AN EFFICIENT ALGORITHM FOR INFORMED EMBEDDING OF DIRTY-PAPER TRELLIS CODES FOR WATERMARKING

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ABSTRACT

Dirty paper trellis codes are a form of watermarking with side information. These codes have the advantage of being invariant to valumetric scaling of the cover Work. However, the original proposal requires a computational expensive second stage, informed embedding, to embed the chosen code into the cover Work. In this paper, we present a computational efficient algorithm for informed embedding. This is accomplished by recognizing that all possible code words are uniformly distributed on the surface of a high n-dimensional sphere. Each codeword is then contained within an $(n-1)$-dimensional region which defines an n-dimensional cone with the centre of the sphere. This approximates the detection region. This is equivalent to the detection region for normalized correlation detection, for which there are known analytic methods to embed a watermark in a cover Work. We use a previously described technique for embedding with a constant robustness. However, rather than moving the cover Work to the closest Euclidean point on the defined surface, we find the point on the surface which has the smallest perceptual distortion.

Experimental results on 2000 images demonstrate a 600-fold computational improvement together with an improved quality of embedding.

1. INTRODUCTION

In 1999, several researchers [1, 2, 3] contemporaneously recognized that watermarking with blind detection can be modeled as communication with side-information at the transmitter [4]. This realization has led to the design of algorithms for *informed coding* and *informed embedding*.

In informed coding, there is a one-to-many mapping between a message and its associated codewords. The code or pattern that is used to represent the watermark message is dependent on the cover Work. The reader is directed to [5] for a detailed discussion of these concepts. Informed coding is based on the work of Costa [6]. Chen [7] first realized the importance of Costa's work to watermarking and Moulin and O'Sullivan [8] have since extended Costa's analysis to noise models more realistic in the context of watermarking.

Costa's result suggests that the channel capacity of a watermarking system should be independent of the cover Work. This is highly unexpected, since previously watermaking systems were modeled as communication systems that operated in very low signal-to-noise regimes due to the strong interference from the cover Work. This limited the number of bits that could be reliably embedded in a cover Work. Costa's result therefore offers the promise of significantly improving watermarking systems.

Costa's result relies on a very large random codebook that is impractical. In order to permit efficient search for the best dirty-paper[1] codeword three main approaches have been proposed based on structured codebooks. These are syndrome codes, lattice codes and trellis codes [2, 3, 9].

Lattice codes, more often referred to as quantization index modulation (QIM), have received most attention due to (i) easy implementation, (ii) low computational cost and (iii) high data payloads. Quantization index modulation has been criticized for being very sensitive to valumetric scaling, i.e. multiplicative changes to the amplitude of the cover Work. For example, changes to the volume of an audio signal can lead to complete loss of the watermark message. Recently, however, considerable progress has been made [10, 11, 12, 13] towards resolving this issue.

Trellis codes are an alternative to lattice codes and were originally proposed [9, 14] to address the issue of valumetric scaling, e.g. changes in image brightness. The codes of a trellis lie on the surface of a high dimensional sphere. For a given message, the trellis structure permits an efficient identification of the most appropriate code to embed in a given cover Work. However, while selection of the best dirty paper code is efficient, subsequent informed embedding of the code word requires a computational expensive iterative procedure.Abrardo and Barni [15] proposed using orthogonal dirty paper codes that can be embedded computationally efficiently. However, we believe that dirty paper trellis codes have the potential for higher data payloads.

In this paper, we described a computationally efficient method for informed embedding of dirty paper trellis codes. The key insights are (i) that all possible codewords are uniformly distributed on the surface of an n-dimensional sphere, (ii) the Voronoi region around each codeword can be approximated by an $(n-1)$-dimensional sphere, (iii) the centre of the sphere and the surface of the $(n-1)$-dimensional sphere define an n-dimensional detection region that is a n-dimensional cone and (iv) this n-dimensional cone is equivalent to the detection region when normalized correlation is used. As such, previously described analytic methods for embedding with constant robustness can be utilized. Surfaces of constant robustness are hyperboloids within the n-cone. Finally, (vi), instead of finding the closest Euclidean point from the cover Work to a point on the hyperboloid, we find the point which has the minimum perceptual distance, as defined by Watson's distance [16].

In Section 2 we briefly summarize dirty paper trellis coding and the original iterative algorithm for informed embedding. Section 3 describes prior work on embedding a watermark with constant robustness using a normalized correlation detector. Section 4 then describes how informed embedding of dirty paper trellis codes can be accomplished using the results from Section 3. Section 5 provides experimental results and Section 6 summarizes the contributions of this paper.

