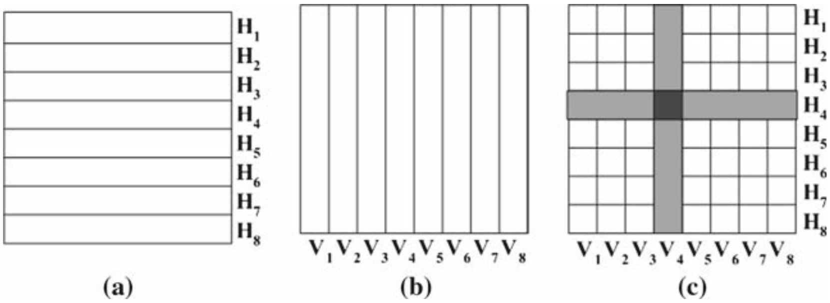


Fig. 4 **a** Horizontally dividing the wavelet blocks row by row to form *row slices*; **b** Vertically dividing the wavelet blocks column by column to form *column slices*; **c** When two shaded slices, H_4 and V_4, contain loss packets. Note that only the intersected slice area is possible to have no packet data at all in the worst case

In summary, the DDCP–MDC system performs the following procedures:

1. Reorder the wavelet coefficients to form the *wavelet blocks*.
2. Partition the wavelet blocks row by row to generate 8 *row slices* and column by column to generate 8 *column slices*.
3. Choose a group of thresholds, denoted as $T_0, \ldots, T_N$, which satisfy $T_{i+1} = T_i/2$ (for $0 \leq i \leq N-1$) and $\max|x| < T_0$.
4. Encode each row slice to form a *row description*:
   - Use an x-tree encoder to generate the structural information and send the output to an arithmetic encoder.
   - Employ an MDSQ to decompose each wavelet coefficient into indices i and j, and send only index i to the arithmetic encoder, and
   - Combine the coded structural information and i-index to form a row description.
5. Encode each column slice to form a *column description*:
   - Use an x-tree encoder to generate the structural information and send the output to an arithmetic encoder, and
   - Employ an MDSQ to decompose each wavelet coefficient into indices i and j, and send only index j to the arithmetic encoder, and
   - Combine the coded structural information and j-index to form a column description.

3.3 Decoding

The decoder makes use of all correctly received packets to reconstruct the source. Since each row packet and each column packet has only limited intersections, a loss of few row packets along with few column packets will not introduce serious distortions. Moreover, since the baseband LL_3 in Fig. 3a contains only low-frequency components, high correlation on magnitude across neighboring coefficients are expected. Thus, it is reasonable to estimate the lost coefficients in the baseband from the correctly received neighboring ones. On the other hand, the lost coefficients in the higher frequency sub-bands have no such privilege for reconstruction via interpolation, they are simply set to zero in this work.

To further elaborate, let H_i and V_j denote the ith row slice and the jth column slice, respectively. If slices H_4 and V_4 (see Fig. 4c) are unavailable at the decoder due to packet loss, the interpolation process to estimate those missing packet data on their basebands LL_3 will be, respectively, conducted based on its neighboring wavelet blocks V_3, V_5, H_3, and H_5.

Any missing coefficient in the baseband (which is a root of a lost wavelet block, in fact, as mentioned in Sect. 3.2) can be estimated from the weighted average of its reconstructed neighboring wavelet coefficients. Considering that the coefficients reconstructed with two descriptions will yield a higher fidelity than those with only one description, the weights for the former are thus set as twice as that of the latter. To quantify explicitly, let $\hat{x}_{0i}$ (for $i = 1, \ldots, N_0$) be the neighboring wavelet coefficients reconstructed with *both* descriptions and $\hat{x}_{1i}$ (for $i = 1, \ldots, N_1$) be the neighboring coefficients reconstructed with *either* description. This leads to the reconstruction of x as

$$\hat{x} = \frac{1}{2N_0 + N_1}\left(\sum_{i=1}^{N_0} 2\hat{x}_{0i} + \sum_{i=1}^{N_1} \hat{x}_{1i}\right).$$

In summary, the decoding procedures of the DDCP–MDC are outlined as follows:

1. Reconstruct the wavelet coefficients of all correctly received packets,
2. Estimate the missing coefficients in the baseband from their neighboring coefficients and set all other missing ones in the higher sub-bands to zero,
3. Restore the original positions of the wavelet coefficients from the wavelet blocks, and
4. Conduct the inverse DWT to reconstruct the image.

