NON-UNIFORM QUANTIZER DESIGN FOR IMAGE DATA HIDING

Ning Liu and K.P. Subbalakshmi

ABSTRACT

Most quantizer based data hiding schemes use uniform quantizer, which is not optimal if the host signal is not uniformly distributed. In this paper, we design a quantizer that is not only *pdf*-matched but also more suited to embedding than the Linde-Buzo-Gray (Lloyd-Max) algorithm for vector (scalar) quantizer design. Experimental results with Barbara as the host image shows that the proposed scheme provides better trade-offs between robustness to attacks, embedding induced distortion and embedding capacity than a simple *pdf*-matched scheme. The proposed algorithm also shows about 3dB improvements in embedding distortion over other popular quantizer based embedding algorithms.

1. INTRODUCTION

Data hiding has become increasingly important in a variety of applications including security. Several aspects of data hiding have been explored by researchers, including theoretical analysis of information hiding capacity [1] [2] [3]. The existing data hiding methods can be classified into quantization based [4] [5] [6] [7], spread spectrum based [8] [9], bit replacement based [10] and prediction based schemes [11] [12], etc. Some work has also been done on bit embedding after compression [13]. All quantization based schemes can be traced back to Costa's work [14], where he proposed a special communication scheme with side information, achieving the theoretical capacity of the standard Gaussian channel. Since the ideal Costa scheme (ICS) can be considered as a data hiding scheme under additive white Gaussian noise (AWGN) attacks, the capacity achieved by ICS becomes the upper bound for all data hiding schemes in the presence of such attacks. However, the ICS is not practical because of the huge size of its random codebook [5]. Practical quantization based schemes that implement Costa's idea include Quantization Index Modulation (QIM) [4], Scalar Costa Scheme (SCS) [5], Quantization Projection (QP) [15].

All these schemes are based on uniform quantizers, which is optimal only if the host signal is uniformly distributed. In our previous work [16], we proposed a *pdf*-matched scheme for embedding in images, in which, the embedding algorithm was based on the Linde-Buzo-Gray (LBG) vector quantizer (VQ) [17] and show that this scheme performs better than uniform quantizer based schemes [16]. Although the LBG VQ is *pdf*-optimal based, our embedding scheme can be further improved if we adopt a quantizer which is not only matched to the *pdf* of the host signal, but which also provides a better trade-off between the three important parameters in data hiding, namely, embedding distortion, embedding capacity and robustness to attacks. In this paper, we propose a new *pdf*-matched scheme by searching for suitable embedding regions.

2. NEED FOR SPECIAL *PDF*-MATCHED QUANTIZERS

Figure 1 shows the structure of the *pdf*-matched embedding (PME) scheme discussed in [16]. In this scheme, a vector quantizer is first designed based on, say, the Linde-Buzo-Gray (LBG) algorithm. This partitions the host signal space into Voronoi regions. A *subset* of each Voronoi region is chosen to act as the embedding region and is denoted by squares in the figure. Host image vectors falling in these regions are used to embed the hidden data. In a 2-D example, the host image is taken as 2-D vectors and 2-D bit vectors are embedded in each region. Each bit vector is associated with a perturbation vector. The image vector in the embedding region (E_i) is replaced by the perturbed vector ($\vec{p}_j$) corresponding to the bit vector to be embedded in the region. The amount of perturbation determines the robustness of the embedding algorithm to additive noise. If D_w denotes the average distortion due to embedding, then as Chen and Wornell's definition we define the parameter $d^2_{\min-\text{norm}}$ as:

$$d^2_{\min-\text{norm}} \equiv \frac{d^2_{\min}}{D_w}. \quad (1)$$

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N. Liu e-mail: nliu@stevens-tech.edu

K.P. Subbalakshmi is with the ECE Department, Burchard 208, Stevens Institute of Technology, Hoboken, NJ 07030 USA, e-mail: ksubbala@stevens-tech.edu, Phone: 201-216-8641, Fax: 201-216-8246

