Multi-Lead ECG Data Compression with Orthogonal Expansions: KLT and Wavelet Packets

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Abstract

In this paper we present the extension of transform coding compression methods to multilead ECG recordings in order to reduce the inter-lead correlation. Two orthogonal expansions are considered: the Karhunen-Loève transform and a fast approximation of it based on wavelet packets, also known as best basis algorithm. The multilead compression algorithm with wavelet packets achieves an average compression ratio of 30.5:1 in two-leads records from MIT-BIH Arrythmia database, in contrast to 21.4:1 for the single-lead algorithm with the same distortion. Better results could be obtained in ECG recordings with more than two leads.

1. Introduction

The growing amount of data coming from digital recording of ECG signals needs data compression techniques. Data compression can be understood as the process of detecting and removing redundancies in a signal [1]. Three different redundancy sources can be distinguished in the ECG signal: time correlation between the samples of a single beat (intra-beat correlation), beat-to-beat quasi-periodic behavior (inter-beat correlation) and the inter-lead correlation.

Data compression methods can be classified in two main families: loss-less and lossy methods. The former can obtain an exact reconstruction of the original signal, but they only achieve very low values of compression ratio (around 3:1 for ECG) [1]. In constrast, lossy methods do not obtain an exact reconstruction, but higher compression ratios can be obtained. This is the reason why the latter family is preferred for ECG signals. Typically three different groups are considered for the ECG signal: *direct methods*, *transform methods* and *parameter extraction* [1]. Most of these methods are independently applied to each lead of the ECG record. As a consequence the inter-lead redundancy is not removed from the signal.

A single-lead ECG compression algorithm based on a fast approximate Karhunen-Loeve transform (KLT) using wavelet packets obtained a better rate-distortion (RD) trade-off than the KLT [2]. In this paper we propose the extension of the algorithm given in [2] to multilead ECG records, achieving a significant performance improvement.

2. Orthogonal expansions for multilead ECG records

Data compression methods based on transform coding techniques can reduce correlation between samples of a signal vector $\mathbf{X}$. Most orthogonal-expansion ECG-coders are applied in a single-lead fashion over a heartbeat (or segment) signal vector. In addition, differential quantization of the coefficient time series can be applied to reduce redundancy due to the beat-to-beat quasi-periodic behavior of the signal. However, the inter-lead correlation is not usually considered in ECG compression.

We propose a multilead segmentation of the signal, where the signal vector $\mathbf{X}$ is the concatenation of signal vectors coming from different leads, i.e.,

$$\mathbf{X} = \left[\mathbf{X}_1^T \, \mathbf{X}_2^T \cdots \mathbf{X}_L^T\right]^T , \qquad (1)$$

being $\mathbf{X}_i$ the signal vector of the i-th lead ant L the number of leads. We can apply the same methodology of orthogonal expansions, but now with higher-dimension vectors. The orthogonal expansion $\mathbf{T}$ will try to decorrelate samples of the signal vector $\mathbf{X}$, and therefore the inter-lead correlation will also be reduced. Next we analyze two particular orthogonal expansions: KLT and a fast approximate KLT based on wavelet packets.

2.1. Optimum KL transform

The optimum orthogonal transform in a mean square error criteria is the KLT [3]. KLT achieves a signal representation with uncorrelated coefficients because its basis functions are the eigenvectors of the covariance matrix. In addition, among all unitary transforms, the KLT is the one that packs most energy into the first coefficients. There are two major problems with KLT, however. First, the KLT is signal dependent, since it depends on the covariance matrix.

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Second, it is computationally complex, since no structure can be assumed for $\mathbf{T}$, and no fast algorithm can be used. This leads to an order N^2 operations for applying the transform. Moreover, a complexity of $O\left(N^3\right)$ is also needed to find the covariance matrix eigenvectors. This computational cost becomes prohibitely expensive for high dimension vectors, as it is the case in multilead ECG records.

