Using perceptual distance to improve the selection of dirty paper trellis codes for watermarking

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***Abstract*— Previous watermarking research based on dirty paper trellis coding [1] proposed a method for informed coding by which the best code from the set of codewords representing the message, was selected based on maximizing the linear correlation between the codewords and the *original* cover Work. However, this does not guarantee that that the linear correlation is maximized in the *watermarked* cover Work. This is because the chosen codeword must be attenuated due to fidelity constraints. Since there is no clear relationship between linear correlation and fidelity, a codeword that is chosen to maximize linear correlation may be very difficult to embed if it is perceptually very different from the underlying cover Work. We show that this is in fact the case and suggest a solution to this problem that involves a cost function that is a linear combination of perceptual distance and linear correlation. Experimental results demonstrate 50% and 25% improvements in bit and message error rates respectively.**

I. INTRODUCTION

WATERMARKING can be modeled as communications with side information [2]. Within this framework, Chen and Wornell [3] highlighted the importance of work by Costa [4] that showed that the channel capacity of a communication system with two noise sources that are both unknown to the receiver, but one of which is entirely known to the transmitter, is independent of the known noise source. This result is relevant to watermarking since the cover Work, e.g. picture, video or music, that a message is to be embedded in, is side information, i.e. an entirely known "noise" source. Costa's result implies that the number of bits we can embed in a cover Work is independent of the cover Work.

A key concept in Costa's paper is that there is no longer a one-to-one mapping between a message and a codeword. Rather, there is a one-to-many mapping, the choice of codeword depending on the particular cover Work. A number of different methods have been suggested for efficiently identifying the preferred codeword to embed and for efficiently detecting the message at the receiver. The three main techniques are lattice codes [5], syndrome codes [6] and dirty paper trellis codes [1].

In this paper, we examine dirty paper trellis coding and demonstrate that the choice of codeword can be improved by accounting for the subsequent perceptual distortion that will be incurred to embed the code word. In section II we briefly review dirty paper trellis coding. Then, in Section III we describe a modification to this algorithm to improve performance. This is experimentally verified in Section IV. Finally, the discussion of Section V suggests some avenues for future work.

II. DIRTY PAPER TRELLIS CODING

Informed watermarking using dirty paper trellis coding is a two-stage process as illustrated in Fig. 1.

During watermark embedding, a message m is first coded in the message coding stage and this produces a watermark pattern w_m that is dependent on the original image c_0. This watermark pattern undergoes modification with the influence of c_0 to produce an added mark w_a that is added to c_0 to form the watermarked image c_w.

To understand the process in detail, let us first consider the watermark detection algorithm.

A. Watermark detector

In a traditional trellis structure, as depicted in Fig. 2, each stage of the trellis has a fixed number of nodes and each node has two arcs emanating from it to two nodes in the next step. Each step corresponds to one bit of the message. A bold arc is traversed if the bit is "1" and an non-bold arc is traversed if the bit is "0". Each message is represented by a unique path from node A0 to one of the rightmost nodes.

Associated with each arc is a cost that is proportional to the likelihood of the corresponding message bit. This cost is defined to be the linear correlation between a unique pattern

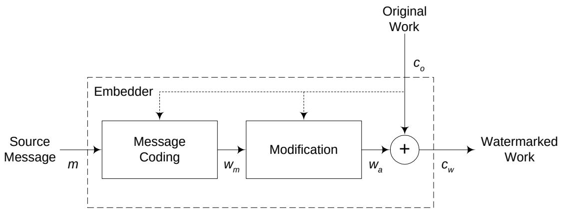

Fig. 1. Watermarking using a dirty paper trellis.

