Wavelet Based Color Image Compression and Mathematical Analysis of Sign Entropy Coding

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Abstract

One of the advantages of the Discrete Wavelet Transform (DWT) compared to Fourier Transform (e.g. Discrete Cosine Transform DCT) is its ability to provide both spatial and frequency localization of image energy. However, WT coefficients, like DCT coefficients, are defined by magnitude as well as sign. While algorithms exist for the coding of wavelet coefficients magnitude, there are no efficient for coding their sign. In this paper, we propose a new method based on separate entropy coding of sign and magnitude of wavelet coefficients. The proposed method is applied to the standard color test images Lena, Peppers, and Mandrill. We have shown that sign information of wavelet coefficients as well for the luminance as for the chrominance, and the refinement information of the quantized wavelet coefficients may not be encoded by an estimated probability of 0.5. The proposed method is evaluated; the results obtained are compared to JPEG2000 and SPIHT codec. We have shown that the proposed method has significantly outperformed the JPEG2000 and SPIHT codec as well in terms of PSNR as in subjective quality. We have proved, by an original mathematical analysis of the entropy, that the proposed method uses a minimum bit allocation in the sign information coding.

Keywords: *Color Image Compression, Wavelet Transform, Entropy Coding, Sign, Magnitude*

1. Introduction

Image compression is necessary for storage and transmission in multimedia applications. In image compression, JPEG (based on DCT) [1] and JPEG2000 [9] (based on DWT technology) are the standards for still image. In DCT, the image is split in blocks of 8 x 8 pixels and the transform is applied to each block as an independent sub-image and Variable Length Coding (VLC) is used to compress the quantized coefficients. The main drawbacks of JPEG are the blocking artifacts at low bit rate. However, in JPEG2000, the image is decomposed in wavelet domain without block splitting; only in the case where image dimensions are large (for example the case of JPEG2000 test images), the standard allows splitting image in tiles for the efficient management of the space memory in DWT computation. A lot of progress has been made in wavelet based image compression [4], [5-8], [9, 10], [12-14], [16-28], resulting in the realization of the JPEG2000 standard. One of the advantages of the DWT is that it provides both spatial and frequency localization of image energy. The WT coefficients are defined by both magnitude (absolute values of coefficients) and sign. In most current wavelet image coding systems, the inefficient coding of the sign of coefficients is accepted as a trade-off for gains obtained through energy compaction which can not give any information about the sign of the wavelet coefficients. Moreover, in [4], the author states that a quantized coefficient is as much likely to be positive and negative. Only recently have some authors begun to investigate the sign of wavelet coefficients in image coding [13-14]. In [13], the authors have combined sign and coefficient extrapolation in their approach. They have proposed the estimation of wavelet coefficient with the probability of the sign being positive or negative. In [14], the authors have assumed that the sign information bit of wavelet coefficients may be encoded with an estimated probability of 0.5 and the same assumption is done for the refinement information bit. In this paper, we propose a new method based on separate entropy coding of sign and magnitude of wavelet coefficients. The proposed scheme is described in section 2. The experimental results and discussions are presented in section 3. A mathematical analysis of the proposed method is presented in section 4. Finally, the conclusion is presented in section 5.

2. Coding of sign and magnitude of wavelet coefficients

2.1 Description of the proposed method

Once the color image is decomposed in wavelet domain, we consider the coefficient as the data which gives two types of information: the sign and the magnitude. Wavelet coefficients are organized as a list of different sub-bands which are horizontal low and vertical low frequencies (LL), horizontal low and vertical high frequencies (LH_i), horizontal high and vertical low frequencies (HL_i), horizontal high and vertical high frequencies (HH_i) where *i* is the scale level number. The sign may be either negative or positive; the magnitude information is the absolute value of the wavelet coefficient. The magnitude is considered significant if its absolute value is greater or equal to a predefined threshold T, similar to EZW codec. In EZW, this coefficient is encoded respectively with POS or NEG symbol if it is positive or negative. In our method, a single symbol which we call Significant (S) is used to encode the magnitude. We use two other symbols ZT and UZT to encode the Zero Tree root and the UnZero-Tree root respectively. ZT and UZT symbols may be considered as ZTR and IZ symbols in EZW codec. In the finest sub-bands HL_1, LH1, and HH_1 where the coefficients have no child, the symbol Zero Coefficient ZC is used to encode the coefficients which are inferior to the threshold. Three types of information are considered in our method:

1) The magnitude information: a magnitude map containing the symbol S is generated. The presence of the symbol S is indicated by the symbol '1' and its absence by the symbol '0'.

2) The sign information of wavelet coefficients: in our method, the probability of the quantized wavelet coefficients to be positive or negative is calculated bit-plane by bit-plane. We have generated a sign map which indicates the presence of a negative or a positive coefficient in HL_i, LH_i, and HH_i sub-bands at scale *i*. The presence of a positive significant coefficient is indicated by the symbol '0' and the presence of negative significant coefficient is indicated by the symbol '1'.

3) The third information is the refinement of the quantized coefficients (quantization index). Since we have used the scalar quantizer, the quantized wavelet coefficient may be set in the low or in the high interval in the uncertainty interval $[T, 2T]$ where T is the current threshold. An uncertainty interval $[\,T, 2T\,]$ is generated progressively, bit-plane by bit-plane, depending on the current threshold T. The probability of the quantized coefficient to belong to the low interval $[\,T, (3/2)T\,[$ or to the high interval $[\,(3/2)T, 2T\,[$ in the refinement processing is also calculated bit-plane by bit-plane. If a quantized coefficient is set in the high interval, the symbol '1' is generated; if it is set in the low interval, the symbol '0' is generated.

It is important to note these considerations:

1) The magnitude information of a given wavelet coefficient may be significant or insignificant depending on the current threshold;

2) The refinement information is not unique for the same wavelet coefficient because it may change. Depending on the current threshold, a given quantized coefficient (in the past and in the current bit-planes) may be set in the high interval or in the low interval;

3) The sign information is unique for a given wavelet coefficient since a coefficient is either positive or negative.

Since we are in the case of color image compression, the above considerations are applied on the luminance Y, blue chrominance Cb and red chrominance Cr coefficients.

2.2 Technical description of the implementation

In each sub-band and depending on the current threshold T, we have developed an algorithm that generates the different symbols described in section 2.1 where each sub-band is transformed from coefficient matrix to a vector of symbols. Among the symbols described in the section 2.1, only the significance symbol, the sign symbol and the refinement symbol are necessary for the reconstruction of the image. Precisely, the presence of the symbol S informs the decoder to reconstruct the magnitude of a significant coefficient using the value of the current threshold; its absence informs the decoder to reconstruct a tree of zero (symbol ZT) except for few coefficients which are significant in this tree (symbol UZT). In the finest sub-bands (HL_1, LH_1, and HH_1), the absence of the symbol S informs the decoder to reconstruct the zeros.

