ELECTROCARDIOGRAM COMPRESSION USING LAPPED ORTHOGONAL TRANSFORM

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ABSTRACT : This paper presents the results of a study to examine the feasibility of Electrocardiogram (ECG) data compression using the lapped orthogonal transform (LOT). The blocking effects in the reconstructed signal are shown to be reduced, while the bit rate and the performance of the proposed scheme remain the same as compared with the traditional discrete cosine transform. A fast computing algorithm of the LOT adaptable for VLSI architecture is also described.

1. INTRODUCTION

With the hundreds of millions of Electrocardiograms (ECG) being recorded yearly in the world, ECG data compression has been an important problem in computer-based medical systems. ECG compression is used in an ambulatory ECG monitoring system [6]. This paper presents the results of a study to examine the feasibility of ECG data compression using the Lapped Orthogonal Transform (LOT).

The existing methods for ECG data compression can be classified into two main categories: the direct data handling methods and the transform methods. Many direct methods have been proposed in the literature [3,4]. These include the turning-point algorithm, the amplitude zone time epoch coding (AZTEC) algorithm, the coordinate reduction time encoding scheme, the delta code method, and a compression method based on prediction, interpolation and entropy coding of the ECGs [9]. Most of these techniques can operate in real-time, however the reconstructed ECGs are not always visually acceptable to the cardiologist.

In the transform method, the signal is generally divided into blocks of N samples; each block is then projected into a particular basis functions set via an orthogonal transform. This can be expressed as $\mathbf{X} = \mathbf{A}\,\mathbf{x}$, where $\mathbf{A}$ is the transform matrix, $\mathbf{X}$ and $\mathbf{x}$ are the vectors for the transform domain and the input respectively. The dominant transform coefficients are then quantized for storage or/and transmission. Orthogonal transforms such as discrete cosine transform (DCT), Karhunen-Loeve transform (KLT), Walsh transform and Haar transform have been used in ECG compression [5]. Most of the transform methods suffer from the basic problem of blocking effect. This is the natural consequence of processing each block independently. As a result, the decoded ECG may introduce artifacts into the QRS complex if it was sampled near the boundary of the block. In addition, most of the transform coding methods require the block length of the transform to be large (>128). This means that a ECG compression by a transform method cannot operate in real-time.

In this paper, a new class of transform for signal coding, collectively referred to as the lapped orthogonal transform (LOT) introduced by Cassereau [2] and Malvar [1], is applied to electrocardiogram compression. The LOT has the property of reducing the blocking effect while maintaining the same bit-rate as traditional transform methods. Moreover, it is shown that the LOT may be decomposed into two stages with the DCT as its first stage and a second stage consisting of butterflies or other transforms. This implies that the proposed method has the potential of operating in real-time through various fast algorithms for DCT and/or using DCT VLSI chips. In section 2, we review the properties of the LOT. A fast computation approximation to the LOT is presented in section 3. In section 4, we present the results obtained by applying the LOT to ECG data.

2. BASIC PROPERTIES OF THE LOT

In this section, we outline the basic properties necessary for the LOT to be able to transform overlapping blocks without increasing the number of coefficients. In addition, the properties of the optimal KLT and its practical substitute, the DCT, are applied to the LOT.

For the block length of M, the LOT is characterized by a set of M basis functions, each of length N > M (usually N=2M). Hence, there 1/2 block length overlap between adjacent blocks. The 2MxM LOT matrix **P** has a basis function in each of its columns. In order to keep the direct and inverse transform matrices as the transpose of each other, so that the direct transform flowgraph is just the transpose of the inverse flowgraph, each LOT basis function must be orthogonal not only to the other functions in the same block but also to the functions in the two adjacent blocks. In terms of the matrix **P** the following conditions must hold

$$\mathbf{P}'\,\mathbf{P} = \mathbf{I} \tag{1}$$

and

$$\mathbf{P}'\,\mathbf{W}\,\mathbf{P} = \mathbf{0} \tag{2}$$

where

$$\mathbf{W} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ \mathbf{0} & \mathbf{0} \end{bmatrix} \tag{3}$$

Equation (1) enforces orthogonality of the basis functions within the same block, whereas (2) enforces orthogonality of the overlapping portions of the basis functions of the adjacent blocks.

In addition to the above orthogonality conditions, a good LOT matrix **P** is expected to have some additional properties not unlike that of the DCT and KLT [1]. Two of these properties are most relevant: odd-even symmetry and the smoothness of the low-order basic functions.