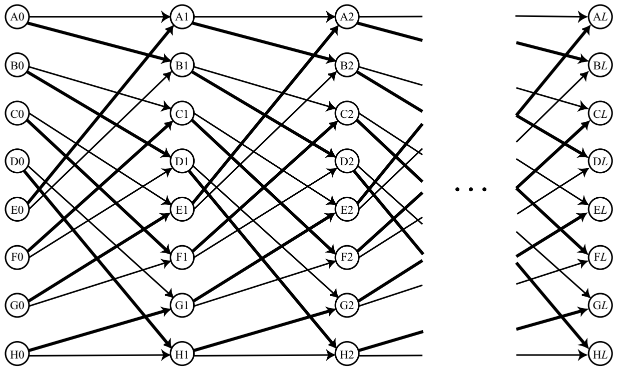

Fig. 2. Simple, 8-state trellis. Each possible message corresponds to a path from node A0 (state A at time 0) to one of the nodes at the right (any state at time L). We refer to the transition from one column of nodes to the next column of nodes as a *step*, and each such step corresponds to one bit in the coded message. A bold arc is traversed if the corresponding bit is a 1, a non-bold arc is traversed if the corresponding bit is a 0.

associated with each arc in a step and the corresponding pattern extracted from the cover Work. More detail of this is provided in Section IV. The optimum path through the trellis can be calculated using the Viterbi algorithm and the corresponding sequences of bits is the most likely message.

In order to provide for a one-to-many mapping of messages to codewords, we introduce additional arcs at each node in the trellis, as depicted in Fig. 3. Once again, a bold arc is traversed if the corresponding bit of the message is a “1”, and a non-bold arc is traversed if the corresponding bit is a “0”.

During watermark detection, the Viterbi algorithm is applied to the dirty paper trellis in order to determine the most likely path and thus the most likely message.

B. Watermark embedding

Given a message, m, watermark embedding begins by selecting the most suitable code to represent the message. This is determined by creating a modified trellis, as illustrated in Fig. 4, in which all paths through the trellis encode the same message. The Viterbi algorithm can then be applied to this trellis in order to find the path with the largest linear correlation between the message and the particular cover Work. Different cover Works will result in different paths, but all paths encode the same message.

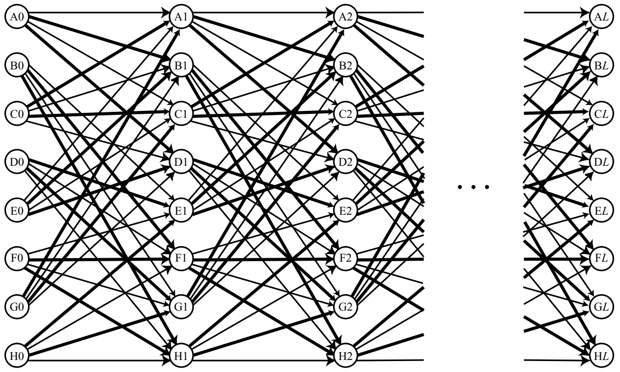

Fig. 3. Ditry paper trellis with 8 states and 4 arcs per state. Each possible message corresponds to two paths from node A0 (state A at time 0) to two of the nodes at the right (any state at time L). Each step corresponds to one bit in the coded message. A bold arc is traversed if the corresponding bit is a 1, a non-bold arc is traversed if the corresponding bit is a 0.

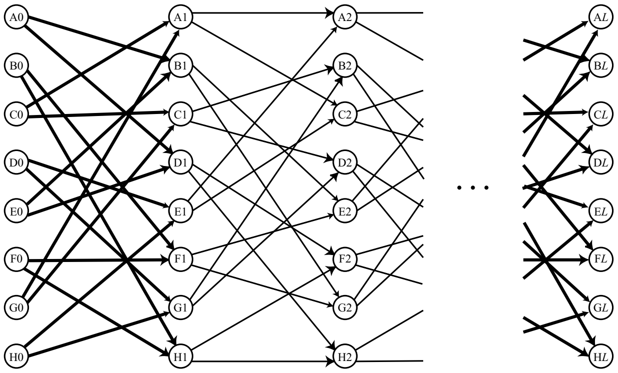

Fig. 4. A modified trellis in which all paths encode the same message. Here, we depict a message whose first three bits are “1 0 0” and last bit is “1”

Once the desired path has been determined, this codeword is embedded into the cover Work using informed embedding techniques. In [1], an iterative algorithm for informed embedding was developed which guarantees a fixed level of robustness to additive Gaussian noise. This algorithm is computationally expensive, although recent results by Abrardo and Barni [7] provide a much more computationally efficient method.

