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THE EFFECT OF QUALITY SCALABLE IMAGE COMPRESSION ON ROBUST WATERMARKING

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ABSTRACT

The effect of quantization based compression in quality scalable image coding on the robustness of wavelet based watermarking is presented. The non-blind direct modification type watermarking is considered for the analysis presented in this paper. First we present the analysis considering any quantization parameter and then restrict it to the integer powers of two to model the bit-plane discarding based quantization used in quality scalable coding, such as JPEG2000. This work assumes that the watermark embedding and compression uses the same wavelet filters. The derived model shows the relationship between the modified coefficients and the quantization factor, which is then used to obtain the conditions for the correct watermark extraction under compression. Based on this analysis, one can select wavelet coefficients for embedding the watermark in a manner that the correct watermark extraction is possible for a given quantization level. The results show higher robustness when this model is used for embedding the watermark. The paper also evaluates the performance of the model when the watermark embedding and the compression wavelet filters are not the same.

***Index Terms*—** Wavelet based Watermarking, Robustness, Compression, JPEG2000, Quality scalability.

1. INTRODUCTION

Watermarking is commonly used as an important technique in multimedia security and digital rights management. Recent years have seen a rapid advancement in wavelet domain watermarking [1]-[9]. In watermarking algorithms, imperceptibility and robustness are widely regarded as two of the main desired features. Usually it is vital that the watermarking scheme is robust to known attacks, such as image coding and scaling. In modern multimedia usage frameworks, multimedia content is encoded at higher quality and resolution formats using scalable coding algorithms and then adapted to lower quality and resolution bitstreams in order to address the transmission bandwidth, display devices and other usage requirements [10]. In such a multimedia usage scenario, the watermarking robustness against the quality and spatial scalability are considered as very important. Therefore, the emerging watermarking algorithms attempt to improve the robustness against scalable coding, such as JPEG2000 [11], either by incorporating the watermarking into the compression algorithm as in JPSec [12] or employing other wavelet domain embedding schemes. For example, in [13], a secure signature scheme is presented based on JPEG2000 image authentication. However, most algorithms do not provide an insight into how these algorithms behave under quantization driven quality scalability or scaling driven resolution scalability. Formal modeling of their robustness behavior is usually restricted to common image processing attacks [14].

In this paper, we analyze the effect of quantization in wavelet based scalable image coding to model the robustness of wavelet based watermarking to quantization driven quality scalability in scalable image coding applications. In the present work, we have considered wavelet domain non-blind watermarking and its robustness to wavelet domain bit plane wise quantization that emulates the quantization in JPEG2000, the scalable image coding standard. The derived model shows the relationship between the modified coefficients and the quantization factor, which is then used to obtain the conditions for the correct watermark extraction under quality scalability. We aim to specify criteria for choosing coefficients for watermark embedding, that can ensure robustness under various quality scalability adaptations of JPEG2000 encoded bitstreams. Since the imperceptibility is reciprocally related to the robustness, we can use our previous work on the imperceptibility model [15] to find the right balance between these two properties for selecting coefficients for watermark embedding.

The rest of the paper is organized as follows: Wavelet based image coding and quantization error modeling is presented in Sec. 2. We briefly discuss wavelet based watermarking, by fitting them into a generalized framework in Sec. 3.

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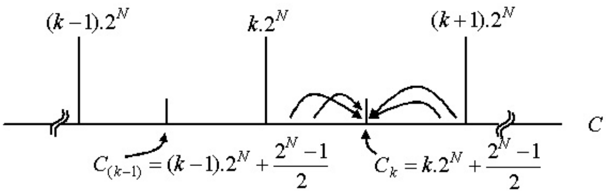

Fig. 1. Quantisation compression scheme considering N level bit-plane discarding.

In Sec. 4, we discuss the conditions for ensuring robustness for watermark embedding taking into account the quantization error in a scalable coding framework. Simulations and experimental results supporting the derived model are shown in Sec. 5, followed by the concluding remarks and future work in Sec. 6.

