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MULTIPLE DESCRIPTION QUANTIZATION OF SINUSOIDAL PARAMETERS

Morten Holm Larsen, Mads Græsbøll Christensen, and Søren Holdt Jensen

Department of Electronic Systems
Aalborg University, Denmark
{mhl,mgc,shj}@es.aau.dk

ABSTRACT
A new scheme for sinusoidal audio coding named multiple description spherical trellis-coded quantization is proposed and analytic expressions for the point densities and expected distortion of the quantizers are derived based on a high-resolution assumption. The proposed quantizers are of variable dimension, i.e., sinusoids can be quantized jointly for each audio segment whereby a lower distortion is achieved. The quantizers are designed to minimize a perceptual distortion measure subject to an entropy constraint for a given packet-loss probability. In experiments, the performance of the quantizers is compared to the corresponding single description spherical quantizer and associated bounds are found to increase robustness towards packet-losses.

Index Terms—Quantization, audio coding, robustness.

1. INTRODUCTION
Parametric audio coding is based on the notion that most audio signals can be efficiently described by a few physically or perceptually meaningful parameters. Perhaps the most common incarnation is sinusoidal coding where the individual audio segments are modeled as sums of sinusoids with each of these being characterized by an amplitude, a phase, and a frequency that combine to form a point in a spherical coordinate system. For each segment of audio, the task is to find the parameters best describing the segment and to quantize these parameters, whereby transmission over channels of limited capacity is facilitated. Various computationally efficient ways of finding the parameters that minimize a perceptual distortion measure exist (see, e.g., [1]). Also, the question of optimal quantization of these parameters has been addressed recently. The so-called polar and spherical quantizers of [2,3] have proven successful in terms of achieved quality and computational complexity by quantization of the parameters of each sinusoid independently. The quantizers were designed to minimize a perceptual distortion measure subject to an entropy constrain based on a high-resolution assumption, i.e., a high number of bits per sinusoid, whereby analytic expressions for the point densities of the quantizers were derived. In [4], the spherical quantizers of [3] were improved by joint quantization of the parameters of a variable number of sinusoids. Under a high-resolution assumption, the optimal point densities of the proposed quantization scheme, named spherical trellis-coded quantization (STCQ), were derived for a given entropy. In services such as speech coding or audio streaming over unreliable networks like the Internet, the transmitted audio parameters should be protected to compensate for packet-losses. One method that aims at doing this is multiple description coding where several complementary coarse descriptions of the audio signal are constructed and transmitted whereby graceful degradation is achieved when packets are lost. Multiple description coding has recently been applied to audio in the form of transform coding [5,6] and low-delay coding using pre- and post-filtering [7]. A limitation of the quantizer used in the latter paper is that the dimension of the vector must be fixed. Therefore, it cannot readily be applied to the problem of joint quantization of sinusoidal parameters. The multiple description trellis-coded quantizer (MDTCQ) of [8] can, on the other hand, handle variable dimensions but requires training for a particular combination of entropy constraint and packet-loss probability.

In this paper, we extend the spherical quantizers of [3] to multiple descriptions by proposing a quantization scheme, named multiple description spherical trellis-coded quantization (MDSTCQ). Based on high-resolution theory, we derive analytic expressions for the expected distortion and point densities for a given target entropy and packet-loss probability. The MDSTCQ is based on a new quantization scheme named modified multiple description trellis-coded quantization (MMMDTCQ) that can be analytically designed from its point density given a packet-loss probability.

2. PROBLEM STATEMENT
We start this section by introducing the mathematical problem of robust quantization in parametric audio coding based on a perceptually relevant distortion measure. Let the audio signal \( x \) at sample time \( n \) be represented as \( x(n) \approx \sum_{l=1}^{L} a_l \sin(\nu_l n + \phi_l) \), where \( L \) is the number of sinusoidal components and \( a_l, \phi_l, \nu_l \) are the amplitude, phase and frequency of the \( l \)-th component, respectively, with \( a_l \geq 0 \) and \( \phi_l, \nu_l \in [0, 2\pi) \). The quantization distortion consists of the contributions from the individual components and the cross-terms between the components. Assuming a sufficiently large window length \( W \) or statistical independence between components, the total expected distortion can be approximated as the sum over the \( L \) expected distortions for the individual components, denoted \( E[D] \), with \( E[\cdot] \) being the expectation operator. Therefore, we will in the rest of this paper be concerned with the quantization of a single set of parameters \((a, \phi, \nu)\) thus ignoring the subscript \( l \). The present work is

