Partially Host-Adaptive Quantization Index Modulation Watermarking in a Baseband-Spread Transformation Domain

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Abstract

In order to reduce the impact of watermark embedding on the perceptual fidelity of the marked signal, watermarking systems process the generated watermark to match it to the local properties of the underlying host signal prior to embedding. However, this adaptation process could distort the watermark, affecting its robustness and information content. In this paper, a new watermark coding technique is proposed, that enables the application of some mark-nondistorting host-adaptation processing, where the intensity of the watermark could be redistributed according to the local properties of the underlying host without changing the way of interpreting the watermark to be embedded. This completely eliminates the need to equalize adaptation distortions prior to decoding, and hence, to pass any side information about the adaptation processing to the decoder, too.

تضم العلامة ا ائية ا كممة وا تكيفة جزئياً للمضيف باستخدام ويلة ا زمة الأساسية-الطيف ا نتشر

علي عصام يد
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ا لاصة

من أجل تقليل التأث الذي دثه تضم العلامة ا ائية على جودة الإشارة، تقوم أنظمة التضم عا ة العلامة ا ائية، من أجل ملاءمتها للخواص ا لية للإشارة ا ضيفة قبل تضمينها. إلا أن عملية التكييف هذه قد تشوه العلامة ا ائية ا ضمنة نفسها، ا يؤثر على متانتها. هذا البحث سيتم اقتراح تقنية جديدة لترميز العلامة ا ائية، تسمح بتطبيق آلية جديدة للتكييف، تاز بعدم تشويهها للعلامة ا ائية ا ضمنة. هذه الآلية تقوم بإعادة توزيع شدة العلامة ا ائية وفقاً للخصائص ا لية للإشارة ا ضيفة بدون تغي ترميز العلامة، ا يلغي ا اجة اولة معادلة تأث التكييف قبل فك ترميز العلامة ا ائية جهة الإستلام، وبالتا إلغاء ا اجة إ رير أي معلومات جانبية حول عملية التكييف إ ا ستلم.

1. Introduction

As digital multimedia get more widely used and also more easily manipulated, replicated and distributed, and with no loss of quality, their copyright protection issues become more challenging. So far, these challenges have been met by *encrypting* the intelligible multimedia contents to restrict unauthorized accesses. Encryption, however, fails to protect the copyrights of these contents as soon as they are decrypted. So, what is needed here is to permanently adhere some owner identifying information to these multimedia contents, that can be retrieved later to prove that these contents are properties of their corresponding creators [1], [2]. This implies, on one hand, that the embedded information should be *robust* enough to survive any intentional or unintentional manipulations that the released multimedia works may undergo, or at least any manipulations that may not render the underlying works commercially useless. On the other hand, embedding this information should not degrade the quality of the underlying works beyond the acceptable limits. Such a piece of information is well-known today as a *digital watermark*.

The idea of watermarking can be traced back into a patent granted at 1954 that has described a method to *imperceptibly* embed an identification code within the music for the purpose of proving ownership [3]. A number of the novice watermarking techniques for the different multimedia formats have been proposed since then. However, digital watermarking did not receive much attention from the academic research community until the beginnings of the 1990's, when it has been recognized as a distinct field of technology. Meanwhile, a better understanding of the subject theory started to develop as the watermarking problem began to be modeled as a communications channel, with the host signal and any distortions applied to the marked signal being treated as additive noise [3]. Later, a better model for the watermarking problem has emerged, that treats the host signal as *the state of the channel* that could be available as *side information* to the encoder and/or the decoder, or neither of them [2]-[6]. This viewpoint is important to understand the watermarking problem, since that the availability of side information, to the encoder and/or the decoder, has many implications on the host-interference rejection properties [4]-[6], and also on the *host-adaptation* capabilities of the different embedding methods.