2. WAVELET BASED IMAGE COMPRESSION

The latest image compression standard, JPEG2000, uses wavelet as its core technology and offers scalable decoding with quality scalability and resolution scalability. Modern scalable image coders use wavelet transforms followed by embedded quantizing and entropy coding. The coefficient quantization, in its simplest form, can be formulated as follows:

$$C_q = \left\lfloor \frac{C}{Q} \right\rfloor, \tag{1}$$

where C_q is the quantized coefficient, C is the original coefficient and Q is the quantization factor. Embedded quantizers often use $Q = 2^N$, where N is a non-negative integer. Such a quantization parameter within downward rounding (*i.e.,* using *floor*), can also be interpreted as bit plane discarding as commonly known within the image coding community.

At the decoder side, a reverse process of the encoding is followed to reconstruct the image, *i.e.,* the entropy decoding is followed by dequantization and inverse wavelet transformation. The dequantization process is formulated as follows:

$$\hat{C} = Q.C_q + \left(\frac{Q-1}{2}\right), \tag{2}$$

where $\hat{C}$ is the dequantized coefficient. In such a quantization scheme, the original coefficient values in the range $k.Q \leq C < (k+1).Q$, where $k \in \pm 1, \pm 2 \pm 3...$, are mapped to $(\hat{C}) = C_k$, which is the center value of the concerned region. Similarly, for bit plane wise coding, we can express the original coefficient vales range as $k.2^N \leq C < (k+1).2^N$. as shown in Fig. 1. This relationship is further exploited in Sec. 4 in terms of watermark embedding to model the robustness to bit plane discarding based quantization driven quality scalability in scalable image coding.

3. WAVELET BASED WATERMARKING

There are many wavelet based watermarking algorithms present in the literature. In an attempt to generalization of such schemes, we have accommodated popular algorithms into a common framework [16] by dissecting the algorithms into common functional modules and deriving a basic embedding form as follows:

$$C'_{m,n} = C_{m,n} + \Delta_{m,n}, \tag{3}$$

where $C'_{m,n}$ is the modified coefficient at (m,n) position, $C_{m,n}$ is the coefficient to be modified and $\Delta_{m,n}$ is the modification due to watermark embedding. Based on the modification algorithms we have broadly categorized the algorithms into two groups: direct modification [1, 2, 6, 8, 9] and quantization based modification [4, 5, 7, 3].

3.1. Direct modification

Direct modification algorithms are generalized in the following modification value $\Delta_{m,n}$ at (m,n) position:

$$\begin{aligned}\Delta_{m,n} = \;& (a_1)\alpha(C_{m,n})^b W_{m,n} + (a_2)v_{m,n}W_{m,n} \\ & +(a_3)\beta C_w + (a_4)S_{m,n},\end{aligned} \tag{4}$$

where $a_1, ..., a_4$ are boolean variables to identify the presence of each of the components for a given methodology, $C_{m,n}$ is the coefficient to be modified, α is the watermark weighting factor, $b = 1, 2...$ is the watermark strength parameter, $W_{m,n}$ is the watermark value, $v_{m,n}$ is the weighting parameter based on pixel masking in a human visual system model, β is the weighting parameter in the case of fusion based scheme, C_w is the watermark wavelet coefficient and $S_{m,n}$ is any other value which is normally a function of $C_{m,n}$.

3.2. Quantization based modification

In this case, the modification $(\Delta_{m,n})$ is performed based on a ranked order quantization update. The median value of a local area (typically a 3x1 coefficient window) is usually modified to a quantized step and the quantization step δ $(-\delta \leq \Delta \leq \delta)$ is decided upon a local minima (C_{min}) and local maxima (C_{max}) of the selected window coefficients. The expression to determine δ varies in different algorithms.

In this paper we considered non-blind direct modification based method as the example case for the quantization error modeling work.

4. QUANTIZATION ERROR ANALYSIS

In this section we shall derive a robustness analysis model against quantisation based compression schemes. A modified non-blind direct modification based algorithm [2] has been used as an example case:

$$C' = C + C\alpha w, \tag{5}$$

where C' is the modified coefficient, α is the watermark strength parameter and w is the watermark information and assigned to w_0 to embed a $'0'$ and w_1 to embed $'1'$. To extract the watermark we need to refer the original host image. The watermark detection can be done by extracting the modification value Δ:

