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Quality-Controlled Compression Method using Wavelet Transform for Electrocardiogram Signals

Redha Benzid, Farid Marir, and Nour-Eddine Bouguechal

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***Abstract*—**This paper presents a new Quality-Controlled, wavelet based, compression method for electrocardiogram (ECG) signals. Initially, an ECG signal is decomposed using the wavelet transform. Then, the resulting coefficients are iteratively thresholded to guarantee that a predefined goal percent root mean square difference (GPRD) is matched within tolerable boundaries. The quantization strategy of extracted non-zero wavelet coefficients (NZWC), according to the combination of RLE, HUFFMAN and arithmetic encoding of the NZWC and a resulting lookup table, allow the accomplishment of high compression ratios with good quality reconstructed signals.

***Keywords*—**ECG compression, Non-uniform Max-Lloyd quantizer, PRD, Quality-Controlled, Wavelet transform

I. Introduction

THE voluminous flows of collected data from ECG data acquisition and monitoring systems require the design of compression algorithms allowing reduction of the amount of stored information.

One can classify developed compression methods to "Open loop" and "closed loop" algorithms:

A. Open loop class

In this case, a method is developed without taking in consideration the fulfillment of a predefined constraint. We can quote the method described in [1], based on the wavelet transform decomposition, the method presented in [2] based on the "Cut and Align" technique associated to the 2D-DCT transform and finally, the method reported in [3] using double logarithmic quantization of the Walsh spectrum of ECG signals.

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B. Closed loop class

In the "closed loop" case, a compression method is subjected to one or more constraints verifying some predefined measure. In the Controlled Wavelet/SPIHT based method [4], the measure to be considered is a user -specified PRD to be matched by searching for an appropriate rate. The method mentioned in [5] based on the SPIHT algorithm, as reported, can attain exact bit rate and generates a bit stream progressive in quality or rate. The method in [6], implements an adaptive scalar quantizer by which a desired mean square error (MSE) is reached. The method in [7] ensures the clinical reconstruction of beat-by-beat ECG signals with the preservation of the beat features (PQ, QRS and ST). Authors of [8, 9] presented a same idea into two methods based on the energy packing efficiency EPE. Finally, we note a progressive technique [10] resulting from the international still image standard designated by JPEG 2000.

II. Review of Existing Measures

The particularity of ECG signals, requires an evaluating criterion, the more accurate possible to evaluate reconstructed signals. A review of several measures criteria, dedicated to electrocardiogram signals, is presented. Some comments are reported and especially focused on the widely popular used criterion which is the PRD.

Let x_i and $\hat{x}_i$ be, the ith samples of the original and reconstructed signals of N samples length. Let be mx, the original signal mean. In the following , the most popular measures are presented:

$$PRD1 = 100 \text{ X} \sqrt{\frac{\sum_N (x_i - \hat{x}_i)^2}{\sum_N x_i^2}} \quad (1)$$

$$PRD2 = 100 \text{ X} \sqrt{\frac{\sum_N (x_i - \hat{x}_i)^2}{\sum_N (x_i - mx)^2}} \quad (2)$$

$$PRD3 = 100 \text{ X} \sqrt{\frac{\sum_{N}(x_i - \hat{x}_i)^2}{\sum_{N}(x_i - 1024)^2}} \quad (3)$$

PRD1 is used in [8],[9] and [11]. PRD2 can be found as example in [12], and [13]. PRD3 is considered as a quality measure in [4,5] , [10] and [14,15].

We can report two remarks on the PRD measure:

- It is apparent that these 3 formulas can be a source of confusion when a comparison between methods is done without care. The evaluation used in [8,9] demonstrates our opinion. As remarked in [16,17] and commented in [17], the error is caused by the use of PRD1 by authors of [8], [9] and results are compared to those in [5] which used the PRD3 evaluation. We note that, the DC-shifting -sensitivity of the PRD criterion is the source of this confusion;
- The second remark is that all the 3 definitions are global (average) measures, so, the instantaneous errors, between samples of original and reconstructed signals are not described by this type of measure.

In papers [6] and [18] the correlation coefficient CC is used as a measure. It is described by (4):

$$CC = \frac{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})(\hat{x}_i - \bar{\hat{x}})}{\sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}\sqrt{\frac{1}{N}\sum_{i=1}^{N}(\hat{x}_i - \bar{\hat{x}})^2}} \quad (4)$$

Where, $\bar{x}$ and $\bar{\hat{x}}$ indicate the mean values of original and reconstructed signals. We note that this measure used to evaluate the similarity between two signals has the drawback of its global (average) nature. So, locally large instantaneous errors (instantaneous distortions) may be also undetectable.

