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Robust SS watermarking with improved capacity

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Abstract

Robustness is a key attribute of spread spectrum (SS) watermarking scheme. It is significantly deteriorated if one tries to achieve high embedding rate keeping other parameters unaltered. In literatures, typically various transformations like DFT, DCT, Fourier–Mellin and wavelet are used for SS multimedia watermarking but little studies have been attempted so far to see what are the possible factors which can improve robustness. The current paper has critically analyzed few such factors namely design of code pattern, proper signal decomposition suitable for data embedding, direction of decomposition, selection of regions for data embedding, signaling scheme, choice of modulation functions and embedding strength. Based on the observation, wavelet based SS watermarking scheme is proposed and improvement in robustness performance is verified through experimental results as well by mathematical analysis.

Keywords: SS watermarking; Robust watermarking; Embedding capacity; Wavelet; Multi-band discrete wavelet transform

1. Introduction

Spread spectrum (SS) modulation, due to its inherent anti-jamming and interference rejection property (Pickholtz et al., 1982), is used widely to design robust watermarking scheme for multimedia signals. Several SS watermarking schemes are proposed in the literature using DCT (Cox et al., 1997), Fourier–Mellin (Ruanaidh and Pun, 1998), and wavelet (Grobois and Ebrahimi, 2001), etc. The major shortcomings of these works are the non-blind detection, low embedding capacity and high decoding overhead. Moreover, the factors responsible for robustness improvement are not taken care. To the best of our knowledge, the issues have not yet drawn much of attention of the watermarking research community although Mayer et al. (2002) discussed about the desirable properties of the code patterns and Malvar and Florencio (2003) improved SS watermarking scheme that minimizes the detection error probability for a given expected distortion. But in both these works, neither any practical watermarking scheme nor about the choice of image transformation that can improve detection reliability at high embedding rate have been discussed.

The motivation of the present work arises from the necessity of finding out the factors that are responsible for greater robustness and capacity aspects of SS watermarking schemes. We conjure that the detection reliability (robustness) improvement depends mainly on (a) the choice of particular transform coefficients for embedding, (b) direction of decompositions, (c) development of spreading codes with specific properties, (d) signaling scheme, (e) embedding strength and (f) the selection of modulation function. In this paper, all of the facts have been verified by experimental results and mathematical analysis. Results show that wavelet transform may be considered as a potential tool for information embedding. Watermark information is embedded in wavelet coefficients of the specific subbands. In this paper we have shown both biorthogonal two-band discrete

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wavelet transform (DWT) and M-band discrete wavelet transform (MbDWT) as possible tools for such purpose. Now onwards we use the terms DWT (discrete wavelet transform with two-band decomposition), BiDWT (bi-orthogonal two-band decomposition) and MbDWT (M-band wavelet transform). Improvement in detection reliability is achieved by choosing appropriate modulation function and by increasing orthogonality among the code patterns using Hadamard basis. Several biorthogonal decompositions for two-band system and M-ary modulation for MbDWT are used here for improvement in embedding capacity. Successive interference cancelation (SIC) is then employed to improve robustness and in turn embedding capacity for practical SS watermarking scheme.

The paper is organized as follows. Section 2 describes spread spectrum watermarking and detection. The criteria for robustness and capacity improvement in SS watermarking are discussed in Sections 3 and 4, respectively. Proposed watermarking algorithm is briefly described in Section 5. Performance evaluation is presented in Section 6 and conclusions are drawn in Section 7.

2. Spread spectrum watermarking and detection

Let B denotes the binary valued watermark bit string as a sequence of N bits.

$$B = \{b_1, b_2, b_3, \ldots, b_N\},\ b_i \epsilon \{1, -1\} \tag{1}$$

Let the symbol I denotes the image of size $(Q \times Q)$. Set P of N number binary valued code patterns, each one of size $(Q \times Q)$, are used to form watermark image W_Q (Langelaar et al., 2000) and watermarked image I_W according to the operations as follows.

$$[W_Q] = \sum_{j=1}^{N} b_j \cdot [P_Q]_j \tag{2}$$

$$[(I_w)_Q] = [I_Q] + \alpha \cdot [W_Q] \tag{3}$$

where α is the gain factor or modulation index. Its proper choice optimizes the maximum amount of allowed distortion and minimum watermark energy needed for a reliable detection. SS watermarking schemes can be called as signal adaptive if α is a function of image coefficients.