2. DIRTY PAPER TRELLIS CODING

In order to describe a dirty paper trellis code, it is helpful to first outline a conventional trellis code.

2.1. Trellis codes

Trellis coding is an efficient method to code and decode a message using an error correcting code. Each step, i, in a traditional trellis is represented by S possible states. The trellis is traversed by following one of the two arcs that emanate from each state. During

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[1]The term derives from that fact that Costa's original paper was entitled "Writing on Dirty Paper".

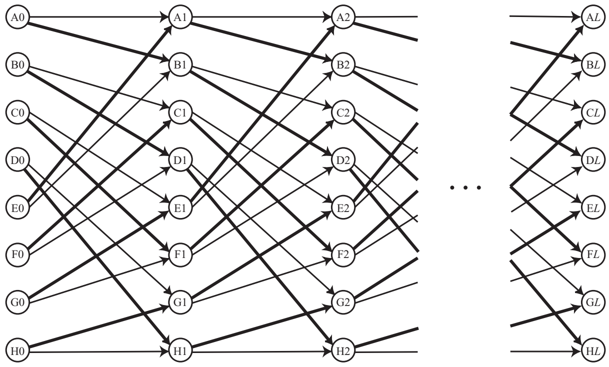

Fig. 1. *Simple, 8-state trellis.*

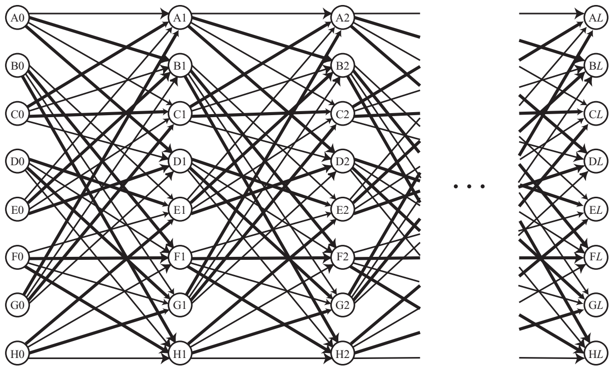

Fig. 2. *Dirty-paper trellis with 8 states and 4 arcs per state.*

decoding, the choice of which arc to traverse is determined by a cost associated with each arc. This cost is the correlation between a randomly generated vector of length N associated with each arc, and the corresponding input vector. Traversing a bold arc corresponds to a message bit-1, and a non-bold arc to a message bit-0. The computationally efficient Viterbi algorithm is used to determine the path with maximum correlation. Figure 1 depicts a simple 8-state trellis.

2.2. Dirty paper trellis codes

In a traditional trellis, there is a unique path or code associated with each message. However, dirty paper coding permits a one-to-many mapping between a message and multiple codes. The choice of which code to embed is determined by the cover Work, i.e. we embed the code that is most similar to the cover Work.

To create a dirty paper code, the trellis is modified such that more than two arcs emanate from each state. Half the arcs represent a 0-bit and half represent a 1-bit. However, each arc has a different random vector associated with it. Figure 2 depicts a dirty paper trellis with 8-states and 4-arcs per state. The two bold arcs represent a 1-bit and the two non-bold arcs represent a 0-bit. It is clear that a given message can be represented by more than one path through the trellis.

During the watermark encoding stage, the dirty paper trellis is modified such that all the paths through the trellis encode the desired message. This is achieved by removing non-bold arcs from steps in the trellis that encode a 1-bit, and vice versa. The original unwatermarked Work is used as input to the modified trellis and Viterbi decoding determines the codeword that is most similar to the cover Work. This codeword is then embedded in the cover Work.

2.3. Iterative embedding of Dirty Paper Trellis Codes

Having selected the preferred dirty paper code for a given cover Work, it is necessary to embed this code. In [14] this was achieved by an iterative Monte-Carlo procedure. Space limitations do not permit a detailed description of this procedure, but can be found in [14].

3. EMBEDDING WITH CONSTANT ROBUSTNESS USING A NORMALIZED CORRELATION WATERMARK DETECTOR

Before proceeding to discuss the improved method for embedding, it is useful to review a procedure for embedding with constant robustness when normalized correlation is used for detection.