2.2. Fast approximation of the KLT based on wavelet packets

An approximate KLT was introduced in [4] based on the application of wavelet packets. The main idea is to generate a very large library of rapidly computable orthonormal wavelet packet bases. Moreover, the library of bases is organized in a binary-tree to facilitate a fast search. Next, *the best basis* is chosen according to a criteria, usually related to an additive cost function, J, evaluated over an ensemble of signal vectors. The cost function is selected according to the application. In data compression, J is a distortion index. Once *the best basis* is selected, the basis vectors are sorted into decreasing order in the same way as in the KLT. Therefore, the first p basis functions retain most of the signal energy. A further decorrelation of the coefficients can be obtained applying the KLT to the selected $p < N$ coefficients in the first-stage [4]. More details and applications of this technique can be found in [4, 5].

3. Results

3.1. Wavelet Packets *versus* KLT

Firstly, it would be very useful to compare the rate-distortion performance of *the best basis* obtained by the wavelet packets methodology to the optimum KLT. We selected 10 minutes of record 100 from MIT Arrythmia database. The 'number of functions'-'distortion' graphic in Fig. 1 illustrates that KLT is optimum, i. e., for any value of the number of functions used, the RMS distortion index is minimum. Moreover, *the best basis* chosen from the wavelet packets obtain a very close performance to KLT.

However, any data compression system must be evaluated in a rate-distortion sense, i.e., taking into account also the number of bits used to code the coefficients and the overhead information. The overhead information for the KLT is very large (mainly composed of the basis functions). In contrast, the overhead information related *the best basis* is very small due to the binary-tree structure of the wavelet packets expansions. We shown in Fig. 2 the RD curves for KLT and WP, where it is shown the clear higher performance of the wavelet packets approach. In next sections we will only consider the wavelet packets based algorithm.

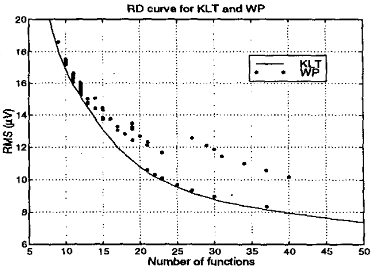


Figure 1: *'Number of functions'-'distortion' graphic of KLT and WP on record 100 from MIT-BIH Arrythmia database.*

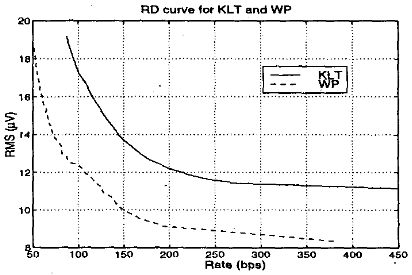


Figure 2: *Rate-distortion curve of KL and WP on record 100 from MIT-BIH Arrythmia database.*

3.2. Multilead vs single-lead wavelet packets

In this section we compare the proposed multilead wavelet packets approach and the single-lead wavelet packets method in [2]. In order to obtain reliable conclusions we reproduce the results in [2] using the same conditions: implementation details and ECG data from MIT-BIH Arrythmia database (see record list in Fig. 3).

We calculated the RD curves of the multilead wavelet packets approach for all ECG records considered in [2]. We manually selected the operating conditions for each record which obtain the same distortion (root-mean-square, RMS, in μV) than reported in [2]. We show in Fig. 3 the data rate (bits per second, bps) obtained with both methods. Black bars represent the multilead wavelet packets data rate (corresponding to both leads). Grey and white bars represent the data rate needed to independently code channel 1 and 2 respectively with the method given in [2]. It can be seen that multilead wavelet packets approach obtain smaller rates than unilead wavelet packets in all records. The average data rate per channel for multilead wavelet packets was 129.9 bps (corresponding to a compression ratio of 30.5:1), compared to 184.7 bps (compression ratio of 21.4:1) for the single-lead wavelet packets approach. The distortion was exactly the same for both methods in all records.