The two valued watermark data is decoded from the decision variable t_i obtained by evaluating the zero-lag cross-covariance between the image block I_w and each code pattern P_i (Depovere et al., 1998). This process is analogous to Match–Filter (MF) operation in digital communication (Sklar, 1988). The decision variable t_i is mathematically expressed as follows:

$$t_i = \langle P_i - m_1(p_i), I_w - m_1(I_w)\rangle(0) \tag{4}$$

where $m_1(S)$ represents the average of the sequence S, I_w is the watermarked image, and P_i's are the code patterns where $i = 1,2,\ldots,N$. The symbol (0) in Eq. (4) indicates the zero-lag cross-correlation. If the code patterns P_i's are so chosen such that $m_1(p_i) = 0\ \forall\ i$, t_i and the bit b_i are computed as follows:

$$t_i = \langle P_i,\ I_w\rangle \tag{5}$$

$$b_i = \operatorname{sgn}(t_i) = \operatorname{sgn}\left(\left\langle P_i, \left[I + \alpha \cdot \sum_{j=1}^{N} b_j \cdot P_j\right]\right\rangle(0)\right) \tag{6}$$

3. Criteria for robustness improvement

3.1. Properties of code patterns and their design

Eq. (6) which results from Eq. (4) and improvement in detection reliability show that the codes should satisfy the following properties (Mayer et al., 2002):

1. P_i, $i = 1,2,\ldots,N$, should be distinct sequences with zero average.
2. The spatial correlations $\langle P_i, P_j\rangle$, for $j \neq i$ should be minimum. Ideally, sequences P_i and P_j should be orthogonal whenever $j \neq i$.
3. If image prediction (for estimating the image distortion) is not used before evaluating the cross-correlation it is desirable that P_i's (for $i = 1,2,\ldots N$) should be uncorrelated with the image block I.
4. Spatial correlation $\alpha \cdot \langle P_i, b_i \cdot P_i\rangle$ should be maximized although detection reliability and image distortion must be properly trade-off.

The frequently used code patterns P_i for SS watermarking are of the form of *pseudorandom noise* (PN) sequences. PN sequences can be defined as the coded sequences of 0's and 1's with some randomness properties and is generated using standard Math Library function. PN seuqences satisfy properties (1) and (2) if only infinite length sequence is considered which is not feasible for practical image processing operations. Mayer et al. (2002) showed robustness improvement in SS watermarking for a small size image block in two cases; spreading codes are generated from (i) Hadamard basis and (ii) by Gram–Schmidt orthogonalization of pseudorandom sequences. But under this circumstance the following problems may arise: (1) unauthorized decoding and possible removal of the embedded data due to the deterministic nature of Hadamard basis; (2) better spectrum spreading is not possible due to small size image block. In the present work, to solve this problem the code patterns are modulated using Hadamard basis function (Gonzalez and Woods, 2002). Each PN code is exclusive-ORed with a row of Hadamard matrix of proper dimension (Peterson et al., 1995).