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based on a perceptual distortion measure [9] defined as

$$D = \frac{1}{2\pi} \int_0^{2\pi} \mu_x(a,\phi,\nu)(\omega) |E(\omega)|^2 \, d\omega,$$  

(1)

with $E(\omega)$ denoting the Fourier transform of the windowed error, i.e., $E(\omega) = \sum_{n=-\infty}^{\infty} w(n)(x(n) - \bar{x}(n)) e^{-j\omega n}$ where $w(n)$ is the window, $\mu_x(a,\phi,\nu)(\omega)$ is the perceptual weighting function, which is calculated from the audio signal $x$ parametrized by $(a, \phi, \nu)$. Further, $\bar{x}$ is the reconstructed audio signal based on the quantized parameters $(\hat{a}, \hat{\phi}, \hat{\nu})$. Next, we introduce the quantization errors $\epsilon_a = a - \hat{a}$, $\epsilon_\phi = \phi - \hat{\phi}$, $\epsilon_\nu = \nu - \hat{\nu}$, and the constant $\|w\|^2 = \sum_{n=-\infty}^{\infty} w(n)^2$. Then, assuming a large $W$, high-resolution, and a smooth masking curve, the perceptual distortion can be approximated as $D \approx \frac{1}{2\pi} \int_0^{2\pi} \left( \epsilon_a^2 + \epsilon_\phi^2 + \epsilon_\nu^2 \right) \, d\omega$.

Similarly to [2, 3], we assume the perceptual weighting function to be quantized and transmitted as side information. To the best of our knowledge, the problem of joint quantization of the perceptual weighting function and the sinusoidal parameters remains unsolved and we will defer from any further discussion of this. Setting $n_0 = -\frac{W}{2}$, and using a Taylor expansion, the distortion can be shown to be

$$D \approx \frac{\mu_x(a,\phi,\nu)}{2\|w\|^2} \left( \epsilon_a^2 + \epsilon_\phi^2 + \epsilon_\nu^2 \sigma^2 \right),$$  

(2)

with $\sigma^2 = \frac{1}{\|w\|^2} \sum_{n=-W/2}^{W/2-1} w(n)^4 n^2$. We observe from (2) that the amplitude, phase and frequency can be quantized independently using the $l_2$ norm by assuming a high-resolution, i.e., $a_\hat{a} \approx \hat{a}^2$. This provides inspiration to the proposed multiple description spherical trellis-coded quantization (MDSTCQ) scheme consisting of multiple description quantizers, one for each of the parameters $a, \phi$ and $\nu$. We here focus on the common case of two descriptions. In this case, a low quality description is obtained when only one description is received. The resulting distortion, called the side distortion, is denoted as $D_s$, with $s \in \{1, 2\}$. The low quality reconstructions of $(a, \phi, \nu)$ is written as $(\hat{a}_s, \hat{\phi}_s, \hat{\nu}_s)$. When both descriptions are received, the resulting distortion is referred to as the central distortion $D_c$, and is based on the reconstruction point $(\hat{a}_c, \hat{\phi}_c, \hat{\nu}_c)$. The aim of this work is to protect the sinusoidal parameters transmitted over a packet erasure channel where packets are dropped independently with probability $p$. Assuming a balanced side distortion, i.e., $E[D_1] = E[D_2]$, the average distortion in such a network is

$$E[D] = (1 - p)^2 E[D_c] + 2p(1 - p) E[D_s] + p^2 E[x^2],$$  

(3)

where $E[x^2]$ is the variance of the audio signal.

### 3. THE PROPOSED QUANTIZER

We now proceed to propose a modified multiple description trellis-coded quantizer (MDSTCQ) inspired by the two-stage coding scheme in [10]. The first stage is to quantize the input signal $y$ using two uniform side quantizers, $Q_1$ and $Q_2$ that are offset to each other and have step-sizes equal to the reciprocal value of the point density, $g_\nu$, as shown in Fig. 1. In the second stage, we perform joint quantization using the joint Voronoi region, which is half the size of the Voronoi region of the side quantizers. Here, $N$ reconstruction points are sorted as $c_1 < c_2 \cdots < c_{N}$ and partitioned into four subsets $C_q = \{q, q+1, \cdots, q + 4\}$, where $q \in \{1, 2, 3, 4\}$. In trellis-coded quantization, the transitions in the trellis specify $C_q$ by one bit, and $\log_2(N/4)$ bits are used to specify the quantization index within $C_q$. Since this refined trellis information is only utilized when both descriptions are received, it is easily split into the two descriptions whereby the otherwise difficult index assignment is solved. Assuming high-resolution such that the probability density function (pdf) inside the Voronoi regions $V_i$ of the side quantizers $Q_i$ is uniform, the mean square-error distortion for each side quantizer can be written as $E[D_q] = \sum_{i=1}^{4} f_{Y}(y) g_q(y)^2 dy \approx g_q^2/12$ with $f_{Y}(y)$ being the source pdf and $\epsilon_q = y - \bar{y}$. An exact expression for the expected distortion does not, however, exist for the TCQ. Therefore, we will employ the approximation proposed in [11] where the expected distortion is written as the distortion for a uniform quantizer corrected by a factor $\Gamma$, which depends on the trellis structure, number of states and dimension, that has been determined numerically in [4]. Also, assuming high-resolution the central distortion can be written as $E[D_c] \approx \frac{1}{2\pi} \int_{\mathbb{R}} E[D_c]$. The entropy of a MMDSTCQ per description is given by $H \approx h(Y) + \int f_{Y}(y) \log_2(g_q(y)dy + \frac{1}{2} \log_2\left(\frac{N}{4}\right))$, where $h(Y)$ is the differential entropy of the source $Y$.

