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On the Guarantee of Reconstruction Quality in ECG Wavelet Codecs

Álvaro Alesanco, José García, Pedro Serrano, Luciano Ramos and Robert S. H. Istepanian

Abstract— **Guaranteeing reconstruction quality in ECG lossy compression is essential to obtain signals useful from a clinical point of view. In this paper we discuss the advantages and drawbacks of using two very well known mathematical error measures (PRD and RMS) in order to guarantee quality in threshold wavelet compression codecs that work segmenting the signal into blocks. We use two different error indices to analyze the results: mathematical (RMS global error) and clinical (MOS error). Although mathematical results conclude that guaranteeing RMS is better than PRD, clinical results have shown that the election is subordinated to the signal specific morphology.**

I. INTRODUCTION

ECG lossy compression is a very well studied topic. In the last 15 years, a high number of papers have been published describing a large variety of ECG compression methodologies [1], [2]. Among them, the use of wavelet transform (WT) have attracted much attention. They are used also for real-time telecardiology applications due to its low-computational cost. These methods are grouped depending on how the wavelet coefficients are coded. Threshold methods are very extended due to its simplicity: a threshold is defined and coefficients below this threshold are removed. Care must be taken with the quality of the reconstructed ECG signals because a highly distorted signal can be useless from a clinical point of view. In this way, if the compression methodology is capable of guaranteeing a desired reconstruction quality, it is possible to keep the reconstructed signal with a clinical acceptable quality.

Reconstruction distortion has been typically measured using two mathematical indices: Root Mean Square (RMS) error and Percentual RMS difference (PRD). PRD is a distortion index very extended among the ECG compression research community. Because it is normalized by the energy of the original signal, no information is given about the absolute error in the reconstructed signal. RMS is also very extended. Like PRD, this is the squared norm of the difference vector between original and reconstructed signals but it is not normalized by the energy of the signal but by the number of samples of the block. Hence, it is an absolute measure, expressed in the same units of the signal amplitude. Guaranteeing RMS means guaranteeing an absolute error in the reconstructed signal.

In this paper we discuss the advantages and drawbacks that present the use of RMS and PRD error indices when guaranteeing reconstruction quality. We use both mathematical results and clinical results so as to determine which one is better and under what conditions.

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A. Alesanco and J. García are with the Communications Technologies Group (GTC), Aragón Institute for Engineering Research (I3A), University of Zaragoza, Spain alesanco@unizar.es

P. Serrano is with the Department of Cardiology, Clinical Hospital Lozano Blesa, Zaragoza, Spain.

L. Ramos is with the Department of Cardiology, Hospital of Santa Marina, Bilbao, Spain.

R. S. H. Istepanian is with the MINT Research Centre, Kingston University, UK.

II. THRESHOLD COMPRESSION METHODOLOGY

Firstly, ECG signal is segmented into blocks and baseline wandering is removed using a low-pass filter to identify it. After that, a wavelet transform is performed to the block and the wavelet coefficients are obtained. In our implementation, *coifflet* wavelet is used [2]. Wavelet coefficients are said to be relevant if they are above a certain threshold. Once the coefficients are selected both their order and amplitude have to be coded. Depending on which techniques are used to code amplitudes and orders of the selected coefficients, different data rates are obtained. In order to use the same rate no matter how coefficients are coded, the entropy H of the selected coefficients is introduced. It is defined as

$$H(x) = \sum_{all\ x} p(x) \cdot \log_2 \left(\frac{1}{p(x)} \right) \quad (1)$$

where $p(x)$ represents the probability of signal value x. It represents the minimum average number of bits needed to noiselessly code a sample from a given signal. In this implementation, coefficients are preserved or removed (placing a zero instead) depending on a unique threshold. In this way, H is calculated to the vector containing the exact value of the amplitude if the coefficient is selected or a zero value if the coefficient is removed. Multiplying H times the sampling frequency we would obtain the data rate (or simply rate as it is called throughout this paper).

