HIGH-QUALITY AUDIO TRANSFORM CODED EXCITATION USING TRELLIS CODES

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ABSTRACT

A trellis source code and novel variable-length lossless code are used in transform coded excitation audio coding. Implemented within the extended adaptive multi-rate wideband (AMR-WB+) audio coding framework, the proposed quantization and lossless coding method provide between 0.4 and 0.7 dB increase in signal-to-noise ratio over the E_8 lattice VQ and spherical lossless code used in the AMR-WB+ standard.

***Index Terms*—** transform coded excitation, trellis code

1. INTRODUCTION

Transform coded excitation (TCX) is used in the AMR-WB+ audio coding standard [1], as a possible coding mode for the compression of wide-band speech and music. For encoding clean speech, the ACELP mode is selected most often (e.g. 59%), while for encoding music the TCX mode is selected dominantly (e.g. 95%). High quality coding of music-like signals can be achieved by the availability of the TCX mode.

The TCX coding in [1] is summarized as follows. 1) Frame sizes of 256, 512, or 1024 are expanded by 12.5% using frame overlap, and 288-, 576-, or 1152-point discrete Fourier transforms (DFT) are computed. 2) The real and imaginary parts of the first half of the DFT coefficients are sequentially ordered, and scaled using a spectral pre-shaping. 3) The energy in sequential blocks of 8 coefficients is computed and used to determine a frame scale factor. Scaled blocks with energy less than a threshold are set to the zero vector and encoded using a 1-bit codeword. The remaining blocks are encoded using a lattice VQ. The frame scale factor is iteratively adjusted so that the total encoding rate for the frame does not exceed a target bit-rate. 4) An inverse DFT is applied to the quantized coefficients and a TCX sequence generated. In closed-loop mode, algebraic code-excited linear prediction (ACELP), and TCX derived for the three different frame sizes, are evaluated in various combinations [1] and the best excitation mode selected for each audio frame. The encoding rate can be determined from the (scaled) block energy, so the rate control is accomplished prior to quantization and lossless coding. The lattice VQ provides granular gain [2] over scalar quantization. The lossless coding, which is only done if the TCX mode is selected, uses a spherical codebook based on the squared radius of the lattice codevectors.

This paper describes an alternative method of quantization and lossless coding for use in TCX-type coding. The quantization is performed using trellis coded quantization (TCQ) [3] based on cosets of quantization reproduction levels. A novel lossless code is used to encode the TCQ levels. The paper is organized as follows. Section 2 briefly summarizes the lattice VQ used in the AMR-WB+ standard and provides a context for understanding the TCQ performance. Section 3 summarizes the trellis source coding and Section 4 describes a novel method for the lossless coding of the TCQ indices. Section 5 presents simulation results comparing the TCQ and lossless coding to the lattice VQ performance, and conclusions.

2. RE$_8$ LATTICE VQ

The simplest lattice is the integer lattice, $Z^n = Z \times Z \times \cdots \times Z$, consisting of all integer n-tuples, $\underline{z}$, where Z denotes the set of integers. Scaling all lattice vectors by the constant Δ yields the scaled cubic lattice, ΔZ^n. A uniform scalar quantizer (SQ) can be constructed to have quantization regions defined by a scaled (and possibly shifted) integer lattice. For example, a mid-tread uniform SQ with step size Δ has quantizer outputs ΔZ and quantization regions $[(i-1/2)\Delta,\ (i+1/2)\Delta),\quad i \in Z$. Assuming that the source input is uniform over each quantization region, the quantization error is uniform over $[-\Delta/2,\ \Delta/2)$ and the mean-square error distortion is

$$D = E\{(X-Y)^2\} = \Delta^2/12. \tag{1}$$

The n-fold Cartesian product of uniform scalar quantizers is an n-dimensional cubic lattice VQ. Assuming a memoryless input that is uniform over each quantization cell, the MSE per dimension is also given by (1).

After the cubic lattice, the D_n lattice is the simplest lattice, defined as $D_n = \{\underline{z} \in Z^n :\ \sum z_i = \text{even}\}$. That is, the D_n lattice is a subset of the cubic lattice, and consists of the cubic lattice vectors whose sum of components is even. To use the D_n

lattice for vector quantization requires finding the closest D_n lattice vector to an input vector, $\underline{x}$. This is easily accomplished [4]. The granular gain of a lattice is the ratio of the normalized MSE for the cubic lattice to the normalized MSE for the lattice. The granular gain for the D_n lattice is known to be [2] 0.366 dB for n = 4, and 0.405 dB for n = 8.