Another measure denoted percentage area difference (PAD) was given in [13].

$$PAD = 100 \text{ X} \frac{\left| \int_{t_i}^{t_f} x(t)dt - \int_{t_i}^{t_f} \hat{x}(t)dt \right|}{(t_f - t_i)(x_{\max} - x_{\min})} \quad (5)$$

Where tf , ti indicate final and initial time of ECG segment. This measure is a normalized surface measure. The numerator indicates the surface limited by the original and the reconstructed signal between ti and tf. However, the denominator is the rectangular surface calculated by $(t_f - t_i)(x_{\max} - x_{\min})$. Also, this measure is an average measure.

The next illustrated measure, is defined in [19]. It is called the normalized maximum amplitude error (NMAE) and expressed by (6):

$$NMAE = 100 \text{ X} \frac{\max\left|x_i - \hat{x}_i\right|}{x_{\max} - x_{\min}} \quad (6)$$

This measure imposes that the maximal (in absolute value) relative error must be equal to some predefined NMAE. In spite of this measure insures that all the instantaneous errors are less than NMAE, however, it does not necessarily insure the preservation of the ECG features.

Finally, the well adapted measure for ECG evaluation is presented in [20]. It is called weighted diagnostic difference (WDD) and described by (7):

$$WDD(\beta, \hat{\beta}) = \Delta\beta^T \frac{\Lambda}{tr(\Lambda)} \Delta\beta \text{ X } 100 \quad (7)$$

Where, β and $\hat{\beta}$ represent 2 vectors of 18 diagnosis features concerning respectively the original beat and reconstructed beat of an ECG signal. $\Delta\beta^T$ is the normalized difference vector and Λ is a diagonal matrix of weights [20]. Its PQRST features depending, qualify it to be, the well correlated measure with cardiologists expertise. Its only drawback is its expensive cost in term of time calculation.

In the following sections, we present the proposed method based on the PRD measure in combination of a root finding technique (the Bisection algorithm). This choice is motivated by:

- The low cost calculation of the PRD compared to the more suitable WDD measure;
- It is the most popular reported measure in the open literature, which make easier the comparison between results of the developed and the other methods.

III. Methodology

First, a schematic describing the different steps of the proposed method is given in Fig. 1.

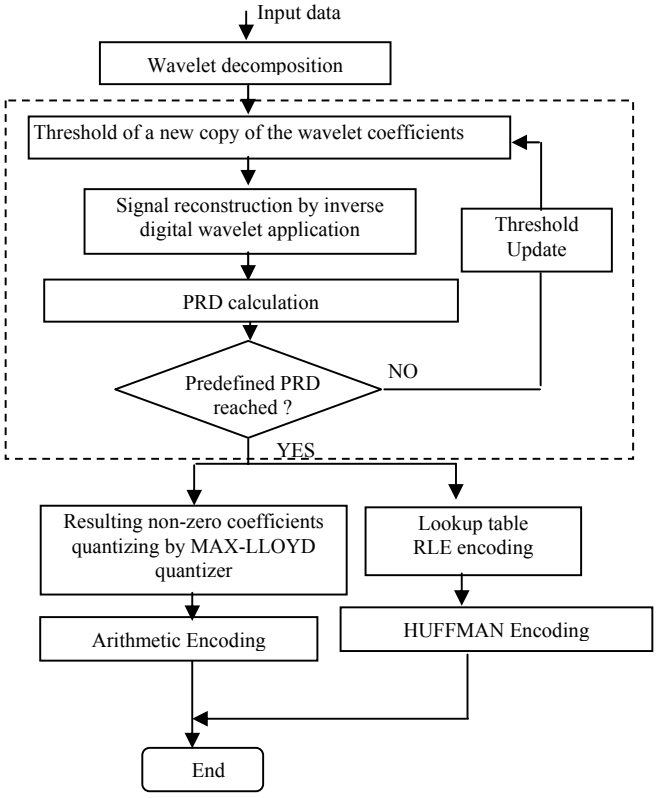

Fig. 1 Encoding Algorithm

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A. Wavelet decomposition

In this step, the zero-mean signal is wavelet based transformed by means of the pyramidal digital wavelet transform (DWT) and using the mother wave bi-orthogonal spline bior6.8 up to the sixth resolution level. The employment of the DWT is motivated by the fact that it produces a good reconstructed signal while high compression ratio is achieved.

Fig. 2 illustrates the pyramidal wavelet decomposition architecture.

