International Journal of Natural and Engineering Sciences 9 (1): 27-33, 2015
ISSN: 1307-1149, E-ISSN: 2146-0086, www.nobel.gen.tr

Improved Multichannel ECG Signal Compression Based on Discrete Wavelet Transform and a Special Scanning Method

Hanieh ZAMANIAN[1] Hasan FARSI[1]
[1] Department of Electrical and Computer Engineering, University of Birjand, Birjand, Iran

*Corresponding author:
Email: hanieh.zamanian@birjand.ac.ir

Received: January 29, 2015
Accepted: March 06, 2015

Abstract

Electrocardiography is one of basic investigative methods in cardiology through which all necessary information about electrical activity of the heart can be collected. Recorded Electrocardiogram, ECG, signals which are huge in size, not only used for diagnosis purpose but it is also stored for future reference. Therefore, compression of huge amount of ECG signal data is required to keep these records for observing a patient. This paper proposes a novel approach to compress a 12-lead set of ECG waveform jointly. The proposed method provides a reasonable trade-off between distortion and compression ratio by using a lossy compression technique. The technique exploits inter-channel correlation of signals in cardio-complex leads by using 1-D wavelet and a special scanning method that improves compression performance. Also we find the best threshold for wavelet coefficients via optimization algorithms. It is shown that the compression ratio of this approach for percent root mean square difference (PRD) equal to almost 5% is higher than similar methods. At the end, we use a zip algorithm to achieve more compression.

Keyword: Signal processing; Compression; ECG; zip algorithm; inter-channel correlation; cardio-complex.

INTRODUCTION

Since the level of interest about individual health has increased recently, many studies that address ambulatory health monitoring in daily normal life have started. Various vital signs can be measured through the health monitoring devices, but Electrocardiogram (ECG) information is one of the most useful signals for assessment of heart health. Electrocardiography is a non-invasive procedure for recording electrical changes in the heart. The records show the series of waves that relate to the electrical impulses which occur during each beat of the heart. The results are printed on paper or displayed on a monitor. Portable heart activity monitoring is also useful for a long-term health monitoring in normal life.

The storage and transmission of bio-signal data necessitate efficient algorithms and methods to cope with the conflicting requirements of high data quality and small storage space. Among the proposed techniques, particular advances in ECG compression have been achieved recently. In this field, one can classify the related techniques into three broad categories, namely, direct methods; transform methods and parameter extraction methods.

In direct methods, the original samples are directly compressed in time domain [1- 3], whereas in transformation methods, the original samples are transformed and the compression algorithm is performed in the new domain. Among the algorithms which employ transform-based techniques, several algorithms based on Discrete Cosine Transform, DCT, [4, 5] and Wavelet Transform, WT, [6, 8] have been proposed. In the last category, namely parameter extraction methods, the idea consists of extracting some signal features being used a posteriori for reconstruction purpose [9].

ECG compression can, in general, be either lossy or lossless. Lossless data compression methods are often unable to meet the strict requirements since they are commonly unable to provide a high compression ratio. Because of this, lossy compression techniques possess more applications nowadays. However, in the case of lossy compression, a reasonable trade-off between Compression Ratio (CR) and distortion should be obtained. For having the optimum CR we use optimization algorithms.

Moreover, encoders also can be characterized as single channel or multichannel [10, 12]. The vast majority of the reported papers in the ECG compression concept deal with a single channel ECG record, while only a few encoders have been proposed for multichannel ECG encoding [13, 15]. For the latter one, even fewer ECG encoders deal with full 12-channel data or the actual eight native channels, possibly due to the lack of such signals.

In following section, the preprocessing algorithms applied to the dataset are introduced and then, the encoding process, including the wavelet transform, threshold selection and implementation, quantization and scanning, are explained. The simulation results by the proposed algorithm using selected ECG records are presented and discussed in section of ‘results and discussions’. Finally, the paper is concluded in the last section.