Host-adaptation processing, defined as that pre-embedding processing, where the watermarking signal is locally adjusted according to the local properties of the underlying host signal [4], can functionally be partitioned into two steps: the *perceptual analysis* step responsible for analyzing the host and the watermarking signals to determine their local features to be used in the following *watermark local-adaptation* step, where the watermark components are accordingly adjusted in order to reduce their perceptibility. Such processing though, can severely *distort* the embedded watermark, making its interpretation, by the decoder, dependent on how much *resistance* that the employed coding technique can show to these distortions.

To lower the effect of this problem, pre-decoding *equalization* for the adaptation distortions is usually applied. This processing, however, imposes a severe limitation on the watermarking problem, that is the need for the availability of the local features of the host signal, used in the adaptation process, to the decoding side. This should immediately suggest that if sufficient side information about the local features of the host signal is available to the decoder, then adaptation distortions could be well equalized, given that the corresponding host-adaptation algorithm, applied by the encoder, is known to the decoder. A similar *private* marking scenario is proposed by Cox *et. al.* [1]. However, since that such information about the host signal is not, generally, available to the decoder, and also cannot be accurately enough approximated out of the received manipulated signal, *blind* host-adaptation scenarios have to be constrained to exploiting the *coarse* host perceptual details those are capable of preserving an adequate level of accuracy after the distortions applied by both the embedding process and the possible attack channels.

In any case, due to the interferences induced by the host signal and/or the attack channels, pre-decoding equalization processing cannot perfectly compensate the adaptation distortions induced into the embedded watermark, even under the private marking scenario. This motivated such trials to trade-off embedding capacity with the resistance to adaptation distortions, as that made by Solanki *et. al.* [7].

In the next section, we will discuss the proposed watermark coding technique that will be shown, in section 3, to enable the application of the partial host-adaptation processing. The structure of the proposed watermarking system is to be developed in section 4, followed by simulation results on image data in section 5. Concluding remarks will be provided in section 6.

2. Quantization index modulation in a baseband-spread transformation domain

In order that a *coded-quantization index modulated* (QIM) piece of information could be locally adapted to another signal, the way it is coded must show flexibility to the adjustments to be applied to the components of the code by the adaptation process. To achieve this, the rigid *direct sequence-based spread transformation* coding is proposed to be *segmented* into an equivalent number of the *repetitions* of some *smaller* spread transformation code. This would provide the required flexibility to *redistribution* adjustments through the *baseband channels* proposed by the *repetition coding* along the distinct dimensions of the code segments. The *integrate-and-dump* processing can then be applied along these baseband channels, in order to *compensate* the reduction in the *processing gain* resulting from lowering the spreading dimensionality.

To be more specific, let the proposed coding technique use an integer number, N/D, of repetitions of some low dimensional, a D-dimensional with $D << N$, spreading sequence segment T^D to code a message m. The aggregate N-dimensional baseband-spread transformation array $\mathbf{T}^N$ is constructed by tiling these N/D identical spreading sequence segments in a similar way to that shown in Fig. 1, where the D baseband channels resulting from repetition coding lay along the columns of the array. The transformation array $\mathbf{T}^N$ is used to *scalar-multiply* the host signal coefficients array $\mathbf{S}^N$ (whose structure is to be discussed in section 4.2) to calculate its *projection* (*inner product*) onto the transformation array's direction, as in Eq. (2.1). The resulting transformed host coefficient x, a *scalar*, is then quantized with the *scalar quantizer* $q(\; . \; ,m)$ to mark it with message m. However, to mark the host coefficients array $\mathbf{S}^N$, it has to be adjusted by the difference array $\mathbf{W}^N$ (also will be called the *watermarking array*), which represents the *error* induced into the host array $\mathbf{S}^N$ by quantizing its projection onto the direction of $\mathbf{T}^N$, see Eqs. (2.2) and (2.3).

$$x = \mathbf{T}^N \cdot \mathbf{S}^N \qquad (2.1)$$

$$\mathbf{W}^N = [q(x,m) - x]\,\mathbf{T}^N \qquad (2.2)$$

$$\mathbf{S}_m^N = \mathbf{S}^N + \mathbf{W}^N , \qquad (2.3)$$

where $\mathbf{S}_m^N$ is the marked coefficients array.