III. GUARANTEEING RECONSTRUCTION QUALITY

The reconstruction distortion is measured by the squared norm of the difference between the original ECG block samples and the reconstructed ECG block samples. If we use the fact that the Euclidean norm is invariant to the wavelet transform (it is a unitary transformation), it can be seen that calculating the distortion using wavelet coefficients is equivalent to calculate it using the original samples in the time domain. For this special case of threshold compression where coefficients are exactly preserved or removed, it is easy to see that

$$D_{RMS/PRD} = \sqrt{\frac{\sum\limits_{allK} c(k)^2}{F_N}} \qquad (2)$$

where $c(k)$ is the kth wavelet coefficient, K is the set of removed coefficients and F_N is the normalization factor with value N or $\sum\limits_{n=1}^{N} c(n)^2$ for RMS and PRD respectively. In this way, the method to guarantee the desired distortion is straightforward: instead of setting the threshold as a value to discard or preserve coefficients, it can be defined in terms of desired distortion. Coefficients are discarded until the desired distortion is reached.

IV. RATE-DISTORTION (RD) CURVES FOR MATHEMATICAL QUALITY MEASUREMENT

The distortion measure used to evaluate all the results is RMS. It is calculated between the complete reconstructed ECG signal and the complete original ECG signal. The easiest way to compare mathematical distortion results is by using RD curves. They can be seen as $r = D(d)$ or $d = R(r)$, where r is the rate, d is the distortion and D and R are the functions which relate them. RD curves are plotted with a set of points obtained operating the compression method at different targets (in this case, desired distortion). In order to obtain D and R functions, RD points are linearly interpolated.

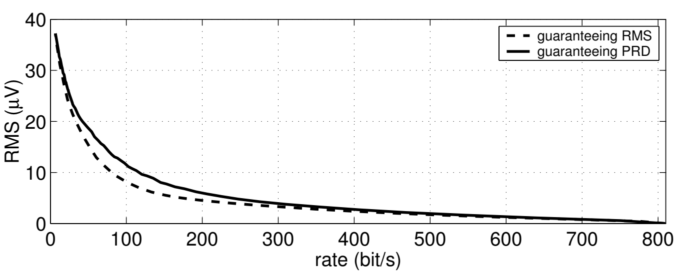

Fig. 1. Example of RD curves.

Fig. 1 shows two RD curves to illustrate the previous concepts. The dotted curve represents generic results obtained when guaranteeing RMS and the continuous curve generically represents results when guaranteeing PRD. At first sight it is easy to conclude that for these curves RMS results are better than PRD results. But if the test are carried out in a large ECG database in order to know which methodology (guaranteeing RMS or PRD) is better, presenting RD curves for all ECG records could be extremely hard. For this reason, we propose two measures of dissimilarity between RD curves so as to summarize all the information a RD curve offers into two numbers. The first one is the RMS-difference. It is defined as

$$RMS_{diff} = \frac{\sum\limits_{\forall i \in C} R_{PRD}(i) - R_{RMS}(i)}{N} \qquad (3)$$

where R_{PRD} and R_{RMS} are the functions for guaranteeing PRD and RMS respectively, C is a set of N rate values. RMS_{diff} is measured in μV. This measure can be seen as a set of N equispaced vertical cuts to the curves of Fig 1. The values obtained from the cuts are then subtracted as explained.

In the same way, the second measure, $rate_{diff}$, is defined as

$$rate_{diff} = \frac{\sum\limits_{\forall i \in \tilde{C}} D_{PRD}(i) - D_{RMS}(i)}{N} \qquad (4)$$

where D_{PRD} and D_{RMS} are the functions which express the rate as a function of the distortion when guaranteeing PRD and RMS respectively, $\tilde{C}$ is a set of N distortion values. $rate_{diff}$ is measured in bit/s. This measure can be seen as a set of N equispaced horizontal cuts to the curves of Fig 1. The values obtained from the cuts are then subtracted as explained. For both RMS_{diff} and $rate_{diff}$ measures, N is selected to be 1000 points.