3.2. Selection of signal decomposition tool for data hiding

The conventional DWT (two-band system) decomposes an image signal into LL, LH, HL and HH subbands while MbDWT system decomposes the same into $(M \times M)$

channels, corresponding to different directions and resolutions (Burrus et al., 1997; Kundu and Acharya, 2003). In the context of SS watermarking, we propose to embed data in wavelet coefficients of LL and HH subbands (for two-band system) (Maity and Kundu, 2004a) and in group of channels with low and high variance (for MbDWT) values. Watermark embedding in these subbands/channels causes better spectrum spreading since the stated subbands/channels, in both the cases, jointly provide wide range of frequency components of the cover image. To further justify the selection of data embedding regions, on the basis of better spectrum spreading, we calculate the cross correlation (C) and covariance ($\sigma_{X_n X_m}$) values among different subbands. It is found that the values of correlation (C) and covariance ($\sigma_{X_n X_m}$) for LL and HH subbands are always smaller compared to those for all other combinations of the subbands. Similarly, in multiband wavelet system with $M(=4)$, the variance of subbands coefficients are studied for large number of natural images. It is found that the values for some of the subbands, for example H_{12}, H_{13}, H_{14} and H_{24} are clustered around some lower end values while the variance for the other subbands (H_{41}, H_{42}, H_{43} and H_{31}) are clustered around the some higher end values. We denote these two types of subbands collectively as channel **A** and all other remaining subbands as channel **B**.

3.3. Signal adaptive SS scheme

The main idea behind the improvement in detection reliability of SS watermarking scheme is to exploit the knowledge about the cover signal X for modulating the energy of the inserted watermark so that signal interference can be compensated (Malvar and Florencio, 2003). We develop two signal adaptive SS schemes using linear and power law modulation function and compare the results with the conventional SS scheme (Maity et al., 2004b). Different forms of the watermarked images are as follows:

$$X' = X + k \cdot [P_i] \tag{7}$$

$$X' = X + k_1 \cdot X \cdot [P_i] \tag{8}$$

$$X' = X + X^{\mu}[P_i] \tag{9}$$

In all the above equations X' represent watermarked image coefficients, X are image coefficients, $[P_i]$ is the two dimensional code pattern with size equal to the image block, k, k_1 and μ are the modulation indices.

Detection reliability is determined by the stability of the decision variable t_i with respect to a given attack distortion. The expression of t_i, for a particular P_i, can be rewritten as

$$t_i = \langle X',\ P_i\rangle = 1/Z\langle X'_l,\ P_{il}\rangle \tag{10}$$

where l corresponds to the positional index in the sequence with values that vary from **1** to **Z**. If we substitute the values of X' from the Eqs. (7)–(9) into the Eq. (10), differentiate t_i's w.r.t X_l, and then put the condition of equal number of 0's and 1's for the code pattern, we have the expressions for $\mathrm{d}t_i/\mathrm{d}X_l$ respectively as follows:

$$\mathrm{d}t_i/\mathrm{d}X_l = 1/Z\sum_{l=1}^{Z} P_{il} = 1/Z(0.Z/2 + 1.Z/2) = 1/2 \tag{11}$$

$$\mathrm{d}t_{i1}/\mathrm{d}X_l = (1 + k_1)/2 = (1 - k_2)/2 < \mathrm{d}t_i/\mathrm{d}X_l \tag{12}$$

$$\mathrm{d}t_{i2}/\mathrm{d}X_l = 1/2 + \mu/Z\sum_{l=1}^{Z} X_l^{\mu-1} \cdot P_{il}^2 \tag{13}$$

In Eq. (12), we have defined $k_1 = X_l(\min)/X_l(\max)$ which is a negative quantity and let $k_1 = -k_2$ where $0 < k_2 < 1$. Lower value of $\mathrm{d}t_i/\mathrm{d}X_l$ indicates better detection reliability against signal degradation.

4. Capacity improvement in SS watermarking

4.1. Biorthogonal decomposition

Data embedding rate can be increased if the cover image is decomposed in different directions using BiDWT. Different watermark information are hidden in the specified subbands of these decompositions. Design of wavelet basis for such type of signal decomposition may be a topic of interest. However, particular decompositions for which property (3) of the code pattern can be satisfied are chosen for embedding. Biorthogonal wavelet decomposition, possibly due to the complementary information of the two wavelet systems, satisfies the property in a better way compared to the classic dyadic wavelet transform. The specified channels of particular decompositions that yield low correlation with the code patterns are embedded first and lower values of α are chosen for embedding in these decompositions. Higher α values are used for other biorthogonal decompositions and are embedded latter.

