Spread Spectrum based *M*-ary Modulated Robust Image Watermarking

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Summary

Spread Spectrum (SS) modulation principle has been widely used in digital watermarking due to its distinguishing characteristics viz. excellent security and robustness in performance. The use of wide spectrum of the host signal in message hiding process puts a limit on the data rate subject to a given embedding distortion. In SS communication the use of *M*–ary modulation is a popular extension to binary antipodal signaling usually resulting in a significant performance improvement. Moreover, with the increasing *M* and for certain schemes, *M*–ary modulation works at the channel capacity. The present work investigates on how to use *M*–ary modulation in the context of transform domain SS watermarking for performance improvement over binary signaling schemes. Furthermore, relevant computational complexity issue of *M*–ary watermarking is also reduced to a greater extent by the implementation of *M*–ary phase modulation. The present work also suggests data embedding in selected sub bands (DWT) or channels (*M*–band) of wavelet transform decomposition. Performance improvement of *M*–ary signaling principle in SS scheme with respect to error rate, complexity and superiority of wavelet domain embedding approach are supported by experimental results against lossy compressions.

Key words:

Spread Spectrum Watermarking, M–ary modulation, Discrete Wavelet Transform.

1. Introduction

Digital watermarking, the art of hiding information in multimedia data, can be considered as communication scheme where an auxiliary message is embedded in digital multimedia signals and are available wherever latter signals move. The decoded message latter on serves the purpose of copyright protection, content authentication, broadcast monitoring, and security in communication etc. Robustness, imperceptibility, payload, computational cost, complexity and oblivious extraction are essential criteria in digital watermarking schemes needed for data hiding and recovery process. But all these requirements are related in conflicting manner and the particular application based algorithm emphasizes on one or more such requirements to a greater extent [1].

The SS modulation technique in digital communication offers anti-jamming and interference rejection property. These had motivated the several researchers for developing SS watermarking algorithms for multimedia signals either in spatial domain or in transform domain by using Discrete Cosine Transform (DCT), Fourier-Mellin, Discrete Hilbert Transform (DHT), and wavelet decomposition [2-5]. SS watermarking schemes, although can be implemented in various different way, the method that uses distinct pseudo noise (PN) spreading codes for embedding each binary digit is popular and proven to be efficient, robust and cryptographically secured. At this point the use of various channel coding schemes and *M*–ary modulation techniques can be found efficient for robustness improvement as they are widely used in digital communication for improving data transmission reliability.

In the applications of digital image watermarking the concept of channel coding scheme becomes inefficient due to difficulty in finding the appropriate code lengths. The problem arises because of the variable nature of channel distortion that depends on host data size, content and the nature of deliberate attacks applied to the stego data. For a given length of binary message and fixed embedding distortion, *M*–ary signaling schemes offer higher resiliency over binary modulation scheme since less number of modulation functions will be required in the latter case that gives rise to the scope of choosing higher modulation index values. *M*–ary principle of certain modulation schemes improve detection performance also by increasing the number of transmitted symbols.

In the channel coding and *M*–ary modulation, computational cost and complexity is much higher over the binary signaling scheme. Nevertheless, this complexity can be greatly reduced in case of *M*–ary modulation without affecting the performance. This complexity lies in the message decoding and PN sequence generation. By circular shifting and phase modulation, PN sequence generation can be made quite simpler and number of correlator detectors can be significantly reduced.

The paper is organized as follows: Section 2 introduces proposed *M*-ary modulation and demodulation in SS watermarking. Watermarking architecture is given in Section 3. Section 4 shows the implementation results of 16 X 16 binary watermark and finally section 5 concludes and remarks about the important findings of the present work.

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2. *M*-ary Modulation and Demodulation in SS Watermarking

2.1 Embedding

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

$$B = \{b_1, b_2, \dots, b_n\}, \qquad b_i \in \{1,0\}$$

To project the host signal or cover image I into watermarking space ξ the image transformation χ is applied to the image *i.e.*

$\chi : (I_L) \rightarrow [C_L]$ where C is the projected image and L, L' are length of vector I and C respectively.