MATERIALS AND METHODS

Preprocessing

Database

As mentioned earlier, we concentrate on the standard system of ECG leads, i.e. we have the basic ECG records I, II, V1, V2,V3, V4, V5, V6 as well as supplementary records III, aVR, aVL, and aVF. As shown in equation (1) to (4), the supplementary records can be recovered from the basic leads. Thus, the compression ratio can improve while the quality of the recovered records will be adequate.

$$II - I = III . \quad (1)$$

$$(I - III) / 2 = aV_L . \quad (2)$$

$$(I + II) / (-2) = aV_R . \quad (3)$$

$$(II + III) / 2 = aV_F . \quad (4)$$

The proposed technique is applied and tested on real life multichannel ECGs provided by the National Metrology Institute of Germany (www.physionet.org/physiobank/database/ptbdb).

Figure 1, shows this database waveform for patient number 1. It is a small part of the original one. As observed, the order of channels in the matrix constructed by the samples of the signals is as same as row number of the matrix.

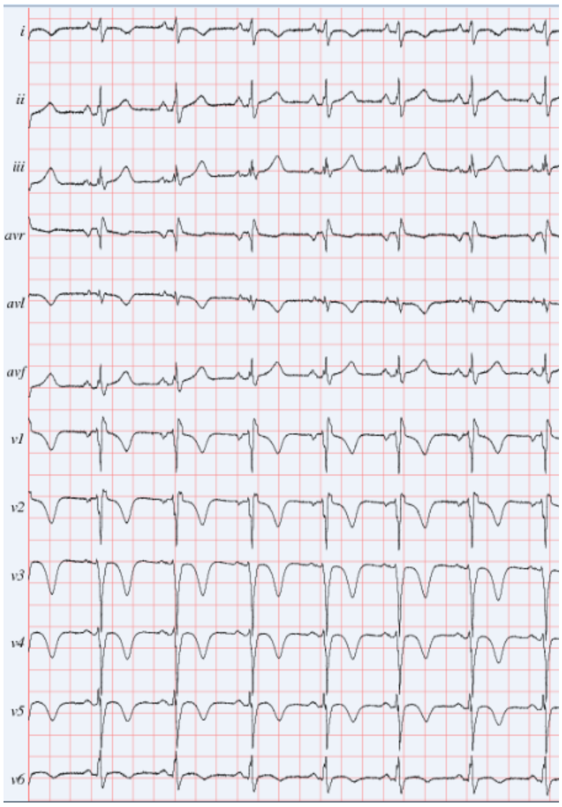

Figure 1. PTB database waveform for patient number 1.

Preprocessing

Energy Normalization

Computing the energy of each leads in input signals, shows that their energies are multiple of 10^4. This means that their difference would be very large and it couses huge distortions in reconstructed signals. To overcome to this problem, we normalize the energy to 1.