4.2. M-ary modulation

Embedding rate can also be increased using M-ary scheme. In binary modulation each bit is treated as a symbol and for a fixed length binary message more number of spreading code patterns are used. On the other hand, a group of symbols are treated as single entity in M-ary modulation and if embedding distortion is held to a constant value more information bit can be embedded. In other words, if embedding rate and distortion are kept fixed higher robustness can be achieved using M-ary modulation. The lower modulation indices are chosen for the initially embedded bits.

4.3. Successive interference cancelation

Successive interference cancelation (SIC) in SS watermarking is a multibit detection technique where a bit's decision statistics is obtained by subtracting an estimate of the already detected bits from the received signal (Verdu, 1998). SIC reduces the effect of multibit interference (MBI) and the decision statistics t_i of Eq. (6), after applying SIC, can be written as follows:

$$\tilde{b}_{i,\mathrm{SIC}} = \mathrm{sgn}(t_i) = \mathrm{sgn}\left(\left\langle P_i, \left[I + \alpha\cdot\sum_{j=1}^{N} b_j\cdot P_j - \alpha\cdot\sum_{j=i+1}^{N}\tilde{b}_j\cdot P_j\right]\right\rangle(0)\right) \tag{14}$$

where $\tilde{b}_i$ is the estimate of b_i. If the estimation is worthy, better detection is possible even for the smaller value of α. This is quite clear from the Eq. (14) as the cross-correlation values $\langle P_i \cdot P_j\rangle$, for $j = i+1$ to N, are removed when calculating the decision statistics t_i. The smaller α values allows more information hiding for a given embedding distortion.

5. Proposed watermarking scheme

Watermark information is embedded according to the Eqs. (7)–(9) in the coefficients of LL and HH subbands of different decompositions (for DWT and BiDWT) and channels H_{12}, H_{13}, H_{14}, H_{24} and H_{41}, H_{42}, H_{43}, H_{31} of MbDWT decomposition of the cover image. In two-band system, to increase embedding rate the cover image is decomposed in different directions using biorthogonal wavelets and for the same purpose M-ary modulation scheme is used in M-band wavelet system. M-ary scheme can also be used for two-band systems but desired robustness can be achieved at relatively higher 'M' values compared to M-band system. The higher M-values increase computation time for decoding to a great extent so that they become sometimes unsuitable for digital watermarking application. For embedding each watermark symbol bit, PN matrix of size identical to the size of LL subband coefficient matrix (the combined size of H_{12}, H_{13}, H_{14}, H_{24} or H_{41}, H_{42}, H_{43}, H_{31}) is generated and modulated by Hadamard matrix. This modulated code pattern pn_a is used to embed data in the LL subband (subbands H_{12}, H_{13}, H_{14}, H_{24} for M-band decomposition). An orthogonal code pattern pn_d is obtained by complementing the bits of pn_a, and is used for data embedding in HH subband (H_{41}, H_{42}, H_{43}, H_{31} for M-band decomposition).

To decode message bit for binary signaling, two correlation values, one (from LL for DWT /BiDWT and specified subbands for MbDWT) and the other (from HH for DWT/BiDWT and specified subbands for MbDWT) are calculated. Total M_w^2 (equal to the number of watermark bits) number mean correlation values (μ_i) are obtained where $i = 1, 2, \ldots M_w^2$. From these mean correlation values, we calculate an overall mean correlation value (T) that is used as the threshold for watermark decoding. The decision rule for the decoded watermark bit is as follows:

if (i) $\mu_i \geqslant T$, the extracted bit is '0' and
if (ii) $\mu_i < T$, the extracted bit is '1'.