V. MEAN OPINION SCORE (MOS) TESTS FOR CLINICAL QUALITY MEASUREMENT

Mathematical distortion measures are very extended to give results when developing a new compression algorithm. Nevertheless, it is very well known that they do not provide a real clinical impression. There is not a direct relation between mathematical distortion measures and clinical acceptability of the signal. Therefore, when a compression algorithm is being evaluated, clinical measurements should be included. In [3] the authors introduced two MOS test in order to clinically evaluate ECG reconstructed signals. Although these tests can be used to evaluate reconstructed ECG signals, consulted cardiologists pointed out that some questions could be misleading because there were not a unique answer. In this way, we have developed new MOS tests, enhancing and completing those presented in [3].

Analysis of ECG signal - code no. i27717

Details of tester

Name: Date:

1. General quality score for the signal (select one number)

1-very bad, 2-bad, 3-acceptable, 4-good, 5-very good

2. Interpretation (select one option in all rows)

P	Normal	yes	no	?	No P	ST	Normal	yes	no
	Pulmonale	yes		no			Depressed	yes	no
	Mitrale	yes		no			Elevated	yes	no
	BAV-I	yes		no			Flat	yes	no
QRS	Normal	yes	no	no			Ascending	yes	no
	IVCD	yes		no			Descending	yes	no
	LBBB	yes		no		AB	EVs	yes	no
	RBBB	yes		no			ESVs	yes	no
	Delta wave	yes		no			Pacemaker	yes	no
	Pacemaker	yes		no			BAV-II	yes	no
T	Normal	yes	no	?	No T		BAV-III	yes	no
	Positive	yes		no			RIVA	yes	no
	Negative	yes		no			TV	yes	no
	Biphasic	yes		no			FV	yes	no
	Symmetric	yes		no					

Comments

Fig. 2. Individual blind MOS test.

In Fig. 2, the individual MOS test is presented. The aim of this is to obtain the cardiologists evaluations in a blind condition, without knowing the compression method used nor compression factor used. Ten seconds of one lead were used to obtain the evaluation.

Analysis of ECG signal - code no. c88763; original-reconstructed

Details of tester

Name: Date:

1. The measure of similarity between the original signal and reconstructed signal (select one number)

1-very bad, 2-bad, 3-acceptable, 4-good, 5-very good

2. Would you give a different diagnosis with the reconstructed signal if you had not seen the original signal (select YES or NO)

YES NO

Comments

Fig. 3. Original-reconstructed semi-blind MOS test.

For the semi-blind test, we use the same test that was introduced in [3]. The aim of the semi-blind test is to obtain the cardiologists evaluation in direct comparison of the reconstructed signal with the original. Fig 3 shows the semi-blind test for original-reconstructed comparison.

Results from tests are combined into a unique measure, a weighted MOS error. It is defined as

$$MOS_{error} = \frac{\sum_{i=1}^{N} MOS_i^B + \sum_{i=1}^{N} MOS_i^{SB}}{2 \cdot N} \quad (5)$$

where N is the number of cardiologist who evaluate the signals and MOS_i^B and $MOS_i^S B$ are the results obtained for the ith cardiologist in the blind and semi-blind test respectively. These values are given by

$$\begin{aligned} MOS_i^B &= f \times \max\left\{\frac{Q_o - Q_r}{Q_o}, 0\right\} \times 100 \\ &+ (1-f)\frac{\sum_{j=1}^{29} |\text{sgn}(I_{oj} - I_{rj})|}{5} \times 100 \quad (6) \end{aligned}$$

$$\begin{aligned} MOS_i^{SB} &= f \times \frac{5 - C}{5} \times 100 + (1-f) \\ &\times (1 - D) \times 100 \quad (7) \end{aligned}$$

where

- Q_o is the general quality score of the original signal (Question 1 in the semi-blind test);
- Q_r is the general quality score of the reconstructed signal;
- I_{oj} is the interpretation of the ith parameter of the original signal (0-YES, 1-NO, 2-?, 3-NoP and NoT) (Question 2 in the semi-blind test);
- I_{rj} is the interpretation of the ith parameter of the reconstructed signal;
- C is the measure of similarity between the original signal and the reconstructed signal (1-5) (Question 1 in the blind test);
- D is the boolean question about the diagnosis (0-YES, 1-NO) (Question 2 in the blind test).