For simplicity, we chose to use a simple form of informed embedding, the E_PERC_GSCALE described in [8]. This algorithm globally adjusts the strength of the added pattern, w_a, in order to maintian a fixed fidelity as measured by the Watson distance [9]. The watermark pattern w_m is embedded into the cover Work, c_0 such that $c_w = c_0 + w_a$, where $w_a = \alpha w_m$. The value of α is a function of the cover Work.

The Watson's [9] perceptual distance, D_{wat}, between the orginal and watermarked cover Works is given by:

$$D_{wat}(c_o, c_w) = \left\{ \sum_{i,j,k} \left(\frac{C_w[i,j,k] - C_o[i,j,k]}{s[i,j,k]} \right) \right\}^{\frac{1}{4}} \qquad (1)$$

where $s[i,j,k]$ is an array of slacks based on estimated sensitivity of the eye and the masking properties of c_o, and i, j denote the pixel in the block number k, $0 \leq i$, $j \leq 7$. More details on slacks can be found on page 217 in [8]. C_o and C_w denote the block DCT transforms of c_o and c_w respectively.

The global scaling constant, α, is set as

$$\alpha = \frac{D_{target}}{D_{wat}(c_o, c_w)} \qquad (2)$$

III. COMPENSATING FOR PERCEPTUAL DISTORTION

When we use the combination of informed coding and informed embedding based using E_PERC_GSCALE, the watermark embedder first selects the preferred code from the set of codewords that represent the desired message. The preferred codeword is chosen to maximize the linear correlation between the pattern to be embedded and the cover Work. The linear correlation is maximized since the watermark detector also uses linear correlation to determine the most likely message.

Once the preferred code work is selected, it is embedded with a strength, α, that is chosen to maintain a fixed fidelity. Unfortunately, there is no clear relationship between linear correlation and perceptual distance. Thus, it is entirely possible that a codeword chosen to have a high correlation with the cover Work, may, in fact, be embedded with a low strength due to the perceptual distortion that it introduces. Conversely, it may transpire that a codeword that has a smaller linear correlation with the cover Work can be embedded with a high strength if the corresponding perceptual distortion is smaller. Ultimately, we are seeking to maximize the linear correlation between the codeword and the watermarked Work, not the original unwatermarked Work, in order to minimize the probability of erroneous detection.

How, then, should the informed code be selected? One alternative is to assign a perceptual distance to each arc in the modified trellis and find the codeword that minimizes the perceptual distortion.

A second alternative is to assign a cost that is a linear combination of linear correlation and perceptual distance. In particular, the arc cost, e_i, is given by:

$$e_i = (1-k)z_i - kd_i \qquad (3)$$

where z_i is the linear correlation of the pattern, d_i is the corresponding perceptual distance for the arc i and k is a constant. Clearly, when $k = 1$, we have the first alternative, which minimizes perceptual distortion only. And when $k = 0$ we have the orginal algorithm, which minimizes the linear correlation.

Other alternatives are possible but are not considered in this paper.

IV. EXPERIMENTAL RESULTS

To determine whether the performance of (i) linear correlation alone, (ii) perceptual distance alone or (iii) a linear combination of the two is superior, we conducted an experiment using a dirty-paper trellis with 64 states and 64 arcs per state.