To decode the received coefficients array $\hat{\mathbf{S}}_m^N$, it is scalar-multiplied again by the transformation array $\mathbf{T}^N$ to make an estimate $\hat{x}$ of its projection onto the latter array. A *minimum-distance* decoding scheme can be applied to determine an estimate $\hat{m}$ of the embedded message

$$\hat{m} = \underset{i}{\operatorname{argmin}} \| \, q(\hat{x}, m_i) - \hat{x} \, \| .$$

Note here that the complexity of the proposed encoding/decoding schemes can be further reduced if the N/D rows of the host coefficients array $\mathbf{S}^N$ are first accumulated into one D-dimensional row vector that is then scalar-multiplied by the D-dimensional spreading sequence segment T^D to calculate the projection scalar x, see Eq. (2.4). The *accumulate-project* processing of Eq. (2.4) is equivalent to the projection processing of Eq. (2.1), given that all the elements on any *distinct* column of array $\mathbf{T}^D$ are identical (repetition coding).

$$x = \mathbf{T}^N \cdot \mathbf{S}^N = \sum_{j=1}^{D} \sum_{i=1}^{N/D} \mathbf{T}(i,j)\,\mathbf{S}(i,j)$$

$$x = \sum_{j=1}^{D} \sum_{i=1}^{N/D} T(j)\,\mathbf{S}(i,j)$$

$$x = \sum_{j=1}^{D} T(j) \sum_{i=1}^{N/D} \mathbf{S}(i,j) , \qquad (2.4)$$

where $T(j)$ in Eq. (2.4) is the *jth* element of the spreading sequence segment T^D. This accumulate-project processing reduces the

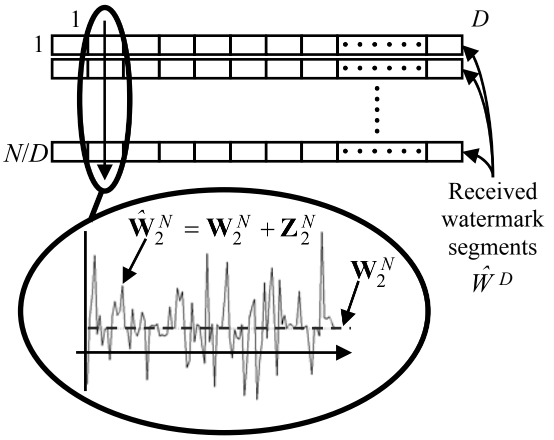

Fig. 1. Structure of the received watermarking array.

complexity of the encoding/decoding schemes by a factor of *N*/*D*, which is a considerable advantage over the spread transformation processing of [4]-[6].

At the receiving end, the marked coefficients array gets *noised* with the interference array $\mathbf{Z}^N$ induced by the attacking channels, where

$$\mathbf{Z}^N = \hat{\mathbf{S}}_m^N - \mathbf{S}_m^N = \hat{\mathbf{W}}^N - \mathbf{W}^N .$$

An important aspect here is that of making sure that the interference array $\mathbf{Z}^N$ inserted into the received watermarking array $\hat{\mathbf{W}}^N$ is such distributed over the *D* dimensions of the constituting watermark segments $\hat{W}^D$ (see Fig. 1), that the error signal inserted into each baseband channel is *white*, as depicted by the magnified signal graph in Fig. 1. This way, an average power advantage equal to the number of accumulated segments *N*/*D* can be granted to the watermarking signal, over the inserted error signals, by the integrate-and-dump processing. This power advantage would completely compensate the reduction in the processing gain resulting from lowering the dimensionality of the spreading sequence from *N* to *D*.