In M-ary signaling, decoding of a symbol at a particular position requires projection of the embedded channels onto the modulation function of that particular position for all the sets of the code patterns. The particular set of code patterns for which the respective modulation function yields the largest correlation value determines the symbol for that position.

The quality of the binary watermark is represented by probability of error and mutual information $I(W;W')$. The latter objective function is defined as follows. Let random variables W and W' represent respectively the original watermark and its decoded version. If $p(w_i)$ represents the probability of occurrence of the ith pixel value in watermark message and $p(w'_j/w_i)$ represents the channel transmission matrix, $I(W;W')$ that represents the average amount of information received from the signal degradation, is expressed as follows (Lathi, 1999):

$$I(W;W') = \sum_i \sum_j p(w_i)p(w'_j/w_i)\log\frac{p(w'_j/w_i)}{\sum_i p(w_i)p(w'_j/w_i)} \tag{15}$$

where $i, j = 0,1$. Higher the value of $I(W;W')$, better is the decoding reliability.

6. Performance evaluation

We study the effect of above factors on robustness-capacity improvement over large number of benchmark images (http://www.cl.cam.ac.uk/fapp2/watermarking). Table 1 shows improvement in properties (1) and (2) of the spreading codes using Hadamard basis. We use Peak Signal to Noise Ratio (PSNR) and mean Structural SIMilarity index (MSSIM) (Wang et al., 2004) as representative objective measures of data imperceptibility where as relative entropy distance (Kulback Leibler distance) (Cachin, 1998) as security measure. Table 2 shows the effect of modulation index values on embedding distortion measure. The numerical values in Table 2 which represent MSSIM and PSNR are computed by averaging over all the test images. Higher the value of MSSIM, better is the imperceptibility of the

Table 1
Improvement in property (1) and (2) of code pattern with size (128 × 128)

Code (PN$_i$) size (128 × 128)	No. of 0s before modulation	No. of 1s before modulation	No. of 0s after modulation	No. of 1s after modulation	Av. corr. before modulation	Av. corr. after modulation
PN1	4130	12254	8170	8214	0.0081	0.0021
PN2	4147	12237	8189	8195	0.0077	0.002
PN3	4167	12217	8216	8168	0.0065	0.0012
PN4	4170	12214	8173	8211	0.0069	0.0014
PN5	4125	12259	8190	8194	0.0074	0.0016

Table 2
Effect of modulation index on PSNR (in dB) and structural similarity measure

α-value of low-var. M-band/LL	α-value of high-var. M-band/HH	MSSIM/ PSNR averaged over all test images (M-band)	MSSIM/PSNR averaged over all test images (DWT)	MSSIM/PSNR averaged over all test images (Biorthogonal)
0.3	0.3	(∼0.988)/40.04	(∼0.971)/37.24	(∼0.982)/38.74
0.3	0.7	(∼0.9459)/37.54	(∼0.925)/36.24	(∼0.934)/36.87
0.7	0.3	(∼0.976)/39.65	(∼0.964)/37.48	(∼0.970)/38.42
0.7	0.7	(∼0.934)/37.12	(∼0.916)/36.09	(∼0.921)/36.35

hidden data. It is to be noted that MSSIM index does not quantify the visual quality of an watermarked image rather it indicates the relative change in structural information of a watermarked image with respect to the cover image. MSSIM index can obtain the maximum value of **1** that indicates no change in structure between the observed and the reference image. The security values for the hidden data have been found (∼0.01786) and (∼0.01444) for DWT and MbDWT domain embedding respectively when averaged over all the test images. Impact of various factors on robustness improvement have been studied by simulating several non malicious as well as deliberate degradations in the watermarked images. However, due to space limitation, only JPEG 2000 compression results are reported.