For binary signaling, optimal modulation functions are antipodal signal pairs. For embedding of N bit watermark, a set PN_k of N two dimensional orthogonal sequence PN_i, $i = \{1,2,\dots,N\}$ is used where k defines the secret key used as initializing seed to generate the set. These sequences/ code patterns can be considered as uniformly distributed random sets of independent random variables having a zero mean, unit variance bi-level distribution. Hence, in order not to introduce inter symbol interference (ISI).

$PN_i = \{(x,y), \forall\ PN_i\ (x,y) \neq 0\}$

PN_i , $PN_j = \phi\ \forall\ i \neq j$

The watermark W is defined as the superposition of all modulated and weighted PN sequence or code patterns PN_i:

$$[W_{L'}] = \sum_{i=1}^{N} (b_i')\ \alpha [PNi_{L'}], \tag{1}$$

where α is the weighting factor or modulation index and b' represents the bit value mapped from {0,1} to {-1,1}. The watermarked or stego image is now given by adding watermark W to image representation in embedding space ξ and applying inverse transformation:

$$[I_W]_L = \chi^{-1}\ ([C_{L'}] + [W_{L'}] \tag{2}$$

Optimal modulation index depends on the visual characteristics of the host image, watermark embedding space and the metric used to measure the distortion. Sophisticated modulation index functions increase watermark energy by maintaining visual distortion and hence results increase of overall performance of the system. Accordingly, SS watermarking schemes can be called as signal adaptive time SS watermarking.

2.2 Detection

The introduced watermarking scheme can be seen as a modulation system in which image acts as additive noise. Nevertheless, it is a common method in digital watermarking to use a linear correlator as detection statistics.

Let the watermarked/ stego image is projected into watermarking space by applying the image transform:

$$\chi : [\hat{I}_W]_L \rightarrow [\hat{C}_W] \tag{3}$$

Now the detection statistics or decision variable t_i is obtained by evaluating the zero lag cross-covariance function between the signal features of projected stego image and each PN sequence/ code pattern PN_i

$$t_i = \left\langle PN_i - m_1(PN_i), \hat{C}_W - m_1(\hat{C}_W) \right\rangle (0) \tag{4}$$

where $m_1(X)$ represents the average of the sequence X. If X_k represents the elements of X with $k = 1, 2, \dots, L'$

$m_1(X)$ can be mathematically expressed as follows:

$$m_1(s) = \frac{1}{L'} \sum_{k=1}^{L'} s_k \tag{5}$$

The symbol (0) in equation (4) indicates the zero lag cross-correlation and for two sequences S and R, the zero lag cross-correlation is given by

$$\langle S, R \rangle (0) = \frac{1}{L'} \sum_{k=1}^{L'} s_k r_k$$

where s_k and r_k are the elements of sequence S and R respectively with k=1, 2,...,L'. The bit b_i' is detected as -1 if $t_i > 0$ and as 1 otherwise. Therefore, the computation of t_i becomes

$$\begin{aligned}
&= \left\langle PN_j - m_1(PN_j), [C + W - m_1(C)] \right\rangle \\
&= \left\langle PN_j - m_1(PN_j), \left[C + \alpha . \sum_{i=1}^{N} b_i' PN_i\right] - m_1(C) \right\rangle \\
&= \left\langle PN_j - m_1(PN_j), C \right\rangle + \alpha . \sum_{i=1}^{N} b_i' \left\langle PN_i . PN_j \right\rangle \\
&- \left\langle PN_j, m_1(C) \right\rangle \\
&= \left\langle PN_j, \hat{C}_W \right\rangle
\end{aligned} \tag{6}$$

The above analysis indicates that code patterns used for spread spectrum watermarking should posses some specific properties. Watermark detection is improved if the following conditions are satisfied.

i) PN_i, i = 1, 2, . . . L' should be distinct sequences with zero average.

ii) The spatial correlation = $\langle PN_i, PN_j \rangle$ $i \neq j$ should be minimized. Ideally, sequences PN_i and PN_j should be orthogonal.

iii) Each PN_i for i = 1, 2, . . ., L' should be uncorrelated with image coefficient block C when image prediction (for estimating image distortion) is not used before evaluating the cross–correlation.