To illustrate the execution of the algorithm, we show below the binary data symbols automatically generated for the Lena luminance (component Y), 512 x 512 pixels, decomposed in 5 scales for the first bit plane:

010000011111110001000111110111110010000111101111100100001111
010100010010111111110101001011111111001010010000111001101 00
100011100011010000001001001111110000111100111101000000111001
111110010011001111011000000100111101100000111010100100000 0
1111111001000000011110000

a) Significant binary symbols (symbol S) automatically generated for the LL_5 sub-band

000000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000000
00000000000000

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b) Significant binary symbols (symbol S) automatically generated for the HL_5 sub-band

000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000
00000000000000

c) Significant binary symbols (symbol S) automatically generated for the LH_5 sub-band

000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000
00000000000000

d) Significant binary symbols (symbol S) automatically generated for the HH_5 sub-band

000000000000000000000000000000000000000000000000000000000
000000000000000000000000000000000000000000000000000000000
00000000000000

e) Sign binary symbols automatically generated for the LL_5 sub-band

000000000000000000000000000000110000000011000000000100000
000000001000000000000000000000000100000000010000001000010
00000100000001

f) Refinement binary symbols (quantization index) automatically generated for the LL_5 sub-band

3. Experimental results and discussions

To evaluate the proposed method, three standard color test images: Lena, Peppers and Mandrill, all 512 x 512 x 3 pixels are decomposed in the wavelet domain using the biorthogonal 9/7 filter bank of Daubechies [11]. Five decomposition scales are performed. Magnitude, sign and refinement information as well for the luminance Y as for the blue chrominance Cb and the red chrominance Cr are together entropy encoded using the arithmetic coding [30].

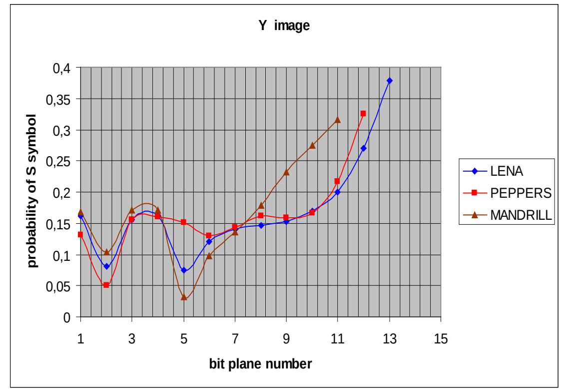
Firstly, we present the results of the online observed probabilities of:

- the magnitude information of Y, Cb and Cr described by the symbol S (fig.1);
- the positive and negative sign informations (fig. 2 to 4);
- the refinement information (fig. 5 to 7).

Secondly, we present the results in terms of Peak Signal to Noise Ratio (PSNR) in dB versus bit rate in bits per pixel (bpp) (fig. 8 to 10).

Thirdly, we present the decoded Lena, Peppers and Mandrill images at 0.08 bpp (fig. 11).

Finally, we present a mathematical analysis of the proposed method (fig. 12 to 14).



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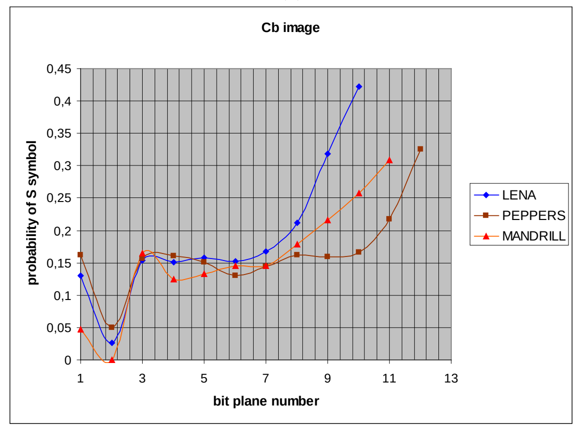
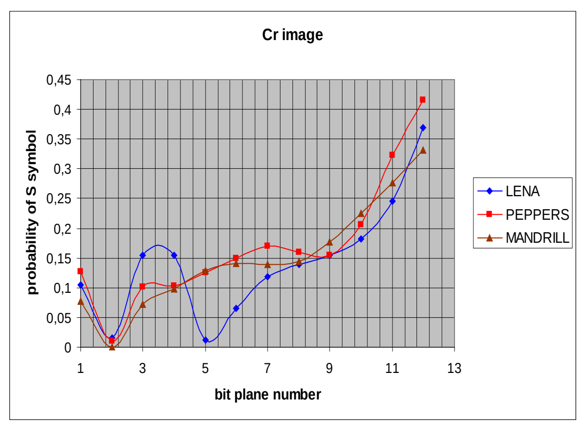
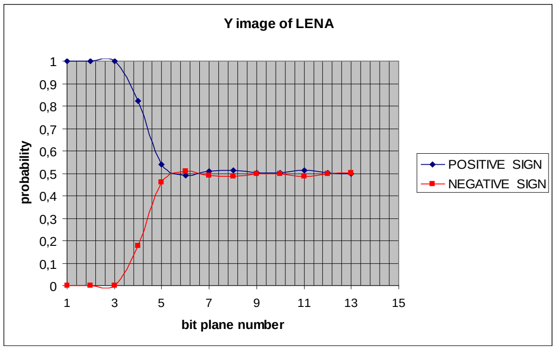


(b)

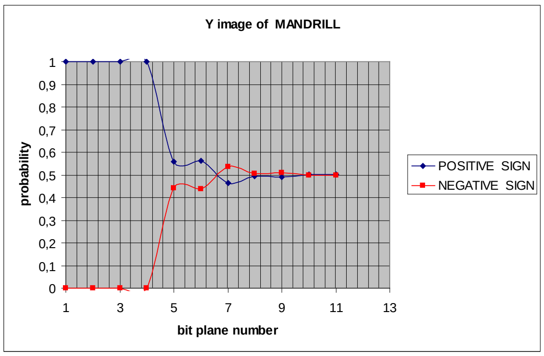


(c)

Fig. 1 Observed probabilities of magnitude information (symbol S) versus bit-plane number of Lena, Peppers and Mandrill (a) for luminance Y, (b) for blue chrominance Cb, (c) for red chrominance Cr



(a)