The E_8 lattice is typically defined as [2] the union of the D_n lattice and the D_n lattice offset by the vector $(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2})$, i.e.,

$$E_8 = D_8 \bigcup \{D_8 + (\tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2}, \tfrac{1}{2})\}.$$

Scaling all lattice vectors by 2 yields the lattice

$$2E_8 = 2D_8 \bigcup \{2D_8 + (1,1,1,1,1,1,1,1)\}. \qquad (2)$$

The right side of (2) is the definition of the "RE_8" lattice defined in the AMR-WB+ standard [1] (and in [5]). Unfortunately, this notation is inconsistent with much of the lattice literature, and in particular with Forney's definition [6] of the rotation "R" operator useful for defining sub-lattices and lattice partitions. With this inconsistency noted, the remainder of the paper will follow the AMR-WB+ standard notation, with the understanding that RE_8 means $2E_8$ in (2). Conway and Sloane calculate the MSE per quantization cell of the E_8 lattice as 929/12960, so that the granular gain of the E_8 and (RE_8) lattice is 0.654 dB,

The RE_8 lattice VQ [1, 5] uses a spherical lossless code to encode the lattice codevectors as binary codewords. The spherical code assigns equal length codewords to lattice codevectors of the same squared radius. The 8-dimensional block encoding rates are restricted to 1 bit (for the zero codevector) and $5m$ bits, for m = 2, 3, 4, … .

3. TRELLIS SOURCE CODING

Consider as a reference design the uniform scalar quantizer with step size $\Delta = 2$ and output levels $y \in 2Z$. A better performing vector quantizer (VQ) is based on the 8-dimensional RE_8 lattice, which is a sub-lattice of $2Z^8$, and has a Voronoi region volume equal to that of the $2Z^8$ VQ. So, with respect to the cubic lattice $2Z^8$, the RE_8 lattice VQ offers an expanded set of quantizer output levels. Specifically, instead of reproduction levels restricted to the even integers, the RE_8 lattice VQ also allows odd integers as reproduction levels, but subject to certain 8-dimensional vector-based constraints (e.g., not all vectors with odd integers are allowed codevectors in the lattice). Intuitively, then, the RE_8 lattice has an advantage over the $2Z^8$ lattice in that the former has an expanded set of reproduction levels, on a per-dimension basis.

A trellis source code offers improvement over scalar quantization by using an expanded set of reproduction levels. The most basic trellis coded quantizer [3] doubles the set of per-dimension reproduction levels over that of a scalar quantizer, and uses a rate-1/2 convolutional code to match the scalar quantizer encoding rate. Again with reference to the cubic lattice $2Z^8$ VQ, a simple TCQ would use an expanded codebook (Z per dimension), partitioned into four subsets, and a rate-1/2 convolutional code to assign subsets to the trellis branches (see [3]). Such a TCQ design will offer improvement over SQ, and also provide some improvement over the RE_8 lattice VQ because the effective TCQ dimensionality can be much larger than that of the 8-dimensional RE_8 lattice. Based on the granular gain of the TCQ [3], an 8-state trellis code will provide roughly 0.43 dB coding gain over the RE_8 lattice VQ, and a 16-state trellis code will provide a coding gain of roughly 0.5 dB over the RE_8 lattice VQ.

We consider TCQ codebooks of the form shown in Fig. 1. Setting the "dead-zone" parameters, A=0, B=0, yields a two-zero codebook (adopted for use in JPEG2000, part 2 [7]), while setting A=0.5, B=0.5 yields a no-zero-level uniform codebook.

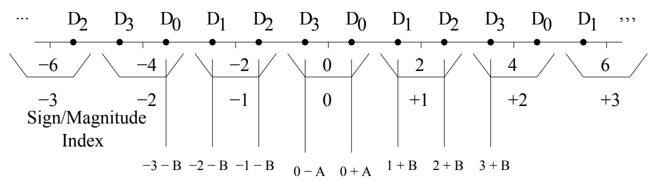

Fig. 1. TCQ Codebook with dead-zone parameters A and B.

The TCQ codebook is partitioned into cosets, and the cosets are assigned as branch labels in a trellis. One such assignment is shown in Fig. 2, where the trellis is defined by the convolutional encoder shown in Fig. 3.

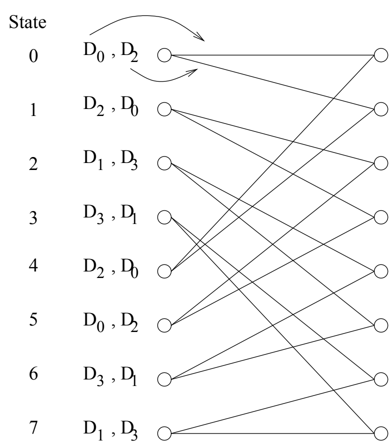

Fig. 2. TCQ trellis and branches labeled with cosets.