The basis functions of the KLT are defined as the eigenvectors of the autocorrelation matrix, $\mathbf{R_{xx}}$, for a first order Gaussian Markov process

$$\mathbf{R_{xx}} = \begin{bmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{N-1} \\ \rho & 1 & \rho & \cdots & \rho^{N-2} \\ \vdots & & & & \vdots \\ \rho^{N-2} & \cdots & \rho & 1 & \rho \\ \rho^{N-1} & \cdots & \rho^2 & \rho & 1 \end{bmatrix} \tag{4}$$

where ρ is the intersample correlation coefficient. Since the above matrix is symmetric and Toeplitz, its eigenvectors are either symmetric or antisymmetric, i.e. $\mathbf{R_{xx}}\ \mathbf{y} = \lambda\ \mathbf{y} \Rightarrow \mathbf{J}\ \mathbf{y} = \mathbf{y}$ or $\mathbf{J}\ \mathbf{y} = -\mathbf{y}$, where $\mathbf{J}$ is the 'counter identity' or 'opposite diagonal' matrix

$$\mathbf{J} = \begin{bmatrix} 0 & \cdots & \cdots & 0 & 1 \\ 0 & \cdots & 0 & 1 & 0 \\ \vdots & & & & \vdots \\ 1 & 0 & \cdots & \cdots & 0 \end{bmatrix} \qquad (5)$$

It is reasonable to expect that the LOT should have this kind of symmetry, i.e. it should be formed by N/2 symmetric (even) vectors and N/2 antisymmetric (odd) vectors. It turns out that the DCT functions also exhibit this even-odd symmetry.

It has been shown that the eigenvectors of $\mathbf{R_{xx}}$ are exactly sampled sinusoids, for any value of ρ. The DCT basis functions are also sampled sinusoids. Hence, it is reasonable to expect that at least the lower order vectors of the LOT should be slowly varying sequences.

3. FAST COMPUTATION OF LOT

It has been shown that the orthogonality conditions are satisfied if P is of the form [1]

$$\mathbf{P} = \frac{1}{2}\begin{bmatrix} \mathbf{De - Do} & \mathbf{De - Do} \\ \mathbf{J(De - Do)} & \mathbf{-J(De - Do)} \end{bmatrix} \mathbf{Z}\ \mathbf{R} \qquad (6)$$

where $\mathbf{Z}$ is an orthogonal matrix of order M, $\mathbf{J}$ is the counter-identity matrix, $\mathbf{R}$ is the permutation matrix, and $\mathbf{De}$ and $\mathbf{Do}$ are the Mx(M/2) matrices containing the even and odd DCT basis functions, respectively.

If $[\mathbf{A}]_{nk}$ denotes the element of a matrix $\mathbf{A}$ in the n^{th} row and the k^{th} column, then we have

$$[\mathbf{De}]_{nk} = c(k)\sqrt{2/M}\cos(2k\pi(n+1/2)/M)) \qquad (7)$$

$$[\mathbf{Do}]_{nk} = \sqrt{2/M}\cos(\pi\,(2k+1)\,(n+1/2)/M)) \qquad (8)$$

for n = 0, 1, ..., M-1 and k = 0, 1, ..., M/2 - 1, where

$$c(k) = \begin{cases} \sqrt{1/2} & k=0 \\ 1 & \text{otherwise} \end{cases} \qquad (9)$$

Equation (6) defines a family of LOTs, since any orthogonal matrix $\mathbf{Z}$ can be used. $\mathbf{Z}$ was obtained as the orthogonal matrix that maximizes the transform coding gain [7], by means of the solution of an eigenvector problem [1]. In [8], $\mathbf{Z}$ was obtained, through a QR decomposition, as the orthogonal matrix that leads to good stopband attenuations for the frequency response of all filters. In both cases, the $\mathbf{Z}$ obtained can be closely approximated with only M/2 - 1 butterflies, and the solutions are very similar [1,8].

In the following, a new definition of the LOT that is fast-computable for any block length is introduced. The basic idea is to use another choice of **Z**. We have found that the product of DST-IV and DCT-II also has a similar form to the **Z** in [1,8], i.e. with highly dominant components along the diagonal. The new **Z** is as follows

$$\mathbf{Z} = \begin{bmatrix} \mathbf{I} & \mathbf{0} \\ \mathbf{0} & \mathbf{S}^{IV}_{M/2}\,\mathbf{C}^{II}_{M/2} \end{bmatrix} \tag{10}$$

here $\mathbf{S}^{IV}$ and $\mathbf{C}^{II}$ are the DST-IV and the DCT-II matrices defined by Wang [10]

