Noname manuscript No.
(will be inserted by the editor)

A New, Enhanced EZW Image Codec With Subband Classification

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Received: date / Accepted: date

Abstract In this paper, an enhanced version of EZW (Embedded zerotree wavelet) image coding algorithm is proposed, referred to as EZW-SC. By exploiting a new principle that relies on a subband classification concept, the enhanced algorithm allows the prediction of insignificant subbands at early passes, along with the use of an improved significance map. This reduces the redundancy of zerotree symbols, speeds up the coding process and improves the coding of significant coefficients. In fact, the EZW-SC algorithm scans only significant subbands and significantly improves the lossy compression performance with the conventional EZW. Moreover, new EZW-based schemes are presented to perform colour image coding by taking advantage of the interdependency of the colour components. Experimental results show clear superiority of the proposed algorithms over the conventional EZW as well as other related EZW schemes at various bit rates in both greyscale and colour image compression.

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Keywords Embedded image coding · Zeotree coding · Wavelet compression

1 Introduction

Data compression systems are founded with the aim of reducing the amount of data necessary to represent any digital data, including images and signals. In fact, data compression is the art or science of representing information in a compact form [1]. Transform coding is a clearly proven and commonly used technique for image compression, with the key objective of removing redundancy and providing uncorrelated coefficients [2–4].The discrete wavelet transforms (DWT), which offers excellent energy clustering, have proved to be extremely useful for image compression as reported in the literature [5–10]. Consequently, many compression schemes have widely adopted the use of such transforms, such as EZW [11], SPIHT [12] and JPEG-2000 [13–15]. In fact, the success of modern wavelet-based image coding algorithms relies on the exploitation of the excellent energy compaction of the wavelet transforms, its multiresolution representations [7, 8], and also its statistical properties such as the self-similarity characteristic of wavelet coefficients across subbands [16–22].

The first and most popular progressive image coding technique based on the wavelet transform is the embedded zero-tree wavelet (EZW) coding algorithm [11]. It introduces the zerotree structure of wavelet coefficients, generates the bits of the bitstream in order of importance and produces fully embedded code by exploiting the inter-subband correlation among insignifcant wavelet coefficients. By embedded coder, it is meant that the encoder can terminate the encoding at any point to each given target bit rate or target distortion metric. Similarly, the decoder can terminate at any point to reconstruct the input image. Many wavelet-based image coding schemes developed later in [12, 23–28] were affected by the idea of zerotree concept (data structure). EZW has proven to provide excellent performance in terms of compression ratio and image reconstruction. However, some redundancies when coding the zerotree symbols remain. During the coding process, the zerotree redundancy was observed in two situations. Firstly, especially in the early passes when most of the detail subbands are insignificant. Through these early passes, EZW scans some insignificant coefficients within these subbands and it codes them as zerotree symbols since their parent are coded as significant coefficients (positive or negative). Consequently, many bits are redundantly used to code these insignificant coefficients although they are found be in insignificant subbands. To avoid the coding of these zerotree symbols we propose to use a new subband classification concept in order to scan only significant subband, to reduce zerotree symbols at the early passes by predicting the insignificance information of detail subbands of the same spatial and orientation.

Secondly, during the coding process of original EZW, it was observed that a noticeable number of significant coefficients have insignificant descendants when compared with significant coefficients whose descendants are significant as reported in [19]. As a consequence, many zerotree symbols are generated by

EZW to encode the insignificant descendants of significant coefficients, which do not need to be encoded again. To improve the coding performance, we use an improved significance map thereby avoiding the coding of zerotree symbols generated from the descendants of significant coefficients. The proposed modified EZW algorithm, namely, EZW-SC, develop a new subband classification principle incorporated with an improved significance map comprising of nine symbols.

EZW and SPIHT (Set partitioning in hierarchical trees) were designed mainly to compress greyscale images. One possible extension to colour images would consist of separating the image into individual components, and then performing the coding of each wavelet transformed colour plane individually. However, this approach requires allocation of bits. It does not also maintain the full embeddedness and the precise rate control of the coder, since the decoder must await the arrival of the full bitstream to reconstruct the colour images [29]. In [30, 31], a colour embedded zerotree wavelet (CEZW) has been proposed using the YUV space. It uses a new spatial orientation tree (SOT) for luminance coefficients (Y) to take advantage of the interdependence of chrominance components (U and V) [32]. In this article, we also propose two new extended versions of EZW for performing a fully embedded colour image coding. The first one, which is a direct extension of EZW-SC to colour images, applies the same SOT as defined in conventional EZW using the codec EZW-SC. The colour components, at first separated and wavelet decomposed, are treated as one unit during the encoding step to generate a one mixed bitstream. The second one, which is a further development of EZW-SC, associates an improved SOT [30] with the codec EZW-SC for permitting an efficient exploitation of interdependencies in chrominance components. Numerical results indicate that our codecs deliver the best performance when compared to the conventional EZW and other improved versions of EZW codecs [11, 19, 25, 30, 33–35] for greyscale and colour test images.

2 Original EZW algorithm

EZW is one of the well-known wavelet based compression methods. It employs a bit plane based coding which generates bits pass by pass, where a pass corresponds to a particular threshold value. Essentially, the EZW scheme is based on four concepts: Hierarchical decomposition of an image by using the discrete wavelet transform, which provides a compact multiresolution representation of an image. Prediction of abscence of significance information across scales by exploiting the self similarity in images. Successive approximation quantization, and adaptive arithmetic coding of symbols.

First, let us define the significance and insignificance of a given wavelet coefficient. A wavelet coefficient is said to be insignificant with respect to a given threshold (T) if its magnitude is less than T. Otherwise, it is significant. EZW, which takes advantage of the tree structure of wavelet coefficients between the interbands, uses the zerotree data structure to predict the insignificance of coefficients. This is performed by grouping the wavelet coefficients corresponding to the same spatial location and orientation to form a spatial orientation tree.

The zerotree representation is based on the hypothesis that if a wavelet coefficient at a coarse scale is insignificant when compared to a given threshold T, then all wavelet coefficients of the same orientation in the same spatial location at finer scales are likely to be insignificant with respect to T. In the discret wavelet transform, each coefficient is related to a set of coefficients at the next finer level that corresponds to the same spatial location in the image. A coefficient at coarse level is called parent, while its spatially related coefficients at the next level are referred to as children. For a given parent, the set of all coefficients at all finer scales of similar orientation corresponding to the same location are called descendants [11]. In subband decomposition, all parent coefficients have four children except the lowest frequency subband. The lowest frequency subband has three children while the highest frequency does not have any children.

During the encoding/decoding procedures, two distinct operations are performed alternately for each threshold value. These are called the dominant pass and the subordinate pass, respectively. First, an initial threshold is determined as the smallest power of 2 that is greater than max(abs(x(i,j))/2, where x(i,j) are the wavelet coefficients.

In the dominant pass, individual coefficients are scanned and tested for significance against the current threshold. The wavelet coefficients are scanned in such way that no child node is scanned before its parent. Each coefficient within a given subband is scanned before any coefficient in the next subband. The scan, in zigzag order, starts at the lowest frequency subband at level N, LL_N, continues with subbands HL_N, LH_N, HH_N and drops to level N-1, where it scans HL_{N-1}, LH_{N-1}, HH_{N-1}, and so on. Two lists are used during the coding as well as the decoding process. The dominant list contains the coordinates of the coefficients that have not been found to be significant. The subordinate list contains the magnitudes of the coefficients that have found to be significant. For each pass, each list is scanned once.

During the dominant coding pass, each coefficient, from the dominant list, is classified as:

Ztr: if the coefficient and all its descendants are insignificant with respect to the current threshold.