CD1, CD2,..,CD6 denote detail coefficients (high frequencies) and CA6 represent the approximation coefficients (low frequencies). The length of each coefficients vector from level 1 to 6 are approximatively from $\frac{N}{2}$ to $\frac{N}{2^6}$, where, N is the length of the original signal. It is noted that the DWT concentrates the signal energy in few number of coefficients. In our case, the most of energy is found in CA6.

Note that the wavelet coefficients resulting from the decomposition step are thresholded with a threshold starting from $TH = \frac{TH_{\min} + TH_{\max}}{2}$, where $TH_{\min}$ and $TH_{\max}$ are the lower and the upper limits respectively of the starting search interval. The $TH_{\min}$, $TH_{\max}$ and TH are updated respecting to the well known bisection (Dichotomy) algorithm.

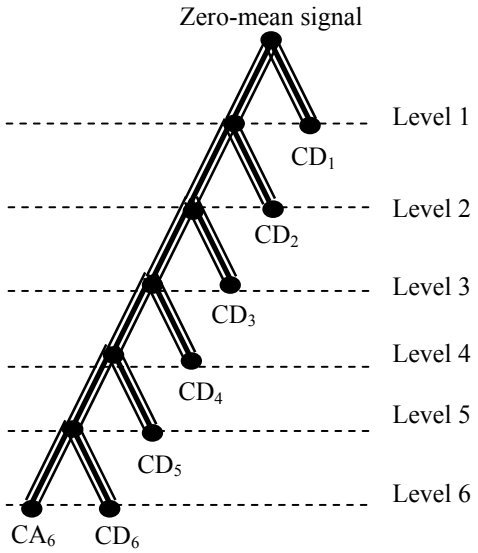

Fig. 2 Pyramidal decomposition up to the sixth resolution level

B. Thresholding mechanism

The thresholding mechanism is shown in Fig. 1. and indicated by the broken lines rectangle.

If we consider the PRD as a function of the threshold TH, it is clear that the PRD(TH) is a non-decreasing function. We solve numerically the problem of finding some TH* which verify:

$$PRD(TH) - GPRD = 0 \quad (8)$$

Where, GPRD is a goal PRD defined in advance by user. By the fact of the non-decreasing nature of PRD(TH), the uniqueness of the solution is guaranteed. For a reason of simplicity, we use the bisection algorithm [21] to solve (8).

In the following we present an illustrative example using the first 10 minutes of the record 117 of the MIT-BIH arrhythmia database of ECG signals. We have fixed in advance GPRD to 2. The reached PRD (before quantization), after 3 iterations necessary to converge with a precision of 1%, was 2.004. The PRD is calculated in a same way as PRD3. We remind that the wavelet decomposition/reconstruction act on zero-mean version of signals, but any of PRD formulas (PRD1, PRD2, PRD3) is calculated after the add of the mean both to the zero-mean original and reconstructed signals.

Fig. 3 shows the PRD and the threshold TH evolution until the convergence.

After the thresholding process, a binary lookup table (BLT) and a vector constituted of the non-zero wavelet coefficients (NZWC) are produced. To reach a considerable compression ratio with a good quality reconstruction, we use the losseless encoding to code these two vectors.

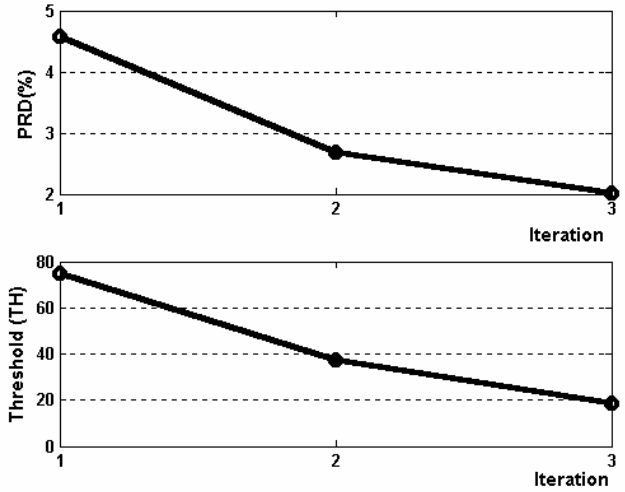

Fig. 3 Convergence process (a) PRD; (b) TH

C. Lookup table encoding

The resulting binary table is a map indicating by '1' the chronological position of a non-zero coefficients and by '0' a zero coefficient. This table is transformed in a vector of 8 bits per element (T8) and coded by an RLE coding. Each RLE code (12 bits) is composed of 2 parts. The first part is an existing code (8 bits) in T8 and the remaining 4 bits indicate the number of successive repetitions of the code. After this, a HUFFMAN coding enhances more the table storage.