$$\Delta = C' - C,$$
$$w_{ext} = \frac{C' - C}{\alpha C}, \tag{6}$$

where w_{ext} is the extracted watermark value. During the watermark extraction, the value of w_{ext} is used to decide the watermark information bit. Often a threshold T is used to decide the extracted watermark bit, i.e. if $w_{ext} > T$ the extracted bit is said to be $'1'$ and else $'0'$. Keeping the generality, first we establish a robustness relationship with the modification value Δ and then use the specific example case. Due to the quantisation Eq. (6) can be rewritten as:

$$\Delta_q = C'_q - C, \tag{7}$$

where C'_q is the quantised value of the watermarked coefficient and Δ_q is the corresponding quantised modification. Due to the quantisation operation as discussed in Sec. 2, all C'_q values are re-mapped to the center points C_k of the corresponding clusters and the modification values changes accordingly. At this point we shall refer the example case where $\Delta = C\alpha w$. We shall use different cases for embedding of $'1'$ and $'0'$ and finally combined them to find the relationships and necessary conditions for correct detection. We have considered same wavelet kernel used for embedding and compression.

4.1. Embed $'1'$

Based on the watermark algorithm, the extracted watermark information is said to be $'1'$ if $w_{ext} > T$. At this point we considered two different cases: 1) C and C' are in the different cluster and 2) C and C' are in the same cluster. We shall discuss these two cases separately in the following subsections.

4.1.1. C & C' are in different cluster

Due to the embedding and positive modification, the modified coefficient C' can be in the different cluster to the original coefficient C. The range of C, for such case can be defined as (refer Fig. 2):

$$\frac{k.2^N}{1 + \alpha w_1} \leq C \leq k.2^N. \tag{8}$$

Due to quantisation any C' value is re-mapped to corresponding center point C_k of cluster k and correct detection of $'1'$s are guaranteed if $k.2^N \leq C' \leq C_k$.

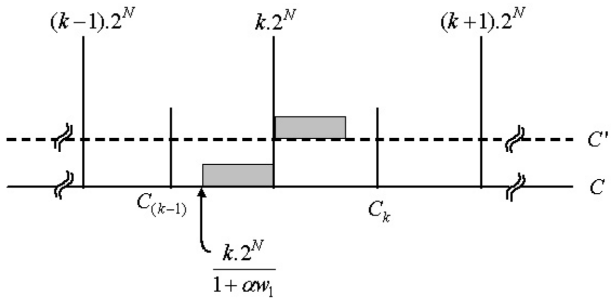

Fig. 2. Range of C (shaded region) to be modified by embedding $'1'$ and corresponding C' is in the next cluster with a guaranteed detection.

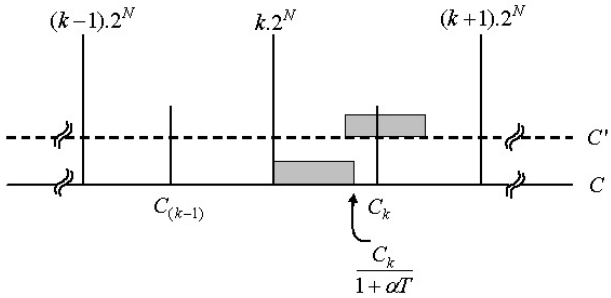

Fig. 3. Range of C (shaded region) to be modified by embedding $'1'$ and corresponding C' is in the same cluster with a guaranteed detection.

4.1.2. C & C' are in same cluster

We assume C and C' are in the same cluster after watermark embedding. In the case of C's in the range from $k.2^N$ to C_k are re-mapped to C_k and C' value is increased. Hence Δ_q is also increased and correct watermark detection is guaranteed. On the other hand if C' is in the range from C_k to $(k+1).2^N$, all C' value will be re-mapped to C_k and a decrease in Δ_q will be observed. In this case $\Delta_q = C_k - C$ should be greater than threshold value T for a correct detection. Hence the range of C to reatin watermark $'1'$ is defined as below (refer Fig. 3):

$$k.2^N \leq C \leq \frac{C_k}{1 + \alpha T}. \tag{9}$$

Now with reference to Fig. 4, combining Eq. (8) and Eq. (9) we can define the range of C to retain the watermark $'1'$ as below:

$$\frac{k.2^N}{1 + \alpha w_1} \leq C \leq \frac{C_k}{1 + \alpha T}. \tag{10}$$

4.2. Embed $'0'$

Using Eq. (6) and the watermark extraction algorithms, the extracted watermark bit is considered to be $'0'$ if $w_{ext} < T$. Based on the watermark extraction condition we assume two different cases as earlier.