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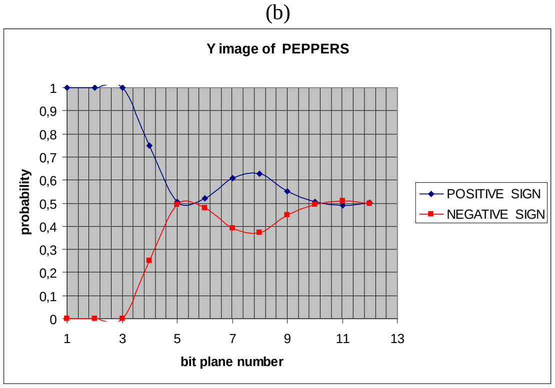
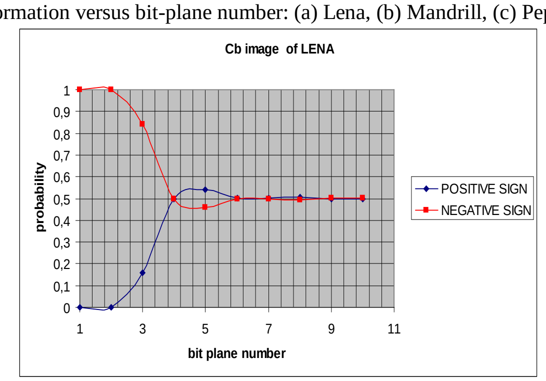
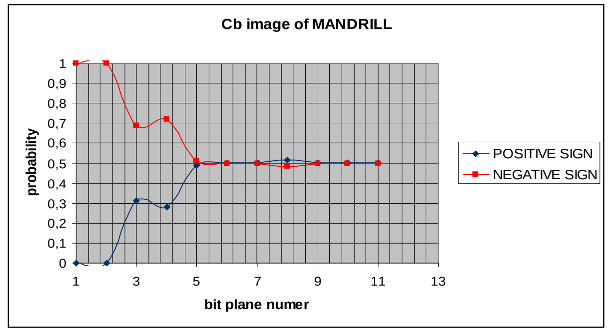


(c)

Fig. 2 Observed probabilities of positive and negative luminance sign information versus bit-plane number: (a) Lena, (b) Mandrill, (c) Peppers



(a)



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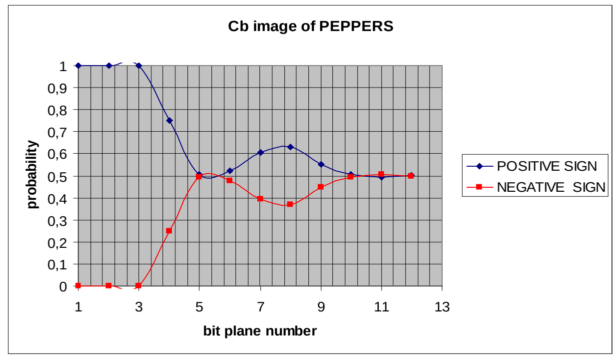
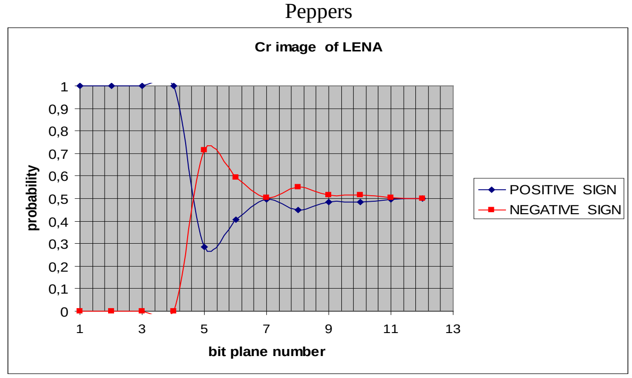
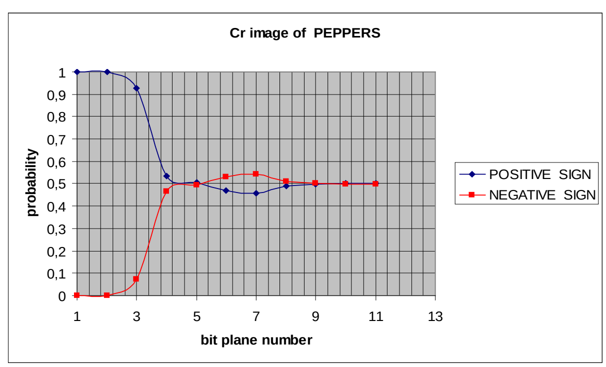


(c)

Fig. 3 Observed probabilities of positive and negative blue chrominance sign information versus bit-plane number: (a) Lena, (b) Mandrill, (c) Peppers



(a)



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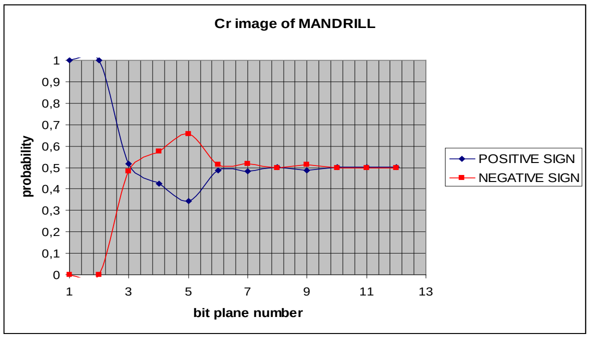
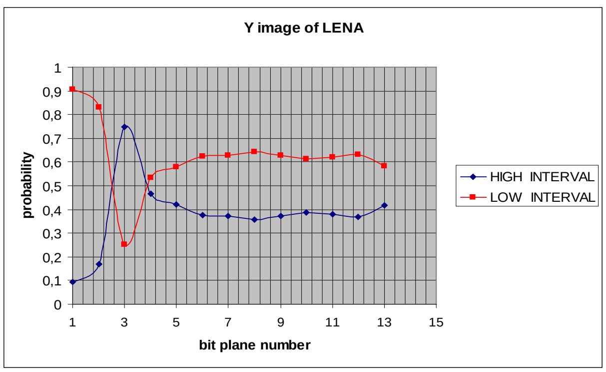
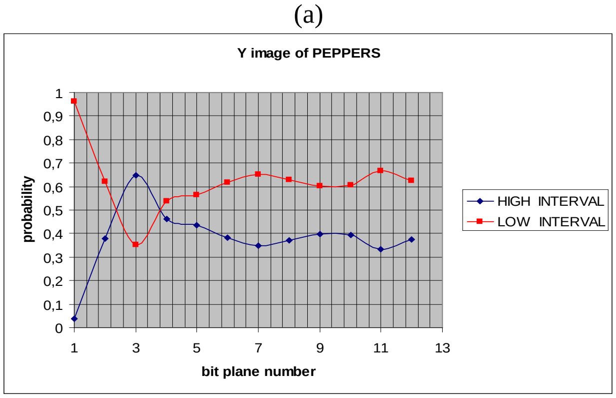