TCQ encoding is performed using the Viterbi algorithm. After encoding, the sequence of TCQ reproduction levels is represented as a sequence of integer indices. Fig. 1 shows one such indexing assignment, in sign-magnitude form. For a general description of TCQ, see [3].

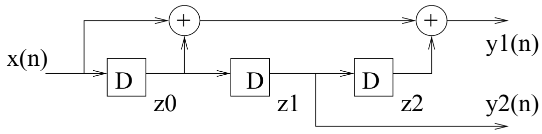

Fig. 3. Convolutional encoder defining trellis in Fig. 2.

4. LOSSLESS CODING OF TCQ INDICES

If the TCQ levels are indexed in sign/magnitude form, it is possible to losslessly encode them and form an embedded bit-stream (e.g., [7]). However, this format may result in some loss in coding efficiency, unless a trellis-state-dependent lossless coding method is used. As an alternative, we map the sign/magnitude index representation into a novel non-negative integer index. This mapping is summarized in Table 1 for the $C_0 = D_0 \cup D_2$ union coset, and in Table 2 for the $C_1 = D_1 \cup D_3$ union coset, assuming dead-zone codebook parameters A=B=0.5. Since each non-negative index represents one level in C_0 and one level in C_1, decoding is accomplished by following the path through the trellis to resolve the ambiguity.

Table 1. Mapping sign-magnitude index to non-negative integer index for $C_0 = D_0 \cup D_2$ union coset.

Coset	D_0	D_2	D_2	D_0	D_0	D_2	D_2
$C_0 = D_0 \cup D_2$ levels	0.5	-1.5	2.5	-3.5	4.5	-5.5	6.5
Sign-magnitude index	0	-1	+1	-2	+2	-3	+3
Non-negative integer index	0	1	2	3	4	5	6

Table 2. Mapping sign-magnitude index to non-negative integer index for $C_1 = D_1 \cup D_3$ union coset.

Coset	D_3	D_1	D_1	D_3	D_3	D_1	D_1
$C_1 = D_1 \cup D_3$ levels	-0.5	1.5	-2.5	3.5	-4.5	5.5	-6.5
Sign-magnitude index	0	+1	-1	+2	-2	+3	-3
Non-negative integer index	0	1	2	3	4	5	6

Observe that the TCQ levels in C_1 are the negative of those in C_0. Moreover, if the codebook is uniform (e.g., for either the case A=B=0, or A=B=0.5), and if the source probability density function, $p(x)$, is zero-mean, symmetric about the origin, and decreasing in $|x|$, then the probabilities of the non-negative indices are decreasing as index size increases, and identically distributed for the two union cosets. Hence, in this case it follows that efficient lossless coding of the non-negative indices can be accomplished using a trellis-state-independent lossless code.

Table 3 compares the zeroeth-order entropy of the TCQ sign-magnitude and non-negative integer indices for encoding the DFT coefficients in the TCX mode of the AMR-WB+ algorithm. There is a clear coding advantage to using to using the non-negative index format.

Table 3. Comparison of TCQ index entropies.

	Stereo Music		Stereo Speech	
	Non-Neg. Index	Sign-Mag. Index	Non-Neg. Index	Sign-Mag. Index
Zeroeth-order Entropy	1.72	1.78	1.70	1.79

Let $x(i)$ denote the TCQ (non-negative integer) indices, representing the quantized DFT coefficients. From the ordering of the DFT values is follows that the index pair ($x(2n)$, $x(2n+1)$) corresponds to the real and imaginary part of the nth DFT coefficient. Let $k(n) = x^2(2n) + x^2(2n+1)$ be the squared radius of the index pair. Since the TCQ indices are non-negative integers, index pairs can be enumerated based on their squared radius, k. This enumeration corresponds to the number of 2-d integer lattice points in the first quadrant. A lossless code for encoding TCQ index pairs is designed based on a one-to-one mapping from an index pair, ($x(2n)$, $x(2n+1)$), to a squared radius, enumeration pair, ($k(n)$, $e(n)$), where the enumeration index, e, is used to represent the various possible index pairs of a given squared radius. Since some values of k cannot occur (e.g., k = 3), it is convenient to eliminate the values of k that cannot occur, and simply map k to the sequential non-negative integer index m. The lossless code is structured as follows: A variable-length code, C_m, is used to encode m; a fixed-length enumeration code, C_e, is used to encode e, conditioned on the value of m. Table 4 lists the values of m, the number of bits needed to encode e, and the form of the index pair, for the first few values of k.