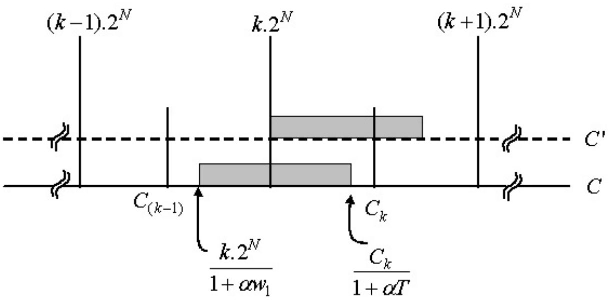

Fig. 4. The complete range of C to be modified to embed $'1'$ with a correct detection at N level bit-plane discarding.

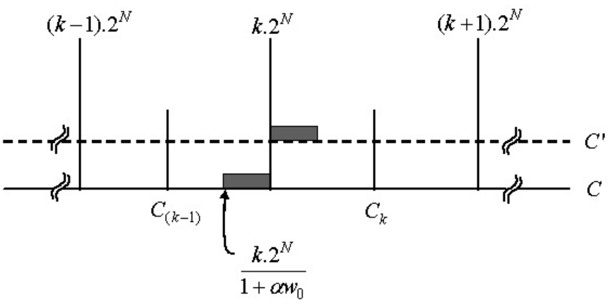

Fig. 5. Range of C (shaded region) to be modified by embedding $'0'$ and corresponding C' is in the next cluster. Detection performance not guaranteed.

4.2.1. *C & C' are in different cluster*

Due to the positive modification, the original coefficient and the modified coefficient can be in different cluster. Using Eq. (2) and Eq. (5), the range of original coefficient value C for the same can be defined as follows:

$$\frac{k.2^N}{1+\alpha w_0} \leq C \leq k.2^N. \tag{11}$$

Due to the quantisation, the modified coefficient C' in the other cluster is re-mapped to the corresponding center point C_k of the cluster k and as a result all C' values in the range $k.2^N$ to C_k (Fig. 5) increased after quantisation operation. Hence the false detection is possible for the coefficients in range as specified in Eq. (11) and for a correct detection of $'0'$s the original coefficients and the corresponding modified coefficients must be in the same cluster.

4.2.2. *C & C' are in same cluster*

The primary condition for C and C' are in the same cluster is the modification value Δ should be less than the cluster size. Due to the quantisation the modified coefficients (C') in the range from $(k-1).2^N$ to $C_{(k-1)}$, are re-mapped to $C_{(k-1)}$ and there is an effective increase in Δ_q during the watermark extraction. Therefore a false detection is possible. On the other hand, all C's in the range from $C_{(k-1)}$ to $k.2^N$ are re-mapped to $C_{(k-1)}$ and there is an effective decrement in Δ_q and all watermark information can be extracted correctly. Also any value less than the threshold T is considered as $'0'$ and therefore to detect a $'0'$ correctly, C and C' must be in the same cluster and C must be within the following range as shown in Fig. 6.

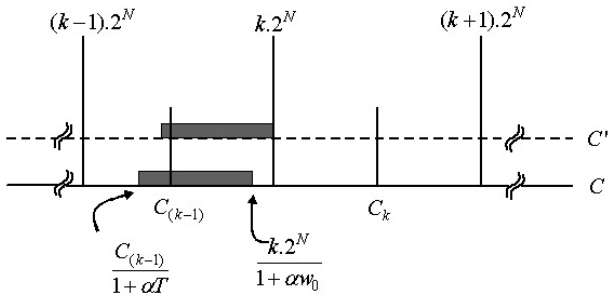

Fig. 6. Range of C (shaded region) to be modified by embedding $'0'$ and corresponding C' is in the same cluster with guaranteed detection.