Since, code patterns are zero mean and non-overlapping orthogonal sequences, so above properties (i) and (ii) are satisfied.

3. Design of the Experiment

The proposed work considers a binary image of size (16 X 16) as watermark and (256 X 256), 8 bits/pixel gray image as host/ cover image. Now, the question is what features of cover signal is suitable for robust watermarking? There is probably no answer to this question as different features have different levels of robustness to certain attacks. Therefore, in order to show better robustness of *M*-ary modulation scheme data is embedded in wavelet transform domain as it provides important class of features for data hiding. Wavelet transform provides the co-joint representation of simultaneous space-frequency resolution of image signal. Wavelet coefficients are more efficient in representing perceptually important signal features and thus potentially more robust to distortion. Wavelet transform also attracts attention in various image processing applications including de-noising and upcoming compression standard JPEG-2000 due to its specific level of robustness. The host image can be modeled as approximately i.i.d., sequence with gaussian distribution by this wavelet transform. Here linear, additive modulation function is used for data embedding. Therefore, all watermark features are treated equally and spread over them evenly. Now, in order to accomplish better spectrum spreading data is embedded in *LL* and *HH* sub bands of DWT decomposition while the same is done into few selected channels with low and high variance value in *M*-Band WT decomposition domain. A single or a set of binary valued PN sequence equal to the size of sub band/ channel are generated and for each PN matrix, the orthogonal code is obtained by complementing the bits of PN code. If PN code is used for data embedding in *LL* sub band (H_{12}, H_{13}, H_{14}, H_{24} in *M*-Band), the orthogonal code $\left(\overline{PN}\right)$ is used for data embedding in *HH* sub band (H_{41}, H_{42}, H_{43}, H_{31}). The variance of different sub-bands and channels along with cross-correlation properties of PN sequences are depicted in fig.1-3.

3.1 Embedder Architecture

Case I: Message as combination of single/ several symbols

W bit long watermark of two symbols is mapped to total $N \geq 1$ number of symbols in the symbol message where each symbol is represented my *m* bits ($m \leq W$). Therefore, distinct symbol in symbol message is $M = 2^m$, formed by grouping log_2M bits of original message to one symbol. Each symbol is represented by a bi-level spread spectrum modulation function. Hence, *M* different sets of code pattern each having *N* numbers of bi-level modulation function are required for *M*-ary embedding in the watermarking space.

Case II: M-ary Phase Modulator

In *M*-ary modulation case I, a total (M X N) number of bi-level code patterns are required where $N \geq 1$ and $M = 2^m$, $m = 1,2,\ldots,L$, L is the length of watermark bit string.

Here a set of (M X N) reference patterns are formed from a single reference bi-level modulation function in the following way:

A reference pseudo noise sequence (PNs) PN_r is generated as an i.i.d., (independent & identically distributed) gaussian distributed sequence: $PN[i] \sim N(0,1)$, $i = 1,2, \ldots L'$, where L' is the length of the feature vector C or

$PN[i] \sim N(0,1)$, $i = 1,2, \ldots(M \text{ X } N)$, M distinct symbol, N total symbol.