$$[\mathbf{C}^{II}{}_K]_{kr} = c(k)\,\sqrt{2/K}\cos(\pi\, k\,(r+1/2)/K) \tag{11}$$

$$[\mathbf{S}^{IV}{}_K]_{kr} = \sqrt{2/K}\sin(\pi\,(k+1/2)(r+1/2)/K) \tag{12}$$

for k,r = 0, 1, ..., M/2-1, where c(k) is defined in (9). We note that $\mathbf{S}^{IV}_{M/2}\,\mathbf{C}^{II}_{M/2} = \mathbf{C}^{II}_{M/2}\,\mathbf{S}^{IV}_{M/2}$, since $\mathbf{S}^{IV}_{M/2}$ is a unitary matrix. The basis functions of the proposed LOT are shown in figure 1. We note that the basis functions decay towards zero at their boundaries. The discontinuity from zero to the boundary is much lower than that of the corresponding DCT functions. This is one of the main reasons why the blocking effects are reduced. The flowgraph of the LOT for the proposed method is shown in figure 2.

Since this LOT implementation consists of a DCT in the first stage and a DCT-II DST-IV in the second stage, existing fast algorithms for the above transforms can be used to speed up the coding/decoding process. Furthermore, due to the popularity of the DCT in digital signal processing, a number of VLSI designs have been proposed. This makes the VLSI implementation of the proposed fast LOT feasible, with only a number of additional shift registers.

4. EXPERIMENTAL RESULTS AND DISCUSSION

In this paper, the ECG signal of a horse is used for the experiments. The ECG signals are digitized using a sampling rate of 200Hz. Each sample has an 8-bit resolution (0-255). The ECG sequences are fed to the LOT coder in figure 2. A number of dominant coefficients are selected to represent each ECG in the transform domain, the remaining coefficients are set to zero. In this study, the bit-rate of 16:5 is used for different blocklengths, i.e. 16:5, 32:10, etc. This ratio is selected since it is inside the range in which the LOT is found to be better than the DCT, see figure 5. The inverse transform is taken to retrieve the ECG. A QRS complex reconstruction with different block lengths is shown in figure 3. From these reconstructions, the LOT is observed to provide better reconstruction. It is interesting to note that for the same bit rate, transformations with longer block lengths (64, 128) provide better reconstructions for both DCT and LOT. This however leads to increased computation time, which may not be desirable for practical applications, such as in the ambulatory ECG monitoring system. Whereas for shorter lengths, the LOT gives noticeable improvements. This is also observed in the variation of the mean squared error (mse) measures of the DCT and LOT coded waveform versus different block lengths, as shown in Table 1.

In figure 4, reconstructions of the ECG under two extreme conditions are shown - one normal and noise-free, the other abnormal and noisy. In these cases, the compression ratio is 128:40. It is observed that the LOT and DCT have produced similar waveforms. This is mainly due to the compaction of the waveforms for display purposes. The mse values of these waveforms however show that the LOT performs better than the DCT (Table 1).

5. CONCLUSION

We have presented an alternative to ECG compression using the LOT. Results have shown that the blocking effect in the reconstructed ECGs has been reduced significantly compared to the traditional transform coding techniques. The proposed system achieves this without sacrificing the bit rate or the performance. The technique can be used in an ambulatory ECG monitoring systems or an ECG storage systems.

REFERENCES

[1] H.S. Malvar and D.H. Staelin, "The LOT: Transform Coding Without Blocking Effects," *IEEE Trans. Acoust., Speech, Signal Processing,* vol. ASSP-37, pp553-559, April 1989.

[2] P.M. Cassereau, D.H. Staelin and G. de Jager, "Encoding of Images based on a Lapped Orthogonal Transform,", *IEEE Trans. Comm.*, vol. COMM-37, pp189-193, Feb. 1989.

[3] J.R. Cox, F.M. Nolle, and R.M. Arthur, "Digital analysis of electroencephalogram, the blood pressure wave, and the ECG," *Proc. IEEE*, vol. 60, pp.1137-1164, 1972.

[4] J.P. Abenstein and W.J. Tompkins, "A new data-reduction algorithm for real-time ECG analysis," *IEEE Trans. Biomed. Eng.*, vol. BME-29, pp.43-48, Jan. 1982.

[5] N. Ahmed, P.J. Milne, and S.G. Harris, "Electrocardiographic Data Compression via Orthogonal Transforms," *IEEE Trans. Biomed. Eng.*, vol. BME-22, pp. 484-487, Nov. 1975.