VI. Results

A. Mathematical results

MIT-Compression [4] has been used to obtain the results. This ECG database is composed by 168 ECG signals of 28.48 seconds and two leads. This database was created to offer compression methods a wide range of cases. These signals were acquired with a sampling frequency of 250 Hz and a resolution of 12 bits per sample. Fig. 4(a) and (b) show the RMS_{diff} and $rate_{diff}$ measures respectively when the threshold method is applied to the database.

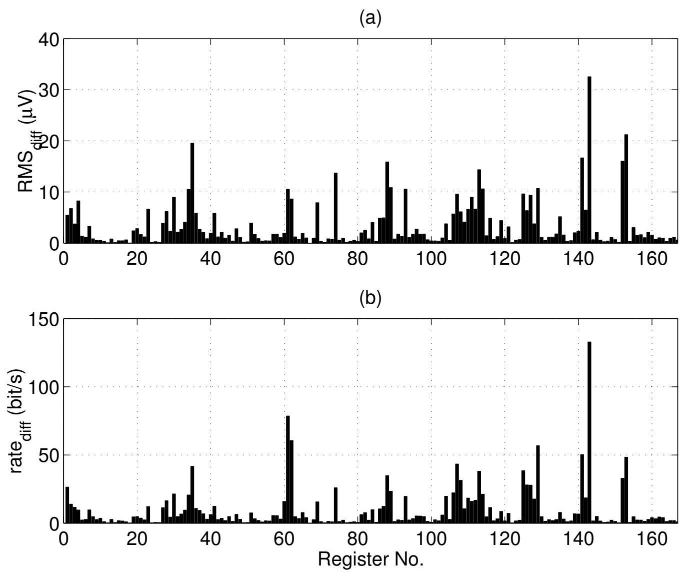

Fig. 4. Threshold compression method. Block length = 256. (a)RMS_{diff}. (b) $rate_{diff}$.

It can be seen that because RMS_{diff} and $rate_{diff}$ are always positive, guaranteeing RMS always leads to better results than guaranteeing PRD.

If the block size used is 512 samples it has been observed that although results for RMS are still better, values of RMS_{diff} and $rate_{diff}$ decrease for all the records in the database.

B. Clinical results

Ten seconds from lead one of records 12490_02 (signal 1) and 13274_04 (signal 2) were selected in order to obtain clinical results. Three points of the RD curves were selected for evaluation corresponding to low, medium and high entropies. In order to obtain a fair comparison, the same entropies were used for both guaranteeing PRD and guaranteeing RMS. Reconstruction error was calculated between the ten-second reconstructed signal and its original. Tab. I shows the results obtained from two cardiologist evaluation.

TABLE I
CLINICAL EVALUATION: MOS VALUES

	Signal 1			Signal 2		
	rate (bit/s)	RMS (μV)	MOS	rate	RMS	MOS
RMS	583	4.7	4.3	573	7.0	4.9
	370	7.5	6.1	224	23.5	14.1
	207	12.0	9.1	171	34.0	45.7
PRD	583	7.5	4.1	576	8.3	0
	371	18.2	47.7	222	26.7	14.3
	206	42.5	48.7	170	40	33.3
MOS values: 0-15 very good; 16-35 good; 36-50 not good; >50 bad						