Based on PN_r, a set of (M X N) PNs are generated to be circular shift versions of PN_r, satisfying

Case I: If $(M \text{ X } N) < L'$

$$PN[i] = \begin{cases} PN_r[i+m] & \text{if } i < L'-m; \\ PN_r[i+m-L'] & \text{otherwise} \end{cases} \quad (7)$$

$$m = 0,1,\ldots,(M \text{ X } N)-1; \qquad i = 1,2,\ldots,L'.$$

Case II: If $(M \text{ X } N) \geq L'$

$$PN[i] = \begin{cases} PN_r[i+m] & \text{if } i <(M \text{ X } N)-m \\ PN_r[i+m-(M \text{ X } N)] & \text{otherwise} \end{cases} \quad (8)$$

$$m = 0,1,\ldots,(M \text{ X } N)-1; \qquad i=1,2,\ldots,L'.$$

Since watermarked feature vector $\hat{C}_W$ and reference modulation function PN_r has different lengths, therefore zeros are appended to $\hat{C}_W$ so that it has the same length as PN_r:

$$\hat{C}_W[i] = \hat{C}_W[i] \quad \text{for } 1 \leq i \leq L$$
$$= 0 \quad \text{for } L+1 \leq i \leq (MXN) \quad (9)$$

3.2 Detector Structure

Case I: Linear Correlators (Matched filter)

To extract/ decode a symbol at one particular position, linear correlation between the test signal (embedded image block) and reference modulation function/ code pattern of that particular position for all the sets of keys are computed. With a maximum likelihood (ML) estimator, the embedded symbol is decoded as the index number of the reference code pattern, which has the maximum correlation with the test signal.

$$\hat{m} = \arg\max C(\hat{C}_W, PN_j) \quad (10)$$

j ε {0,1,…M-1} if $m = L$
$MN = M$ (*since* N=1)

$$\hat{m}_j = \arg\max C(\hat{C}_W, PN_j)_k \quad (11)$$

k ε {0,1,…M-1} if $m < L$
$MN > M$

Case II: Method of Elimination (based on tree structure)

To detect the embedded reference modulation function at one particular position, all the relevant code patterns are first divided into two groups.

$$\{PN_{j,0} \ldots PN_{j-1}\} = \{PN_{j,0} \ldots PN_{j,(\frac{N}{2}-1)}\} \cup \{PN_{j,\frac{N}{2}} \ldots PN_{j,N-1}\} \quad (12)$$

j ε {1,2,…,N}

Then the test signal $\hat{C}_W$ is correlated with the sum of all code patterns in each group:

$$C_1 = C(\hat{C}_W, \sum_{i=0}^{N/2-1} PN_i)$$

j ε {1,2,…,N}

$$C_2 = C(\hat{C}_W, \sum_{i=0}^{N-1} PN_i) \quad (13)$$

j ε {1,2,…,N}

If $C_1 > C_2$, the embedded pattern PN_m must be in the first group and otherwise in the second group. The group with PN_m is then divided into two ¼ size groups to decide the location of PN_m. This process continues until the exact position of PN_m is located; whose index number is the estimate of the embedded message.

Case III: With the circular versions of PNs as reference set, it is no longer need to compute (M X N) correlations between the watermarked feature vector $\hat{C}_W$ and (M X N) PNs desired from PN_r can be computed by a simple method as follows:

The linear correlation between $\hat{C}_W$ and PN_k is given by:

$$C[k] = \frac{1}{L''} \sum_{i=0}^{L''-1} \hat{C}_W[i]\, PN_k[i])$$
$$= \frac{1}{L''} \sum_{i=0}^{L''-1} \hat{C}_W[i]\, PN_k[i-k])$$

$k = 0, 1, \ldots, L''-1$

$L'' = L'$ (M X $N < L'$)
$= M$ X N (M X $N > L'$)