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D. Non-zero quantization and encoding

The thresholded vector containing the floating point non-zero wavelet coefficients must verify that:

$$\left|PRD(TH) - GPRD\right| \le 0.01GPRD \quad (9)$$

Solution is found by bisection as mentioned previously.

It is well known that the quantization introduces more degradation to the reconstructed signal. So, the PRD of the quantized thresholded wavelet coefficients denoted by (QPRD) must guarantee:

$$\left|QPRD - GPRD\right| \le 0.1.GPRD \quad (10)$$

It means that the reconstructed signal resulting from quantized thresholded wavelet coefficients must be within a tolerance of 10%. So, the extracted non-zero quantized coefficients can be then, coded with an arithmetic encoder.

For illustration, we continue with the previous example concerning the record 117 with a GPRD=2. We have found that a quantization of the non-zero coefficients with 8 bits per coefficient (using MAX-LLOYD quantizer), gave a QPRD equal to 2.02 which is within the imposed tolerance of 10%. Fig. 4. shows visual results of our algorithm.

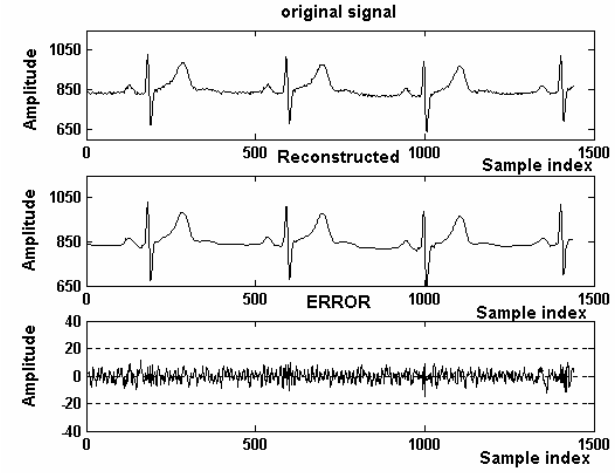

Fig. 4 Visual results of record 117(CR=17.98:1, QPRD3=2.02)

As mentioned above, the quantization has been accomplished using the well known non-uniform MAX-LLOYD quantizer [22]. The optimized algorithm uses the smallest codebook of {512, 256, 128} verifying that, the QPRD is within the 10% tolerance. So, the index indicating a codeword is represented with 9, 8 or 7 bits respectively.

An extra information, constituted from codewords of the codebook (each codeword is coded by a 12 bits linear quantizer) , is taken in consideration when calculating the CR.

IV. Experimentation and Results Discussion

The proposed algorithm efficiency is carried out by the experimention on the well known ECG database, MIT-BIH Arrhythmia. Each record contains two channels of sampling frequency of 360 Hz and a resolution of 11 bits.

We demonstrate by results exposed in Table 1. the controllability efficiency of our method. We have used the data set, composed from 11 records, reported in [5]: 100, 101, 102, 103, 107, 109, 111, 115, 117, 118 and 119. The fixed goal PRD (GPRD) is 6.5.

TABLE I
OBTAINED PARAMETERS FOR THE FIXED GPRD OF 6.5 (PRD3).
10 MINUTES FOR EACH RECORD

Record	PRD% (before quantization)	QPRD%	CR	Q bits
100	6.47	6.49	16.78:1	8
101	6.52	6.78	20.33:1	8
102	6.52	6.55	15.97:1	8
103	6.50	6.53	15.54:1	8
107	6.51	6.58	16.57:1	8
109	6.51	6.53	18.52:1	8
111	6.55	6.65	16.76:1	8
115	6.53	6.55	20.10:1	8
117	6.49	6.49	31.47:1	8
118	6.49	6.53	20.94:1	8
119	6.46	6.48	22:68:1	8
Average	**6.50**	**6.56**	**19.60:1**	**8**

Table 2 shows comparative results between some powerful methods and the proposed one.

