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Uniform polar quantizer with three-stage hierarchical variable-length coding for measurement signals with Gaussian distribution

Milan R. Dincic *, Zoran H. Peric, Dragan B. Denic

Faculty of Electronic Engineering, University of Nis, Aleksandra Medvedeva 14, 18000 Nis, Serbia

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ABSTRACT

In this paper, a new model of the uniform polar quantizer with three-stage hierarchical coding is proposed, for the analog-to-digital (A/D) conversion of measurement signals with the Gaussian distribution. The aim is to design quantizer with small complexity which can achieve very good performances. Proposed model accomplishes this aim. Applied code uses variable-length codewords, in order to achieve compression. The proposed model achieves much better performances (for 2–3 dB higher SQNR (signal-to-quantization noise ratio) for the same bit-rate) compared to the uniform scalar quantizer. Due to its small complexity and very good performances, the proposed model is suitable for using in many measurement systems for A/D conversion of measurement signals. This model especially can be useful in measurement systems where transmission of measurement signals is performed (e.g. telemetry, telemedicine, wireless sensor networks, etc.). The proposed model is applied for compression of a vibration signal.

1. Introduction

The most of modern digital measurement systems are digital, based on computers and digital processing of the measurement signals. Also, in many modern measurement systems (e.g. telemetry, telemedicine, wireless sensor networks), digital transmission of measurement signals is performed. On the other hand, the most of measurement signals are analog. Therefore, analog-to-digital (A/D) conversion of measurement signals is an indispensable part of modern measurement systems. One of the main parts of the A/D converters is a quantizer. Measurement signals often have to be stored in memory or transmitted to a remote location for further processing. Due to resource constraints (limited memory space and limited bandwidth of telecommunication channels), one of the important requirements in modern measurement systems is the compression of measurement signals (i.e. the decrease of the number of bits required for digital representation of measurement signals, maintaining satisfactory signal quality). Compression can be achieved by proper design of quantizers and using suitable coding techniques. Based on all the foregoing, we can say that the study of quantization and coding techniques in measurement systems is an important and topical subject. Papers [1–3] show some possible applications of quantization in measurement systems.

This paper deals with signals with the Gaussian distribution, since a lot of measurement signals, which are stochastic in nature, can be modeled with the Gaussian distribution. Furthermore, signals with some non-Gaussian distribution can be transformed into signals with the Gaussian distribution by passing through an appropriate filter [4].

Quantizers can be scalar (where each sample of the signal is separately quantized) or n-dimensional vector (where n consecutive samples are jointly quantized) [5,6]. Vector quantizers can achieve much better performances

* Corresponding author.
E-mail addresses: mdincha@hotmail.com (M.R. Dincic), zoran.peric@elfak.ni.ac.rs (Z.H. Peric), dragan.denic@elfak.ni.ac.rs (D.B. Denic).

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than scalar quantizers but on the other hand their complexity exponentially increases with the increase of dimension n [6]. Hence, two-dimensional quantizers represent a very good solution since they are the simplest of all vector quantizers but they still have much better performances than scalar quantizers. For the design of two-dimensional quantizers for measurement signals with the Gaussian distribution, polar coordinates are more appropriate than Cartesian coordinates [7–9]. Quantizers designed in polar coordinates are called polar quantizers.

Two types of polar quantizers are known in literature: product (also called restricted, where all magnitude levels have the same number of phase levels) and unrestricted (where optimization of the number of phase levels is performed for each magnitude level). Unrestricted polar quantizers can achieve better performances than restricted polar quantizers, but on the other hand they are more complex. Unrestricted polar quantizers were analyzed in [9–13] while product polar quantizers were analyzed in [7,8,14–17].

Polar quantizers can also be used in measurement systems for solving two-dimensional problems, such as deployment of image sensors in cameras [18] or laser interferometry measurement of magnitude and phase [19].