Watermark embedding proceeds as follows:

1) Compute the discrete cosine transform (DCT) of each 8×8 block of an image.
2) Extract the 12 lowest-frequency AC terms of each block to form a single, $12 \times N$ length vector, v, where N is the number of blocks in the image. The vector v is referred to as the extracted vector.
3) Use the dirty-paper trellis to encode the desired message, m, into a watermark vector, w_m. This was done by running Viterbi's algorithm on v using a trellis modified for message m. The cost associated with an arc is given by (3).
4) Embed w_m into v with informed embedding: $v_w = v + \alpha w_m$, where α is the embedding strength and is chosen such that the fidelity of the watermarked image is fixed at a desired Watson distance.
5) Place the values of v_w into the corresponding low-frequency AC terms of the block-DCT of the cover image.
6) Convert the image back into the spatial domain to obtain the watermarked image.

Watermark detection proceeds as follows:

1) Extract a vector, v', from the image in the same manner as in steps 1 and 2 of the embedding algorithm.
2) Apply the Viterbi algorithm to v', by using the whole trellis, to identify the path whose code vector yields the highest linear correlation.
3) Record the decoded message, m' associated with the corresponding path.

To evaluate the different algorithms, we used a database of 2000 images, each of dimension 240×368. Thus, the number of 8×8 blocks is $N = 1380$. The bit error rate (BER) and message error rate (MER) are computed. The Message Error is defined a being zero if all 1380 bits are correctly decoded and one, otherwise.

The BER and MER are shown in Fig. 5 and Fig. 7 for three values of fidelity, i.e. three values of embedding strength, α and for k ranging from 0 to 1. The percentage improvements in BER and MER are illustrated in Fig. 6 and Fig. 8.

Fig. 5 and Fig. 7 clearly reveal that the BER and MER are worse for $k = 0$ and $k = 1$, i.e. maximizing linear correlation or minimizing perceptual distortion. The performance when minimizing the perceptual distortion alone is much worse than for linear correlation alone.

Significantly improved performance is, however, obtained when a combination or the two measures is used, i.e. $0 < k < 1$. Fig. 6 indicates that the BER is improved by almost 50% for a fidelity of 100. A watermarked image with a Watson distance

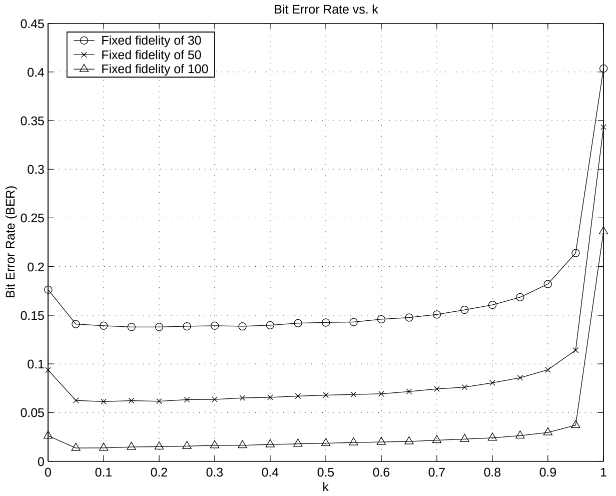

Fig. 5. The bit error rate (BER) as a function of k for three values of fidelity.

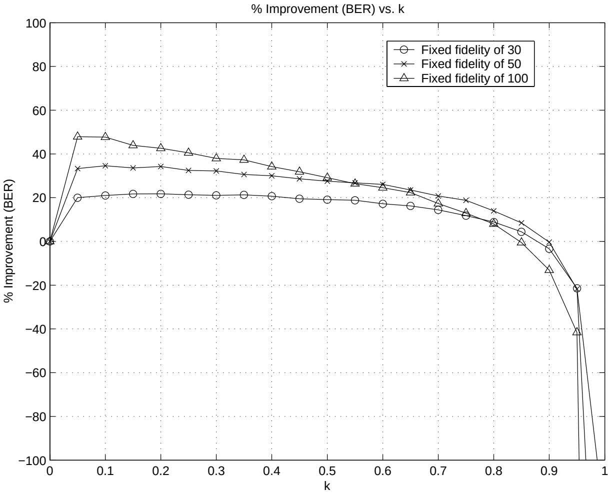

Fig. 6. The percentage improvement in bit error rate (BER) as a function of k for three values of fidelity.