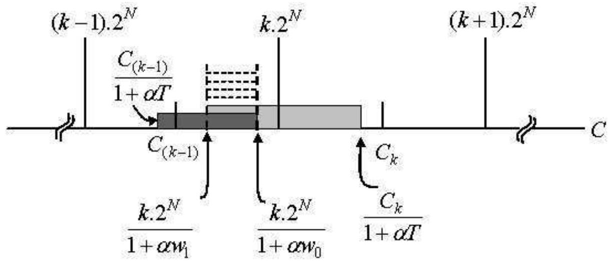

Fig. 7. Range of C (overlapping region) to retain the watermark bit $'1'$ or $'0'$ correctly after the quantisation of N bit-plane discarding.

$$\frac{C_{(k-1)}}{1+\alpha T} \leq C \leq \frac{k.2^N}{1+\alpha w_0}. \tag{12}$$

4.3. Embed $'1'$ or $'0'$

Combining all the possible cases presented before we can state the conditions and the range of C for a correct watermark detection ($'1'$ or $'0'$) at a given quantisation level. Refereing Fig. 7, it is clearly understandable that the overlapping range of the of C values can retain the correct watermark information after the modification with given N bit-plane discarding. Thus the range for C can be defined as below considering $w_1 > w_0$:

$$\frac{k.2^N}{1+\alpha w_1} \leq C \leq \frac{k.2^N}{1+\alpha w_0}. \tag{13}$$

These conditions are verified experimentally in the experimental simulations section.

4.4. Conditions for optimisation

Based on this robustness analysis, we can choose the coefficients efficiently so that correct watermark extraction at a given compression level is possible. At the same time one can decide the minimum modification value for a given coefficient to be modified due to the fact that a greater modification value results in poor imperceptibility and the impact of modification on imperceptibility has been shown in an embedding distortion model in [15]. With the help of this robustness analysis model, it is possible to offer an adaptive watermark weighting parameter which can control the modification value locally along with an effective coefficient selection, so that the guaranteed watermark detection is possible for a given compression ratio with a better imperceptibility.

5. EXPERIMENTAL SIMULATIONS

We have simulated the example case mentioned before with quantisation based compression including JPEG2000. Two different sets of results are obtained to verify the derived model. The experimental arrangements are shown below:

5.1. *Experiment Set 1:*

Using the direct modification scheme as described in Sec. 4, we applied the quantisation based compression by discarding the bit-planes to verify the robustness. As an experimental parameter set we chose $\alpha = 0.5$, $w_1 = 0.8$, $w_0 = 0.3$, the threshold $T = 0.5$ and a data set from 1 to 512 which is considered as coefficients C in all the cases.

Now to emulate the robustness effect on embedding $'1'$, we embedded $'1'$ in all Cs and the resultant watermarked data set is quantised with discarding lower $N = 7$ bit planes. The watermark extraction is done on quantised data set. In Fig. 8(a) the original un-watermarked coefficients which retained the watermark information after compression are shown. In order to embed $'0'$ and analyse its robustness, we performed the same experiments as with embedding $'1'$ with the same data set and the results are shown in Fig. 8(b) considering $\alpha = 0.5$. For a combined detection region for either $'1'$ or $'0'$ thus can be identified and shown in Fig. 8(c).

A similar simulations are carried out with a different watermarking weighting parameter ($\alpha = 0.05$). The results of robustness effect on embedding $'1'$, $'0'$ and combined $'1'$ or $'0'$ are shown in Fig. 9(a), Fig. 9(b) and Fig. 9(c), respectively.

5.2. *Experiment Set 2:*

In this case, an JPEG2000 based quality scalability compression is applied. In stead of only $'1'$s or only $'0'$s, a general random combination of $'1'$s and $'0'$s are chosen as watermark information. With the parameter set of 3 level wavelet decomposition, $\alpha = 0.05$, four different quantisation bit planes (at $N = 0$, $N = 5$, $N = 7$ and $N = 9$) are assumed and accordingly the coefficients of the low frequency subbands are