Scalar uniform quantizer is the most used type of quantizers. Its polar counterpart, the unrestricted uniform polar quantizer (UUPQ) [10,11], is polar quantizer where the uniform quantization of the magnitude is done and optimization of the number of phase levels is performed for each magnitude level. UUPQ can achieve much better performances than the scalar uniform quantizer (for about 2–3 dB higher SQNR for the same bit-rate), but on the other hand, UUPQ is very complex for realization for two reasons. Firstly, calculation and storage of numbers of phase levels should be done for all magnitude levels. Since the number of magnitude levels can be very large (several hundred), it means that the number of parameters which have to be calculated and stored is very large. Secondly, coding and decoding is performed by an exhausting search of the entire codebook (this is the set of all codewords used for the coding of representation points of the quantizer). The codebook contains 2^{2R} codewords, where R denotes the bit-rate. Since the codebook can be very large (e.g. for the bit-rate of $R = 8$ bps (bits per sample), the codebook contains $2^{16} = 65{,}536$ codewords), coding and decoding in UUPQ are very complex.

The aim of this paper is to design polar quantizer which can achieve very good performances (near to performances of UUPQ) but which has small complexity (much smaller than the complexity of UUPQ). To achieve this, we propose the **u**niform **p**olar **q**uantizer with **t**hree-stage **h**ierarchical **c**oding (UPQTHC). One important feature of UPQTHC is the fact that segments are formed by the joining of several consecutive magnitude levels. Numbers of phase levels on all magnitude levels within one segment are the same. In this way, it is not necessary to calculate and store numbers of phase levels for all magnitude levels; instead of that, we have to calculate and store numbers of phase levels for all segments. Since the number of segments is much smaller than the number of magnitude levels, it means that in UPQTHC we have to calculate and store much smaller number of parameters than in UUPQ (e.g. for the bit-rate of $R = 8$ bps, in UUPQ we have to calculate and store 219 different numbers of phase levels while in UPQTHC only 7 different numbers of phase levels). Another important feature of UPQTHC is the use of the three-stage hierarchical coding, which consists of three stages: segments are coded in the first stage, magnitude levels within the appropriate segment are coded in the second stage and phase levels on the appropriate magnitude level are coded in the third stage. The hierarchical coding uses variable-lengths codewords, in the aim of compression [20]. The hierarchical coding is much simpler than the exhausting search of the entire codebook, applied in UUPQ. Hence, coding and decoding complexity of UPQTHC is much smaller than of UUPQ. Based on all the above, we can say that complexity of UPQTHC is much smaller than complexity of UUPQ. Besides, UPQTHC achieves very good performances, even better than performances of UUPQ.

The proposed model is checked by simulation in MATLAB and by an experiment with a vibration signal (vibration signals are used in many applications, such as machine condition monitoring, structural health monitoring, etc.). Very high level of matching between theoretical, simulation and experimental results is obtained.

The most of papers about the polar quantization are based on the asymptotic analysis [7–17], which is also applied in this paper. Since the asymptotic analysis is valid for medium and high bit-rates (higher than 4 bps), it follows that the model developed in this paper is also valid for medium and high bit-rates.

The proposed model can be used in all measurement systems where A/D conversion of measurement signals has to be done. This model can be especially useful in measurement systems where transmission of measurement signals is performed (telemetry, telemedicine, wireless sensor networks, etc.).

This paper is organized in the following way. Basic theory of polar quantizers, as well as a short description of the unrestricted uniform polar quantizer, are presented in Section 2. In Section 3, the model of the uniform polar quantizer with three-stage hierarchical coding is described and its performances are presented. Section 4 concludes the paper.

2. Polar quantizers

2.1. Definition of polar quantizers

As it was said before, this paper considers two-dimensional quantizers for measurement signals with the Gaussian distribution. Quantizers are always designed for some referent signal variance. Without losing the generality, it is usual to design quantizers for the unit signal variance $\sigma^2 = 1$ [5], hence this approach will be used in this paper. For the design of two-dimensional quantizers we have to use two-dimensional Gaussian distribution, which is defined with the joint probability density function $f(x_1, x_2) = \frac{1}{2\pi}\exp\left(-(x_1^2 + x_2^2)/2\right)$, where x_1 and x_2 are consecutive samples of the measurement signal. In polar coordinates (magnitude $r = \sqrt{x_1^2 + x_2^2}$ and phase $\phi = \arctan(x_2/x_1)$) the joint probability density function becomes