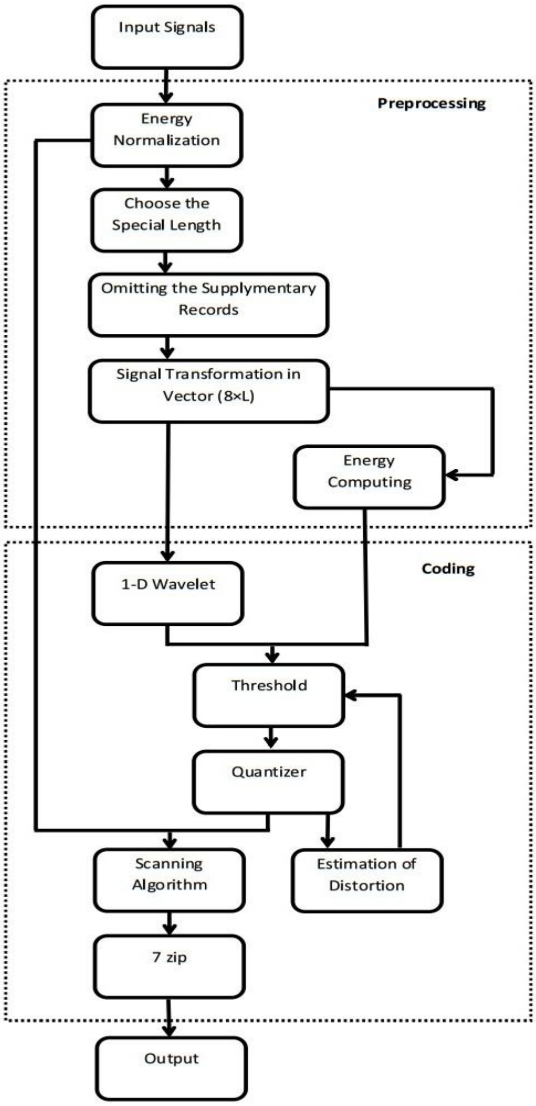

Figure 2. Block diagram of the proposed method.

Choosing the Special Length

The aim of the proposed method is to compress a long term ECG report due to having a huge number of samples. Depending on sampling ferequency, the volume of data for being processed will vary, but obviousely as the number of samples increases, the computational process will be more complicated and consumes too long time. So, to overcome to this problem, we devide the signal into a specific length. The selected time length is one minute for any kind of frequency.

Removing the Supplymentary Records

As mentioned before, we can omit the supplymentary records and recover them at the end of process, based on corresponding based channels. Only the based channels including I, II, V1, V2,V3, V4, V5, V6 are used for the next steps of process. We will show that this channel selection causes that the compression ratio will improve.

Signal Transformation in Vector

Because of using one demementional wavelet transform for compressing the ECGs in the proposed method, we need to have a vector as the input of 1-D wavelet transform.

Therefore, we need to reorder the multichannel input signals into a vector. This is achieved by ordering each base channel, consecutively. This means that L samples of one channel place in L adjacent positions in the vector; then, the L samples of the next channel locate in the next L adjacent positions. This is performed for eight base channels. At the end, we have a vector with the length of 8×L.

Energy Computing

In the coding steps, the wavelet coefficients threshold is applied to obtain higher compression ratio. The threshold should be dependant on the signal. Hence, the best way is to make a ralationship between the energy of that special length defined in the second step and the threshold applied for the transformed signal. Therefore, the energy of L samples should be computed and stored for the next steps.

Encoding

Clearly, the performance of the coder presented in Fig. 2 depends on several factors. The main factors are as follows: First, coder efficiency depends on the employed operations of the data preprocessing. Second, the mother wavelet and the number of decomposition levels are also important. Third, threshold selection influences both CR and percent root mean square difference (PRD) which are given by:

$$CR = \frac{\text{length of data before compression}}{\text{length of data after compression}} \quad (5)$$

$$PRD = \sqrt{\frac{\sum_{n=0}^{N-1}\left(x_{org}(n) - x_{rec}(n)\right)^2}{\sum_{n=0}^{N-1} x_{org}(n)^2}} \times 100 \quad (6)$$

Where x_{org} means original signal and x_{rec} means reconstructed signal.

Forth, the algorithm of wavelet coefficient scanning influences the CR. Fifth, the employed lossless coder plays some role as well.

In following, we focus on the influence of these factors. With respect to the second factor, our research has shown that the best compression ratio is obtained by applying Bi-orthogonal 3.3 as the mother wavelet with seven level of decomposition. A comparison between different mother wavelet functions is shown in Table 1 for patient number 104. Note that the obtained results are before using 7zip algorithm.