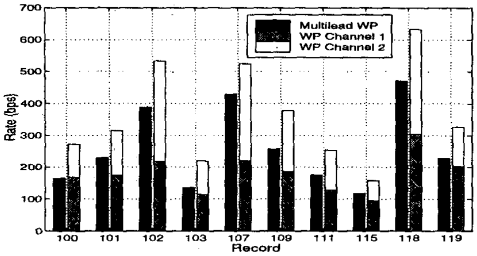


Figure 3: *Rate (bps) of multilead wavelet packets versus single-lead wavelet packets.*

3.3. Multilead wavelet packets

In the previous section we showed the higher performance of multilead wavelet packets algorithm *versus* single-lead algorithm. The operating conditions were defined by the number of coefficients selected from both compression-stages, best wavelet packet expansion and posterior KLT. In actual applications, the number of coefficients at each stage are determined automatically. Two marginal thresholds (one for each stage) are used. A coefficient is selected to represent the signal if its marginal variance is higher than the corresponding threshold.

In order to find the threshold values we calculated the average data rate and distortion in all selected records for a large range of threshold values (8 values uniformly distributed between 0.005 and 0.25). The performance of the 64 different operating conditions, corresponding to pairs of both threshold values, are shown as dot marks in the RD plane of Fig. 4. The cross mark is the average performance obtained in previous section where the operating conditions were different and manually chosen for each record. A good choice for the operating conditions would be the pair of marginal variance thresholds that get a point near to the cross (0.04 and 0.04 for the first and second stage respectively).

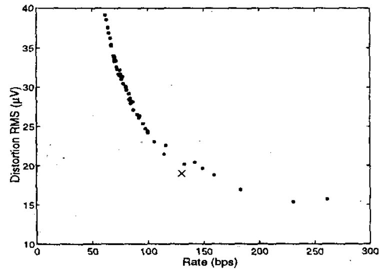


Figure 4: *Average rate-distortion performance of multilead wavelet packet algorithm for different marginal variance thresholds in the selected records from MIT database.*

If these operating conditions are applied to the same records selected in [2], we obtain the rate-distortion performance shown in Fig. 5. The average compression ratio is 34.7:1 with a mean distortion of RMS 21.51 μV. This average distortion is very low (equivalent to 0.21 mm in a standard ECG printout). Note that the amplitude resolution of the A/D converter used in the adquisition was 5 $\mu V/LSB$. Several distortion indexes are used in the literature to quantify distortion. One of the most common used is the *PRD*(%) [1]. The distortion values given in Fig. 5 correspond to an average PRD of $5.44\pm2.30\%$. To the author's knowledge, the performance of the multilead wavelet packet algorithm is higher than all previous algorithms (including the recent multichannel algorithm in [6]).

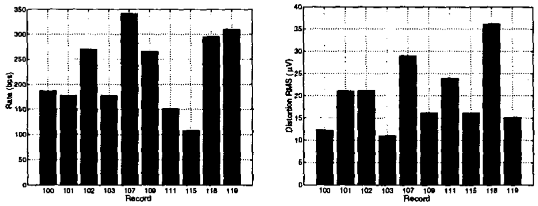


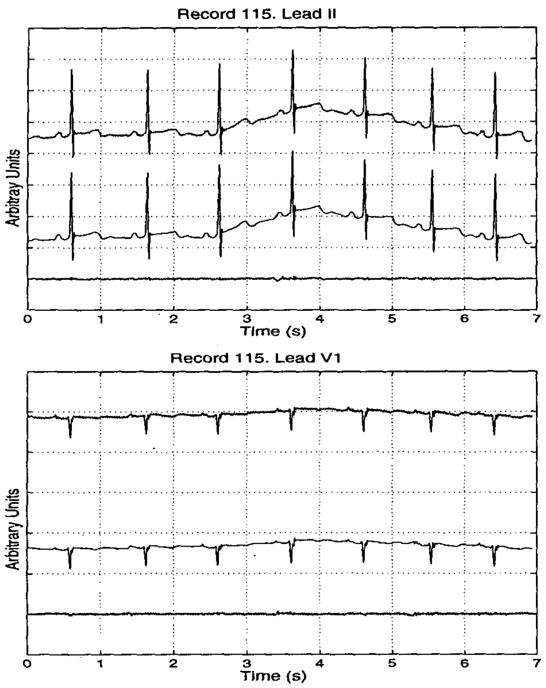
Figure 5: *Data rate (bps) and distortion (RMS μV) of multilead wavelet packets algorithm in several records from MIT Arrythmia.*