It's DFT

$$C[y] = \frac{1}{L''} \sum_{k=0}^{L''-1} \Big(\sum_{i=0}^{L''-1} [\hat{C}_W[i] \bullet PN_0[i-k])\, e^{-j\frac{2N}{L'}yk}$$
$$= \frac{1}{L''} \sum_{k=0}^{L''-1} \hat{C}_W[i] \sum_{i=0}^{L''-1} PN_0[i-k])\, e^{-j\frac{2N}{L'}yk}$$
$$= \frac{1}{L''} \sum_{i=0}^{L''-1} [\hat{C}_W[i] e^{-j\frac{2N}{L'}yi} \bullet \Big(\sum_{k=0}^{L''-1} PN_0[i-k])\, e^{-j\frac{2N}{L'}y[i-k]}$$
$$= \frac{1}{L''} F(\hat{C}_W) F^*(PN_0),$$

$y = 0, 1, \ldots, L''-1$

This becomes

$$c[k] = \frac{1}{L''} F^{-1}[F(\hat{C}_W) F^*(PN_0)], \quad (14)$$

$k = 0, 1, \ldots, L''-1$

where $F(.)$ and $F^{-1}(.)$ denote DFT and IDFT operations respectively.

Therefore, using equation (14), symbol decoding can be computed conveniently and efficiently. Here $c=(c[0], c[1],\ldots,c[L''-1])$, $c[i]$ is the correlation between $\hat{C}_W$ and PN_i with $c[0], c[1],\ldots, c[N-1]$ calculated according to equation (14), one can immediately estimate the embedded message through maximum likelihood estimation.

4. Results and Discussion

The Spread spectrum (SS) M-ary watermarking scheme is applied in wavelet transform domain (DWT & M-Band WT) over large number of benchmark images. It is quite clear that imperceptibility and robustness efficiency are improved with the increase of payload amount i.e. M value but at the same time computational cost and complexity regarding code pattern and decoding process are also increased. The reason for the latter point is that for data hiding we need two steps: (1) code pattern generation for embedding and (2) detection statistics computation by correlators. Both the steps incorporate significant computational complexity. That's why the embedding algorithm-case I at the condition $N > M$ provides relatively low computational complexity but at the cost of comparatively low robustness which is again better than binary antipodal signaling. The same algorithm is maximally improved in respect to robustness efficiency at the condition N=M with highest level of computational cost. This is because the number of code pattern increases with the decreasing number of embedding thereby increasing the number of correlators also. This problem of computational cost and complexity is relatively solved in the detection algorithm-case II: method of elimination type correlators but with relatively higher detection errors.

Therefore, it is a general expectation to evolve with *M*-ary method where robustness and computational complexity will be improved with increase in payload (i.e. *M* values). *M*-ary phase modulation satisfies our requirement towards code generation and detection to a greater extent. The robustness performance for any value of *M* in *M*-ary modulation is better for both DWT and *M*-Band WT decomposition than spatial domain *M*-ary SS watermarking. This is because code patterns are of gaussian nature (i.i.d.) but the host image distribution is not that type. But DWT and *M*-Band WT can approximate the host features to a gaussian one so that correlator detector can decode at optimally best. The result is reported against lossy compression operation. However, the result is also valid for other types of intentional and deliberate image impairment operations. In order to substantiate our claim for the present work numerical results are shown in fig. 4 -9 and in Table 1 & 2.

5. Conclusion

The paper critically analyzes the usage of *M*-ary modulation principle in SS watermarking scheme. It is found that *M*-ary modulation significantly improves the robustness performance of SS watermarking scheme for values of *M* larger than 4. The inherent computational cost and complexity issues with increasing value of *M* (e.g. *M* > 256) is also mitigated by the implementation of *M*-ary phase modulation SS watermarking and method of elimination type detection statistics.

M-ary modulation scheme is found to be more efficient compared to channel coding scheme because of non-availability of proper code length. This is because of the variable nature of channel distortion, which depends on the size, content and various types of operation applied on the watermarked data. It is also found that, the robustness performance of wavelet transform (DWT and *M*-Band WT) is better over spatial domain as wavelet transform models the host data towards gaussian i.i.d. (independent & identically distributed) nature. But wavelet coefficients are never gaussian distribution in a strict sense thereby correlator functions (matched filter) work at the sub optimally best level. During embedding, linear additive, non-adaptive modulation function is used. But the problem is that different host features have different capabilities in carrying a watermark due to their perceptual roles and magnitudes. Therefore these areas of SS watermarking need further improvement in the context of *M*-ary modulation.