Fig. 1(a) and (b) show graphically the improvement in detection reliability against JPEG 2000 compression for M-band embedding due to Hadamard basis and the choice of proper subbands respectively. The role of using different modulation functions in robustness improvement is shown graphically (Fig. 2(a)) against JPEG 2000 operation. It is also found that with the increase of depth of noise addition linear modulation function shows better detection

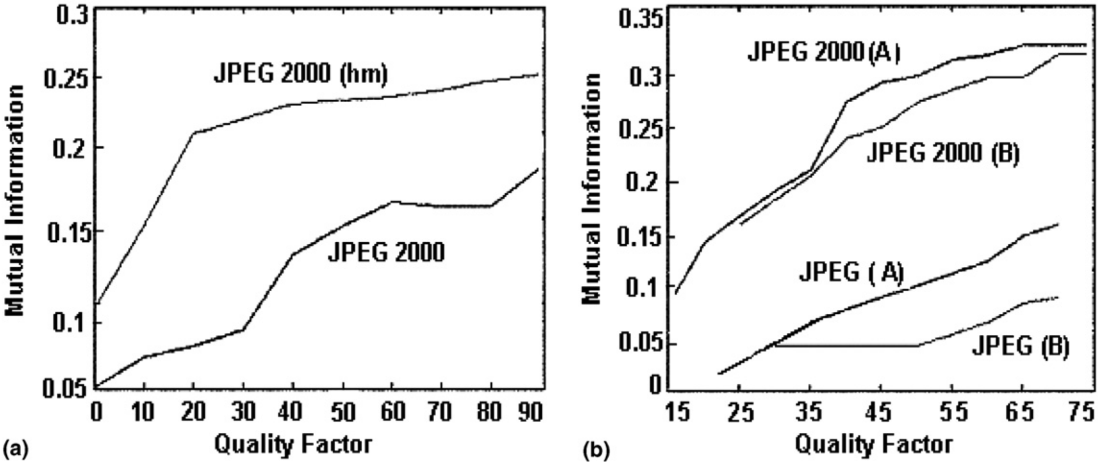

Fig. 1. (a) Effect of the use of Hadamard basis, where hm indicates modulation by Hadamard basis and (b) effect of channel selection on detection reliability, where **A** indicates the set of subbands as mentioned in text and **B** indicates other set of subbands.

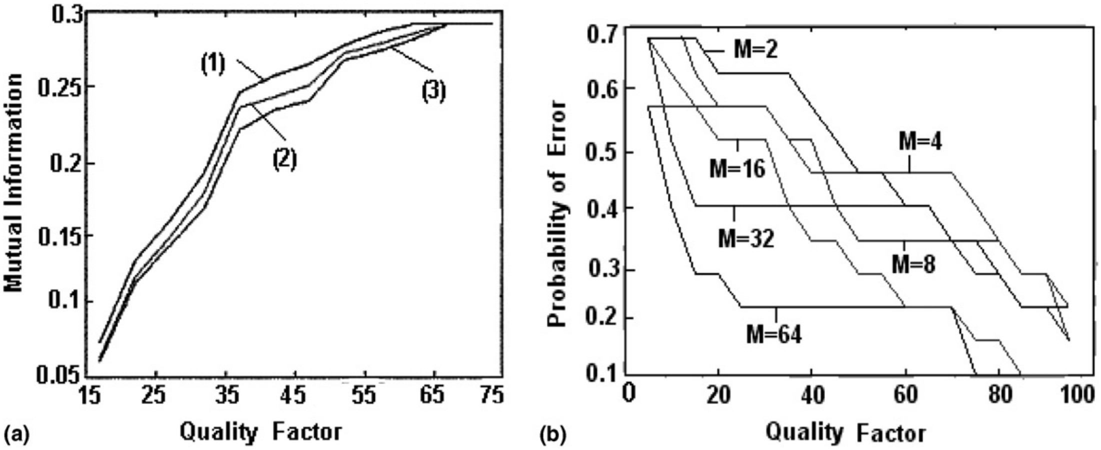

Fig. 2. (a) Effect of modulation functions on detection reliability: lines (1), (2) and (3) denote the power–law, linear and conventional SS scheme, respectively and (b) effect of M values on detection reliability in M-ary signaling scheme.