The variable-length code used to encode $m(n)$ can be of any convenient design. For example, using a Huffman code provides average codeword length about 0.14 bit/index less than the zeroeth-order index entropy. Extending the idea, two pairs of TCQ indices can be jointly coded by first mapping ($x(4n)$, $x(4n+1)$, $x(4n+2)$, $x(4n+3)$) into ($m(2n)$, $e(2n)$, $m(2n+1)$, $e(2n+1)$). Pairs ($m(2n)$, $m(2n+1)$) are then jointly coded using a variable-length code (e.g., using a Huffman code), and $e(2n)$, $e(2n+1)$ are enumeration coded as before (conditioned on the value of squared radius). Note that the sequence $m(n)$ corresponds to the squared DFT magnitude spectrum, so that dependence in the magnitude spectrum can be exploited by proper design of a lossless code for encoding the $m(n)$ sequence. The simulation results in Section 5 are based on this form of joint coding of 4-tuples of TCQ indices.

Table 4. Enumeration codeword length and codevector leaders for $0 \le m \le 7$.

k	0	1	2	4
m	0	1	2	3
# e bits	0	1	0	1
$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 1 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 1 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 2 \\ 0 \end{pmatrix}$
k	5	8	9	10
m	4	5	6	7
# e bits	1	0	1	1
$\begin{pmatrix} x_1 \\ x_2 \end{pmatrix}$	$\begin{pmatrix} 2 \\ 1 \end{pmatrix}$	$\begin{pmatrix} 2 \\ 2 \end{pmatrix}$	$\begin{pmatrix} 3 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 3 \\ 1 \end{pmatrix}$

5. SIMULATION RESULTS AND CONCLUSIONS

The TCQ and lossless coding was implemented in the AMR-WB+ framework to allow direct comparison with the RE_8 lattice VQ performance. In the TCX coding mode using the RE_8 lattice VQ, the AMR-WB+ energy threshold algorithm was used to select those blocks to be encoded as zero (and termed here as "insignificant"). This threshold was then used as a starting point for the TCQ-based coding, and the threshold iteratively adjusted so that the total bit rate needed for TCQ encoding the frame satisfied the frame bit rate requirement. Typically this resulted in a small change in the number of insignificant blocks, compared to the RE_8 lattice VQ-based coding. A 16-state trellis and the TCQ codebook parameters A=B=0.5 were used in the simulations. Since the RE_8 lattice VQ and TCQ bit rates are adjusted to satisfy the frame rate requirement, the relative performance of the two coding methods is evaluated by the coding gain defined as

$$G = 10\ \log_{10} \frac{MSE_{RE8\ VQ}}{MSE_{TCQ}}\ \text{dB}, \qquad (3)$$

where the respective mean-square errors (MSE) are averages over all blocks and all frames.

Table 5 summarizes the improvement of the TCQ coding performance compared to the RE_8 lattice VQ for stereo speech and music sources. Each source was of 236 sec duration with a sampling rate of 48 kHz. The speech data was selected roughly equally from male and female speakers of Japanese, English, French, German, Chinese, and Korean. The music was a combination of pop, jazz, orchestra, and solo instrumental. The fraction of blocks set to the zero vector and encoded using a single bit can range from about 40% to 60%, depending on the encoding rate. Since most of these insignificant blocks are common to both the RE_8 lattice VQ and TCQ coding, they contribute roughly the same amount to the respective overall MSEs, and in particular do not contribute to the coding gain in (3). Hence, for the significant blocks alone, the coding advantage of the TCQ-based method is somewhat higher than reflected in the overall coding gains in Table 5. The granular gain of the 16-state trellis [3] suggests a TCQ coding advantage of about 0.50 dB over the RE_8 lattice VQ. This was consistently observed for the coding of significant blocks for the various frame sizes and encoding rates. The variation in overall coding gain in Table 5 is due primarily to the relative efficiency of the lossless code used with the TCQ, compared to the spherical lossless code used with the RE_8 lattice VQ. The TCQ appears more efficient than the RE_8 lattice VQ for music and for shorter frame sizes. In addition, some further increase in coding gain is to be expected by increasing the joint TCQ index coding to 8-dimensional, to match the dimensionality of the RE_8 lattice VQ lossless coding.

Table 5. Coding gain (in dB in the spectrally pre-shaped transform domain) of the TCQ and lossless coding compared to the RE_8 lattice VQ. (16-state trellis and TCQ codebook parameters A=B=0.5.)

		Frame Size		
	Rate (kb/s)	256	512	1024
Music	16	0.71	0.58	0.48
	24	0.56	0.47	0.43
	32	0.51	0.44	0.41
Speech	16	0.65	0.55	0.48
	24	0.53	0.47	0.43
	32	0.50	0.46	0.43

6. REFERENCES

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