3. Partial host-adaptation

In order to keep the proposed adaptation processing as simple and efficient as possible, here we resort to the *elementwise-scaling-based* watermark adjustment scheme, where the adapted watermarking array $\mathbf{U}^N$, to be embedded, is the elementwise-product of the original watermarking array $\mathbf{W}^N$ by some scaling array $\boldsymbol{\alpha}^N$, whose constituting elements represent the adaptation adjustments necessary to increase the imperceptibility of the corresponding watermarking elements with respect to the underlying host components, as indicated by the employed perceptual analysis computation. That is:

$$\mathbf{U}(i,j) = \boldsymbol{\alpha}(i,j)\mathbf{W}(i,j), \qquad (3.1)$$
$$\text{for } i = 1 \ldots N/D,\ j = 1 \ldots D,$$

where *N*/*D* and *D* are the number of rows and columns of these arrays, respectively.

The proposed host-adaptation technique to be described in here is based on the watermark coding technique discussed in section 2, and is completely dependent on its new implementation of redundancy and on the way this redundancy is processed.

Referring to Fig. 1 of the general structure of the received watermarking array $\hat{\mathbf{W}}^N$, it may be noticed there that the way this array is interpreted depends on the *summations* of the elements lying along the columns of the array (along the baseband channels) rather than the values of the individual elements themselves. This means that the actual values of the elements constituting these columns may *deviate* from their original values without disturbing the decoder output, as long as their corresponding summations remain the same. The latter condition, however, suggests that the adjustments to be applied to the elements of the watermarking array should induce a *zero total deviation* into the signal at each individual baseband channel, or simply should keep the summation of deviations to be induced into the elements of each column of the watermarking array equal to zero, if the decoder interpretation of the corresponding watermarking array is to be preserved. Here, a simple mechanism will be devised, that is aimed at enforcing the compliance of any scaling array (which could be generated using any perceptual model) with the zero total deviation constraint above, in order to *equalize* the distortions to be induced into the adapted watermarking array, by the corresponding elementwise-scaling process, *prior to embedding* it within the host signal.

So, given some scaling array $\boldsymbol{\alpha}^N$ that can be represented by a similar structure to that is shown in Fig. 1, the elements of each column of array $\boldsymbol{\alpha}^N$ are to be *scaled* by the reciprocal of the mean value of the elements of the same column, to produce the *equalized scaling array* $\breve{\boldsymbol{\alpha}}^N$. The latter would, then, have the mean value of the elements over each of its constituting columns equal to one, or equivalently have the *summation* along each of them equal to *N*/*D*, the length of the columns of this array, which is a necessary and sufficient condition for it to comply with the zero total deviation condition, given the adjustment scheme in (3.1). That is

$$\sum_{i=1}^{N/D} \breve{\boldsymbol{\alpha}}(i,j) = \sum_{i=1}^{N/D} \frac{\boldsymbol{\alpha}(i,j)}{\overline{\alpha}_j} = \frac{N}{D}, \quad \text{for } j = 1 \ldots D,$$

where $\overline{\alpha}_j$ is the mean value of the elements of the *jth* column of the array $\boldsymbol{\alpha}^N$. This makes the sum of the elements along each column of the adapted watermarking array

$$\sum_{i=1}^{N/D} \mathbf{U}(i,j) = \sum_{i=1}^{N/D} \breve{\boldsymbol{\alpha}}(i,j) \cdot \mathbf{W}(i,j)$$

$$\sum_{i=1}^{N/D} \mathbf{U}(i,j) = w_j \cdot \sum_{i=1}^{N/D} \breve{\boldsymbol{\alpha}}(i,j) = w_j \cdot \frac{N}{D}, \quad \text{for } j = 1 \ldots D,$$

which is the same result that would have been achieved when summing the *N*/*D* repetitions of the corresponding elements w_j (the element of the *jth* column) constituting the original watermarking array columns.

It is important to note here that unlike the other adaptation techniques in watermarking literature, which generally aim at adjusting the components of the watermark to be embedded in order to *rescale* the distortion, induced by these components, according to the local properties of the host signal, the proposed partial adaptation technique adjusts the elements of the watermarking array columns in order to *redistribute* the total amount of distortion induced by these elements in such a way that *minimizes* the overall perceptual significance of this distortion with respect to the local properties of the underlying host signal. Here, the total watermarking signal intensity over the corresponding array columns is *conserved*. This can be described as the *blockwise-optimal robustness-conserving* solution to the host-adaptation problem.