Iz: If the coefficient is insignificant and has at least one descendant that is significant.

Pos: if it is a significant positive.

Neg: if it is a significant negative.

Note that when a coefficient is found to be significant, its magnitude is added to the subordinate list and is replaced by zero for the purpose of zerotree formation.

In the subordinate pass a progressive refinement is performed to those coefficients that are already found to be significant and stored in the subordinate list.

Once the subordinate pass is performed, the current threshold is halved and the process is repeated iteratively through a dominant and subordinate pass until a predefined bit budget is reached or a predefined distortion objective is met.

3 Proposed Subband Classification-based EZW (EZW-SC)

In this section, we describe the idea behind our enhanced EZW coding scheme with subband classification, EZW-SC. After performing the dyadic wavelet transform, the transformed image shows a pyramidal structure after N levels of decomposition. In fact, there are 3N+1 subbands.

Let us define:

A subband is said to be significant if it has at least one coefficient whose magnitude is greater than or equal to a given threshold value.

Except for the highest frequency subbands at the first level, each subband can be considered as a parent-subband. Given a parent-subband, a children-subband is of the same orientation in the same location at the next finer scale. All subbands corresponding to the same spatial location at all finer scales of the same orientation are called descendant-subband.

A subband is of type "A" if it is significant and has at least one significant descendant-subband. It is of type "B" if it is significant but it has no significant descendant-subbands. During the coding process of conventional EZW, it was noticed that the detail subbands corresponding to the same spatial orientation exhibit a high similarity in terms of insignificance, as shown in Tables 1-3, in particular at the early passes with a higher value of the threshold. However, in such a situation, EZW codes several insignificant coefficients as Zerotree although they were found to be in insignificant detail subbands. The coding of the zerotree symbols is mainly due to the fact that these insignificant coefficients have parents which are significant (positive or negative). As a consequence, many bits are spent by using zerotree symbols in these cases. To avoid the coding of these zerotree symbols, we propose to use a new subband classification concept. The purpose of this is to scan only significant subbands, and reduce zerotree symbols at the early passes by predicting the insignificance information of detail subbands of the same spatial orientation. With this observation, EZW-SC is elaborated on the basis of the following hypothesis:

At the early passes (bit planes) with a larger threshold value, if a parent-subband is insignificant compared to a given threshold, then all its descendant-subbands are also significant with respect to the same threshold.

This hypothesis is always true for our test natural images, as can be seen from Tables 1, 2 and 3. The purpose of this hypothesis is to use only one bit '0' for encoding a given insignificant parent-subband with their descendant-subbands. Note that if a given parent-subband is found to be insignificant at the early passes, then there is no need to check its descendant-subbands, since they are also insignificant.

It is worth to point out that the redundancy of coding zerotree symbols, during the dominant pass coding of original EZW, starts at the early passes in the detail subbands of the coarse scale since the parent of insignificant coefficients are located in the lowest frequency subband where several coefficients are significant. Next, the redundancy of zerotree moves to the detail subband at finer scales.

3.1 Description of the coding process of the proposed EZW-SC codec

Similar to EZW, EZW-SC is also a bit plane based image coding algorithm. It is comprised of two main stages within each bit plane : dominant and subordinate passes. Prior to the dominant pass, a start threshold is derived from the maximum value in the wavelet coefficients pyramid (chosen as power of 2). During the dominant pass, the encoder first traverses through the (3N+1) subbands comparing the maximum of magnitudes of each subband against the current threshold in order to classify a given subband as either significant subband or insignificant subband. The scanning order of the subbands is similar to that of coefficients. It begins with the lowest frequency subband at level N, denoted LL_N, and scans subbands HL_N, LH_N, HH_N at which point it moves to scale N-1, etc.

For each test of a subband, a single bit ('0' or '1') is used to describe its significance. If a subband is not significant, then a '0' is transmitted. Consequently, insignificant coefficients are accumulated and encoded in group with only one bit, whereas EZW consumes an important amount of bits to encode the insignificant coefficients. Then, the next subband will be tested for significance following the scanning order described previously. Otherwise, if a subband is significant the bit value of 1 is sent. At this stage, their descendant-subbands must be tested, in order to determine if a subband is of type "A" or "B". If the subband has at least one significant descendant-subband, then it is of type "A" and the bit value of '1' is transmitted. The insignificant coefficients, within this subband, are then encoded, like in EZW, using the symbols Ztr and Iz.

The significant coefficients are encoded using an improved significance map, unlike EZW, using the following symbols [19]:

Sa: if a wavelet coefficient is positive significant but all its descendants are insignificant.

Sb: if a wavelet coefficient is negative significant but all its descendants are insignificant.

Sc: if a wavelet coefficient is positive significant and has at least one descendant that is significant.

Sd: if a wavelet coefficient is negative significant and has at least one descendant that is significant.

On the other hand, if a subband is of type "B", then a '0' is added to the compressed bitstream. While the insignificant coefficient, found to be within this subband, are coded with only one bit '0' (ztr' symbol , see Fig. 1), the

Table 1 Significance test of various subbands HL at different scales during the early passes for several test images (1: the subband is significant, 0: the subband is insignificant)

Image	Pass	HL6	HL5	HL4	HL3	HL2	HL1
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Airplane	4	1	1	1	**0**	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	1
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
Boat	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Lena	4	1	**0**	0	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
Peppers	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Barbara	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Goldhill	4	1	**0**	0	0	0	0
	5	1	1	**0**	0	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0

significant coefficient are coded with 2 bits : the bit value of '1' and the sign information (Sa' and Sb' symbols, see Fig. 1). Note that the purpose of these symbols is to avoid the coding of the zerotree found from significant wavelet coefficients. Thus many bits are saved using this significant map. The flow chart for encoding a coefficient in EZW-SC is shown in Fig. 1. It is worth

Table 2 Significance test of various subbands LH at different scales during the early passes for several test images (1: the subband is significant, 0: the subband is insignificant)

Image	Pass	LH6	LH5	LH4	LH3	LH2	LH1
Airplane	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
Boat	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	1	**0**	0
	6	1	1	1	1	1	0
	7	1	1	1	1	1	0
Lena	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	1	0
	7	1	1	1	1	1	0
Peppers	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	0	0
	7	1	1	1	1	1	0
Barbara	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	1	0
	7	1	1	1	1	1	1
Goldhill	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
	4	1	1	**0**	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	0	0
	7	1	1	1	1	1	0

noting that the symbols Sa, Sb, Sc and Sd use 3 bits to encode a coefficient while the symbols Iz and Ztr use 2 bits. However, at the lowest level, the symbols Sa and Sb only use 2 bits for their encoding, while only one bit is used to encode the Ztr symbol.

Table 3 Significance test of various subbands HH at different scales during the early passes for several test images (1: the subband is significant, 0: the subband is insignificant)

Image	Pass	HH6	HH5	HH4	HH3	HH2	HH1
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Airplane	4	1	**0**	0	0	0	0
	5	1	1	**0**	0	0	0
	6	1	1	1	**0**	0	0
	7	1	1	1	1	**0**	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	1	**0**	0	0	0	0
Boat	4	1	**0**	0	0	0	0
	5	1	1	**0**	0	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Lena	4	1	**0**	0	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	**0**	0	0
	7	1	1	1	1	**0**	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Peppers	4	1	1	**0**	0	0	0
	5	1	1	**0**	0	0	0
	6	1	1	1	**0**	0	0
	7	1	1	1	1	**0**	0
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Barbara	4	1	**0**	0	0	0	0
	5	1	1	1	**0**	0	0
	6	1	1	1	1	**0**	0
	7	1	1	1	1	1	1
	1	**0**	0	0	0	0	0
	2	**0**	0	0	0	0	0
	3	**0**	0	0	0	0	0
Goldhill	4	**0**	0	0	0	0	0
	5	1	1	**0**	0	0	0
	6	1	1	1	**0**	0	0
	7	1	1	1	1	**0**	0

The dominant pass is followed by a subordinate pass whose goal is to refine the representation of the magnitude of those significant coefficients stored in the subordinate list. Once the subordinate pass is completed, the current threshold is divided by 2 and the dominant and refinement stages are continued until a desired bit rate is achieved or a predefined distortion is met.

