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Efficient thresholding-based ECG compressors for high quality applications using cosine modulated filter banks

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Abstract— **The aim of electrocardiogram (ECG) compression is to achieve as much compression as possible while the significant information is preserved in the reconstructed signal. Lossy thresholding-based compressors have shown good performance needing low computational resources. In this work, two compression schemes that include nearly perfect reconstruction cosine modulated filter banks for the signal decomposition are proposed. They are evaluated for highly reliable applications, where the reconstructed signal must be very similar to the original. The whole MIT-BIH Arrhythmia Database and suitable metrics are used in the assessment, to obtain representative results. Results show that the proposed compressors yield better performance than discrete wavelet transform-based techniques, when high quality requirements are imposed.**

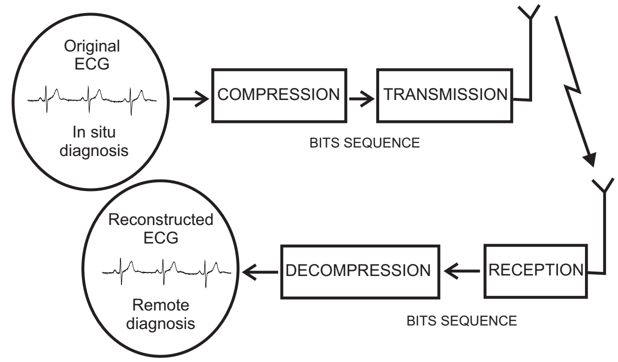

Fig. 1. ECG compression in the field of telemedicine.

I. INTRODUCTION

Electrocardiograms (ECG) are signals that represent the electrical activity of the heart. Therefore, they can be used to analyze the cardiac activity and to detect malfunctions. In 1961, Holter [1] proposed new techniques to continuously register ECGs of several hours in outpatients. These long-term records, also called ambulatory ECGs, usually cover around 24 hours of signal and are widely used in common electrocardiography. Remote applications such as ECG monitoring, databases and diagnosis are spreading out due to the advance of the Internet [2]-[4]. In this context, data compression increases the transmission speed of the information, allowing the reception of high resolution signals in real time. Remote diagnosis, as it is depicted in Fig. 1, is among the most challenging, versatile and interesting applications of ECG compression.

In lossy ECG compression, some information is lost and the reconstructed signal is not identical to the original. These techniques are under constant research because they achieve high levels of compression. Nonetheless, lost information during compression should always be under control in such a way that the diagnosis with either the original or the reconstructed signal would not change.

Increasing compression ratio (CR) is the main objective of compressing ECGs. Recent approaches have improved very much the CR [5], [6], but little attention has been focussed on the quality of the recovered signal. As a result, the CR improvement is usually reported within intervals of quality where the recovered signals are not fully valid. For this reason, we restrict our interest to those areas where the quality of the reconstructed ECGs can be considered sufficient for correctly diagnosing cardiac disease with compressed ECGs. For this purpose, thresholding-based compression techniques are very suitable because they are efficient in terms of implementation and they do not rely on any *a priori* knowledge of the ECG. This second characteristic allows the design of robust and versatile compressors [5]-[12].

In this work, we analyze the design of thresholding-based ECG compression schemes when high levels of quality are required for the reconstructed signal. For this purpose, several compressors are implemented using both the Discrete Wavelet Transform (DWT) [13] and Nearly-Perfect Reconstruction Cosine Modulated Filter Banks (N-PR CMFB) [14] in the signal decomposition stage to determine which of the combination is the best in terms of compression and quality. In order to provide the real performance of the compressors, two issues have been taken into account. The first concerns about the variety of data. Instead of using a reduced dataset, as in prior works, the full MIT-BIH Arrhythmia Database has been considered, capturing thus a wider variability given by both the amount of patients and the duration of the signals. The other one is referred to the real implementation of the encoding algorithms, where the actual bitstream that would be fed into the channel is obtained. Thus, instead of giving a theoretical compression value related with the entropy of the source [15], we provide the real performance of the algorithms. The result of this study is the proposition of two novel compression methods based on N-PR CMFB.

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II. EVALUATION PARAMETERS

The evaluation of compressors is carried out in terms of compression capability and quality of the reconstructed signal. CR informs about the bit reduction. It is calculated according to the following equation:

$$CR = \frac{b_x}{b_c}, \quad (1)$$

where b_x y b_c are the amount of bits needed for the original and the compressed signal representation, respectively.

