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Performance analysis of random angle based quantization modulation

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ABSTRACT

The random angle based quantization modulation (RAQM) is a new watermarking method invariant to valumetric scaling attack. In this paper, the performance of RAQM is theoretically evaluated in two aspects: the embedding distortion and the decoding performance against additive noise attack. The analyses are developed under the assumptions that the host and noise vectors are mutually independent and both of them have independently and identically distributed components. We establish the stochastic models for several concerned signals. Based on them, the expressions of the embedding distortion and the decoding bit-error probability are derived in closed form. We also present the simplified but effective approximations to these analytical results. The analyses allow us to get more insight into the impact of various factors on the performance of RAQM. Numerical simulations confirm the validity of our analyses and exhibit the performance advantage of RAQM over similar modulation techniques.

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1. Introduction

Digital watermarking is viewed as a communication problem with side information [1]. For the problem, Costa [2] theoretically showed that the channel capacity is independent from the known host signal at the encoder. Costa's result implies that it is possible to design a watermarking system that completely rejects the interference from the host signal. Inspired by the work of Costa, a lot of down-to-earth implementations have sprung up, in most cases, consisting of quantization procedures.

One of the most important methods proposed so far is quantization index modulation (QIM) [3], where watermark embedding is obtained by quantizing the host signal with a quantizer chosen among a set of quantizers that are each associated with a different message. The basic implementation of QIM, called dither modulation (DM), adopts a set of scalar and uniform quantizers [3]. For its simplicity and good performance, DM becomes very popular, but the gap to the theoretical capacity for DM is still substantial. As a special case of DM, the spread-transform dither modulation (STDM) works by quantizing the projection of the host vector along a random direction. The idea of STDM is then explored in the quantized projection (QP) method [4]. With the use of the projection operation, the spreading stage is involved and significant performance improvement is brought to the original DM. Later, the distortion compensation technique was combined with QIM, resulting in the distortion-compensated QIM (DC-QIM) [3]. DC-QIM follows Costa's guidelines and closes the gap to capacity. The Scalar Costa Scheme (SCS) proposed in [5] can be regarded as a special case of DC-QIM. The theoretical performance of QIM methods has been extensively investigated [4–6].

One main weakness of quantization-based watermarking is its vulnerability against valumetric scaling attack (VSA). A lot of solutions have been proposed to overcome this limitation [7]. Typically, spherical codes were utilized for quantization watermarking [8,9]. The drawback is that watermark embedding and recovery get very complicated [10]. A gain-invariant quantization step was chosen for embedding in Rational Dithered Modulation (RDM) [10]. However, RDM just approaches the performance of DM against additive noise. In angle QIM (AQIM), the angle formed by the host signal vector was quantized [11]. A practical implementation of AQIM, multiscale gradient direction quantization, was presented in [12]. Like RDM, AQIM manifests the low robustness against additive noise. In [13], the slope of a line segment constructed by the host samples was considered for data hiding. This method can resist stronger noise than the former two methods, while keeping invariance against gain attacks. A more recent work in [14] coped with VSA by quantizing the ratio of magnitudes of host signals. The method is only valid for a nonzero host signal. By quantizing the angle formed by the host signal vector and a random vector, the random angle based quantization modulation (RAQM) [15] achieves the invariance to VSA and

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involves the use of the spreading stage as in STDM. Impressively, RAQM improves robustness against a wide range of attacks.

In this work, the performance of RAQM is theoretically evaluated, in terms of the embedding distortion and the decoding error probability. For the analysis, the attack channel is modeled by an unknown noise, and no distribution is specified to the host and noise signals. The noise attack gives a good indication of the performance of RAQM in the presence of unintentional manipulations. By the obtained results, we may get more insight into the impact of various factors on the performance of RAQM and provide a baseline for performance comparisons among different watermark embedding techniques.