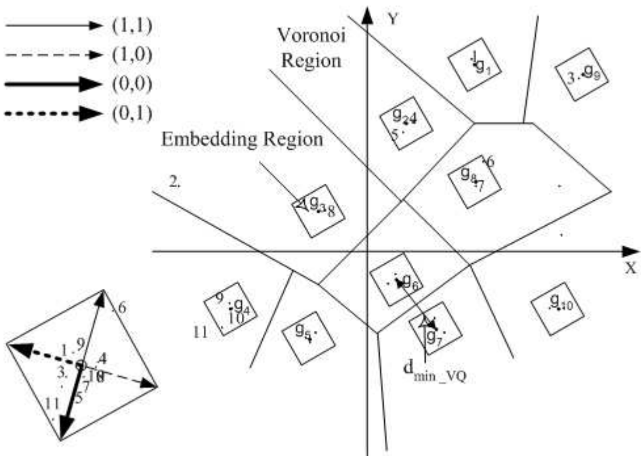

Fig. 1. The 2-D PME Scheme

2.1. Need for Special Non-Uniform Quantizer Design Algorithm

Although the LBG algorithm is *pdf*-matched to the host image, it is not optimal for embedding process. This is because, a generic *pdf*-matched quantizer design algorithm minimizes the average distortion due to quantization. If $\vec{g}_i$ represents the centroid of the i^{th} Voronoi region V_i and $\vec{x}$ denotes the host image vector, the average distortion of the VQ is given by D_C:

$$D_C = \sum_i \int_{V_i} \|\vec{x} - \vec{g}_i\|^2 f_X(\vec{x}) d\vec{x}, \qquad (2)$$

while the average distortion caused by embedding is given by D_E:

$$D_E = \sum_i \int_{E_i} \sum_j \|\vec{x} - \vec{p}_j\|^2 \operatorname{Pr}(\vec{p}_j) f_X(\vec{x}) d\vec{x}. \qquad (3)$$

Since $D_E \neq D_C$ in general, a generic vector quantizer (non-uniform scalar quantizer) design algorithm is not optimal for embedding applications. In the next section we present a simple algorithm that searches for the best embedding region for the scalar embedding case.

3. THE PROPOSED NON-UNIFORM QUANTIZER DESIGN ALGORITHM

Let $d_{\min}$ be the size of the embedding region. Let $\mathcal{R}_i$ be the search region for the i^{th} iteration of the algorithm. Let R be the range of the signal (0 to 255 for images). Select a threshold value T_h for the $d^2_{\min-\text{norm}}$ (as in Equation 1). This value determines the robustness of the embedding algorithm and will determine the number of codewords in the quantizer. Set μ as the displacement unit for the search algorithm. Then the

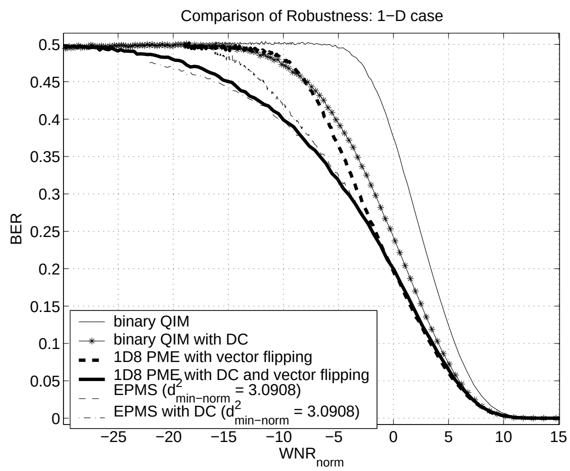

Fig. 2. Comparison of robustness between QIM, DC-QIM, VF-PME, DC-VF-PME, ERSS, and DC-ERSS (1-D case)

algorithm is given by:

Set $\mathcal{R}_0 = \text{R}$, Set $i = 0$;
$\star$: Slide embedding region in steps of μ along
the all of $\mathcal{R}_i$ from the left to right, and
calculate $d^2_{\min-\text{norm}}$ for each displacement;
Find max value of $d^2_{\min-\text{norm}}$: $\max_i(d^2_{\min-\text{norm}})$;
If $\max_{R_i}(d^2_{\min-\text{norm}}) < T_h$
STOP;
else Set the corresponding embedding region
as the i^{th} embedding region E_i.
$\mathcal{R}_i \longleftarrow \mathcal{R}_i - E_i$;
i++;
Goto $\star$;
end

Note: For applications where more than one host image is used to embed different messages, a training set of images can be used to design a general non-uniform quantizer that can then be used for an entire class of host images.