References

[1] H. S. Malvar and D. A. F Florencio, "Improved Spread Spectrum: A new Modulation Technique for Robust Watermarking," *IEEE Trans on signal processing*, pp 898-905, April 2003.

[2] I. J. Cox, J. Killian, F. T. Leighton, T. Shamoon, "Secured Spread Spectrum Watermarking for Multimedia," *IEEE Trans on Image Processing*, vol. 6, pp 601-610, June 2000.

[3] R. Grobois, T. Ebrahim, "Watermarking in JPEG-2000 Domain," *Proc. of IEEE Workshop on Multimedia Signal Processing,* pp. 3-5, 2001.

[4] J. Mayer, A. V. Silverio, J. C. M. Bermudez, "On the Design of Pattern Sequences for Spread Spectrum Image Watermarking," *International Telecommunications Symposium,* Brazil.

[5] S. P. Maity, M. K. Kundu, T. S. Das, P. K. Nandi, "Robustness Improvement in Spread Spectrum Watermarking using M-ary Modulation," *Proc. of Nat. conf. on Communication*, pp. 569-573, Jan 2005.

[6] M. Kutter, "Performance Improvements of Spread Spectrum Based Image Watermarking Schemes Through *M*-ary Modulation," *Preliminary Proceedings of the Third International Information Hiding Information Hiding Workshop*, pp 245-260, Dresden, 1999.

[7] I. Daubechis, "Orthogonal bases for Compactly Supported Wavelets", *Comm., Pure Appl. Math*, Vol. 41, pp 909-996, 1988.

[8] M.K.Kundu and M.Acharya, "M-Band Wavelets: Application to Texture Segmentation for Real Life Image Analysis," *International journal of wavelets, Multiresolution and Information proceeding*, vol 1, pp115-149, 2003.

[9] C. S. Burrus, R. A. Gopinath, H. Guo, "Introduction to Wavelets and Wavelet Transform," *A Primer, Prentice Hall, NJ*, 1997.

[10] I. Selesniek, "Hilbert Transform Pairs of Wavelet Bases," *IEEE Signal Processing Letters* Vol. 8, No.6, 2001.

[11] C-S. Lu, S-K. Huang, C-J. Sze, H-Y. M. Liao, "Cocktail Watermarking for Digital Image Protection," *IEEE Transaction on Multimedia* Vol. 2, No. 4, 2000.

[12] D. V. Sarwate, M. B. Purseley, "Correlation Properties of Pseudorandom and Related Sequences," *Proceedings of IEEE* Vol. 68, No. 5, pp. 583-619, 1980.

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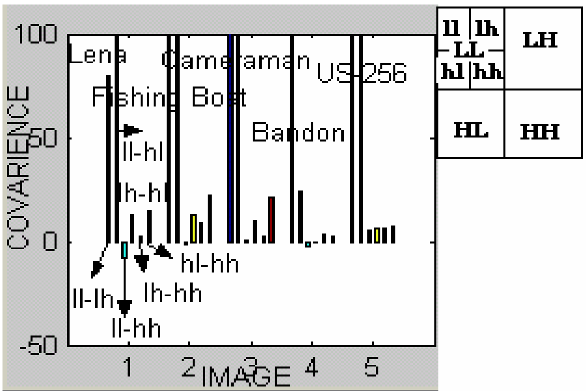