(c)

Fig. 4 Observed probabilities of positive and negative red chrominance sign information versus bit-plane number: (a) Lena, (b) Mandrill, (c) Peppers



(a)



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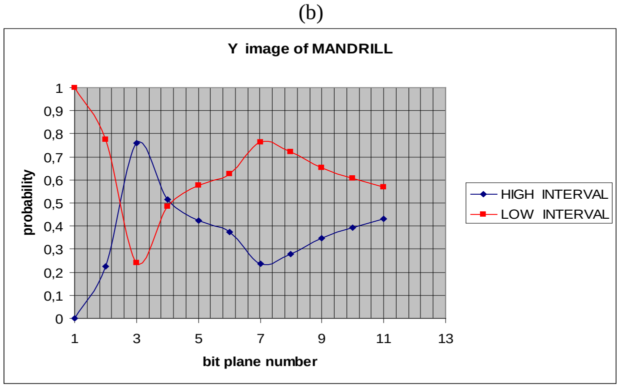
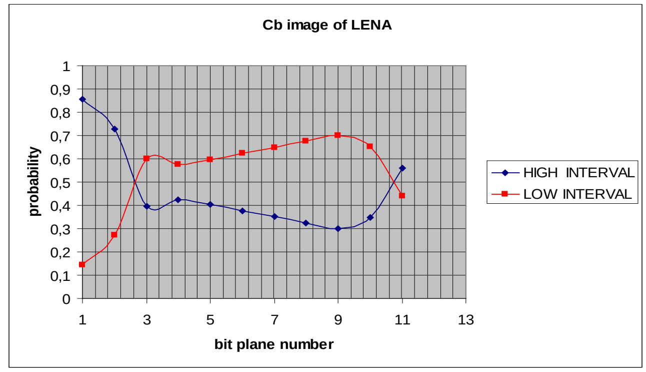
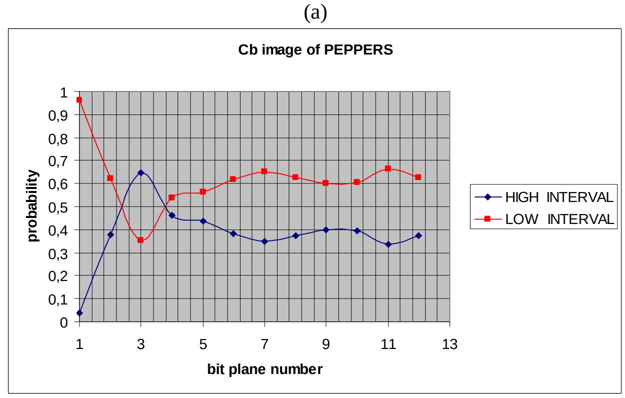


(c)

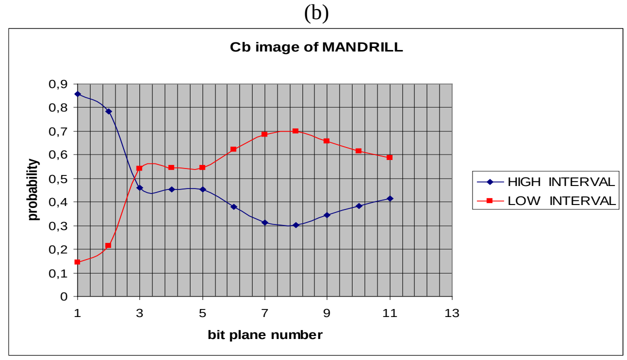
Fig.5 Observed probabilities of luminance refinement information versus bit-plane number: (a) Lena, (b) Peppers, (c) Mandrill



(a)

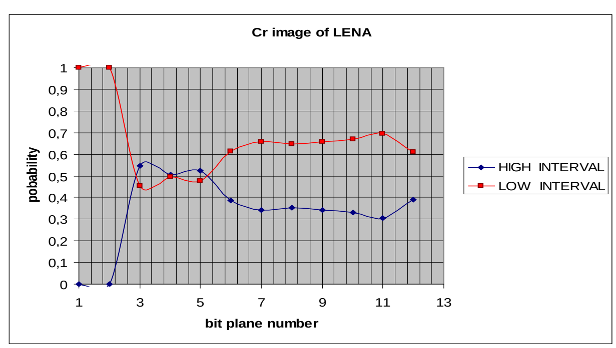


(b)

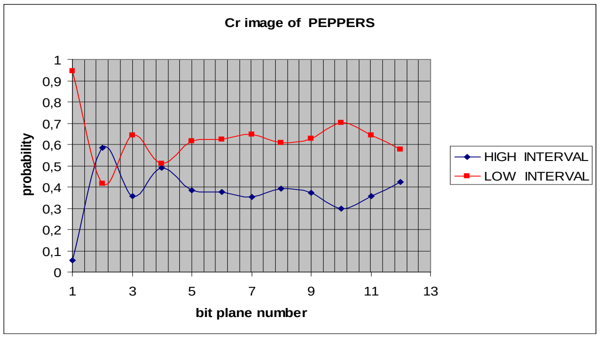


(c)

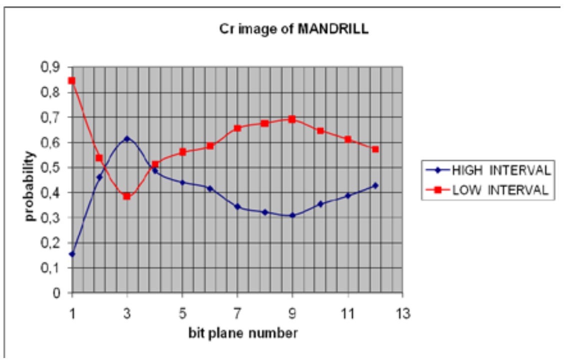
Fig.6 Observed probabilities of blue chrominance refinement information versus bit-plane number: (a) Lena, (b) Peppers, (c) Mandrill



(a)



(b)



(c)

Fig.7 Observed probabilities of red chrominance refinement information versus bit-plane number: (a) Lena, (b) Peppers, (c) Mandrill

Fig. 1 presents the probabilities of the S symbol of the luminance Y, the chrominance Cb and Cr; we observe from this figure that the probability to find significant coefficient is less than 0.5. This indicates that less than 50 percent of the wavelet coefficients contribute to the best reconstruction quality.