It can be noted that EZW-SC, which is based on subband classification and uses an improved significance map, is faster, scans only significant subbands, and reduces both scanning and the number of zerotrees found to be in EZW as well as increases the number of significant coefficients. It should also be noted that the proposed coding system EZW-SC is designed for lossy image compression, especially at very low and low bit rates. It can be enhanced with adaptive arithmetic coding of the proposed symbols at a higher complexity cost. For lossless image compression, some modifications are required since the number of symbols Sa Sb Sc and Sd increases as well as the number of significant subbands. This leads to consuming a large amount of bits. Therefore, a way to improve the performance of lossless coding is to switch to the original EZW algorithm at a certain threshold value.

4 Embedded colour image compression

EZW was firstly developed for encoding greyscale images. A direct approach to code colour images affords an opportunity to process the three colour components as three greyscale images and the same coding technique is then employed for each plane. There are some redundancies that can also be avoided in luminance / chrominance color spaces (LC) [21, 29, 36] despite the fact that RGB to luminance and chrominance (LC) colour transformations are achieved with the aim to reducing the correlation found to be in colour images. These redundancies are announced for those coefficients within chrominance planes at the same spatial location which guarantee the same significance test result when assessed against a given threshold. In other words, if a wavelet luminance and its descendants in the luminance plane are found to be insignificant with respect to a given threshold, chrominance coefficients at the same location will also be probably insignificant. To exploit the interdependence between the colour planes, a spatial orientation tree renowned as the colour embedded zerotree wavelet (CEZW) [32] has been proposed in [30, 31] (see Fig. 2). The percentage of insignificant luminance wavelet coefficients having no significant descendants, including those in luminance and chrominance planes, is greater than that of luminance coefficients having at least one significant descendant (in luminance or chrominance planes) [19]. It is also noted that the descendants of a luminance coefficient in chrominance planes occupy the same location. Indeed, the chrominance coefficients exhibit significant similarities to luminance coefficients at the same location as zerotree symbols are more significant than their Iz counterparts in percentage terms.

4.1 Proposed EZW-SC codecs for colour images:CCEZW-SC and CEZW-SC

CCEZW-SC (conventional colour EZW-SC) makes reference to the proposed colour EZW image coder, described in section III, and applied to compress colour images using the same SOT described in conventional EZW, referred

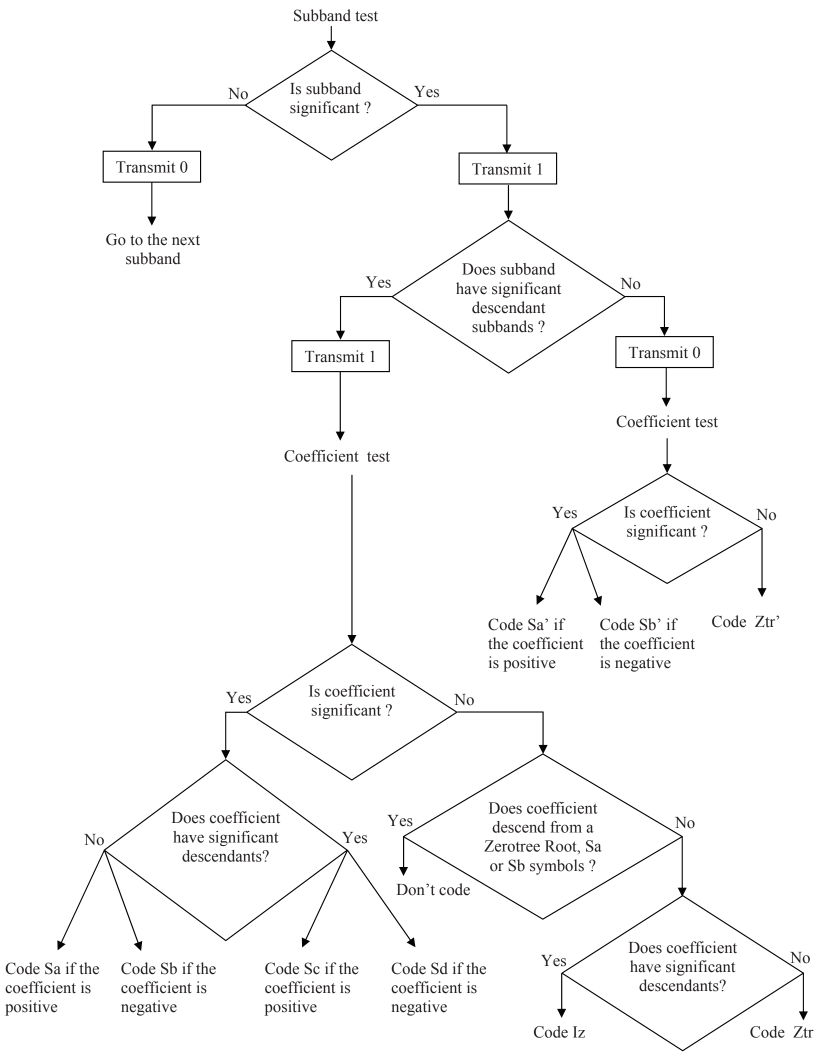

Fig. 1 Proposed flow chart for encoding a coefficient in EZW-SC

to as SOT_A. The chrominance planes are scanned after the luminance plane during the dominant pass. As a result, a mixed bitstream is generated. The innovative idea behind the second proposal of the EZW coder for colour images, CEZW-SC (proposed alternative colour EZW-SC), is to associate the SOT described previously [30] [31], known as SOT_B, with luminance coefficients considered insignificant during the dominant pass of the coding stage (see Fig. 2). CEZW-SC performs two passes (dominant pass and subordinate pass)). During the dominant pass, the luminance is first processed. Hence, the (3N+1) subbands of the luminance are classified as either significant subband or insignificant subband. For each luminance subband, a signification test is performed. If a given subband is significant and has significant descendant subbands, six symbols (Sa, Sb, Sc, Sd, Ztr and Iz) are used to encode the given coefficient. At this stage, if the luminance coefficient is found to be insignificant, all its descendants, in luminance and chrominance planes, should be tested. If they are all insignificant, the zerotree symbol (Ztr) is assigned. Otherwise, the symbol Iz is transmitted. On the hand, three symbols (Sa', Sb', Ztr') are employed to encode a given coefficient found to be in a significant subband which does not have significant descendant subbands, as is illustrated in Fig. 1. In this case, the symbol (Ztr') is only transmitted if the luminance coefficient and its descendants in chrominances are all insignificant. The chrominance planes are processed alternately after the luminance plane has been examined. It is worth nothing that the coefficients in the chrominance planes previously considered insignificant and whose parent luminance coefficients at the same spatial location were coded as ztr symbols, when scanning the luminance plane, are not examined during the chrominance scan. The subordinate pass is similar to the one at the conventional EZW. Typically, the amplitude of the luminance coefficients is greater than that of the chrominance planes. As a result, chrominance components are only processed if their corresponding threshold is greater than or equal to the current threshold.