Given a reference pattern w and a Work, c, the normalized correlation, z_{nc} is $z_{nc} = c \cdot w/(|c||w|)$. A watermark is said to be present if $z_{nc} > \tau_{nc}$, where τ_{nc} is a threshold chosen to meet a specific false alarm rate. If c and w are considered to be points in a high dimensional space, then the detection region is conical. When we consider the hyperplane defined by c and w, the detection region can be represented as depicted in Figure 3. The goal of the embedding process is then to move the unwatermarked work c so that it lies inside the detection region.

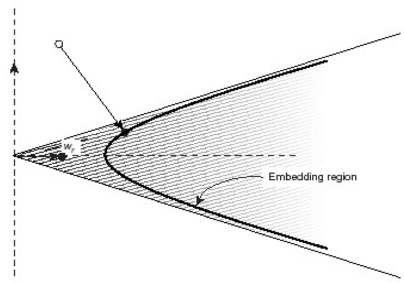

Fig. 3. Detection region using normalized correlation.

It is desirable to detect the watermark after the Work has undergone some distortion, often modeled as additive noise, provided the noise does not exceed a threshold, e.g. $|n| \leq R$. When normalized correlation is used for detection, this condition is expressed as [9]:

$$R^2 = \left(\frac{c_w \cdot w}{\tau_{nc}|w|}\right)^2 - c_w \cdot c_w \tag{1}$$

From a geometrical point of view, this means that the watermarked content c_w has to lie on the n-dimensional hyperboloid defined by Equation 1 so that the embedded watermark survives the addition of noise up to a magnitude R. As a result, the goal of the embedding process is now to find the point c_w on the hyperboloid which is closest to the original Work c.

In practice, exhaustive search is performed to identify this point, x_{c_w}, y_{c_w}. Watermark embedding is then performed by:

$$c_w = x_{c_w} w + y_{c_w} \frac{c - (c \cdot w)w}{|c - (c \cdot w)w|} \tag{2}$$

assuming that $|w| = 1$.

4. INFORMED EMBEDDING USING N-CONES

The set of all possible codes defined by a dirty paper trellis are uniformly distributed on the surface of an n-dimensional sphere. This is because the codewords all share the same unit variance. The dimension N is equal to $M - 1$ where M is the length (dimension) of the codewords since codewords are zero mean. The centre of the sphere defines an arbitrary origin for an n-dimensional coordinate system. For a given trellis with S states, A arcs per state and message length L, the number N_c of all possible codewords is $N_c = SA^L$.

Let us assume that the Voronoi region around each codeword is approximated by an $(n-1)$-dimensional sphere on the surface of the

n-sphere. The region of each codeword is then a circle on the surface of the sphere. The distance between the centres of neighboring $(n-1)$-dimensional spheres (circle), c_i and c_j is simply $D = |c_i - c_j|$. [2]

For a given codeword, i.e. the best path through the trellis, the nearest incorrect codeword can be efficiently determined by finding the second best path, etc. This is accomplished by applying the Viterbi algorithm to modify trellis in which the costs associated with each of the arcs representing the correct code word are set to minus infinity. Note that this calculation need only be performed once for a given trellis and does not need to be computed each time an image is watermarked.

By applying a trellis decoder to an unwatermarked Work and a modified trellis, the codeword most closely associated with the cover Work is identified. [3] This codeword defines the centre of the $(n-1)$-dimensional spherical region of the desired codeword. The radius of this region is assumed to be half the distance between the correct codeword and the nearest neighboring codeword, i,e, $r = D/2$. The boundary of the $(n-1)$-dimensional sphere and the centre of the n-sphere define the n-conical detection region for the correct codeword.

Now, given a cover Work and the detection region for the desired dirty paper codeword, we apply Equation 2 to embed the watermark. However, instead of determing the point on the hyperboloid with minimum Euclidean distance, we identify the point with minimum perceptual distance, as defined by Watson's measure.

Figure 4 shows how the perceptual distance varies as we move along the surface of the hyperboloid, for one specific image. The curves differ from image to image. However, on tests of 2000 images from the Corel database, we observed that the curves are always smooth. This permits a very quick search to locate the point with the minimum perceptual distance.