4 Experimental results

Computer simulations have been conducted using multiple commonly used test images to evaluate the performance of the proposed DDCP–MDC. In the following, only the results of "Lena" (512 × 512; 8-bit grayscale image) are shown in the paper for demonstration. First, the performance of the DD–MDC over typical erasure channels is evaluated. Note that in this case each description is transmitted as one entity without packetization. Further simulation experiments are then conducted to evaluate how well the DD–MDC with cross packetization (thus, DDCP–MDC) performs over packet-switching networks. The x-tree encoders along with the 9/7 bi-orthogonal wavelet filters and a five-level dyadic DWT are used to encode the primary information in all the aforementioned experiments. A multiple description scalar quantizer $A(\bullet)$ [2] is used to encode the complementary part, which is the simplest implementation of the index assignment by employing two quantizers whose decision regions are shifted by half of the quantizer interval with respect to each other [2].

4.1 Performance evaluation of the proposed DD–MDC scheme

The PSNRs of the decoded "Lena" image obtained by employing the PTSQ [5], the MDSQSC [7], the CWJ2000 [8], and the proposed DD–MDC coded at the target bit rates of 0.25, 0.5, and 1.0 bpp, respectively, are presented in Table 1 and Fig. 5 (for the case of 0.5 bpp).

From the experimental results as shown in Table 1, where "Center" means both descriptions are received and used for the source reconstruction and "Side" indicates the averaged PSNR (in dB) based on the cases of either description only, it can be seen that the proposed DD–MDC yields the best results consistently.

4.2 Performance evaluation of the proposed DDCP–MDC scheme

As mentioned before, the purpose of extending DD–MDC into DDCP–MDC with incorporation of the proposed cross packetization is to address the robustness and error resilience on transporting packetized image data over packet-switching (packet-erasure) networks. For this scenario, the wavelet-coefficient blocks of the image are partitioned into 16 packets in our simulation experiments—8 row packets and 8 column packets, as illustrated in Fig. 4a, b, respectively. With the targeted total bit rate of 0.5 bpp, the results of the proposed

Table 1 The PSNR (in dB) simulation results of the proposed DD–MDC based on image "Lena"

Bit rate (bpp)	Averaged distortion	Algorithms			
		PTSQ [5]	CWJ2000 [8]	MDSQSC [7]	DD–MDC (proposed)
0.25	Center	32.97	–	–	33.21
	Side	29.10	–	–	29.58
0.50	Center	36.15	36.21	36.00	36.25
	Side	32.07	32.12	30.98	32.54
1.00	Center	39.30	39.28	39.29	39.32
	Side	35.09	35.38	32.45	35.55

Fig. 5 The simulation results on Lena at 0.5 bpp by exploiting the proposed DD–MDC. **a** Both channels are available (36.25 dB). **b** Only channel 1 is available (32.74 dB). **c** Only channel 2 is available (32.34 dB)

algorithm are shown in Fig. 6, where DDCP-1 denotes the case that for each wavelet block, at least its information in one (either) description is received at the decoder (no wavelet block is totally lost), and DDCP-2 for at least one wavelet block is totally lost.