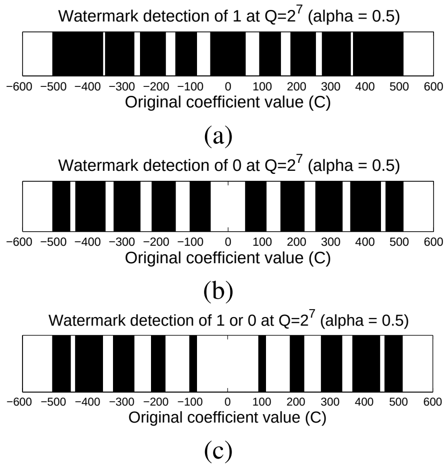

Fig. 8. Map of original coefficient (C) values which can retain: (a) $'1'$, (b) $'0'$ and (c) combinations of $'1'$ or $'0'$at $Q = 2^7$ with $\alpha = 0.5$. Black region represents correct detection where white region represents incorrect detection.

estimated to embed the watermark. Other parameters are kept same as in experiment set 1. In case of $N = 0$ all the coefficient are selected for the embedding. A JPEG2000 quality scaling is then performed to the watermarked image and Hamming distance is calculated between the original watermark and the extracted watermark in each of the four cases. We have considered the cases for same and different wavelet kernels at embedding and compression as shown in Fig. 10. In the case of same wavelet, $Wv_1 = Wv_2$ where Wv_1 is the embedding wavelet and Wv_2 is the compression wavelet, biorthogoanl $9/7$ as in JPEG2000 is considered for embedding and compression. For $Wv_1 \neq Wv_2$, we considered Haar as the embedding wavelet, keeping $9/7$ as compression wavelet in JPEG2000. For a set of different images (refer Fig. 11), the results for JPEG200 quality scaling at different compression ratios are shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16 and Fig. 17. The effect of bit-plane based robustness at a given JPEG2000 compression ratio such as $64 : 1$ or $80 : 1$ are shown in Fig. 18 and Fig. 19, and same embedding and compression wavelet i.e. bi-orthogonal 9/7 is considered here.

Now as an example using the experimental parameters we shall calculate different model parameters and then compare these with the experimental results.

Embed $'1'$: From Eq. (10), to embed $'1'$, we can calculate the range of original coefficients which can retain the watermark correctly by discarding $N = 7$ lower bit-planes. For different k values we can estimate the range for the experimental data set as shown in Table 1. The experimental simulations support the the same as shown in Fig. 8 and Fig. 9.

Embed $'0'$: Using Eq. (12) and the experimental parameter set following the range for the C to retain $'0'$ can be calculated and shown in Table 1 with different k values. The range calculated above can be verified by the experimental result

Table 1. Data set range to retain watermark $'1'$ and $'0'$ at $Q = 2^7$ quantisation level.

(a) $\alpha = 0.5$

	$k \rightarrow$	-5	-4	-3	-2	-1		1	2	3	4	5
$'1'$	min	-512	-460	-358	-256	-153	-51	91	183	274	366	457
	max	-457	-366	-274	-183	-91	51	153	256	358	460	512
$'0'$	min	-512	-445	-334	-223	-111		51	153	256	358	460
	max	-460	-358	-256	-153	-51		111	223	334	445	512

(b) $\alpha = 0.05$

	$k \rightarrow$	-4	-3	-2	-1		1	2	3	4
$'1'$	min	-512	-437	-312	-187	-62	123	246	369	492
	max	-492	-369	-246	-123	62	187	312	437	512
$'0'$	min	-504	-378	-252	-126		62	187	312	437
	max	-437	-312	-187	-62		126	252	378	504

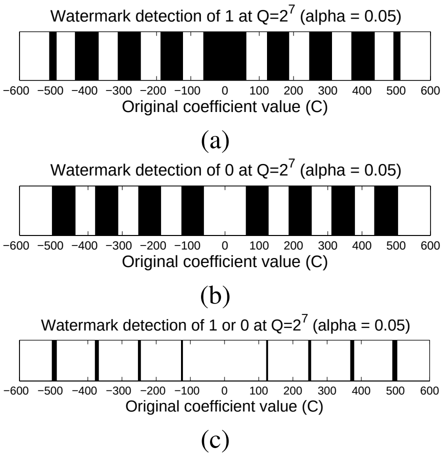

Fig. 9. Map of original coefficient (C) values which can retain: (a) $'1'$, (b) $'0'$ and (c) combinations of $'1'$ or $'0'$ at $Q = 2^7$ with $\alpha = 0.05$. Black region represents correct detection where white region represents incorrect detection.

shown in Fig. 8 and Fig. 9.