VII. DISCUSSION

Taking into account only mathematical results, it can be said that guaranteeing RMS leads to better results than guaranteeing PRD. Nevertheless, this difference decreases as the block length increases. The reason behind this fact is the normalization by the block energy performed when guaranteeing PRD. Fig. 5 illustrates this effect. Fig. 5(a) represents block energy (block length equal to 256 samples) for record 13431_03. On the other hand, the number of coefficients used to code one block when guaranteeing RMS and PRD is shown in Fig. 5(b). In both cases the RMS global error obtained is approximately equal (11.25 μV) but the entropies are very different, 57 for RMS and 116 for PRD. In this case, when the energy of the block is low, PRD is calculated normalizing by a low value thus leading to the use of a large number of coefficients in order to guarantee the PRD threshold (see Eq. 2) compared with a block of higher energy. On the contrary, if the error to be guaranteed is RMS, block energy does not determine so dramatically the number of coefficients. Because many coefficients are used to code low energy blocks when guaranteeing PRD, an increase in the entropy is produced while the global error decreases only in a low quantity due to the low energy of the extra coefficients coded.

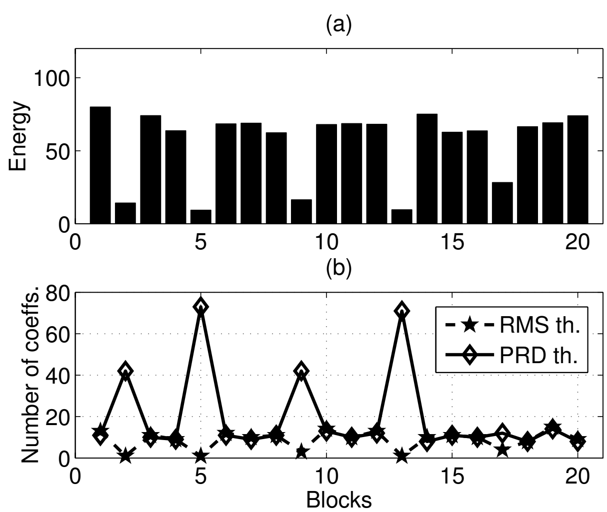

Fig. 5. Block energy and number of coefficients in the coding of record 13431_03.dat. RMS global error when guaranteeing RMS and PRD equal to 11.3 μV and 11.2 μV respectively. Entropy when guaranteeing RMS and PRD equal to 57 and 116 respectively. Block length 256 samples.

The increase in the block length has a positive effect for PRD guarantee. The larger the block, the more probable a QRS is placed inside the block, thus increasing the block energy. But care must be taken increasing the block length if the compression method has to work in real-time because large blocks mean larger initial delay.

Clinical results show that the decision between PRD and RMS thresholds depends on the characteristics of signal being compressed. In the case of record 12490_02 (see Fig. 2) is very interesting to note that despite the mathematical error is higher for PRD threshold, its clinical results are better. In this case, the negative effect in the rate increase due to low energy blocks is completely shadowed by the fact that there is one block of low energy where P waves are removed when guaranteeing RMS. Due to the increase of rate in PRD threshold, P wave is very well preserved while RMS threshold removes it in the case of entropy 147 (see Tab. I). In the example of record 13431_03 (Fig. 3), the primary effect in derived from the presence of a high number of low energy blocks. Obtaining the same rate in both PRD and RMS has a hugh negative effect in PRD threshold regarding to global reconstructed error. Thus, clinical results are much better for RMS threshold rather than PRD threshold.

VIII. CONCLUSIONS

In threshold compression methods, guaranteeing RMS is always better than PRD when mathematical global error is taken into account due to the rate increase for low energy blocks in PRD threshold. The effect of block size increasing the block energy makes that PRD results are closer to RMS results. Clinical results have shown that the choice between guaranteeing PRD and RMS depends on the characteristics of the signal being compressed. If the signal presents many low energy blocks after segmentation, guaranteeing RMS could be a better choice than PRD. Nevertheless, because a PRD threshold treats better low amplitude waves (such as P wave) when placed inside a low energy block, the use of PRD threshold could lead to better clinical results than RMS using for both cases the same rate. Because clinical results are the most relevant ones when working with biomedical signals, the final conclusion is that there is not an optimum selection when guaranteeing quality: it depends on the signal characteristics. Anyway, more clinical test with different ECG records have to be carried out in order to obtain definitive conclusions about the detailed effects of guaranteeing RMS or PRD in ECG compression.

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