The interesting behaviors observed are the sign and the refinement information of the luminance and the chrominance components. Fig. 2 to 4 show that the positive and negative sign information of the luminance, the blue chrominance and red chrominance have an equal probability after few bit-plane numbers. From these figures, we can notice that wavelet coefficients are not all equally distributed in the positive and negative domains (particularly for the first bit-plane numbers); this is due to the presence of the approximation sub-band where there is no negative coefficient. However, some coefficients are equally distributed in positive and negative domains after few bit planes and it is due to the contribution of the high frequency sub-band coefficients. The fact that the probabilities to find negative significant and positive significant coefficients are almost equal to 0.5 after few bit-plane numbers may be explained by the generalized Gaussian distribution of the detail sub-bands of photographic images. So, the estimated probability of 0.5 may not be used to encode the sign information for all bit planes contrarily to the work presented in [14] since the positive sign information is also provided by the approximation sub-band. Fig. 5 to 7 present the probabilities of the quantized wavelet coefficients to be set in the low interval or in the high interval in the refinement processing. It appears that the refinement information bit may not be encoded with an estimated probability of 0.5 such as used in [14]. In these figures, we see that the probabilities of the quantized wavelet coefficients of the luminance and the chrominance images to be set in the low interval or in the high interval in the refinement processing present symmetry with the probability value of 0.5. So, encoding the refinement information with the probability estimated of 0.5 is not accurate.

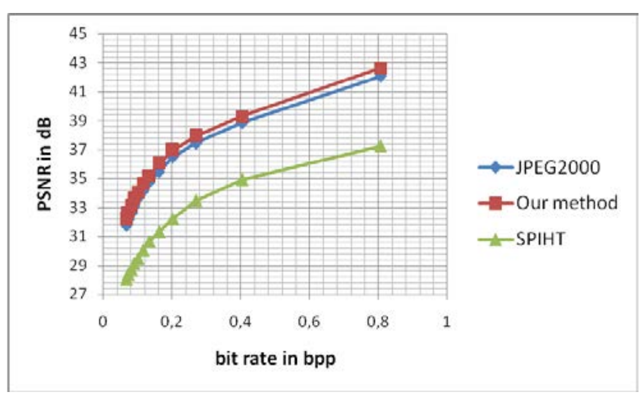
Some relevant questions may arise: for example these observations are image dependant? In an attempt to answer to this question, we have deal with the other color test images such as Boat, Goldhill, Barbara and we have observed the same behavior.

Fig. 8 to 10 present the PSNR in dB versus bit rate in bit per pixel of Y, Cb and Cr for the three standard color test images: Lena, Peppers and Mandrill. The JPEG2000 (jpeg2000 J2K-Tool) [15] and the SPIHT codec [5][29] are run for the same test images and the results are compared with our results. The PSNR in dB for Y, Cb and Cr is calculated by equation (1) where MSE (Mean Square Error) is defined by equation (2).

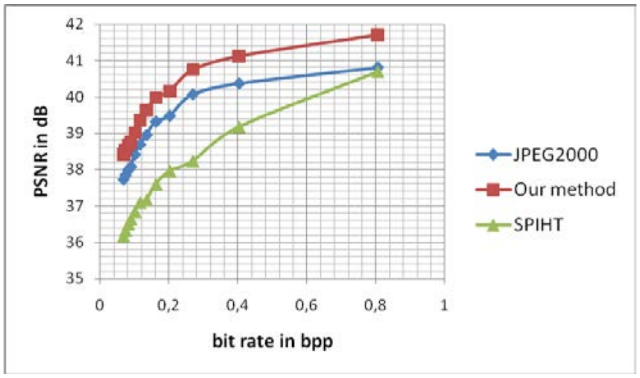
$$PSNR = 10\log_{10}\left(\frac{255^2}{MSE}\right) \quad (1)$$

$$MSE = \frac{1}{HL}\sum_{i=1}^{H}\sum_{j=1}^{L}\left(I(i,j) - \hat{I}(i,j)\right)^2 \quad (2)$$

Where H and L are respectively the height and width of the image; I and $\hat{I}$ are respectively the original and the decoded images.



(a)



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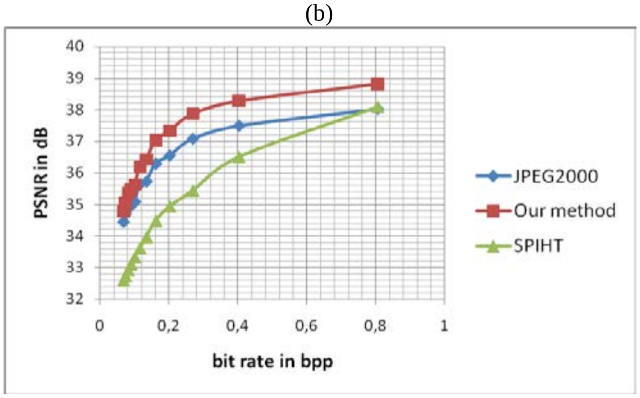
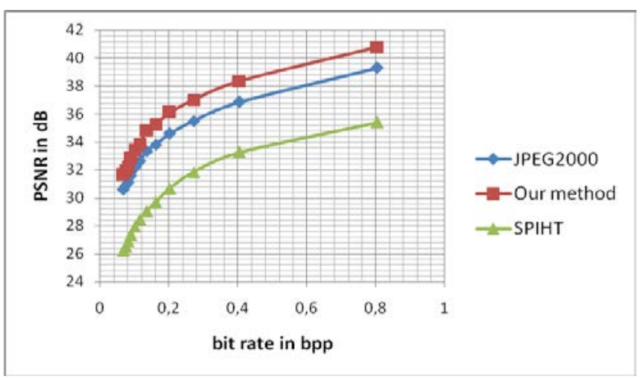
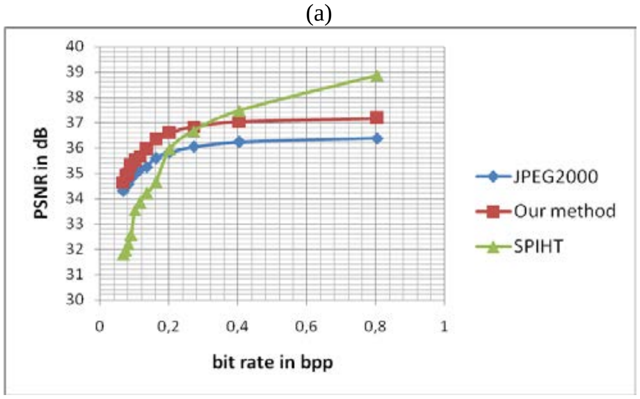


(c)