The most usual parameter to measure the quality of the reconstructed signal is the Percentage Root-mean-square Difference (PRD), which is defined as:

$$PRD = \sqrt{\frac{\sum_{n=1}^{N}(x[n]-\hat{x}[n])^2}{\sum_{n=1}^{N}(x[n])^2}} \times 100, \quad (2)$$

where $x[n]$ is the original ECG signal and $\hat{x}[n]$ is the reconstructed one. Since the PRD is strongly dependent on the signal mean value, high mean values can mask the actual quality performance assessment [16], [17]. To avoid this effect, it can be used the modified criterion $PRD1$, which is derived as follows:

$$PRD1 = \sqrt{\frac{\sum_{n=1}^{N}(x[n]-\hat{x}[n])^2}{\sum_{n=1}^{N}(x[n]-\bar{x}[n])^2}} \times 100, \quad (3)$$

where $\bar{x}[n]$ is the signal mean value.

As the PRD is a relative measure of the error amplitude with respect to the original ECG, the Root Mean Square Error ($RMSE$) is also recommended [18]. The $RMSE$ provides a measure of the deviation in microvolts and is given by:

$$RMSE = \sqrt{\frac{\sum_{n=1}^{N}(x[n]-\hat{x}[n])^2}{N}}. \quad (4)$$

These quality criteria provide global approaches that do not take into account local effects. On the other hand, measuring the maximum differences in microvolts could contribute to give some idea about local effects. This can be achieved by means of the MAXimum amplitude error (MAX) parameter, which is calculated as:

$$MAX = max(|x[n]-\hat{x}[n]|). \quad (5)$$

III. COMPRESSION SCHEMES

Lossy compressors based on thresholding achieve excellent results both in terms of compression and quality of the reconstructed signal [5]-[12]. Their main advantage is that they do not rely on any *a priori* knowledge of the signal, which reduces their complexity and makes them more versatile and efficient. A thresholding based compression scheme follows the block diagram depicted in Fig. 2.

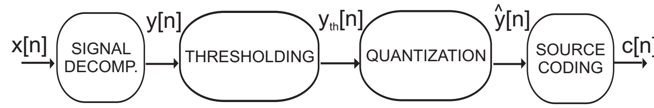

Fig. 2. Block diagram of thresholding-based compressors.

In this work a set of four different compression schemes is implemented. Two of them uses the DWT for signal decomposition, while the other two applies N-PR CMFB. The thresholding methodology is carried out taking the PRD as target to guarantee the quality [13]. For quantization and source coding, we have chosen two methods that have reported good performance in ECG compression [5], [6]. In order to simulate real conditions, the bit sequence to be transmitted is generated and sent to the corresponding decoder, where the ECG signal is reconstructed.

The first pair of compressors, which are named compressors A, are based on the scheme proposed in [5]. The second pair, identified as compressors B, uses the same scheme as in [6]. Thus, the compressor A-DWT uses the DWT with the mother wave bior4.4 and a number of layers up to the fifth level. On the other hand, the compressor B-DWT utilizes the DWT with the 9/7 tap filter bank up to the fifth level. Finally, the compressors A-CMFB and B-CMFB apply N-PR CMFB using the Blackman window as in [9].

IV. STUDY OF THE DECOMPOSITION METHODS

The suitability of either N-PR CMFB or DWT in ECG compression schemes is studied when high levels of quality are imposed for the reconstructed signal. For this analysis, signals from the MIT-BIH Arrhythmia Database [19] are used. These records contain two leads sampled at 360 Hz with 11 bits per sample of resolution. A reduced group that is comprised of the first 120 seconds of the first lead of the signals 100, 101, 102, 103, 107, 109, 111, 115, 117, 118 and 119 is used for this approach.

The study of the coefficients obtained from the signal decomposition arises two main conclusions:

- The amplitudes of the samples obtained by N-PR CMFB are distributed in a smaller range than the DWT ones, as it can be seen in Fig. 3 for signal 117. Therefore, less quantization levels would be needed with N-PR CMFB, i.e. less bits to represent the quantized coefficients, which is favorable for increasing compression.
- The energy distribution is concentrated in fewer coefficients for DWT, as it can be seen in Fig. 4 for signal 117. In order to retain a specific energy, the narrower the distribution, the higher the amount of coefficients to be canceled. Thus, when DWT is used, more sequences of zeros are obtained, which may increase compression.

The first effect dominates if high quality levels are needed, i.e low PRD target (PRD_{target}) values. In this case, the amount of energy that is retained is high, so less samples are canceled and the second effect presents a smaller influence.