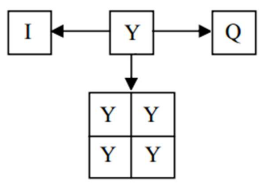

Fig. 2 Diagram of parent desendant relations [30] used in the proposed CEZW-SC

5 Experimental results: assessment and analysis

5.1 Performance of lossy compression algorithms on greyscale images

With the aim to assessing the lossy compression performance of the proposed scheme, numerical experiments were conducted on a number of 20 natural standard images of size 512 x 512, each sample is quantified at 8 bits per pixel (bpp). The compression performance at several bit rates is compared to that of the conventional EZW, the method in [35], and the improved EZW version (IEZW) reported in [25]. To make the comparison as fair as possible, a 6 level dyadic wavelet decomposition of the image is performed using the biorthogonal 9/7 wavelet filters. In addition, the results are reported in terms of binary uncoded versions. Initially, the comparison is made in terms of the number of bits generated at different passes for several threshold values. The corresponding results of the following 7 images (Airplane, Boat, Lena, Peppers, Barbara, Goldhill, Sailboat) are shown in Tables 4-5. As can be seen, our method generates fewer bits, especially at the last pass. This can be justified by the features of EZW-SC which are based on two key elements : firstly, EZW-SC uses an improved significance map to reduce the number of zerotree symbols, and increase significant coefficients. Secondly, it is based on a subband classification concept whose role is prominent in the early passes where the threshold is high. In this situation, many subbands remain insignificant, as shown in Tables 1-3, and as indicated previously, EZW-SC scans only significant subbands. Thus, only one bit '0' is used to code all the insignificant coefficients as accumulated, saving consequently many bits.

For lossy image compression that was actively involved in our study, the distortion is measured by the peak signal to noise ratio (PSNR) and the Structural SIMilarity (SSIM) index. Tables 6 and 7 highlight the performance comparisons of the PSNR and the number of significant coefficients at several compression bit rates (from 0.007812 to 1 bpp). As expected, our method far outperforms all others, which is particularly evident in the medium bit rate (1 bpp) where the gains of 2.40 dB, 2.33 dB on EZW, 2.24 dB and 2.31 dB on IEZW are obtained for the Lena, Peppers, Airplane and Barbara images respectively. Likewise, for Lena and Peppers images, EZW-SC also shows an improvement of 2.62 dB and 2.27 dB over the original EZW at the lowest bit rate (0.0078125 bpp) respectively. This improvement at very low bit rate is due to the subband classification characteristic of EZW-SC, which allows predicting the insignificance of detail subbands at the same spatial location and orientation, and hence code more efficiently many insignificant coefficients at early bit planes, using few bits. In addition, EZW-SC has more number of significant coefficients, as shown in Table 7, which allows the best reconstruction of images. As can be seen from Table 6 , the coding gain of EZW-SC over IEZW [25] is increased when the threshold value decreases (see the gain at 1 bpp), although both EZW-SC and IEZW use a principle of subband classification. IEZW has a drawback as the threshold decreases since many subbands will be significant and hence more bits will be generated. The advantage of

Table 4 Number of bits used at different passes with EZW-based codecs for Airplane, Boat and Lena greyscale test images

Image	Pass	Threshold	EZW	IEZW [25]	Proposed EZW-SC
Airplane	1	8192	548	204	**189**
	2	4096	1004	296	**266**
	3	2048	1461	446	**402**
	4	1024	2135	998	**895**
	5	512	3703	2164	**1884**
	6	256	8690	5868	**4818**
	7	128	22486	18011	**13639**
	8	64	57154	51769	**39553**
	9	32	116724	111373	**85868**
	10	16	214119	208802	**166369**
Boat	1	8192	422	168	**153**
	2	4096	886	288	**258**
	3	2048	1387	585	**535**
	4	1024	2160	1127	**1033**
	5	512	4107	2652	**2212**
	6	256	9876	7658	**5905**
	7	128	27231	21780	**16923**
	8	64	66875	60611	**46283**
	9	32	143281	137051	**107370**
	10	16	273139	266943	**219688**
Lena	1	8192	317	138	**123**
	2	4096	832	294	**264**
	3	2048	1327	455	**413**
	4	1024	2149	946	**863**
	5	512	4342	2659	**2179**
	6	256	9433	7205	**5511**
	7	128	23705	19002	**14350**
	8	64	54554	46873	**35099**
	9	32	111727	104080	**78737**
	10	16	207976	200363	**157859**

EZW-SC is due to the fact that it has an improved significance map which significantly reduces the zerotree symbol redundancy of the existing EZW and IEZW. Note also that the gain of EZW-SC over EZW surpasses 1.04 dB at all bit rates for the test images Lena and Peppers, as shown in Table 6. Overall, the gain of EZW-SC obtained for greyscale images vary between 0.57 dB and 2.62 dB over EZW, and between 0.19 dB and 2.31 dB over IEZW at different bit rates. Furthermore, the average rate distortion and coding gain curves for EZW-SC, IEZW and EZW, taken over all test images at several bit rates [0.0078125-0.25] bpp, in terms of PSNR and SSIM, are plotted in Fig. 3. Obviously, EZW-SC performs better than IEZW and EZW. The observable average gains, at all used bit rates exceed 0.96 dB, 0.59 dB and 0.25 dB against EZW, IEZW and IMP1EZW, respectively. We can observe that the results of the SSIM are similar to those of the PSNR. In Fig. 3.e, Fig. 3.f and Table 8, we also report the performance of the methods in [33] and [34] in terms of

Table 5 Number of bits used at different passes with EZW-based codecs for Peppers, Brabara and Goldhill greyscale test images

Image	Pass	Threshold	EZW	IEZW [25]	Proposed EZW-SC
Peppers	1	8192	324	140	**125**
	2	4096	830	292	**262**
	3	2048	1300	449	**405**
	4	1024	2149	1103	**985**
	5	512	4113	2669	**2226**
	6	256	9224	6867	**5458**
	7	128	22171	17873	**13835**
	8	64	49435	44672	**33356**
	9	32	96375	91646	**69440**
	10	16	175703	170994	**133259**
Barbara	1	8192	282	128	**113**
	2	4096	800	292	**262**
	3	2048	1279	451	**407**
	4	1024	2213	1055	**944**
	5	512	4598	2927	**2388**
	6	256	10853	8600	**6359**
	7	128	30304	27488	**19946**
	8	64	88920	86138	**66988**
	9	32	196442	193694	**158324**
	10	16	359983	357268	**262144**
Goldhill	1	8192	275	126	**111**
	2	4096	774	286	**256**
	3	2048	1940	380	**335**
	4	1024	1232	733	**669**
	5	512	3655	1816	**1605**
	6	256	8426	5760	**4616**
	7	128	21791	17393	**13173**
	8	64	56327	51523	**38012**
	9	32	133030	125191	**96631**
	10	16	286218	278413	**226981**

PSNR and SSIM listed against our proposed scheme. It is worth mentioning that these competing techniques were implemented in their binary forms for fair analysis. It can be seen that the average values of PSNR and SSIM of the proposed method are the highest at each bit rate. EZW-SC delivers better performance than the method in [34] with significant gains. For each test image, the PSNR and SSIM values of [34] are lower than those of EZW-SC at all bit rate. The overall average improvement in PSNR with the proposed EZW-SC on the method of [34] is up to 1.2 dB in the range [0.0078125-1] bpp. Compared to [33], the overall average gain is up to 2 dB and 4 dB in the ranges from 0.0078125 bpp to 0.25 bpp, and from 0.0078125 bpp to 1 bpp, respectively. It is worth mentioning that the coding performance of EZW-SC can be improved by using an entropy encoder such as the arithmetic coder. At last, it is worth noting that our method delivers better subjective image quality, clearly superior to that obtained with the conventional EZW. In Fig.