Fig. 8 PSNR versus bit rate in bpp for Lena: (a) luminance Y, (b) Blue chrominance Cb, (c) red chrominance Cr: our method compared to JPEG2000 and SPIHT codec



(a)



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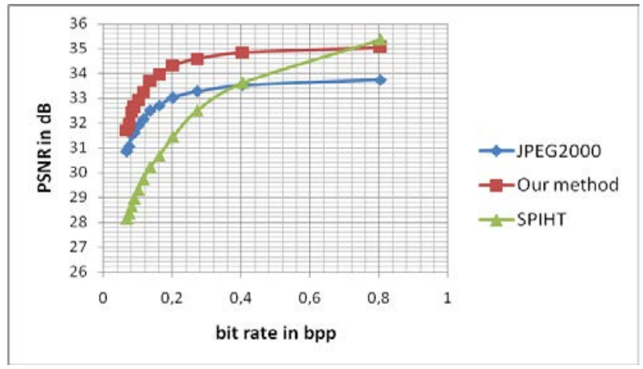
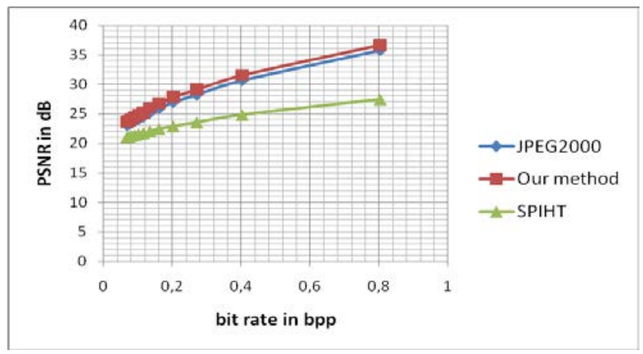
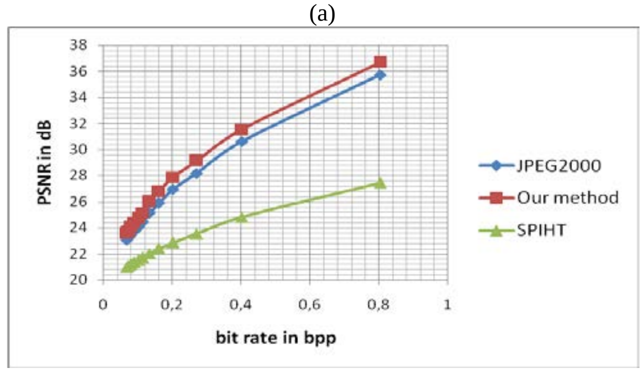


(c)

Fig. 9 PSNR versus bit rate in bpp for Peppers: (a) luminance Y, (b) Blue chrominance Cb, (c) red chrominance Cr: our method compared to JPEG2000 and SPIHT codec



(a)



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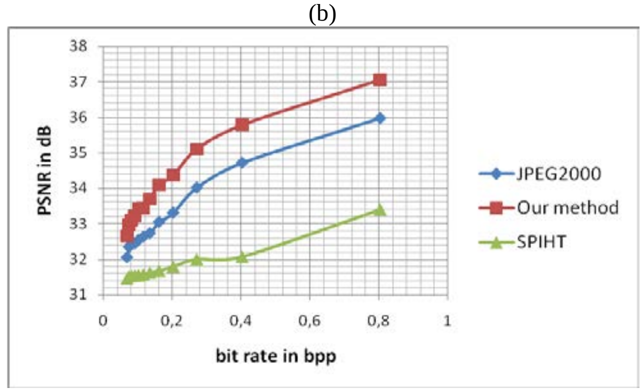


(c)

Fig.10 PSNR versus bit rate in bpp for Mandrill: (a) luminance Y, (b) Blue chrominance Cb, (c) red chrominance Cr: our method compared to JPEG2000 and SPIHT codec