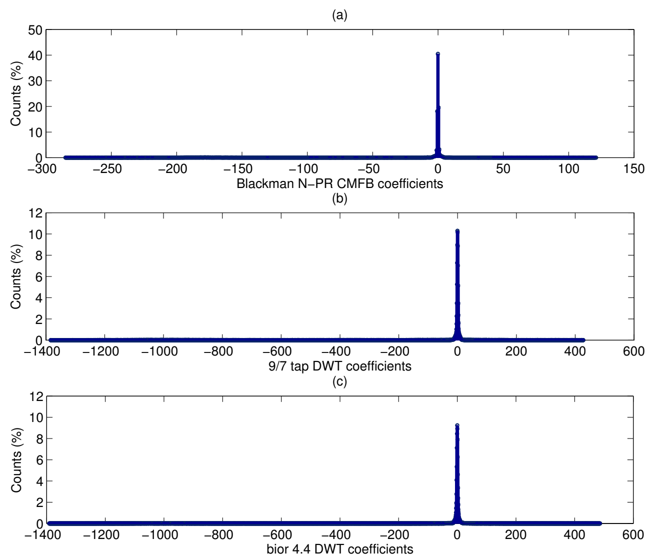

Fig. 3. Distribution of coefficient amplitude for signal 117 with: (a) N-PR CMFB (b) and (c) DWT.

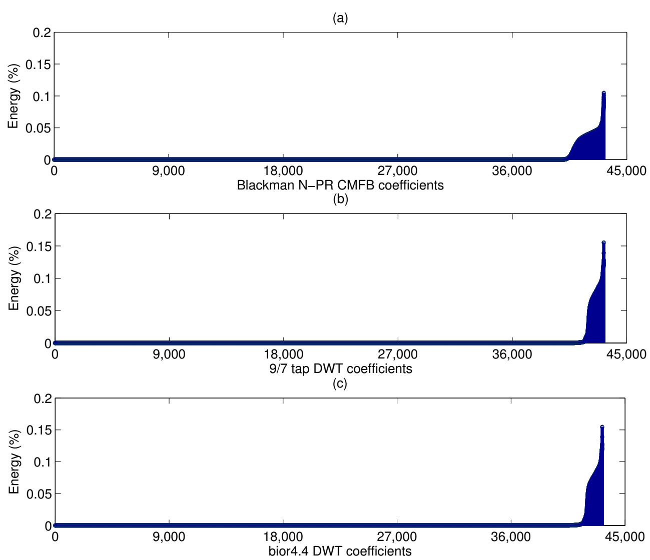

Fig. 4. Energy distribution sorted in increasing order for signal 117 with: (a) N-PR CMFB (b) and (c) DWT.

Therefore the N-PR CMFB technique is proposed as more suitable for the compression schemes, when a high quality reconstructed signal is required.

V. EXPERIMENTAL RESULTS

In this work, the complete first leads, which are 30 minutes long, of the 48 records from the MIT-BIH Arrythmia Database are applied. The use of a wide set of long-term signals allows to cover many different cases, in order to obtain representative results. This is not a question of minor importance because the size of the database affects the performance of the algorithms. As it can be seen in Fig. 5, the results are significantly different whether the reduced dataset described in section IV or the complete database is used.

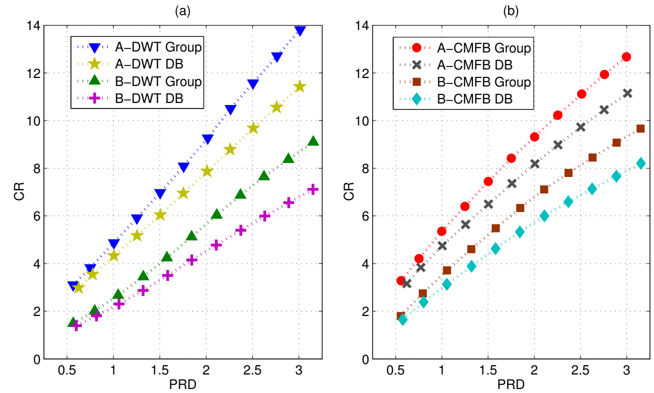

Fig. 5. CR as a function of PRD with the reduced dataset (Group) and the whole database (DB) for the compressors that use: (a) DWT and (b) N-PR CMFB.