Hence from the above derived range of the coefficients C for embedding $'1'$ and $'0'$ can be combined and the using Eq. (13) the range for this example is calculated and shown in Table 2.

A combined random $'1'$ and $'0'$, watermark information is embedded and compressed against JPEG2000 quality scalability and the results are shown in Fig. 12, Fig. 13, Fig. 14, Fig. 15, Fig. 16 and Fig. 17. In case of same embedding and compression wavelet, the simulations strongly supports our derived model for various host images. Whereas, using a different embedding wavelet does not follow the derived model due to the fact that the coefficient values varies in transform domain for different wavelet. From Fig. 18 and Fig. 19, the trend at a given compression ratio is observed. The coefficient selection are based on assumed bit plane discarding. Consideration of more bit-plane discarding, results in more robustness at a given compression ratio. But at the same time, watermark capacity is reduced. Thus using this study a trade off can be done based on the application requirement.

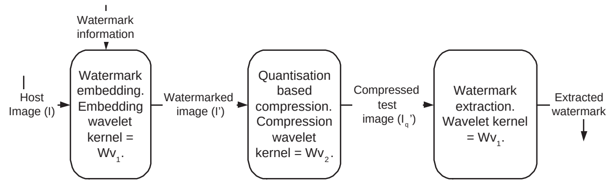

Fig. 10. Experiment set schematic with wavelet based watermark embedding and compression.

Fig. 11. Image test set (Image5 is from Kodak test set).

6. CONCLUSIONS

A mathematical analysis of robustness is presented here with reference to wavelet based watermarking schemes. The main focus has been given to quantisation based scalable compression schemes such as JPEG2000. Firstly a relationship is established between the wavelet coefficients to be modified and the quantisation compression parameters such as no of bit-plane to be discarded. Then necessary conditions are made to select the coefficients which can retain the watermark information at a given quantisation levels. The derived model is supported by experimental simulations along with JPEG2000 compressions. Such an analysis is very useful to optimise the coefficient selection procedure during watermark embedding which helps to reduce the embedding distortion while keeping the robustness. In this work, it is also indicated a future work to optimise the modification value due to watermark embedding by using a locally adaptive watermark weighting factor.

Table 2. Data set range to retain watermark $'1'$ or $'0'$ at $Q = 2^7$ quantisation level.

(a) $\alpha = 0.5$

min	-512	-445	-334	-223	-111	91	183	274	366	460
max	-460	-366	-274	-183	-91	111	223	334	445	512

(b) $\alpha = 0.05$

min	-504	-378	-252	-126	123	246	369	492
max	-492	-369	-246	-123	126	252	378	504

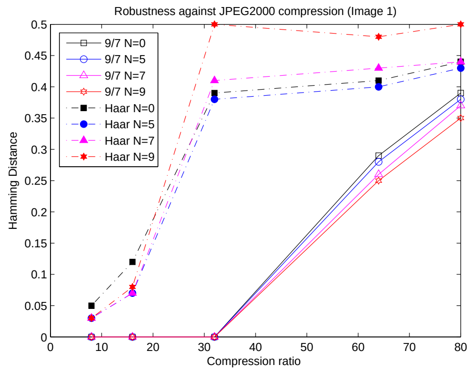

Fig. 12. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 1. Quantisation steps: $Q = 2^0$, $Q = 2^5$, $Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

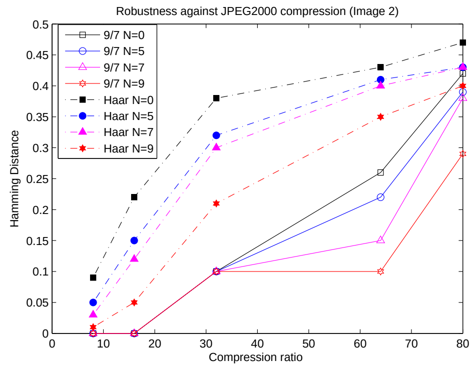

Fig. 13. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 2. Quantisation steps: $Q = 2^0$, $Q = 2^5$, $Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