We will now introduce the details of the proposed MDSTCQ coding scheme consisting of three MMDSTCQs, one for each of $a, \phi$ and $\nu$. In deriving the optimal MDSTCQ design, we need expressions for the quantization point densities and the number $N$ for the three MMDSTCQs. To obtain these, we first introduce the joint pdf $f(A, \phi, \nu)$ thereafter we can express the expected side distortion as

$$E[D_q] \approx \sum_{i_a \in I_A} \sum_{i_{\phi} \in I_{\phi}} \sum_{i_{\nu} \in I_{\nu}} \int_{V_{i_a}} \int_{V_{i_{\phi}}} \int_{V_{i_{\nu}}} f(A, \phi, \nu) \frac{1}{2} \mu_\nu(\nu) \left[ \left( \epsilon_a^2 + a_\hat{a} (\epsilon_{\phi}^2 + \epsilon_{\nu}^2 + \sigma a_\hat{\phi} a_\hat{\nu} \epsilon_{\phi} \epsilon_{\nu}) \right) \right] \, dA \, d\phi \, d\nu$$

$$\frac{|w|^2}{24} \int_{A} \int_{\phi} \int_{\nu} f(A, \phi, \nu) \mu_\nu(\nu) \left( g_q^2 + a_\hat{a}^2 (g_q^2 + \sigma g_q^2) \right) \, dA \, d\phi \, d\nu$$

(4)

by assuming that $\mu_\nu(a,\phi,\nu)$ is constant over the joint Voronoi region of $a, \phi, \nu$. We have assumed high-resolution such that $a_\hat{a} \approx \epsilon_a^2$ and the probability mass function of the reconstruction points, $Pr(\hat{a}_s, \hat{\phi}_s, \hat{\nu}_s)$ can be found from the joint pdf $f(\hat{a}_s, \hat{\phi}_s, \hat{\nu}_s)g_q^{-1}(g_q^{-1}g_q^{-1})$ [3] for more details on this]. Here, the quantization point densities for $a, \phi, \nu$ are written as $g(a,\nu,\nu)$, although they at this point still depend on $a, \phi, \nu$. 

![Fig. 1. Structure of the MMDSTCQ with the vertical lines being the Voronoi regions of the two side quantizers $Q_i$, and dots the refined reconstruction points.](image-url)
Similarly, we can express the expected central distortion as
\[
E[D_0] \approx \frac{\|w\|^2}{96} \left[ \int_A \int_\nu \int_{\nu'} f_{\cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot 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investigate the impact of the number of jointly quantized sinusoids and the number of states in the trellis on the expected distortion. Furthermore, we will illustrate the impact of the number of jointly quantized sinusoids and the number of states in the trellis on the expected distortion. Experiments have shown significant performance improvements of the proposed scheme as the number of dimensions is increased. Furthermore, a significant performance gain compared to the single description spherical trellis-coded quantization scheme of [4] has been observed for a large range of packet-loss probabilities.

5. CONCLUSION

We have proposed multiple description spherical trellis-coded quantization of sinusoids. The quantizers are suitable for parametric audio coding where the number of sinusoids may vary and for transmission over unreliable networks like the Internet. Under high-resolution assumptions we have derived analytical expressions for the optimal design and the expected perceptual distortion for a given target entropy and packet-loss probability. Experiments have shown significant performance improvements of the proposed scheme as the number of dimensions is increased. Furthermore, a significant performance gain compared to the single description spherical trellis-coded quantization scheme of [4] has been observed for a large range of packet-loss probabilities.

6. REFERENCES