The rest of this paper is structured as follows. Section 2 presents a description of RAQM. Next, in Section 3, the stochastic models are established for the performance analysis. Section 4 is devoted to the computation of the embedding distortion. The bit-error probability in presence of additive noise is derived theoretically in Section 5. The analyses are validated through numerical simulations in Section 6 with performance comparison of RAQM and other related modulation techniques. Also, the applications of the theoretical results are discussed. Finally, Section 7 concludes.

2. Random angle based quantization modulation

The RAQM first computes the angle between the host signal and a random signal, and then modulates it with the watermark message by the quantization operation. The uncoded binary RAQM can be summarized as follows [15].

Let $\boldsymbol{x} \in \mathbb{R}^L$ denote a host signal vector. To embed the watermark message $b \in \{-1, 1\}$, a random vector $\boldsymbol{u} \in \mathbb{R}^L$ is generated by a random number generator (RNG) initialized with the cryptographic key K. Particularly, each element of $\boldsymbol{u}$ follows a zero-mean independent normal distribution. The normalized correlation (NC) between $\boldsymbol{x}$ and $\boldsymbol{u}$ is thereafter computed as

$$c_x = \frac{\boldsymbol{x}^T\boldsymbol{u}}{\|\boldsymbol{x}\|\,\|\boldsymbol{u}\|}, \tag{1}$$

where $\|\cdot\|$ stands for Euclidean (i.e., ℓ_2) norm. The angle θ_x formed by $\boldsymbol{x}$ and $\boldsymbol{u}$ is obtained by the inverse cosine of c_x, i.e., $\theta_x = \cos^{-1}(c_x)$. Clearly, θ_x is in the range $[0, \pi]$.

Watermark embedding is accomplished by modulating the obtained θ_x. In the binary RAQM, two one-dimensional uniform quantizers $Q_{-1}(\cdot)$ and $Q_1(\cdot)$ are constructed, whose centroids are given by the sets $\Lambda_{-1} = \{\Delta\mathbb{Z} + d\} \cap [0, \pi]$ and $\Lambda_1 = \{\Delta\mathbb{Z} + d + 1/2\Delta\} \cap [0, \pi]$ with Δ denoting the quantization step and d a key-dependent dither value. One of them is chosen to quantize θ_x according to the message bit b, yielding

$$\theta_b = Q_b(\theta_x). \tag{2}$$

The resulting quantization error q_e is computed as $\theta_e = \theta_b - \theta_x$.

The meaning of the sets Λ_{-1} and Λ_1 as well as the operation (2) can be explained as follows. The range $[0, \pi]$ of θ_x is divided into quantization bins of size Δ. Within each bin, two points having the distance $\Delta/2$ are selected as the elements of Λ_{-1} and Λ_1 respectively. By (2), the host angle θ_x is replaced with one of the two points belonging to the quantization bin which ensures that the quantization error is minimal. The dither d introduces an additional degree of uncertainty in the positions of the selected points, which enhances the security of the operation (2). The distance $\Delta/2$ between the selected two points ensures that the quantized angles containing $b = -1$ and $b = 1$ are differentiated with the maximum possible distance from each other. Clearly, with the increase of Δ, the number of quantization bins decreases, and the average quantization error grows up.

Next, the watermarked signal $\boldsymbol{y} \in \mathbb{R}^L$ is produced such that $\theta_y = \theta_b$, where $\theta_y = \cos^{-1}(c_y)$ with c_y being the NC between $\boldsymbol{y}$ and $\boldsymbol{u}$, defined similarly to (1). Suppose that $\boldsymbol{y}_d$ represents the unit vector along the direction of $\boldsymbol{y}$. Similar definition follows for $\boldsymbol{x}_d$ and $\boldsymbol{u}_d$. We can derive