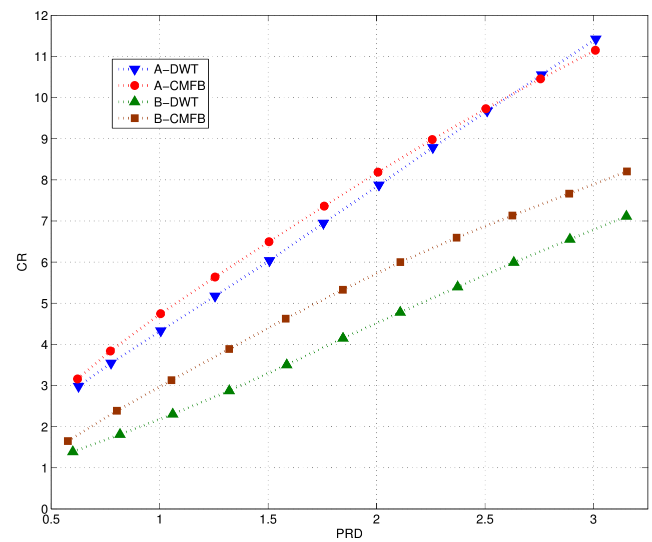

Fig. 6. CR as a function of PRD for the different compression schemes.

The signals are processed in blocks of 1024 samples each, simulating real time applications. The mean of every segment is removed beforehand, so it is included in the transmission frames. Given that high quality levels are required, eleven values of PRD_{target} are computed from 0.5 to 3 in steps of 0.25.

The CR as a function of PRD is depicted in Fig. 6. It can be observed that the compressor that uses N-PR CMFB yields better compression for the high quality values. The compressor A-DWT exceeds its N-PR CMFB counterpart after a certain level of PRD. This occurs because the energy concentration effect gains importance as the quality requirement is reduced.

The relation between PRD, $PRD1$ and $RMSE$ for some of the experiments can be seen in table I. The reported values are very similar, as the PRD_{target} must be fulfilled with a maximum error of 10%. The accuracy of compressors B is higher because the coefficient quantization is adaptive. In [20], a quality study assessment for ECG compression is

TABLE I

PRD, $PRD1$ AND $RMSE(\mu V)$ AS A FUNCTION OF PRD_{target} FOR THE DIFFERENT COMPRESSION SCHEMES.

	PRD_{target}	0.5	1	1.25	1.5	2.25	3
A-DWT	PRD	0.63	0.78	1.26	1.51	2.26	3.01
	$PRD1$	0.90	1.17	1.90	2.29	3.42	4.56
	$RMSE(\mu V)$	3.14	3.98	6.47	7.77	11.6	15.5
A-CMFB	PRD	0.62	0.77	1.26	1.50	2.26	3.01
	$PRD1$	0.90	1.16	1.90	2.28	3.42	4.56
	$RMSE(\mu V)$	3.11	3.97	6.46	7.75	11.6	15.5
B-DWT	PRD	0.60	0.82	1.32	1.59	2.37	3.15
	$PRD1$	0.88	1.23	2.00	2.40	3.59	4.76
	$RMSE(\mu V)$	3.03	4.19	6.81	8.17	12.2	16.2
B-CMFB	PRD	0.58	0.80	1.32	1.58	2.37	3.15
	$PRD1$	0.86	1.21	2.00	2.40	3.58	4.76
	$RMSE(\mu V)$	2.92	4.13	6.81	8.15	12.2	16.2

conducted with the MIT-BIH Arrhythmia Database. Some cardiologists were involved in a Mean Opinion Score (MOS) test. They stated that a reconstructed signal could be considered *good* if its $PRD1$, when computed as in (3), is lower than 9. The quality is classified as *very good*, if $PRD1$ is lower than 2. Our experiments have been carried out in such a way that in all the cases the quality can be considered at least as *good*. The equivalent PRD and $RMSE$ values, computed with (2) and (4), for considering the quality to be *very good*, have to be lower that 1.3 and 6.8 μV, respectively.

The MAX levels that are derived from the experiments, which are not shown in this work, do not present significant differences, with regard to local errors, between the presented compressors.

VI. CONCLUSIONS AND DISCUSSION

The lack of a benchmark for assessing the quality of compressed ECG is the major drawback for utilizing compression in electrocardiography. In fact, clinicians are reluctant to deal with ECG when they know that lossy compression is applied. To date, there is no appropriate metric for establishing which level of quality is sufficient to ensure correct diagnosis. Therefore, in this work efforts are concentrated in quality requirements which at least give rise to highly reliable reconstructed signals.

Several thresholding-based compression algorithms are analyzed, while high quality requirements are imposed in the signal reconstruction. The quality is assessed globally as well as locally through parameters that are usual in the state of the technique. We have seen that a limited dataset does not provide the actual performance of the compressors and that a larger dataset must be used in order to cover the variability of cardiac signals. For this reason, the whole set of signals from the MIT-BIH Arrhythmia Database is used.

Results show that within this high quality interval, the N-PR CMFB decomposition method is more appropriate than the DWT. Therefore, this technique is used to design two efficient compressors schemes, which present better compression rates than their DWT counterparts when high levels of quality are required for the reconstructed signal.

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