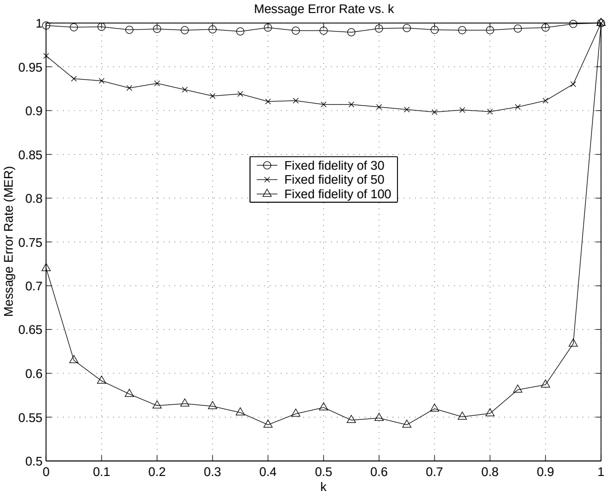

Fig. 7. The message error rate (MER) as a function of k for three values of fidelity.

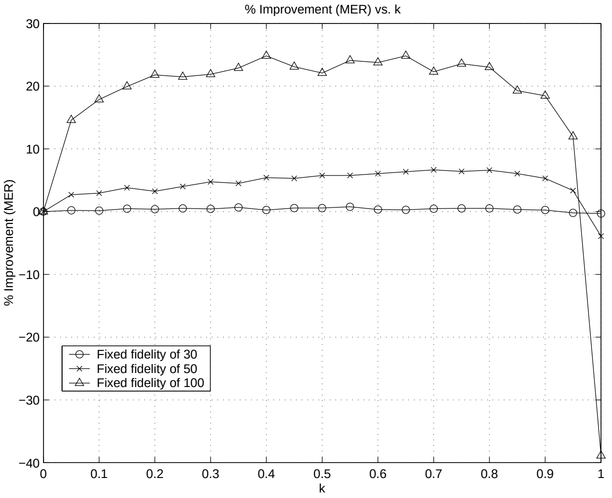

Fig. 8. The percentage improvement in message error rate (MER) as a function of k for three values of fidelity.

of 100 is almost identical to the original unwatermarked image. For a fixed fidelity of 50 and 30, the improvement is smaller but still significant.

Fig. 8 shows that the MER is also improved, this time by almost 25% for a fixed fidelity of 100. Curiously, the MER continues to increase for values of k up to 0.65, even though the improvement in BER peaks at about 0.1. It is unclear why this is so. As with the BER, the improvement in MER is less when the fidelity is constrained to a Watson distance of 50 and no improvement is measurable for a Watson distance of 30.

V. DISCUSSION

We have demonstrated that the choice of code to embed in a cover Work can be significantly improved by maximizing a cost function that is a linear combination of linear correlation and perceptual distortion, rather than linear correlation alone.

Finding the codeword that maximizes the linear correlation with the original cover Work, does not guarantee that the linear correlation is maximized after embedding. This is because said codeword may need to be attenuated more strongly than alternative codewords in order to satisfy a perceptual constraint.

Finding the codeword that minimizes the perceptual distortion with the original permits said codeword to be embedded more strongly. However, the codeword may have a very low linear correlation with the cover Work and result in very poor performance at the detector.

A linear combination of perceptual distortion and linear correlation was shown to be superior, improving the bit error rate by about 50% and the message error rate by about 25% for a fixed fidelity of 100.

Further investigation is needed to determine the optimal criterion, which would maximize the linear correlation *after* watermark embedding, subject to a fidelity constraint.

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