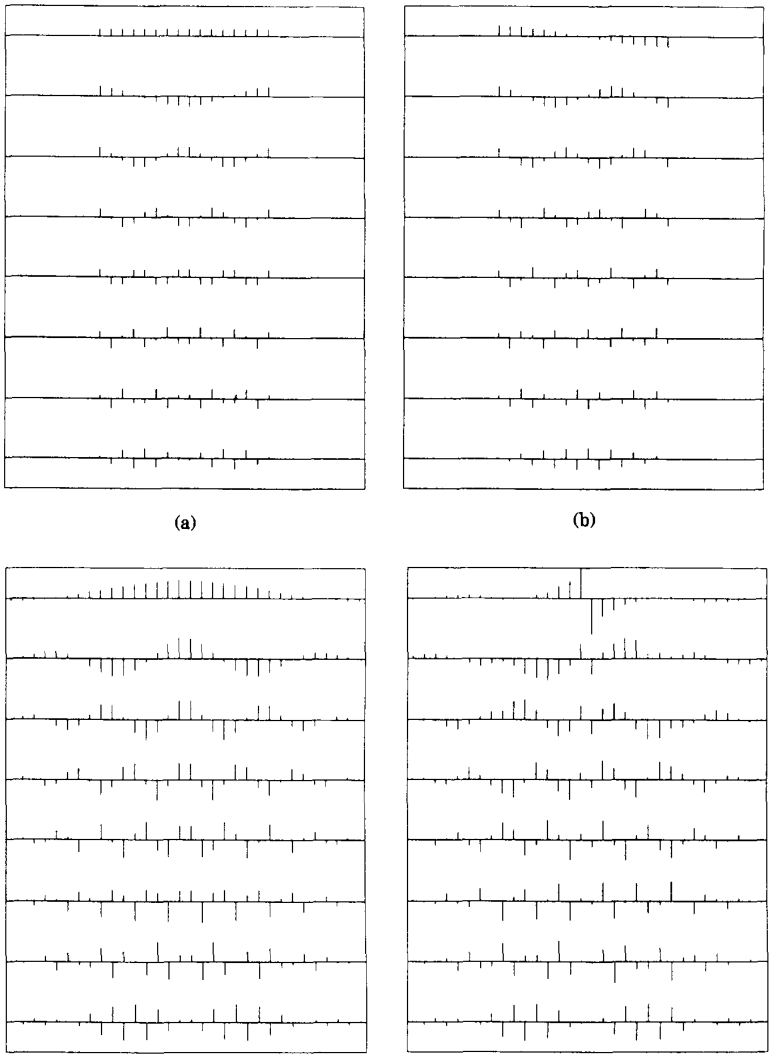
[6] W.J. Tompkins and J.G. Webster (ed), "Design of Microcomputer-Based Medical Instrumentation," Prentice-Hall, 1981.

[7] N.S. Jaynant and P. Noll, Digital Coding of Waveforms. Prentice-Hall, 1984.

[8] H.S. Malvar, "The LOT: A link between block transform coding and multirate filterbanks," in Proc. IEEE Int. Symp. Circuits Syst., pp. 835-838, Espoo, Finland, July, 1988.

[9] U.E. Ruttimann and H.V. Pipberger, "Compression of the ECG by prediction or interpolation and entropy encoding," *IEEE Trans. Biomed. Eng.*, vol. BME-26, pp. 613-623, Nov. 1979.

[10] Z. Wang, "Fast algorithms for the discrete W transform and for the discrete Fourier transform," IEEE Trans. Acoust., Speech, Sig. Process., vol. ASSP-32, pp. 803-814, August 1984.



(a) (b)

(c) (d)

Figure 1 : The basis functions of the DCT and the LOT for M=16. (a) even DCT, (b) odd DCT, (c) even LOT and (d) odd LOT.