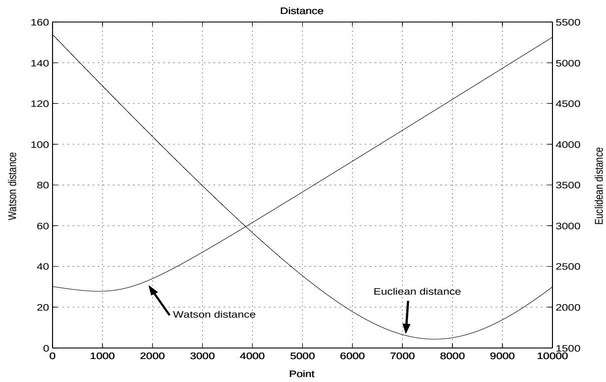

Fig. 4. The Euclidean and Watson distance from the each point on the hyperboloid.

5. EXPERIMENTAL RESULTS

We first watermarked 2000 images of dimension 240×368 using the original algorithm described in [14]. We used a trellis with 64 states and 64 arcs per state. Each arc was labeled with a vector of length $N = 12$. The label for each arc is drawn from an independent identically distributed Gaussian distribution. We modified the $N = 12$ low frequency DCT coefficients (excluding the dc term) of each of the 1380 8×8 blocks. The 12×1380 coefficient were then pseudo-randomized to form the extracted vector v_o. A message of length 1380-bits was then embedded, i.e. one bit per 8×8 block, i.e. the dimension of the message codeword is $n = 1380 \times 12 = 16560$. The average Watson distance for the 2000 watermarked images was 86. The computational time to process each image is about 20 minutes on a PC Pentium 4, 2.4 GHz, 512 MB RAM.

For the given trellis structure and codeword dimension, the resulting value for D is 0.55. For comparison purposes, we then set the robustness parameter $R^2 = 30$ in Equation 1, which provided similar robustness results to the original algorithm. The average Watson distance was, however, 55. Even with this improved fidelity, Figure 5 shows that the robustness to additive white Gaussain noise, as measured by bit error rate, is marginally better than that of the original algorithm.

The computational time to embed a watermark in an image was approximately 2 seconds, representing a 600-fold improvement in computational efficiency.

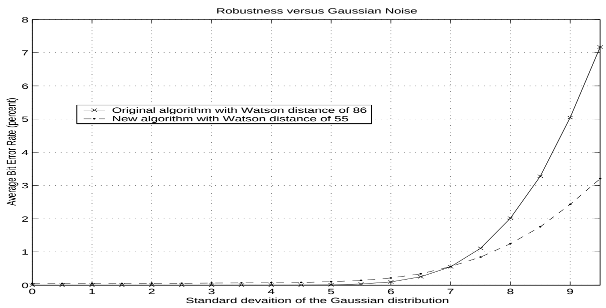

Fig. 5. Comparison result of the robustness test versus Gaussian Noise. The solid curve is for the original algorithm. The average Watson distance of watermarked images is 86. The dashed curve is performance of the new algorithm. The average Watson distance of 55.

6. CONCLUSION

We described an improved algorithm for embedding dirty paper trellis codes. The algorithm is based on the observations that (i) the codewords are uniformly distributed on the surface of an n-sphere, (ii) the Voronoi region around each codeword can be approximated by an $n-1$ dimensional circle on the surface of the n-sphere and (iii) this Voronoi region together with the centre of the sphere defines an n-dimensional conical detection region. This last observation allows us to use prior results for embedding with constant robustness when using normalized correlation for detection. By so doing, we eliminate the computationally expensive iterative procedure originally proposed for dirty paper trellis coding.

For a fixed robustness to additive noise, the embedding region is a hyperboloid surface within the conical detection region. Moving the cover Work to any point on this surface provides the same level of robustness. Previously, the closest Euclidean point on the hyperboloid to the cover Work was chosen. However, this point is not necessarily the perceptually closest point. Examining 2000 images, we observed that the Watson distance changes smoothly as we traverse the hyperboloid surface. This property permit a very quick identification of the point with minimum Watson distance. Experimental results on 2000 images showed that marginally better robustness to additive white Gaussian noise can be obtained with an improved fidelity as measured by a Watson distance of 55 compared with 86 for

[2] This assumes that all the codewords share the same minimal distance between a codeword and its nearest neighbor. This is a much more stronger assumption than uniform distribution. For a uniform distribution, we might expect that the minimum distance between codewords is Gaussian distributed about some mean value. This is an area of future investigation.

[3] The closest codeword was originally defined as the codeword with the highest linear correlation with the unwatermarked cover Work. More recently, [17] has shown that improved results can be obtained by minimizing a metric that is a linear combination of perceptual distance and linear correlation.

the original algorithm. The computational complexity of the final algorithm is approximately 600-times faster than the original.

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