4. EXPERIMENTAL RESULTS

We used the 512x512 Barbara image as the host and a random bit sequence with $P_r(0) = P_r(1) = \frac{1}{2}$, was embedded. The number of bits embedded depends on the capacity of the scheme. We test the performance of our scheme with QIM and the scheme using the Lloyd-Max quantizer (PME scheme). In [4] Chen and Wornell proposed a distortion compensation (DC) technique to their embedding scheme,where, the compensated stego-signal (S) is equal to the summation of the stego-signal (Xq) and a compensation parameter, which is a scaled

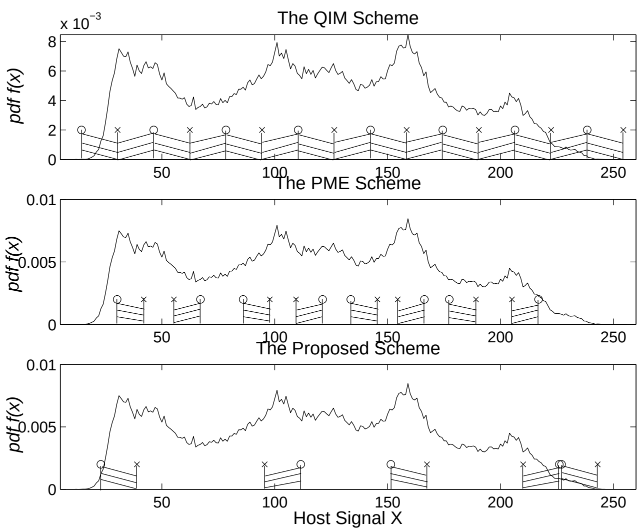

Fig. 3. x: the coset for hidden bit '1'; o: the coset for hidden bit '0'; Y axis: *pdf* of Barbara image. Shaded area is embedding region.

watermarking signal (X -Xq):

$$S = X_q + (1-\alpha)(X - X_q) \quad (4)$$

Here the scaling factor (α) depends on the average embedding distortion (D_w) and the variance, σ_n^2, of the AWGN attack:

$$\alpha = \frac{D_w}{D_w + \sigma_n^2} \quad (5)$$

We also extend our current scheme using the same technique and compare it with the distortion compensated versions of QIM and PME. Finally, we note that reversing the perturbation vector corresponding to a '0' and '1' improves the robustness of the scheme. We also present comparisons of the vector flipped (VF) versions of all algorithms here.

Figure 2 compares the performance of the ERSS and DC-ERSS against that of the *pdf*-matched scheme with vector flipping [16] (VF-PME), DC-VF-PME, QIM and DC-QIM in terms of the probability of bit error under AWGN attacks. We base the robustness comparison on the normalized watermark distortion to noise ratio ($\mathrm{WNR}_{\mathrm{norm}} = \frac{D_w}{\sigma_n^2 * R_m}$) in order to ensure a fair comparison between our schemes and these. The results of our comparison in 1-D case are presented as bit error rate (BER) versus $\mathrm{WNR}_{\mathrm{norm}}$ plots in this Figure. It can be seen that the binary QIM performs worst in all the three sets of experiments, as expected. On the other hand, the best performing algorithm is DC-ERSS.

In Figure 3, we plot the *pdf* of the host image (512x512 Barbara) and mark the embedding regions

Scheme	$d_{\min}$	R_m	α	VF	$d^2_{\min-\mathrm{norm}}$
QIM	16	1	N/A	N/A	2.9969
PME	10.40	0.423	0.25	N	2.9931
	20.81	0.846	0.5	Y	3.0204
	11.78	0.475	0.283*	Y	3.0206*
ERSS	16	0.658	N/A	Y	3.0613
	16	0.343	N/A	Y	3.0908

Table 1. Embedding Rate for 1-D QIM, PME and ERSS (* means optimal value)

for the QIM, PME and the ERSS schemes. As can be seen from the figure, the QIM scheme uses all of the image to embed, but the embedding regions are not matched to the image *pdf*. In the PME scheme using the Lloyd-Max algorithm, the embedding regions are better matched to the *pdf*, but comparing this to the embedding regions in the proposed scheme shows that the proposed scheme has the best embedding regions, since they are centered around the peak regions in the *pdf*. Finally, Table 1 shows the embedding rates R_m and $d^2_{\min-\mathrm{norm}}$ for all three schemes. As can be seen from this table, the proposed scheme has comparatively higher values of $d^2_{\min-\mathrm{norm}}$ implying that it is more robust to additive noise attacks.

5. CONCLUSION

This paper showed that using a generic *pdf*-matched quantizer design algorithm is not optimal for data-hiding application. We then proposed a non-uniform quantizer design algorithm for data-hiding in images which essentially searches for the best regions to place the embedding region within the image range. The proposed algorithm shows better performance in terms of embedding rate-embedding distortion-robustness trade-offs than a scheme using the Lloyd-Max quantizers, and QIM. We note that although we showed examples of data hiding in the spatial domain, this method can easily be adapted to frequency domain embedding as well.

6. ACKNOWLEDGMENT

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