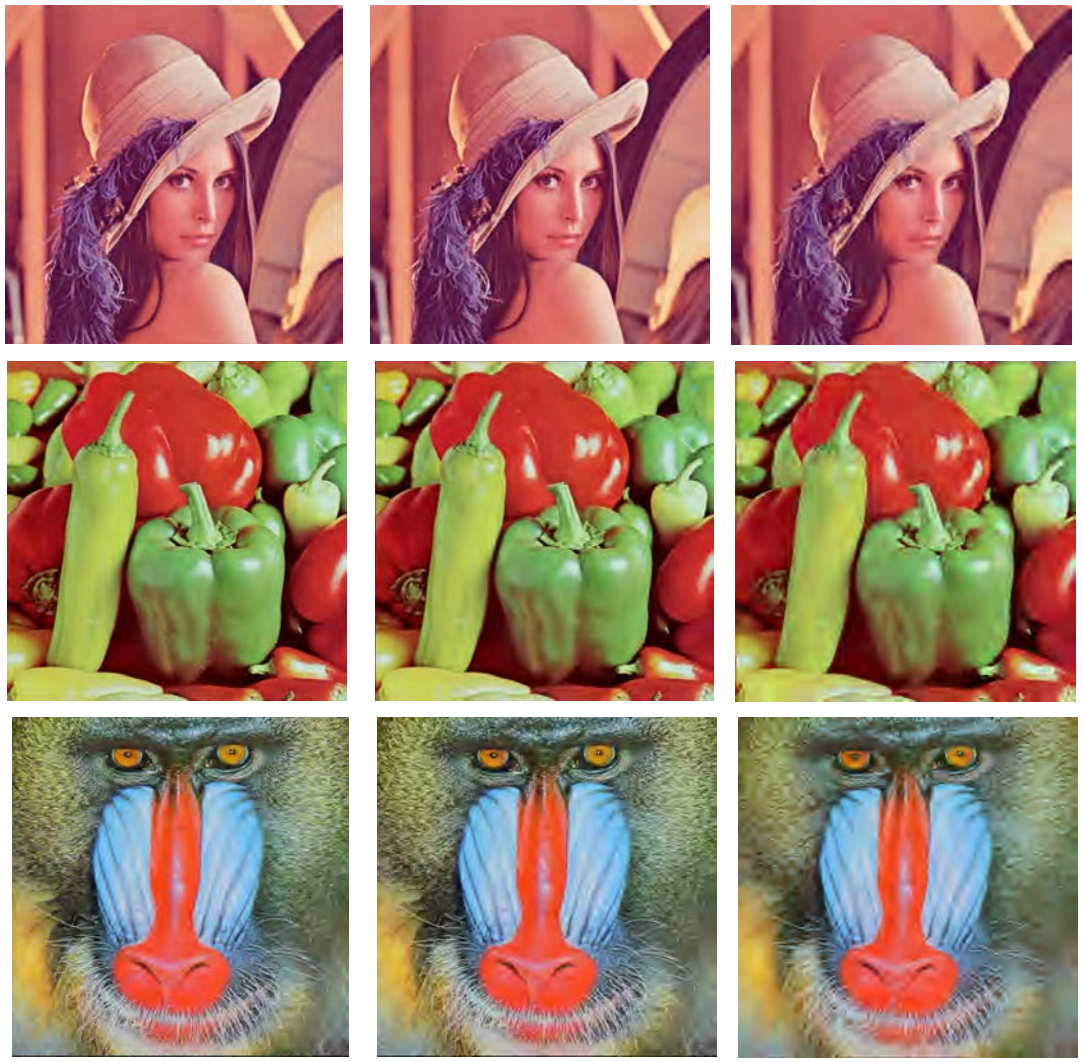


Fig.11 Comparative subjective qualities of decoded Lena, Peppers and Mandrill at 0.08 bpp
Top left: Lena for our method, Top middle: Lena for JPEG2000, Top right: Lena for SPIHT
Center left: Peppers for our method, Center middle: Peppers for JPEG2000, Center right: Peppers for SPIHT
Bottom left: Mandrill for our method, Bottom middle: Mandrill for JPEG2000, Bottom right: Mandrill for SPIHT

Fig.11 presents the subjective qualities of Lena, Peppers and Mandrill decoded at 0.08 bpp for our method, for JPEG2000 and for SPIHT codec.

These results show that our method is competitive with JPEG2000 Tool as well in objective quality as in subjective quality, and significant gains are obtained in terms of PSNR in dB, particularly for the chrominance components. We have also shown that the proposed method gives significant gains in dB compared to some recent published works [23, 24, 27, 28] for Lena in grey scale.

4. Mathematical analysis of the entropy sign coding

4.1 Analysis of the variations of the sign entropy coding

To explain the performance of the proposed method, we present the analysis of separate coding of sign information. Let us consider *x*, the probability to find the significant positive coefficient which we call a *POS* event. A significant negative coefficient is the complementary of the *POS* event and is called the *NEG* event. *POS* and *NEG* form a set of two events. Let us consider *p(POS)* and *p(NEG)* the probabilities of the *POS* and *NEG* events respectively. The probability density law allows the equation (3).

$$p(POS)+p(NEG)=1 \quad (3)$$

Where

$$\begin{cases} p(POS)=x \\ p(NEG)=1-x \end{cases} \quad (4)$$

With $0 \le x \le 1$

In equation (4), $x = 1$ concerns the absence of negative coefficients and $x = 0$ concerns the absence of positive coefficients. Let us consider the entropy *H* of the positive or negative sign information:

$$\begin{cases} H(x)=-x\log_2(x) \text{ if } NEG \text{ is absent} \\ H(x)=-(1-x)\log_2(1-x) \text{ if } POS \text{ is absent} \end{cases} \quad (5)$$

In this case ($x = 1$ or $x = 0$), the entropy of sign information is equal to zero bit; this case is not interesting.

Let us consider the case where x is neither equal to zero nor equal to one, precisely $0 < x < 1$; in this case the *POS* and *NEG* invents are both present: it is the case where both the low frequency subbands coefficients and the high frequency subbands coefficients are superior or equal to the current threshold. The entropy of the sign information is given by equation (6).

$$H=-x\log_2(x)-(1-x)\log_2(1-x) \quad (6)$$

The entropy *H* depends of the probability *x*, we will represent *H(x)* using the neperian logarithm function and the equation (6) is replaced by equation (7).

$$H(x)=\beta(-x\ln(x)+x\ln(1-x)-\ln(1-x)), \quad (7)$$

Where $\beta = 1/\ln(2)$

Let us consider *f(x)*, the first derivative of *H(x)*. This function is given by equation (8).

$$f(x)=\frac{dH(x)}{dx}=\beta(\ln(1-x)-\ln(x)) \quad (8)$$

In equation (8), the first derivative of the entropy of the sign information *f*(*x*) is such that:

$$f(x)\begin{cases} >0 \text{ if } x<0.5 \\ =0 \text{ if } x=0.5 \\ <0 \text{ if } x>0.5 \end{cases}$$

$$\lim_{x\to 0} H(x)=0 \text{ and } \lim_{x\to 1} H(x)=0$$

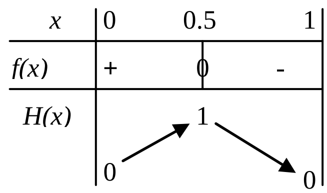


Fig.12 Variations of the entropy *H(x)*

Fig.12 shows the variations of the entropy of the sign information. Fig.13 is the graphical representation of the entropy *H(x)* versus the probability *x* of the sign information for $x \in [0.00001; 0.99999]$.

Fig.12 shows that the maximum value of the entropy is equal to one bit and for $x = 0.5$; this means that the coast of the positive and negative sign information coding is at most one bit. Therefore, for $x < 0.5$ and $x > 0.5$, the entropy *H(x)* is less than 1 bit. For example, if $x = 0.99999$, then $H(x) = 0.00018$ bit and if $x = 0.00001$ then $H(x) = 0.00018$ bit (we may notice the symmetrical behavior of the entropy's curve for x = 0.5). We may also see that Fig.12 and 13 are in accordance with the results presented from fig. 2 to fig. 4.

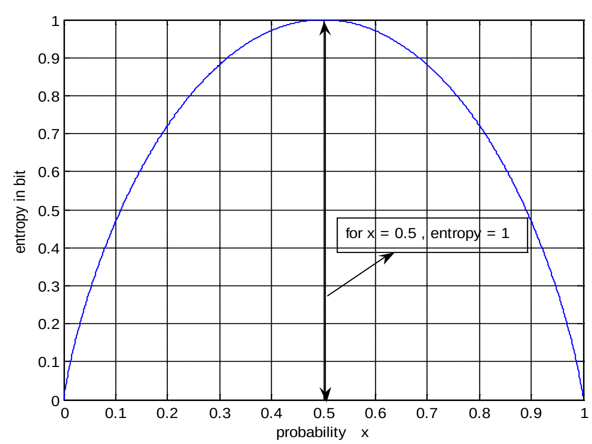


Fig.13 Entropy of positive and negative sign information

We can see that the entropy curve *H(x)* is concave and has a maximum at $x = 0.5$. Mathematically, a function *H(x)* is concave and has a maximum at x_0 if and only if $\frac{dH(x)}{dx}=0$ at this point and $\frac{d^2H(x)}{dx^2}<0$. To prove this observation, let us consider *g(x)* the second derivative of the entropy *H(x)*; this function is given by equation (9):

$$g(x) = \frac{d^2H(x)}{dx^2} = \frac{df(x)}{dx} = \frac{-\beta}{x(1-x)} \quad (9)$$

Fig.12 shows that $\frac{dH(x)}{dx} = 0$ for $x_0 = 0.5$ and $\frac{d^2H(x)}{dx^2}$ is strictly negative because $0 < x < 1$ and $\beta = 1/\ln(2) > 0$. Then, the entropy behavior curve in figure 13 is mathematically proved.