4, we provide an example of the lossy image compression and reconstruction of Peppers and Cameraman obtained at 0.25 bpp.

5.2 Performance of lossy compression algorithms on colour images

The experimental results were carried out using 5 colour test images Airplane, Baboon, Lena, Peppers and Sailboat of size 512 x 512 (24 bpp), employed in YIQ colour space. 6 decomposition levels were conducted using the 9/7 bi-orthogonal filters. To conduct a fair assessment, the colour lossy compression performance of binary coded of CCEZW (conventional colour EZW), CEZW [30] [31], CCIMPEZW and CIMPEZW [19], the method in [35], and the proposed codecs: CCEZW-SC (conventional colour EZW-SC) and CEZW-SC were evaluated at different compression ratios (from 8:1 to 1024:1) using the overall PSNR given by:

$$PSNR = 10\ \log_{10}\left(\frac{255^2}{\left(\frac{MSE(Y)+MSE(I)+MSE(Q)}{3}\right)}\right) \tag{1}$$

where MSE is the mean square error. The results are summarised in Table 9 and Figs. 5-7. It is clear from Table 9 that CCEZW-SC and CEZW-SC provide the best performance for all test images. Moreover, CCEZW-SC produces a gain more than 0.84 dB for Airplane, Peppers, Lena and Sailboat at all considered bit rates. Particularly, the gains are as significant as 3.85 dB, 3.15 dB, 1.97 dB, 1.95 dB and 1.5 dB at the very low bit rate for Lena, Peppers, Airplane, Sailboat and baboon respectively. The gains reach [1.66, 1.77, 1.81, 1.26 , 0.61] dB at [0.0625, 0.125, 0.5, 0.03125, 1] bpp respectively for the same test image. On average, CCEZW-SC achieves a gain of [1.08-2.49] dB. The improvements obtained in overall average PSNR over CEZW are also significant and vary between 0.68 dB and 2.16 dB. In particular, CCEZW-SC outperforms CEZW up to 1.57 dB, 1.75 dB and 1.51 dB for Airplane at the bit rates 0.25, 0.5 and 1 bpp, up to [1.29, 1.49, 1.22] dB, [1.05, 0.91, 0.68] dB at the range of bit rates [0.125, 0.25 ,0.5] bpp for Peppers and Lena respectively. The second proposed technique CEZW-SC provides also significant improvements where the gain outperforms 1.8 dB for Lena, Peppers, and Airplane at 0.0625, 0.125 and 0.5 bpp respectively when compared to CCEZW. The gain alternates between 0.92 dB and 3.86 dB for Airplane, Lena, Sailboat and Peppers. It is up to 3.26 dB and 3.86 dB at low very bit rates for Peppers and Lena. Additinally,CEZW-SC stands to gain at least 1.27 dB for Peppers and Lena at all considered bit rates. If one refers to CEZW, the use of the proposed technique CEZW-SC aims at improving significantly the performance. In particular, CEZW-SC shows an improvement of [1.17, 1.44, 1.09] dB , [1.4, 1.79, 1.7] dB and [1.69, 1.93, 1.68] dB at the bit rates [0.03125, 0.0625, 0.125] bpp, [0.125, 0.25, 0.5] bpp, and [0.25, 0.5, 1] bpp for Lena, Peppers and Airplane respectively. The improvement is up to 2.5 dB and 3.48 dB for Peppers and Lena image at very low bit rates. On average, CEZW-SC

Table 6 Lossy performance comparison of the proposed EZW-SC, IMP1EZW [19], IEZW [25], and EZW [11] image codecs for several greyscale test images. G1 and G2 represent the gain of the proposed EZW-SC greyscale codec against EZW and IEZW codecs, respectively

Image	Bit rate (Bpp)	EZW	IEZW [25]	IMP1EZW [19]	Proposed EZW-SC	G1	G2
Airplane	0.03125	23.0369	23.8106	23.8403	**24.1613**	1.1244	0.3210
	0.0625	25.2801	25.44	25.7746	**25.9812**	0.7011	0.5412
	0.125	27.0272	27.5713	28.1217	**28.3373**	1.3101	0.7660
	0.25	29.8712	30.3278	31.2195	**31.3708**	1.4996	1.0430
	0.5	33.5873	33.7779	34.9951	**35.0899**	1.5026	1.3120
	1	37.9931	38.1555	40.3689	**40.3952**	**2.4021**	**2.2397**
Boat	0.03125	22.0179	22.3037	22.5333	**22.7323**	0.7144	0.4286
	0.0625	23.6797	24.2149	24.6006	**24.7667**	1.0870	0.5518
	0.125	25.3461	26.0021	26.3312	**26.4493**	**1.1032**	0.4472
	0.25	27.7107	28.0317	28.7099	**28.8113**	1.1006	0.7796
	0.5	31.0003	31.1332	31.9414	**31.9909**	0.9906	**0.8577**
	1	35.168	35.2571	36.0863	**36.1148**	0.9468	0.8577
Lena	0.03125	23.1295	23.6435	23.8158	**24.1736**	1.0441	0.5301
	0.0625	25.1688	25.8174	26.2563	**26.4385**	1.2697	0.6211
	0.125	27.4979	28.1392	28.9792	**29.1999**	1.7020	1.0607
	0.25	30.1838	30.69	31.6442	**31.8549**	1.6711	1.1649
	0.5	33.4046	33.6187	34.7179	**34.9487**	1.5441	1.3300
	1	37.0065	37.1582	38.6311	**38.7179**	**1.7114**	**1.5597**
Peppers	0.03125	23.5973	24.3384	24.5045	**24.7924**	1.1951	0.4540
	0.0625	26.0735	26.5059	27.0365	**27.2134**	1.1399	0.7075
	0.125	28.3923	28.8523	29.8714	**29.9488**	1.5565	1.0965
	0.25	31.1927	31.4977	33.0125	**33.0485**	**1.8558**	**1.5508**
	0.5	34.4034	34.5392	35.7291	**35.7477**	1.3443	1.2085
	1	37.0137	37.1188	38.3256	**38.3606**	1.3469	1.2418
Barbara	0.03125	20.7364	20.8728	21.1572	**21.312**	0.5756	0.4392
	0.0625	21.8887	22.1424	22.4375	**22.507**	0.6183	0.3646
	0.125	22.9503	23.1445	23.4877	**23.5161**	0.5658	0.3716
	0.25	24.2573	24.3393	25.925	**25.9536**	1.6963	1.6143
	0.5	27.1892	27.2483	29.0292	**29.1533**	1.9641	1.9050
	1	31.5741	31.5936	33.8263	**33.9075**	**2.3334**	**2.3139**
Goldhill	0.03125	22.656	23.5243	23.5271	**23.8053**	**1.1493**	0.2810
	0.0625	24.4855	24.8229	25.1736	**25.3165**	0.8310	0.4936
	0.125	26.0731	26.4052	26.9261	**27.0836**	1.0105	0.6784
	0.25	28.0296	28.2716	28.7573	**28.8366**	0.8070	0.5650
	0.5	30.3132	30.5538	31.1567	**31.2114**	0.8982	0.6576
	1	33.6686	33.7536	34.4445	**34.4819**	0.8133	**0.7283**
Sailboat	0.03125	21.5291	21.8738	21.9762	**22.2199**	0.6908	0.3461
	0.0625	23.031	23.602	23.8868	**24.1239**	1.0929	0.5219
	0.125	24.6114	25.2835	25.6648	**25.8265**	**1.2151**	0.5430
	0.25	27.12	27.3304	28.0411	**28.1454**	1.0254	**0.8150**
	0.5	29.896	30.2623	30.8656	**30.9799**	1.0839	0.7176
	1	33.3393	33.6265	34.1861	**34.2334**	0.8941	0.6069