$$\boldsymbol{y}_d = \alpha\boldsymbol{x}_d + \beta\boldsymbol{u}_d, \tag{3}$$

where $\alpha = \sin(\theta_b)/\sin(\theta_x)$ and $\beta = \cos(\theta_b) - \alpha c_y$. Please refer to [15] for the detailed derivation of (3). Then, by projecting $\boldsymbol{x}$ onto $\boldsymbol{y}_d$, the watermarked signal is obtained as

$$\boldsymbol{y} = \boldsymbol{x}^T\boldsymbol{y}_d\boldsymbol{y}_d. \tag{4}$$

The above results are given for the common case where $\|\boldsymbol{x}\| \neq 0$ and $|c_x| \neq 1$. It is sufficient to consider the case in our analyses. The difference vector $\boldsymbol{w} \triangleq \boldsymbol{y} - \boldsymbol{x}$ is called the watermark signal. Clearly, the vectors $\boldsymbol{w}$ and $\boldsymbol{y}$ are orthogonal.

Before arriving at the decoder, the watermarked signal $\boldsymbol{y}$ goes through an unknown channel, resulting in a distorted signal denoted by $\boldsymbol{z} \in \mathbb{R}^L$. At decoding time, the random vector $\boldsymbol{u}$ is reproduced by the RNG seeded with the key K. The NC c_z between $\boldsymbol{z}$ and $\boldsymbol{u}$ is then computed as (1), and the angle θ_z is obtained by $\theta_z = \cos^{-1}(c_z)$. Last, a message $\hat{b}$ is extracted from θ_z by applying

$$\hat{b} = \arg\min_{b\in\{-1,1\}} |\theta_z - Q_b(\theta_z)|. \tag{5}$$

As described above, in RAQM, the signal to be quantized is the angle transformed from the host signal instead of the host signal itself, which differs from the traditional quantization modulation. The change results in the complex form of the embedding function as Eqs. (3) and (4). At the same time, the performance analysis of RAQM becomes a difficult issue and remains to be unsolved. In this study, we will theoretically analyze the performance of RAQM with respect to the embedding distortion and the decoding error probability. The theoretical results are definitely important for designing and evaluating RAQM based watermarking methods.

3. PDF models

The basis for an accurate performance evaluation is stochastic models for several angle signals θ_x, θ_y and θ_z. In order to simplify the derivation of stochastic models, we make the hypothesis that the samples of vector $\boldsymbol{x}$ are independent and identically distributed (i.i.d.) random variables with zero-mean (otherwise, the nonzero mean can be subtracted). We believe the assumption to be valid for most practical cases of interest.

Considering the dependency of the angles θ_y and θ_z on the host angle θ_x, we will first statistically characterize θ_x. According to [16], for a monotonic function $r_2 = h(r_1)$ we have

$$p_{R_1}(h^{-1}(r_2)) = p_{R_2}(r_2)|h'(h^{-1}(r_2))|, \tag{6}$$

where $p_{R_1}(\cdot)$ and $p_{R_2}(\cdot)$ are the probability distribution functions (pdfs) of the random variables r_1 and r_2, respectively. By this rule and due to the relation $\theta_x = \cos^{-1}(c_x)$, the pdf $p_X^\theta(\cdot)$ of θ_x can be written as

$$p_X^\theta(t) = \begin{cases} p_X^c(\cos(t))\sin(t), & t \in [0, \pi], \\ 0, & \text{else}, \end{cases} \tag{7}$$

where $p_X^c(\cdot)$ denotes the pdf of c_x. However, it is very difficult to derive an exact expression for $p_X^c(\cdot)$ with large L, even if the stochastic models for $\boldsymbol{x}$ and $\boldsymbol{u}$ are known. Mathematically tractable approximations may thus be used for some specific cases [17]. Under the introduced assumptions and when the host vector dimension L is large enough, we can apply the central limit theorem (CLT) to state that the NC c_x approximately obeys a Gaussian distribution $\mathcal{N}(0, 1/L)$, i.e.,

$$p_X^c(t) = \mathcal{N}(0, 1/L). \tag{8}$$

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