The proposed adaptation technique has two important advantages. *First*, is that the host-adaptation process here does not induce any distortion into the embedded watermark, since that the adaptation distortions are now equalized prior to embedding. And *second*, is that the decoder does not need to know anything about the adaptation processing applied to the embedded watermark (nor if any adaptation process has been applied). This enables the encoder to select the perceptual adaptation processing that can achieve the highest perceptual fidelity *during* the marking process, without worrying about the ability of the decoder to equalize the resulting adaptation distortions while recovering the embedded watermark. This result cannot be achieved even with the private marking scenario, where it is necessary for the decoder, there, to know about the specific adaptation processing that has been applied to the embedded watermark in order to be able to equalize its effect.

4. Partially host-adaptive quantization index modulation watermarking system

4. 1. The spreading sequences generator

In order to reduce the chances of an attacker to make an estimate of the spreading sequence segment used to code a given watermark, a number of the *uncorrelated* sequences are proposed to be generated here, through:

1. seeding a pseudorandom generator with the secret key 1 to generate up to *D* sequences of length *D*, and
2. applying *Gramm-Schmidt* orthonormalization algorithm to *decorrelate* the generated sequences.

4. 2. The embedding system

As is shown in Fig. 2, the proposed watermark embedding system receives four inputs: the original host signal, the binary message sequence to be embedded, the set of orthonormal spreading sequence segments produced by the spreading sequences generator, and secret key 2 necessary for randomizing the host coefficients blocks.

The proposed embedding system proceeds as follows:

1. The embedding system starts by transforming the input host signal into the watermark embedding domain. To achieve high robustness, the watermark is proposed to be embedded within the mid-frequency coefficients of some standard *blockwise* transformation. Blocks of transformed host coefficients are then passed to the next stage of the embedding system.
2. The passed host coefficients blocks are then to be *randomly grouped* together to form the host coefficients arrays, corresponding to the rooms where watermarking arrays are to be embedded. This randomization process, which is controlled through the secret key 2, is actually important to distribute the *locally-stationary* statistics of the host signal over the different arrays. However, in order to make these arrays compliant with the assumption made about the whiteness of the interference signals to be inserted into the baseband channels, which is necessary to optimize the performance of integrate-and-dump receivers, it is proposed here

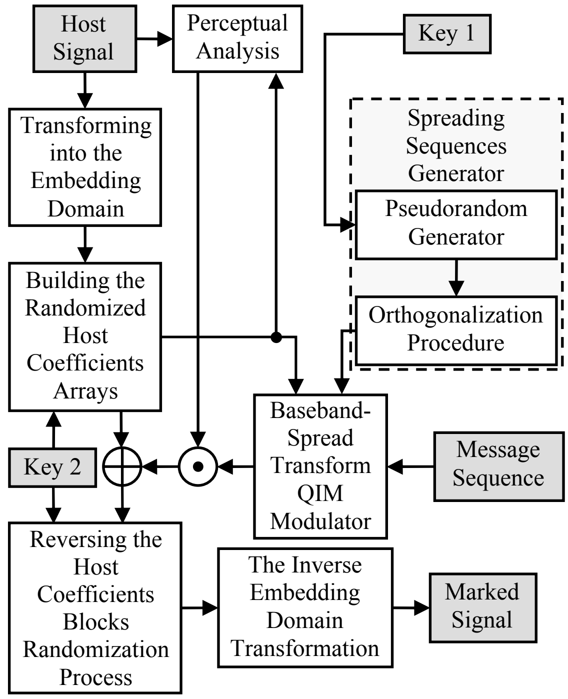

Fig. 2. The structure of the proposed watermark embedding system.

that only the coefficients with the *same frequency indexes* should be *aligned* into the same baseband channels, so to get *symmetrical distributions* for the coefficients under accumulation.