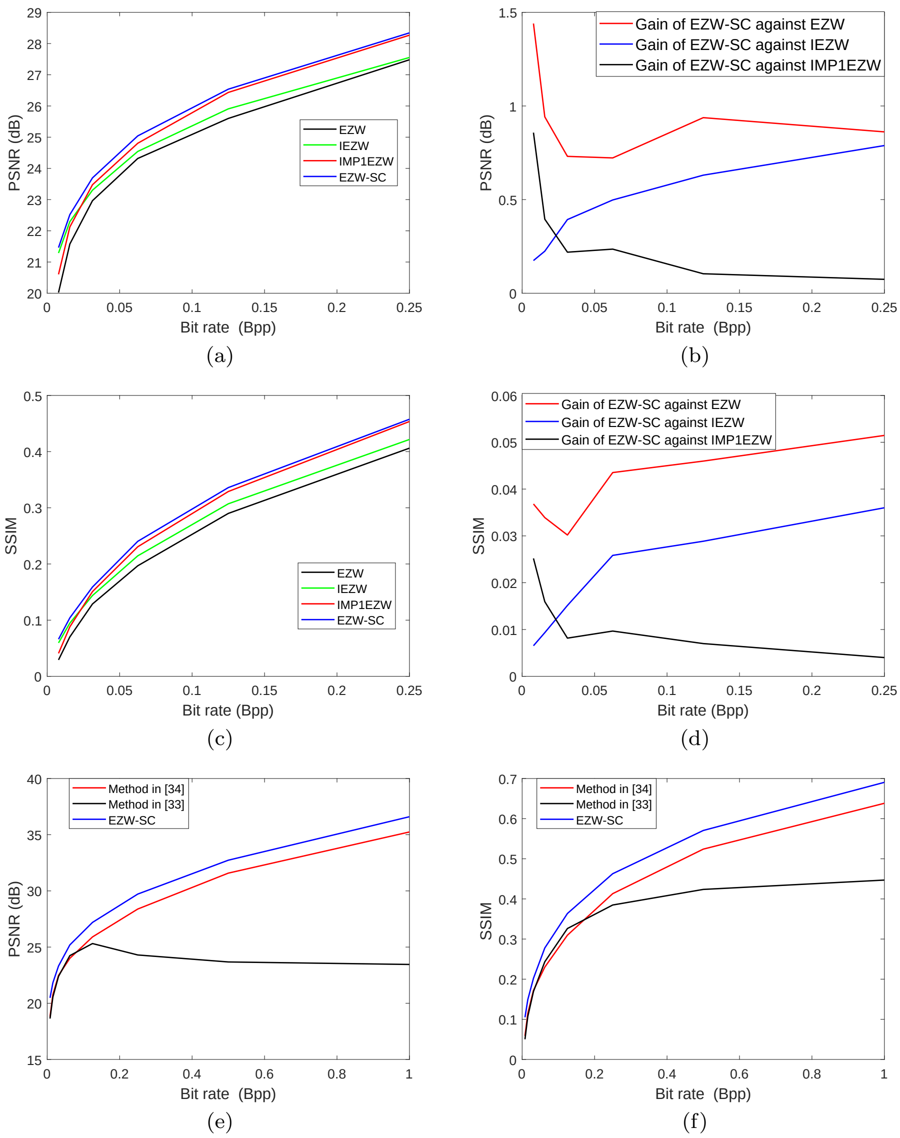

Fig. 3 Average PSNRs and SSIMs of the proposed EZW-SC codec and other algorithms for greyscale test images. (a) Average PSNRs. (b) Average gains of PSNR. (c) Average SSIMs. (d) Average gains of SSIM. (e) Comparison between EZW-SC and the methods reported in [33] and [34] in terms of PSNR. (f) Comparison between EZW-SC and the methods reported in [33] and [34] in terms of SSIM

Fig. 4 Subjective evaluation of EZW-SC and EZW algorithms for Peppers and Cameraman images: (a) The Peppers image reconstructed by the original EZW with PSNR of 28.39 dB at 0.25 bpp. (b) The Peppers image reconstructed by EZW-SC with PSNR of 29.95 dB at 0.25 bpp. (c) The Cameraman image reconstructed by the original EZW with PSNR of 23.41 dB at 0.25 bpp. (d) The Cameraman image reconstructed by EZW-SC with PSNR of 24.52 dB at 0.25 bpp. (e) An enlarged part of the Cameraman image reconstructed by EZW. (f) An enlarged part of the Cameraman image reconstructed by EZW-SC

Table 7 Gain of significant coefficients of EZW-SC over original EZW and IEZW [25]

	Compression ratio	8	16	32	64	128	256
Airplane	Gain of EZW-SC over EZW	**9414**	**4115**	**2198**	**1064**	**473**	**456**
	Gain of EZW-SC over IEZW	**8616**	**3518**	**1468**	**618**	**405**	145
	Gain of IEZW [25] over EZW	798	597	730	446	68	311
Boat	Gain of EZW-SC over EZW	**6222**	**3400**	**2628**	**1236**	**444**	**318**
	Gain of EZW-SC over IEZW	**6222**	**3399**	**1925**	**516**	**205**	**228**
	Gain of IEZW [25] over EZW	0	1	703	720	239	90
Lena	Gain of EZW-SC over EZW	**9972**	**4535**	**2321**	**1104**	**522**	**357**
	Gain of EZW-SC over IEZW	**8967**	**3825**	**1556**	**645**	**332**	**206**
	Gain of IEZW [25] over EZW	1005	710	765	459	190	151
Peppers	Gain of EZW-SC over EZW	**9950**	**2880**	**1959**	**893**	**531**	**353**
	Gain of EZW-SC over IEZW	**9189**	**2500**	**1564**	**585**	**384**	**144**
	Gain of IEZW [25] over EZW	761	380	395	308	147	209
Barbara	Gain of EZW-SC over EZW	**9348**	**5373**	**2490**	**1035**	**495**	**320**
	Gain of EZW-SC over IEZW	**9222**	**5152**	**2269**	**683**	**328**	**284**
	Gain of IEZW [25]over EZW	126	221	221	352	167	36
Goldhill	Gain of EZW-SC over EZW	**5999**	**5093**	**2085**	**1071**	**622**	**483**
	Gain of EZW-SC over IEZW	**5999**	**3921**	**1452**	**712**	**470**	**116**
	Gain of IEZW [25] over EZW	0	1172	633	359	152	367
Sailboat	Gain of EZW-SC over EZW	**4484**	**3269**	**2136**	**1478**	**574**	**310**
	Gain of EZW-SC over IEZW	**3341**	**2544**	**2010**	**604**	**275**	**204**
	Gain of IEZW [25] over EZW	1143	725	126	874	299	106

demonstrates an improvement in terms of PSNR varying between 1.08 dB and 2.49 dB over CCEZW, and from 0.79 dB to 2.19 dB over CEZW as shown in Table 9 (see the gains G5 and G6). The improvement varies according to the image content and the used bit rate. It should also be noted that CEZW [30, 31] shows a medium average gain of [0.22-0.89] dB in comparison with CCEZW. For Airplane image, small gain was achieved less than 0.2 dB. In comparison with CIMPEZW [19], EZW-SC provides superior performance for all considered bit rates. The improvement is obvious at low and very low bit rates. The PSNR and SSIM performance criteria at different bit rates, varying from 0.0078125 bpp to 1 bpp, of our method CEZW-SC are also compared to those of the method in [35], as illustrated in Figs. 6 and 7. The method in [35] always obtains the worst results for each image and at each bit rate, because the subbands HL, LH and HH of the finest level are omitted before begining the coding process. In addition, the restoration process creates hence an evitable distortion of the reconstructed images. The PSNR gain of the proposed CEZW-SC increases by an average of 2.7 dB than the method in [35]. With the same compression ratio, the higher the PSNR, the generally better the SSIM. Fig. 7 illustrates the decoded Peppers and Airplane images compressed using CCEZW, CEZW-SC and the method reported in [35] at 0.25 bpp and 0.5 bpp. According to Fig. 7, we can notice some improvement on the