The most important criterion for judging any ECG compression algorithm is the clinical quality of its reconstructed signals. Comparisons between orignal recordings and the signals which result after compression by the multilead wavelet packet algorithm are shown in Figs. 6-7. The original ECG appears as the first tracing, the reconstructed signal as the middle tracing and the reconstruction error as the bottom tracing. A normal sinus rythm is shown in Fig. 6. The data rate per channel was 53.9 bps (compression ratio of 73.5:1) with a RMS value of 16.1 μV. An episode of ventricular bigeminy with uniform ventricular beats appears in Fig. 7. The data rate per channel was 154.7 bps (compression ratio of 25.6:1) with a RMS value of 15.1 μV.

Neither the RMS index nor PRD are a true measure of the compression algorithm accuracy. Most of the energy of the reconstruction error is due to presence of noise in the original signal and it does not have any clinical relevant information, as it can be seen from Figs. 6 and 7.

4. Conclusions

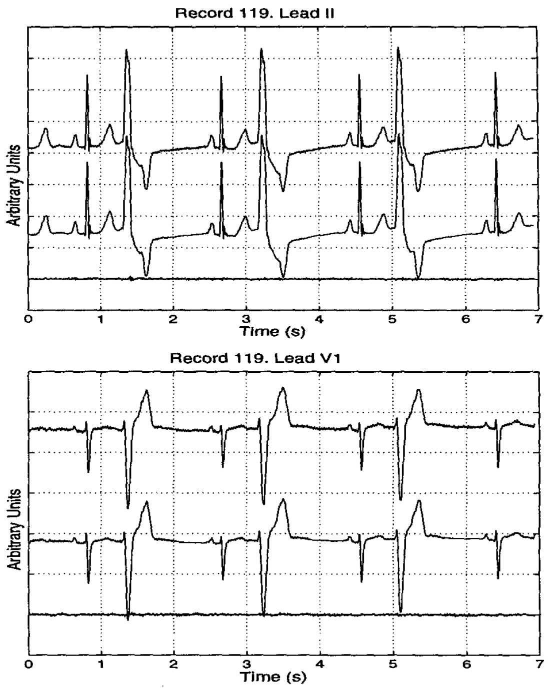
In this paper an extension of data compression methods based on transform coding to multilead ECG recordings was shown. Two orthogonal transforms were analyzed: the Karhunen-Loeve transform and a fast approximation using wavelet packets. In spite of the optimality of the Karhunen-Loeve transform, it obtained a lower performance (in a rate-



Record 115. Lead II

Record 115. Lead V1

Figure 6: *Original and reconstruction excerpts from record 115, leads II and V1. (Top tracing) Original ECG signal. (Middle tracing) Reconstructed ECG. (Bottom tracing) Reconstruction error.*



Record 119. Lead II

Record 119. Lead V1

Figure 7: *Original and reconstruction excerpts from record 119, leads II and V1. (Top tracing) Original ECG signal. (Middle tracing) Reconstructed ECG. (Bottom tracing) Reconstruction error.*

distortion sense) than wavelet packets due to the overhead information needed to code its basis functions. As an alternative a two-stage compression algorithm is proposed: in the first stage *the best basis* is chosen from wavelet packets expansions. In the second stage the KLT is applied to lower-dimension vector. In order to reduce the inter-lead correlation, a multilead segmentation was used. The signal vector was defined as the concatenation of signal vectors (a heartbeat) from each lead.

The average rate-distortion performance obtained by the proposed algorithm evaluated in some records from MIT-BIH Arrythmia Database is: data rate per channel 114.1 bps (compression ratio of 34.7:1) with a distortion of 21.51 μV (PRD 5.44%).

Acknowledgements

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