3. The baseband-spread transformation QIM modulator, then, sequentially codes the bits of the input data sequence. Here, to code a message bit, the modulator starts by selecting a spreading sequence segment from the set of available orthonormal sequences (using a selection rule with a uniform distribution over all the sequences) to build the baseband-spread transformation array, described in section 2. The modulator then projects the host coefficients array onto the direction of the transformation array. The transformed host coefficient is then quantized with the appropriate scalar quantizer to code the message bit. The watermarking array is then produced by scaling the transformation array by the quantization error.
4. The generated watermarking arrays are then to be adapted to the local properties of the host signal. This perceptual host-adaptation process is

carried out in two separate steps: the perceptual analysis step responsible for calculating the adjustments those need to be applied to the elements of the watermarking arrays in order to increase their imperceptibility with respect to the underlying host signal components, and the elementwise-scaling step, denoted by the dot block in Fig. 2, where the scaling arrays received from the analysis step, are first equalized and then used to accordingly adjust the corresponding elements of the watermarking arrays (see section 3).

5. The adapted watermarking arrays are then embedded into the host signal by *adding* them to the corresponding host coefficients arrays.
6. At the final stage of the embedding system, the marked host coefficients arrays are decomposed back into their constituting coefficients blocks. The randomization process performed on the host coefficients blocks at the beginning of the embedding process is then reversed to reassemble the embedding domain-expressed marked signal, while the final marked signal is generated after applying the inverse of the blockwise transformation applied in the first stage.

4. 3. The decoding system

As is shown in Fig. 3, the proposed decoding system receives three inputs, these are: the received marked (and possibly manipulated) signal, the set of orthonormal spreading sequence segments, and the secret key 2.

Here, the decoding system consists of three main stages, the first two of which have been described in the context of the watermark embedding system, while the third, the baseband-spread transformation QIM demodulation stage, is the one responsible for decoding the extracted watermark for an estimate of the coded message.

After transforming the received signal into randomized coefficients arrays, the demodulator *sequentially* processes these arrays for an estimate of the embedded bit sequence. Initially, the arrays are projected onto the corresponding baseband-spread transformation arrays. The resulting projection scalars are then fed into a minimum distance decoder to find estimates of the embedded message bits. Note that a *synchronized* decoder can always select the correct sequence, from the set of available spreading sequence segments, to decode an embedded watermark.

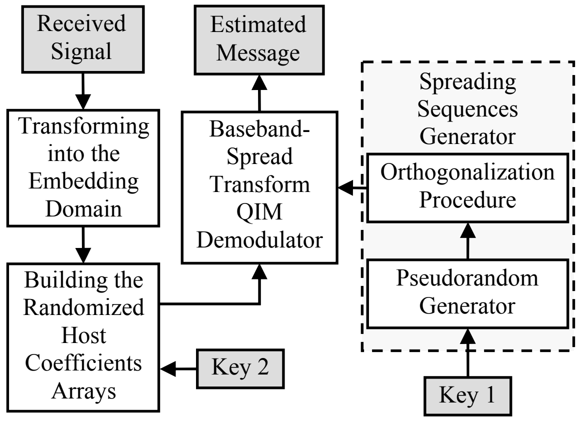

Fig. 3. The structure of the proposed watermark decoding system.

5. Simulation results

In this section we project the general model developed in section 4 onto the field of *image watermarking*, on which most of the watermarking literature focuses, in order to be able to practically evaluate the performance of the proposed partially host-adaptive baseband-spread transformation QIM watermarking system and compare it with the nonadaptive spread transformation QIM system. However, before we proceed to evaluate our system, we should adopt some implementation-specific details those are to be used in the image watermarking simulations:

- To achieve high robustness here, the watermarking signal is chosen to be embedded within the mid-frequency 2-dimentional discrete cosine transformation (2D-DCT) coefficients of the 8×8 nonoverlapping blocks of the image luminance component, see Fig. 4. In order to drive the proposed coding

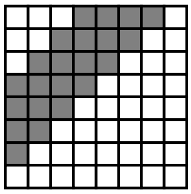

Fig. 4. 2D-DCT coefficients chosen for embedding.

technique to its furthest extreme away from the ordinary spread-transformation coding technique, the dimensionality of the spreading sequence segments used in our experiments will be restricted to the minimum possible. This corresponds to the length of the host coefficients blocks (the width of mid-frequency band here), which means that the number of repetitions of each segment (the repetition coding dimensionality) will be equal to the size of the embedded watermarking arrays in units of host coefficients blocks.