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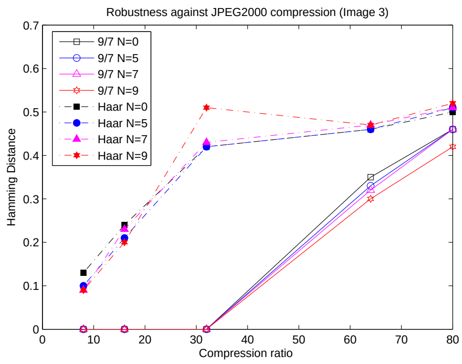

Fig. 14. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 3. Quantisation steps: $Q = 2^0, Q = 2^5, Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

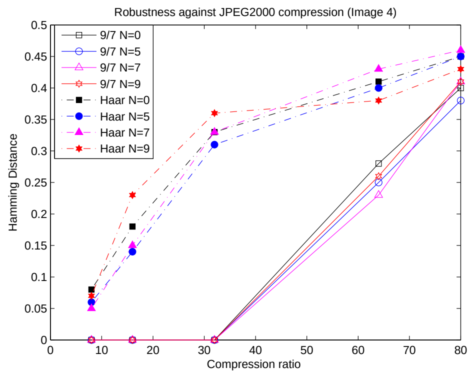

Fig. 15. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 4. Quantisation steps: $Q = 2^0, Q = 2^5, Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

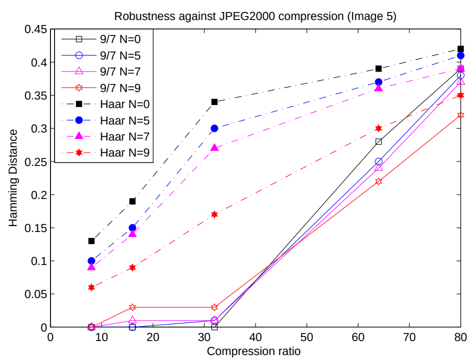

Fig. 16. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 5. Quantisation steps: $Q = 2^0, Q = 2^5, Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

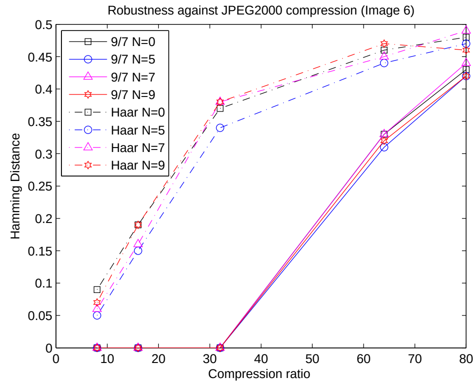

Fig. 17. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling for image 6. Quantisation steps: $Q = 2^0, Q = 2^5, Q = 2^7$ and $Q = 2^9$. Two sets of results displayed for same embedding wavelet: 9/7 and different embedding wavelet: Haar.

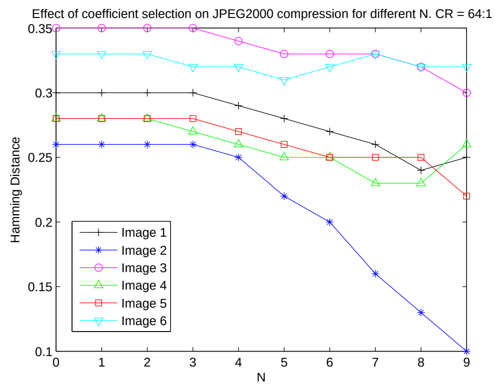

Fig. 18. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling considering 64:1 compression ratio. Quantisation steps: $Q = 2^0$ to $Q = 2^9$.

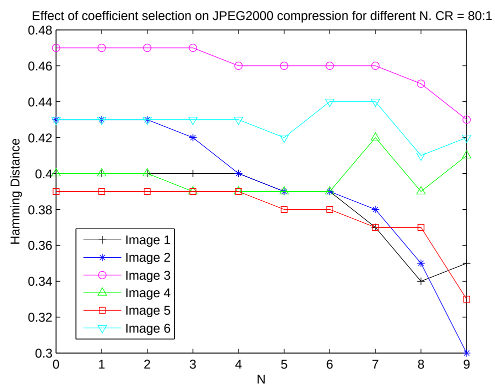

Fig. 19. Effect of bit-plane based coefficient selection procedure against JPEG2000 quality scaling considering 80:1 compression ratio. Quantisation steps: $Q = 2^0$ to $Q = 2^9$.