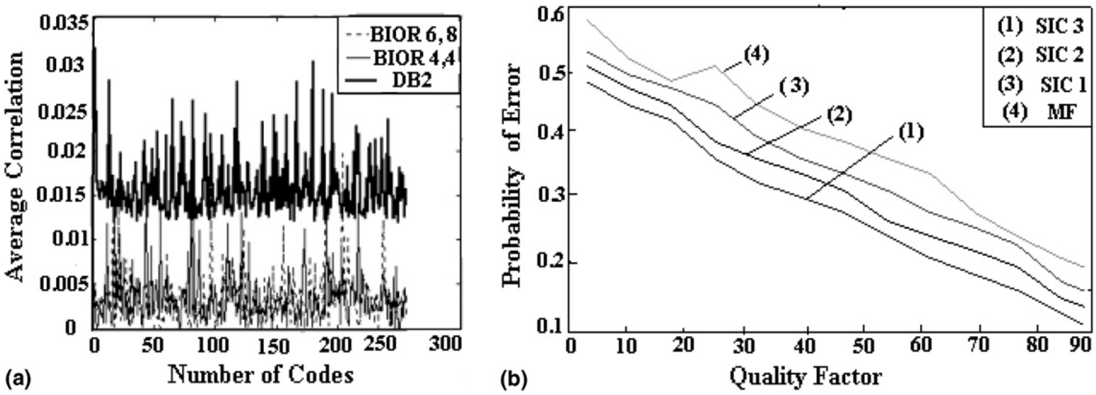

Fig. 3. (a) Correlation between the code pattern and image decomposition using a few selected wavelets and (b) effect of SIC on detection reliability: MF, SIC1, SIC2, SIC3 indicate performance without and after the removal of one, two and three embedded watermarks respectively.

compared to traditional SS watermarking scheme. This is quite clear from the Eqs. (11) and (12) where for a given attack distortion the change in decision variable t_i in the case of linear modulation function is less compared to the conventional modulation function. Under the same circumstance a better detection is achieved if power–law function is used instead of linear modulation function. This is due to the fact that with the decrease in numerical value of μ, the variance of the subbands coefficients used for embedding is increased. The increased variance value is the reason of low correlation between the image blocks and code patterns (Eq. (13)). Low correlation value reduces the value of $\mathrm{d}t_i/\mathrm{d}X$ for a given attack distortion. Fig. 2(b) shows the effect of M-value in M-ary modulation for robustness improvement against JPEG 2000. However, higher M-values increase the computation cost of decoding. Correlation between the code patterns and the image block have been studied for large number of filters and it is shown in Fig. 3(a) that the biorthogonal wavelet decompositions provide a better performance to satisfy property (3) of the code pattern. Moreover, it is found from the study over large number of natural images that the energy of HH subband is higher for BiDWT compared to the same for DWT and is the reason of better robustness in the former compared to the latter. Fig. 3(b) shows the effect of SIC for robustness–capacity improvement in SS watermarking using BiDWT. The graphical results show the detection performance of the first embedded watermark without (indicated by MF) and after successively removing the three other embedded watermarks. Improvement can be explained from Eqs. (6) and (14).

7. Conclusions

In this paper, we have critically analyzed few factors that have significant impact on detection reliability in SS watermarking. It is found that data embedding in LL and HH subbands (DWT) and in the channels (H_{12}, H_{13}, H_{14}, H_{24} or H_{41}, H_{42}, H_{43}, H_{31}) (MbDWT) offer higher resiliency against various types of image distortions. Detection reliability is improved by increasing orthogonality among the code patterns using Hadamard basis functions. The use of linear and power-law modulation functions further improve detection reliability. Embedding capacity is increased by hiding data using biorthogonal decompositions and using M-ary modulation. M-ary modulation significantly improves the robustness performance of SS watermarking scheme for higher values of M but at an increased computation cost for decoding. SIC improves robustness-capacity significantly compared to matched filter detection.

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