- As a host perceptual analysis computation, we will employ the algorithm briefed in [8] for determining the high frequency contents of the host image blocks.

The experiments to be performed in here are all applied to the 512×512 grayscale "Lena" image. In these experiments, the test image is watermarked with 100 different watermarks, at a host-to-watermark power ratio of 25 dB, for each different value of the watermarking array size (in units of host coefficients blocks), using the proposed partially host-adaptive baseband-spread transformation and the nonadaptive spread transformation QIM watermarking scenarios. The embedded watermarks are extracted and decoded to determine the bit error rate (BER) induced by each attacking channel into these watermarks, which can be regarded as a good indication of the robustness of the corresponding watermarking systems to these channels.

The simulation results in Fig. 5 show the robustness, in terms of induced BER, of the mentioned systems against:

- adaptive additive white Gaussian noise (AWGN) channel, with 50 dB noise-to-watermark ratio (NWR),
- JPEG2000 lossy compression into 25:1 ratio,
- linear filtering with 5×5 Gaussian kernel,
- nonlinear filtering with 4×4 median kernel, and
- space-variant filtering with 5×5 adaptive Wiener filter.

Note that the overall bit error rates achieved by the proposed watermarking technique are lower than those achieved by the nonadaptive spread transformation QIM watermarking technique, for the tested attacking channels. This shows the *robustness-conservation* property of the proposed technique in relation to adaptation distortions.

In addition to achieving a relatively higher robustness level, the proposed watermarking technique can also improve the perceptual fidelity of the marked image. This can be easily seen in Fig. 6, where we show two differently marked versions of the test image along with their corresponding embedded watermarks. The first image in Fig. 6(a) is marked with the watermark of Fig. 6(c), generated by the nonadaptive spread transformation QIM marking technique, while the second image in Fig. 6(b) is marked with the watermark of Fig. 6(d), generated by the proposed partially host-adaptive baseband-spread transformation QIM marking technique. Note here that the watermark embedded into the first image induces many *undesirable perceptual artifacts* into that image. These undesirable artifacts are avoided by the proposed system, where the distribution of the watermarking signal is controlled by the local properties of the underlying host.

6. Concluding Remarks

In the course of the work here, a new watermark coding technique has been developed, which can generally be viewed as the combination of the direct sequence spread spectrum (DSSS) modulation technique, the baseband (*repeat-integrate-and-dump*) coding technique, and QIM embedding technique.