Table 1. Comparison of Mother Wavelets

Mother Wavelet	Results for special thresholds and PRD≈5%		
	Threshold/Energy	CR	PRD
Db1	0.00027	21.4199	4.9566
Db5	0.00051	37.4046	4.9835
Bior 1.3	0.00027	21.0283	4.9473
Bior 3.3	0.00061	44.3361	4.9868
Coif 1	0.00047	36.0563	4.9793
Coif 3	0.00051	39.3183	4.9623
Sym 1	0.00027	21.4199	4.9566
Sym 6	0.00052	39.7516	4.9933

As mentioned before, selecting the threshold is a very important issue, because it is related to the signal. Since ECG signals are usually very different, it is not reasonable to set a fixed threshold for all ECGs. The solution is to make a relationship between the energy of the vector constructed in the preprocessing step and the threshold applied on the vector of wavelet coefficients. The experimental results have shown that the best CR will be obtained if the threshold is adjusted according to the mentioned PRD for each ECG. However, a long time is required to adjust the threshold. In order to overcome to this problem, a predefined threshold should be indicated. Due to the various ECGs, the threshold is chosen to be a coefficient dependent to the energy of the vector constructed in the previous step. The best coefficient is 0.00055 which has been achieved by average of the optimum thresholds found using optimization algorithms for many different signals. In Table 2, PRD and CR are shown for 10 patients associated by the numbers of 104, 105, 116, 150, 169, 234, 240, 241, 242 and 243 using the mentioned threshold.

Table2. CR and PRD for Threshold/Energy=0.00055

Patient Number	Results for special threshold=0.00055×energy	
	CR	PRD
104	43.0547	4.6451
105	37.8657	5.0387
116	50.4783	4.2863
150	41.4737	4.5724
169	33.8473	4.7150
234	36.8436	5.7428
241	46.2415	4.5593
242	34.9312	5.2972
243	46.2415	4.6574
244	31.1060	5.6574

An alternative method to find the best threshold with respect to maximizing the CR for PRD equal to 5% is using optimization algorithms. We tested different algorithms such as PSO, cuckoo search, GSA and so on. We also examine the signals with multi-objective optimization algorithms such as MOPSO and MOCFO. The main problem to find the optimum threshold is definition of the cost function. Obviously, the cost function for multi-objective algorithms differs from single objective algorithms. We define the cost function as follows: the first algorithm shows that we emphasis on PRD almost 5%. This means that the optimization algorithm minimizes the cost function for PRD in interval %4.5 to 5% when CR has maximum value. We force the cost function to be negative in this interval. This guarantees that it is less than the other obtained values out of this range.

```
 if  PRD<5.5
if PRD<4.5
cost=((PRD)^-1)*10;
else
cost=-((CR)^4)*10^-4;
end
else
cost=(PRD)*10^3;
end
```

Also the cost function for the multi-objective algorithms should be defined in a way such that when one parameter increases the other should decreases. In the proposed method, the problem is when the PRD increases the CR increases as well. Therefore, we define the cost function such that to maximize the PRD and minimize the inverse of the CR simultaneously. It is given by:

Cost(1)=PRD
Cost(2)=CR^-1

After applying the optimum threshold found in the last step, the next step is quantization.

In analysis of the discrete time systems, values are displayed in real domain. But when the digital signal processing systems are implemented, the signals and coefficients in a digital system are limited by numerical precision. Most of digital computers use a binary numerical system. Output samples of an A/D transducer are quantized, so they could be displayed by a fixed point binary numbers.

In the proposed method, wavelet transform coefficients are real numbers; therefore, we need to quantize them. The used quantization algorithm is called fixed point quantization. The quantization algorithm is implemented as follows:

Quantization of vector X=[x_1 x_2 … x_N] is performed by:

$$X_q = round\ [(X/max(|X|)) \times (2^{(nbit-1)})] \quad (7)$$

In (7) *nbit* is the number of bits representing the quantized value after quantization. As shown in Table 3, by choosing 8 bit for quantization, the PRD increases from 0.1% to 0.2%.

After applying threshold and quantization, many wavelet coefficients are become to zero. Scanning algorithm is used to remove the resulted zeros and save the position of nonzero coefficients. In fact, just nonzero coefficients and their positions are saved and sent to the receiver. Due to existing much more zeros compared to nonzero coefficients, scanning can considerably reduce the volume of data. Hence, the CR will improve. In following, the scanning algorithm is explained.