TABLE II
PERFORMANCE COMPARING WITH OTHER METHODS (TEST RECORDS LENGTH IS 10 MINUTES)

Method	Record	PRD%	CR
Belgin et al JPEG2000 [10]	117	1.03 (PRD_3)	10:1
Lu et al (SPIHT) [5]	117	1.18 (PRD_3)	8:1
Wei et al [23]	117	1.18 (PRD_3)	10 :1
Proposed	117	1.05 (PRD_3)	9.6:1
Rajoub [8]	117	1.06 (PRD_1)	22.19 :1
Abo-Zahhad et al [9]	117	1.64 (PRD_1)	22.4:1
Proposed	117	1.04 (PRD_1)	27.93:1
Miaou et al [4]	101	5.98 (PRD_3)	19.31:1
Miaou et al (WT+AVQ) [12]	101	6.27 (PRD_2)	9.65 :1
Proposed	101	6.28 (PRD_3)	19.64:1
Miaou et al [4]	111	5.99 (PRD_3)	14.09:1
Miaou et al WT+AVQ[12]	111	6.26 (PRD_2)	8.80:1
Proposed	111	6.15 (PRD_3)	15.95:1
OZWC [24]	100	0.57(PRD_1)	8.16:1
Proposed	100	0.56(PRD_1)	17.84:1

First, we give the remark that results of Miaou et al ,[12] and [4], are extracted respectively from :

Table 2. of [4] (mean rate of 101 is 205 bps i.e., CR=19.31 , mean rate of 111 is 281 i.e., CR=14.09);

Table 2. of [12] (mean rate of 101 is 410 bps i.e., CR=9.65 , mean rate of 111 is 450 i.e., CR=8.80).

The relation between the CR and the rate R is:

$$CR = \frac{3960}{R} \quad (11)$$

where, 3960 =11x360(11 bits/sample x the sampling frequency).

From the above results, we can conclude that our proposed

method can be considered as a valid concurrent of the two high performance methods published in [5] and [10] and the controlled PRD-wavelet-SPIHT based method reported in [4]. Finally, for the aim of a visual inspection, we present, in the following, some visual results.

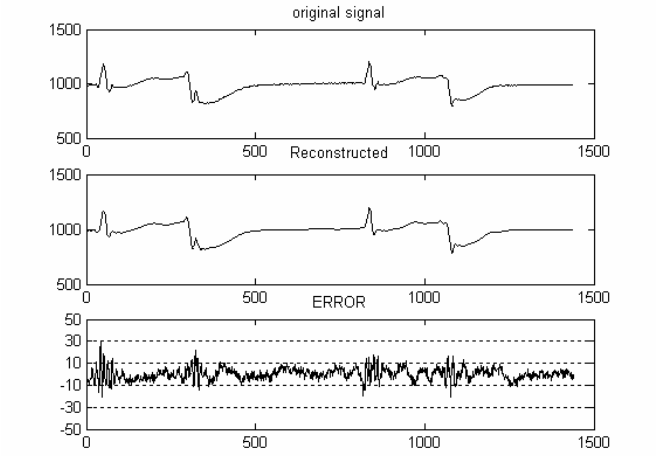

Fig. 5 Visual results of record 207 (CR=24.80:1, QPRD3=7.16)

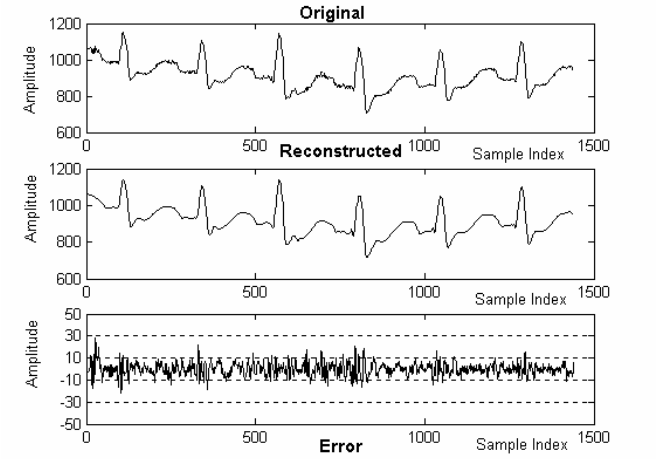

Fig. 6 Visual results of record 109 (CR=15.91:1, QPRD3=5.06)

These visual results confirm the efficiency of our proposed algorithm.

V. Conclusion

In this paper, we have presented a closed loop compression method based on the wavelet transform. It has some advantages which are:

The quality control: It means that reconstructed signals can be guaranteed to be clinically useful, by the correct choice of the GPRD.

The adaptive quantization: The mentioned strategy allows using the minimum resolution for the representation of the non-zero wavelet coefficients by the use of the MAX-LLOYD quantizer.

We note that, the arithmetic encoding of the NZWC and the RLE and HUFFMAN encoding of the lookup table ensure the high performance of the developed method.

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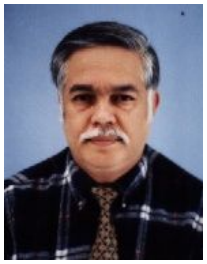

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