Fig. 1. Covariance of different sub-band combinations of DWT decompositions

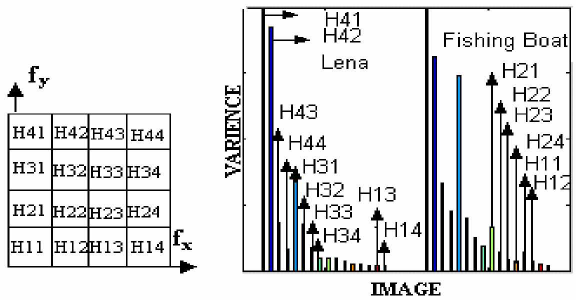

Fig. 2. Variance of different channels of M-band WT decomposition

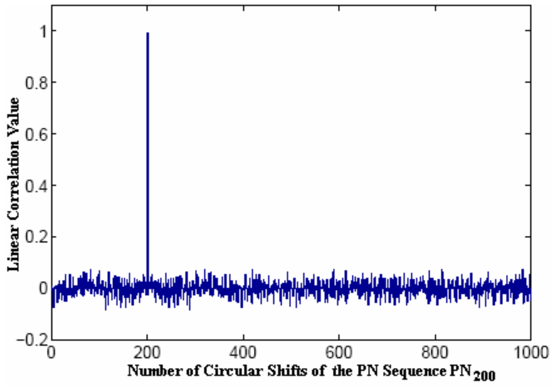

Fig. 3. Cross-correlation of Circular shifted PN sequences

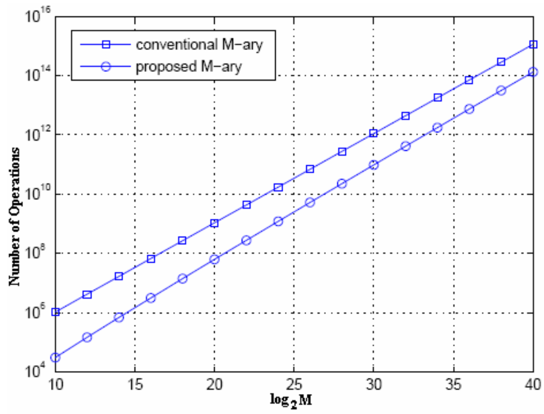

Fig. 4. Comparisons of Conventional & Proposed *M*-ary scheme

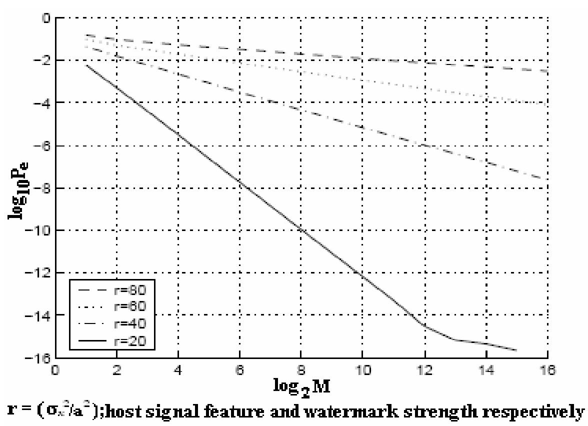

Fig. 5. Probability of Error Vs Symbol length (M)

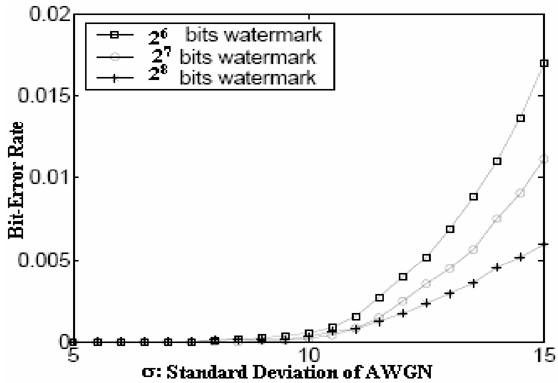

Fig. 6. Robustness against Additive White Gaussian noise (AWGN) with increasing symbol rate