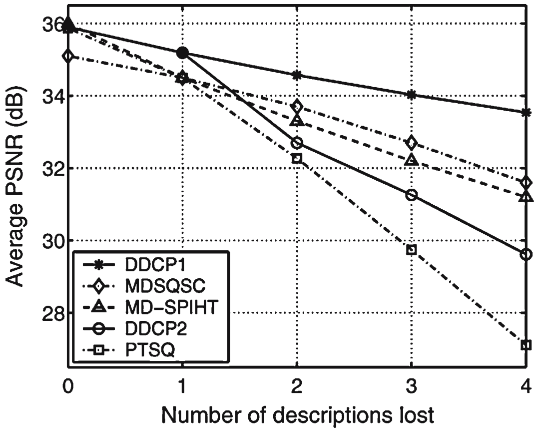


Fig. 6 A performance comparison based on the test image "Lena" (all coded at 0.5 bpp)

The performances of the proposed DDCP–MDC are evaluated and compared with that of PTSQ [5], MD-SPIHT [6], and MDSQSC [7] as shown in Fig. 6. In all cases, image data are packetized into 16 packets and coded at the total bit rate of 0.5 bpp. The PSNR curves presented in Fig. 6 consists of a set of performance points, respectively, indicating the mean values of the experimental results averaged over all possible combinations of packet-loss cases. For instance, in the case of one packet loss, there are 16 possibilities; hence, the average PSNR is computed over the simulation results of the 16 cases by taking their mean value. From this figure, it can be seen that if no wavelet block is totally lost (represented by DDCP-1), the proposed DDCP–MDC method can yield a very high coding gain, especially when the number of packet loss increases.

Figure 7 illustrates four reconstructed images by the proposed algorithm with a loss of 4 packets out of total 16 packets (i.e., 25% packets got loss) respectively rows 3∼6; columns 3∼5 plus the 4th row; columns 4∼5 and rows 4∼5; rows 3∼5 plus the 4th column. Each case is coded at the target bit rate of 0.5 bpp with the redundancy rate ρ = 20%. The redundancy rate is defined as $\rho = (R_1 + R_2 - R')/R'$, where R_1 and R_2 denote the bit rates used in both descriptions, respectively, and R' is the desired bit rate by a normal (single description) codec with the same distortion as the outcome of the center decoder. From Fig. 7, one can see that the packetization strategy of the proposed DDCP–MDC provides a fairly strong error-resilience capability for robust transmission and yields good subjective image quality even under 25% packet loss rate.

5 Conclusion

In this paper, a novel wavelet-based multiple description coding (MDC) scheme is proposed by first employing

Fig. 7 Four examples of reconstructed images of "Lena" with 4 packets got lost (out of 16 packets in total). They are coded at the total bit rate of 0.5 bpp with the redundancy rate $\rho = 20\%$. **a** 4 row packets lost (33.72 dB); **b** 1 row packet and 3 column packets lost (30.87 dB); **c** 2 row packets and 2 column packets lost (30.37 dB); **d** 3 row packets and 1 column packet lost (31.04 dB)

dual decomposition (DD) to the wavelet coefficients, followed by the application of *cross packetization* (CP) to strengthen the codec's error-resilience capability for packet-switching networks. The proposed dual decomposition process produces the primary part and the complementary part for each description, which contains the structural information and the residual information, respectively. The structural information is most essential and requires to be duplicated into both descriptions for image reconstruction at the decoder. Therefore, the proposed DD–MDC framework provides a highly robust codec system to combat large channel noise and interference that lead to a large number of missing packets.

The proposed cross packetization provides a simple and yet effective error-resilient packetization scheme to form the row packets for one description and the column packets for another description. Owing to the very limited amount of intersection for any given pair of row and column packets, the entire codec system inherently offers a fairly strong error-resilience capability to transmit the bitstreams over the packet-switching networks. As demonstrated by our simulation results, even when the packet loss happens on both descriptions, the proposed DDCP–MDC scheme still outperforms the PTSQ and is comparable to the MD-SPIHT.

One should note that the proposed DD–MDC and DDCP–MDC schemes provide a generic MDC framework such that, instead of employing an x-tree in our work, other wavelet encoding methods (e.g., zero-tree, SPIHT, or future developed wavelet-coefficient coding methods) can be directly incorporated into our proposed multiple-description codec system.

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