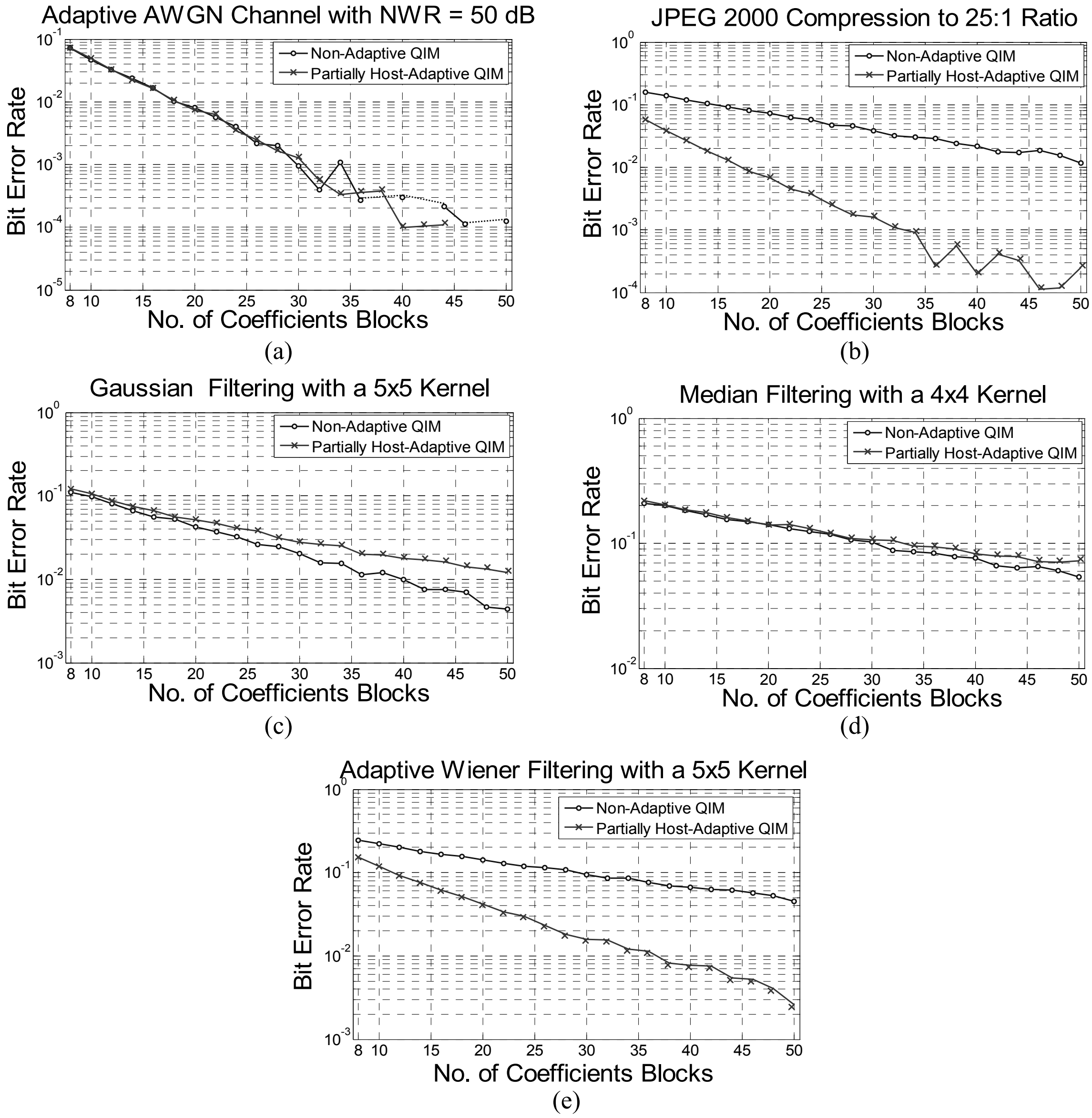

Fig. 5. Average decoding BER for the partially host-adaptive baseband-spread transform QIM technique vs. the nonadaptive spread transform QIM technique over (a) adaptive AWGN, (b) JPEG2000, (c) Gaussian filtering, (d) median filtering, and (e) adaptive Wiener filtering, channels. The host-to-watermark power ratio is fixed to 25 dB, while testing a wide range of the watermarking array sizes in terms of coefficients blocks No.

As it has been proved both theoretically and experimentally, the proposed baseband-spread transformation QIM technique is equivalent to or is relatively better than the spread transformation QIM technique, in terms of robustness, yet, it offers an additional opportunity to apply some form of host-adaptation processing that is shown to induce no distortion into the embedded watermarking signal, which could completely eliminate the need for any pre-decoding equalization processing to the distortions induced by the adaptation process. This would also enable the encoder to freely select any perceptual adaptation model, without notifying the decoder or updating the decoding system.

Another important advantage for the proposed technique over the spread transformation QIM marking technique is the higher level of *efficiency* that can be achieved by the proposed technique, which replaces the array multiplication processing with the much less time consuming accumulation processing. This could enable the implementation of simpler and more efficient marking systems.

Fig. 6. Two differently marked versions of the test image using (a) the nonadaptive spread transform QIM marking technique, and (b) the proposed partially host-adaptive baseband-spread transform QIM marking technique, along with the watermarks embedded within, shown in (c) and (d), respectively.

7. References

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