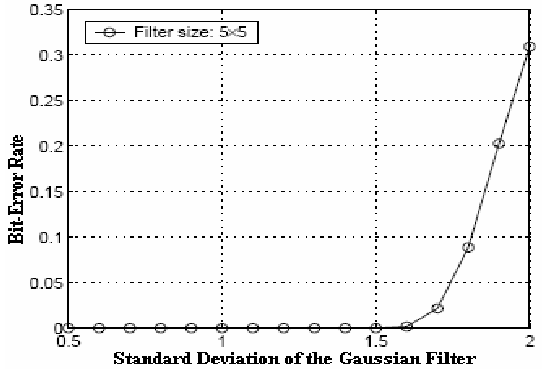

Fig. 7. Gaussian Filtering

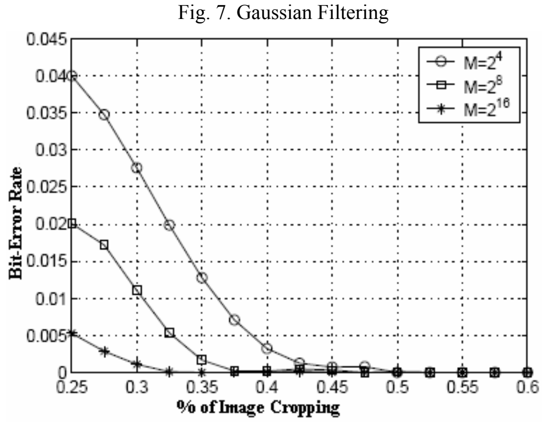

Fig. 8. Image Cropping with increasing symbol rate

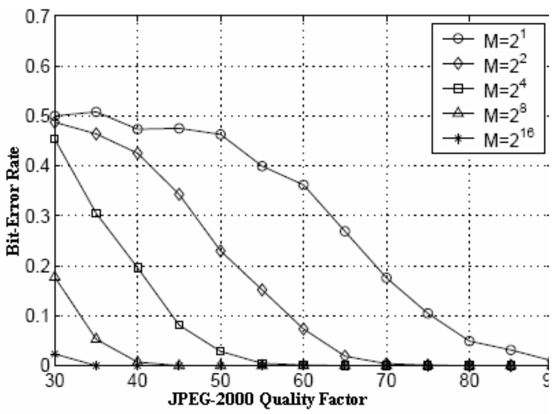

Fig. 9. JPEG-2000 with varying symbol rate

Table 1: Numerical Results of Robustness against different image impairments

Type of Attack	Parameter of Attack	Bit-Error Rate (BER)
White Gaussian Noise	σ = 5	0
	σ = 10	0
	σ = 15	0
Salt & Pepper Noise	D = 0.01	0
	D = 0.03	0
	D = 0.05	3.33×10^{-2}
Histogram Equalization	N/A	0
Median Filtering	f.size = 2 x 2	0
	f.size = 3 x 3	0
	f.size = 4 x 4	5.89×10^{-2}
Wiener Filtering	f.size = 2 x 2	0
	f.size = 3 x 3	0
	f.size = 4 x 4	7.19×10^{-4}
Sharpening	Moderate	0
	High	0

Table 2: Stirmark Test Results

Attack Type	Average BER
Remove 17 rows and 5 columns	0.0430
Remove 5 rows and 1 columns	0.0605
JPEG 15	0.0137
JPEG 20	0.0039
JPEG 25-90	0
Change aspect ratio x: 0.80 y: 1.00	0.0020
Change aspect ratio x: 0.90 y: 1.00	0
Change aspect ratio x: 1.00 y: 1.10	0.0137
Rotation -0.25	0.0215
Rotation -2.00	0
Rotation 10.00	0
Rotation 90.00	0
Scale 0.25	-1
Scale 0.50	0.0020
Scale 0.75	0
Scale 0.90	0
Scale 1.50	0
Scale 2.00	0
Sharpening 3x3	0.1328
Shearing x: 5.00 y: 0.00	-1
Stirmark random bend	-1