Table 8 Lossy coding performance comparison between the proposed EZW-SC and the methods reported in [33] and [34]

		SSIM			PSNR(dB)		
Image	Bit rate (Bpp)	Method in [33]	Method in [34]	Proposed EZW-SC	Method in [33]	Method in [34]	Proposed EZW-SC
Airplane	0.03125	0.1411	0.1465	**0.1778**	23.0764	23.2628	**24.1613**
	0.0625	0.2195	0.2041	**0.2479**	25.2815	24.9135	**25.9812**
	0.125	0.2971	0.2657	**0.3247**	26.5600	26.6486	**28.3373**
	0.25	0.3437	0.3610	**0.4257**	24.7824	29.6342	**31.3708**
	0.5	0.3970	0.4620	**0.5308**	24.4328	33.7357	**35.0899**
	1	0.4457	0.5630	**0.6463**	24.2795	38.2790	**40.3952**
Boat	0.03125	0.1385	0.1343	**0.1605**	22.0138	21.9918	**22.7323**
	0.0625	0.2103	0.1909	**0.2476**	23.7216	23.3253	**24.7667**
	0.125	0.2957	0.2921	**0.3379**	24.3576	25.4881	**26.4493**
	0.25	0.3557	0.4021	**0.4330**	23.5002	27.8674	**28.8113**
	0.5	0.3725	0.5131	**0.5443**	22.4936	30.9523	**31.9909**
	1	0.4051	0.6144	**0.6547**	22.4551	34.9761	**36.1148**
Lena	0.03125	0.2076	0.2101	**0.2407**	23.1220	23.2411	**24.1736**
	0.0625	0.2826	0.2751	**0.3172**	25.1760	25.1482	**26.4385**
	0.125	0.3756	0.3439	**0.4096**	26.9146	27.1524	**29.1999**
	0.25	0.4344	0.4428	**0.5034**	25.8454	30.1577	**31.8549**
	0.5	0.4663	0.5384	**0.5941**	25.2052	33.6651	**34.9487**
	1	0.4854	0.6388	**0.7075**	24.9704	37.3648	**38.7179**
Peppers	0.03125	0.2126	0.2193	**0.2452**	23.5803	23.8387	**24.7924**
	0.0625	0.2809	0.2746	**0.3075**	26.082	25.8789	**27.2134**
	0.125	0.3619	0.3479	**0.3855**	27.5785	28.3184	**29.9488**
	0.25	0.3939	0.4271	**0.4640**	26.3000	31.3664	**33.0485**
	0.5	0.4455	0.5130	**0.5341**	26.4228	34.5947	**35.7477**
	1	0.4477	0.6170	**0.6768**	26.0948	37.2610	**38.3606**
Barbara	0.03125	0.1953	0.1935	**0.2253**	20.7348	20.6327	**21.312**
	0.0625	0.2656	0.251	**0.3041**	21.8770	21.7147	**22.507**
	0.125	0.3351	0.3268	**0.3782**	21.8998	22.8848	**23.5161**
	0.25	0.3922	0.4432	**0.4946**	20.6758	24.7114	**25.9536**
	0.5	0.4340	0.5772	**0.6368**	20.1153	27.9786	**29.1533**
	1	0.4495	0.7062	**0.7508**	19.8966	32.2976	**33.9075**
Goldhill	0.03125	0.1411	0.1674	**0.1935**	22.6815	23.051	**23.8053**
	0.0625	0.23	0.2237	**0.2572**	24.4906	24.4344	**25.3165**
	0.125	0.3192	0.2913	**0.3600**	25.5407	25.8487	**27.0836**
	0.25	0.4076	0.4208	**0.4770**	25.0101	27.9544	**28.8366**
	0.5	0.4367	0.5670	**0.6113**	23.7916	30.3795	**31.2114**
	1	0.4526	0.7182	**0.7534**	23.5712	33.4461	**34.4819**
Sailboat	0.03125	0.1461	0.1335	**0.1723**	21.5181	21.3133	**22.2199**
	0.0625	0.2145	0.1906	**0.2627**	23.0471	22.5751	**24.1239**
	0.125	0.2991	0.2999	**0.3500**	24.3747	24.9691	**25.8265**
	0.25	0.3664	0.3949	**0.4421**	23.9665	27.006	**28.1454**
	0.5	0.4138	0.4980	**0.5424**	23.2655	29.766	**30.9799**
	1	0.4427	0.6107	**0.6443**	22.9052	33.0909	**34.2334**

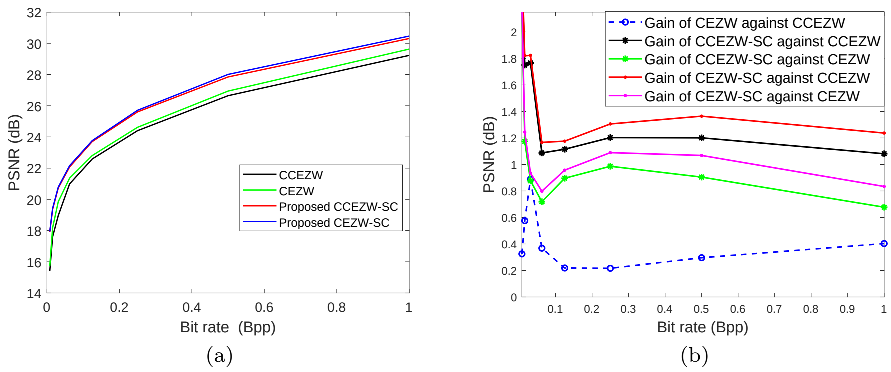

Fig. 5 Coding performance assessment of the proposed embedded colour image codecs (CEZW-SC, CCEZW-SC), CEZW [11] and CCEZW [30,31] algorithms for all colour test images: (a) Average value of PSNRs. (b) Average value of gains when the conventional EZW and CEZW are taken as reference competing techniques

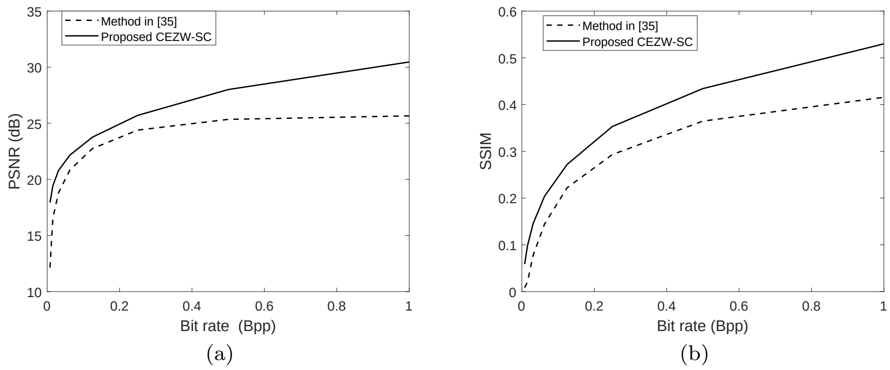

Fig. 6 Average performance of CEZW-SC and the method reported in [35] for different colour test images

images quality showed in Figs. 7.b, 7.d and 7.f. Overall, the CCEZW-SC and CEZW-SC versions are a clear improvement over their predecessors (CCEZW, CEZW, [35]). Moreover, the overall results demonstrate clearly that the correlation between colour planes is exploited more efficiently by CEZW-SC than CEZW.