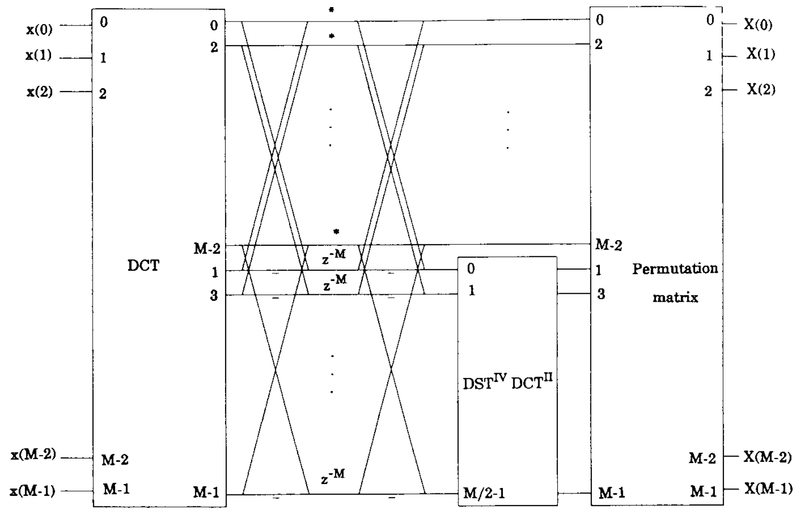


Figure 2 : Flowgraph of the fast LOT. The flowgraph of the inverse transform is just the transpose, with the z^{-M} delay units being moved to the branches with asterisks.

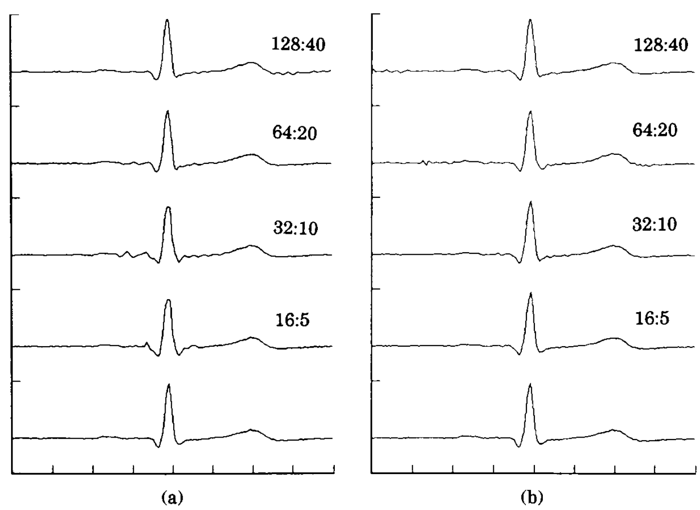


Figure 3 : Reconstruction of a QRS complex using (a) the DCT and (b) the LOT for the same bit-rate. The bottom waveform is the original for both.

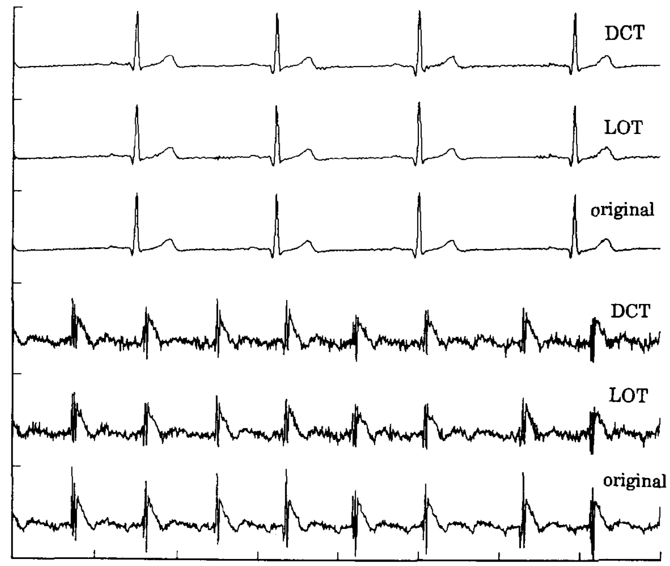


Figure 4 : Reconstruction of a normal ECG and an abnormal ECG at 128:40.

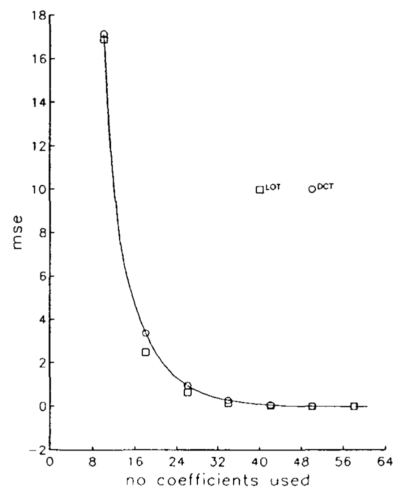


Figure 5 : Mean square error of ECG versus bit-rate (number of coefficients selected) for the block length of 64.

Table 1: mse values for LOT and DCT at the same bit-rate.

normal	16:5	32:10	64:20	128:40
LOT	7.30	4.13	3.00	2.94
DCT	7.31	4.29	3.14	2.86

abnormal	16:5	32:10	64:20	128:40
LOT	121	116	106	91.9
DCT	129	116	107	101