Figure 13 shows that the entropy of the image wavelet coefficients sign coding may be modeled by the parabolic approximation, precisely by the second order polynomial function. Let us consider $P(x)$ the polynomial function, defined by equation (10) where x is the probability of the sign information

$$P(x) = a_0 + a_1x + a_2x^2 \quad (10)$$

The polynomial approximation will consist to determine a_0, a_1, and a_2. If we consider figure 12, we can establish three equations necessary for the determination of a_0, a_1, and a_2. Let us consider $x_0 = 0$, $x_1 = 0.5$, and $x_2 = 1$

$$\begin{cases} P(x_0) = H(x_0) = 0 \\ P(x_1) = H(x_1) = 1 \\ P(x_2) = H(x_2) = 0 \end{cases} \quad (11)$$

Then $\begin{cases} a_0 = 0 \\ 0.5a_1 + 0.25a_2 = 1 \\ a_1 + a_2 = 0 \end{cases}$ (12)

The resolution of equation (12) gives $a_0 = 0$, $a_1 = 4$, and $a_2 = -4$; hence the parabolic approximation function is given by equation (13).

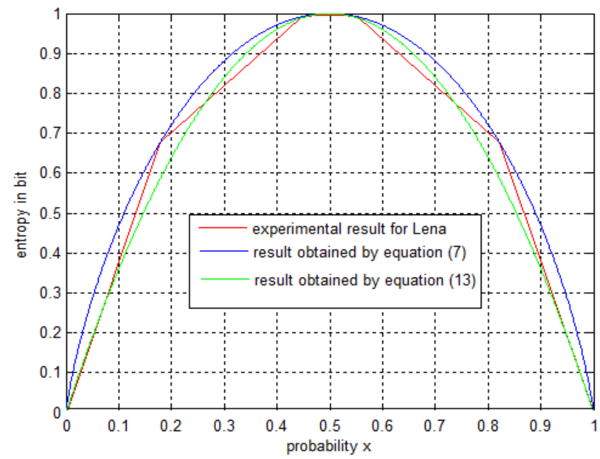
$$P(x) = 4x - 4x^2 \quad (13)$$

Fig.14 a shows that:

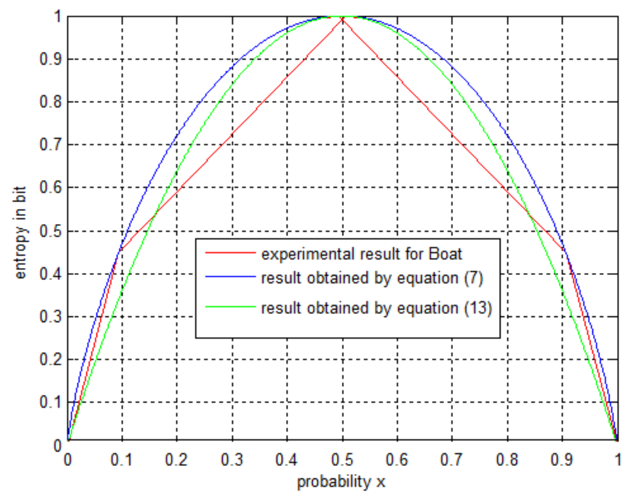
- in red curve the experimental result obtained for Lena image;
- in blue curve the theoretical result obtained by equation (7);
- in green curve the model result obtained by equation (13).

Fig.14 b shows:

- in red curve the experimental result obtained for Boat image;
- in blue curve the theoretical result obtained by the equation (7);
- in green curve the model result obtained by the equation (13).



(a)



(b)

Fig.14 Entropy of positive and negative sign information and its model: (a) for Lena, (b) for Boat

This analysis proves that a separate sign information coding requires a minimum bit budget. Consequently, for a same reconstruction quality, the proposed method uses a minimum bit allocation and it explains the performance in terms of PSNR of our method over the JPEG2000 standard and SPIHT codec. Therefore, the observation of figures 2 to 4 is confirmed by this mathematical analysis.

5. Conclusion

We have proposed a new method based on separate entropy coding of sign and magnitude of wavelet coefficients. An algorithm is developed and the probabilities of magnitude, sign and refinement information are calculated online, bit-plane by bit-plane for the luminance, blue chrominance, red chrominance and these data are entropy encoded using arithmetic coding. We show that the sign information of wavelet coefficients as well for the luminance as for the chrominance components may not be encoded by an estimated probability of 0.5; the encoding of the sign information of wavelet coefficients using estimated probability of 0.5 may be used only after a few bit planes.

We also show that the refinement information coefficients for the luminance and the chrominance components may not be encoded by the estimated probability of 0.5. In fact, the probabilities of the quantized wavelet coefficients of the luminance and the chrominance components to be set in the low interval or in the high interval in the refinement processing present symmetry with the probability value of 0.5.

All the informations (magnitude, sign and refinement) are encoded using arithmetic coding. Three standard color images are compressed using our method. The JPEG2000 Tool (jpeg2000 J2K-Tool) [15] and the SPIHT codec [5][29] are run for the same test images. The obtained results are compared to JPEG2000 standard tool and SPIHT codec in terms of objective quality (PSNR) for Lena, Peppers, and Mandrill color test images.

The comparison is also done in terms of subjective quality (visual quality) with JPEG2000 standard tool and SPIHT codec for the same standard color test images decoded at 0.08 bpp. We show that the proposed method outperforms the JPEG2000 standard tool and significant gains in terms of PSNR in dB are obtained on JPEG2000. Our method outperforms the SPIHT codec except for the chrominance of Peppers at high bit rate; however in average, significant gains are obtained by our method on SPIHT codec. The proposed method gives also significant gains in dB compared to some recent published works [23, 24, 27, and 28] for Lena in grey scale (the luminance component).

Furthermore, we have proposed an original mathematical analysis which proves that the coast of the sign information requires a minimum bit budget allocation and consequently, explains the performance in terms of PSNR obtained by our method on JPEG2000 and SPIHT codec. Finally, we have shown that it is possible to operate the modeling of the positive and negative signs entropy by a parabolic approximation.

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