6 Conclusion

In this paper, a new wavelet-based lossy compression scheme that builds upon the EZW coding scheme is proposed. The presented algorithm, namely EZW-

Fig. 7 Subjective assessment of three codecs: the proposed CEZW-SC, the method reported in [35] and CCEZW [11] for Peppers and Airplane colour images: (a) The Peppers image reconstructed by the original CCEZW with PSNR of 22.79 dB at 0.125 bpp. (b) The Peppers image reconstructed by CEZW-SC with PSNR of 24.67 dB at 0.125 bpp. (c) The Peppers image reconstructed by the the original CEZW with PSNR of 25.15 dB at 0.25 bpp. (d) The Peppers image reconstructed by CEZW-SC with PSNR of 27.15 dB at 0.25 bpp. (e) The Airplane image reconstructed by the method reported in [35] with PSNR of 26.6 dB. (f) The Airplane image reconstructed by CEZW-SC with PSNR of 30.99 dB

SC, uses a new subband classification concept which helps to predict insignificant subbands in the first passes, as well as an improved significance map representing 9 symbols, in order to reduce the zerotree symbol number and to save bits by analysing only the significant subbands. Furthermore, the EZW-SC coding system is extended for scalable colour image coding by taking advantage of the information redundancy across the colour components. Without any entropy coding, numerical results show clear improvements in performance with the proposed coding versions for greyscale and colour images, notably at low bit rates.The superiority of the proposed system over related EZW-based algorithms has also been shown through experiments using standard test images.

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Table 9 Lossy coding performance comparison of different embedded colour images codecs. G3 and G4 represent the gains of the proposed CCEZW-SC colour codec against CCEZW [11] and CEZW [30,31] colour codecs using the SOT_A, respectively. G5 and G6 represent he gains of the proposed CEZW-SC colour codec against CCEZW and CEZW colour codecs using the SOT_B, respectively

		Codecs with SOT_A			Codecs with SOT_B			Gains			
Image	Bit rate (Bpp)	CCEZW	CCIMPEZW [19]	Proposed CCEZW-SC	CEZW	CIMPEZW [19]	Proposed CEZW-SC	G3	G4	G5	G6
Airplane	0.0078125	17.04	18.44	**19.01**	17.04	18.45	**19.01**	1.97	1.97	1.97	1.97
	0.015625	19.09	20.25	**20.59**	19.14	20.28	**20.58**	1.50	1.45	1.49	1.44
	0.03125	21.02	21.8	**22.18**	21.13	21.90	**22.19**	1.16	1.06	1.16	1.06
	0.0625	22.54	23.26	**23.48**	22.63	23.30	**23.48**	0.93	0.85	0.93	0.85
	0.125	24.02	24.88	**25.06**	24.16	24.93	**25.07**	1.05	0.90	1.06	0.91
	0.25	26.08	27.61	**27.74**	26.15	27.75	**27.84**	1.66	1.6	1.75	1.69
	0.5	29	30.77	**30.83**	29.06	30.95	**30.99**	1.83	1.77	1.99	1.93
	1	32.54	34.23	**34.26**	32.74	34.40	**34.42**	1.72	1.52	1.87	1.68
Lena	0.0078125	15.51	16.63	**19.36**	15.88	17.84	**19.37**	3.85	3.48	3.86	3.48
	0.015625	18.33	20.31	**21.24**	20	20.74	**21.28**	2.91	1.24	2.95	1.28
	0.03125	21.23	22.33	**22.89**	21.77	22.66	**22.94**	1.66	1.11	1.71	1.17
	0.0625	23.21	24.27	**24.87**	23.64	24.42	**25.08**	1.66	1.23	1.88	1.44
	0.125	25.35	26.43	**26.74**	25.68	26.53	**26.77**	1.39	1.05	1.42	1.09
	0.25	27.41	28.66	**28.83**	27.92	28.75	**28.87**	1.42	0.91	1.46	0.95
	0.5	29.93	31.07	**31.15**	30.48	31.16	**31.19**	1.23	0.68	1.27	0.72
	1	32.42	33.50	**33.52**	33.09	33.56	**33.57**	1.10	0.43	1.15	0.48
Peppers	0.0078125	14.21	15.42	**17.36**	17.90	15.53	**17.47**	3.15	2.45	3.26	2.56
	0.015625	17.12	18.32	**19.03**	17.86	18.42	**19.16**	1.91	1.17	2.04	1.30
	0.03125	19.07	20.13	**20.65**	19.79	20.36	**20.70**	1.58	0.86	1.63	0.91
	0.0625	20.84	22.17	**22.36**	21.76	22.28	**22.41**	1.52	0.60	1.57	0.66
	0.125	22.79	24.36	**24.57**	23.27	24.55	**24.67**	1.78	1.30	1.88	1.40
	0.25	25.15	26.72	**26.86**	25.37	27.01	**27.15**	1.71	1.49	2.01	1.79
	0.5	27.77	29.17	**29.31**	28.09	29.74	**29.78**	1.54	1.23	2.02	1.70
	1	30.48	31.50	**31.56**	30.98	31.96	**31.96**	1.08	0.59	1.48	0.98
Baboon	0.0078125	15.40	16.08	**17**	15.54	16.43	**16.98**	1.61	1.46	1.58	1.43
	0.015625	16.70	17.27	**17.94**	16.91	17.65	**17.97**	1.24	1	1.03	1.06
	0.03125	17.97	18.38	**18.63**	18.12	18.53	**18.65**	0.65	0.51	0.67	0.53
	0.0625	18.76	18.95	**19.06**	18.89	18.99	**19.05**	0.30	0.17	0.29	0.16
	0.125	19.33	19.80	**19.90**	19.42	19.85	**19.92**	0.57	0.48	0.59	0.50
	0.25	20.39	20.66	**20.74**	20.48	20.69	**20.74**	0.35	0.26	0.35	0.26
	0.5	21.71	22.17	**22.22**	21.86	22.21	**22.23**	0.51	0.36	0.52	0.38
	1	23.70	24.29	**24.32**	23.80	24.34	**24.38**	0.62	0.51	0.68	0.57
Sailboat	0.0078125	14.93	16.36	**16.88**	15.34	16.39	**16.89**	1.95	1.54	1.96	1.55
	0.015625	16.80	17.67	**18.09**	17	17.83	**18.15**	1.30	1.09	1.36	1.15
	0.03125	18.14	19.01	**19.44**	18.45	19.15	**19.46**	1.30	0.99	1.32	1.01
	0.0625	19.60	20.48	**20.72**	19.88	20.56	**20.76**	1.12	0.84	1.16	0.88
	0.125	21.45	22.17	**22.31**	21.50	22.27	**22.39**	0.86	0.81	0.93	0.89
	0.25	22.97	23.76	**23.88**	23.17	23.82	**23.93**	0.91	0.72	0.96	0.77
	0.5	24.81	25.69	**25.74**	25.22	25.79	**25.84**	0.92	0.52	1.02	0.62
	1	26.99	27.86	**27.89**	27.53	27.98	**27.99**	0.90	0.36	1.00	0.46