It would be helpful if the scanning algorithm is explained by an example. Suppose that the vector C contains the coefficients, for instance as:

C = [1 2 4 5 0 0 0 9 6 8 11 0 12 13 0 0 0 0 16]

According to our experiment we can scan these numbers in two columns to provide a better result. So the coefficients order in a matrix is shown as:

$$\begin{matrix}1\\2\\3\\4\\5\\6\\7\\8\\9\\10\end{matrix}\quad\begin{bmatrix}1 & 2\\4 & 5\\0 & 0\\0 & 9\\6 & 8\\11 & 0\\12 & 13\\0 & 0\\0 & 0\\16 & 0\end{bmatrix}$$

The numbers in the left side show the number of rows. In some rows, both elements are zero. So we omit these rows. Also we will send nonzero rows with their row numbers. In the last row of the above matrix we have an additional zero, but it would not cause any confusion, because the number of the coefficients in matrix C will be sent. To make sure that there is a gap between the coefficients and their row numbers; we fix two consecutive zero rows after the coefficients and then place their row numbers. Also additional information like norm of each original signal and the number of coefficients should be ordered in the final matrix which will be sent for the receiver. For instance, the output matrix of our example is constructed as follows: we assume to have four channels with norms of n1, n2, n3 and n4. In 16th row, the number of 19 shows the whole coefficients in the matrix C. Also, Xmax shows the $max(|X|)$ in the quantization step.

$$\begin{bmatrix}1 & 2\\4 & 5\\0 & 9\\6 & 8\\11 & 0\\12 & 13\\16 & 0\\0 & 0\\0 & 0\\1 & 2\\4 & 5\\6 & 7\\10 & 0\\0 & 0\\0 & 0\\19 & Xmax\\n1 & n2\\n3 & n4\end{bmatrix} \quad (7)$$

In fact, due to having many rows including zero, the CR improves significantly. The effect of the number of the columns in the scanned matrix is shown in Table 4.

The last step of compression in the proposed method is using an entropy encoder, e.g. the *7zip* as the encoder. 7zip is free software provided under the GNU Lessor Public License. The program and its default compression algorithms, LZMA and LZMA2, were created by Igor Pavlov. The 7zip program can also decompress the data.

LZMA is a lossless compression algorithm that uses a dictionary compression scheme followed by a range encoder, which attains very high compression ratios. It was introduced by Igor back in 1998. Among several studied lossless encoders, LZMA with 64MB dictionary in size and word size of 273 at ultra-compression level demonstrates the best performance.

It is obvious that a better result indicates lower PRD and higher CR. The PRDs mentioned in this paper are calculated for eight basic channels. Obviously, computing it for 12 channels shows often lower PRDs. The compression rate is the ratio of the output file resulted to the proposed algorithm to the original input file. In Table 5, the influence of using 7zip on CR is shown. It has negligible effect on PRD, because it is a lossless encoder.

RESULTS AND DISCUSSION

Commonly the efficiency of encoder is described in terms of percentage root mean square difference (PRD) and the compression ratio (CR).

It is assumed that the PRD should not be larger than 5% in order not to distort diagnostic features of ECGs [7]. In order to analysis the performance of the quantization and the scanning approach in the proposed method, Table 3 and Table 4 show the effect of quantization method on PRD and the effect of the variations in the number of columns in the scanned matrix on CR, respectively.

Table 3 demonstrates that choosing 8 bits for quantization of the coefficients results in a negligible effect on PRD. However, it is tested for many patients and showed that the increase of the distortion was in the range of 0.1% to 0.2%.

Table 3. Effect Of Quantization With 8 Bits On PRD

Patient Number	PRD before Quantization	PRD after Quantization
104	3.7581	3.9178
105	4.0484	4.1450
116	3.1922	3.2834
150	3.6619	3.7965
169	4.0780	4.2276
241	3.5497	3.7341
242	4.2179	4.3787
243	3.5811	3.6336

Table 4. Effect Of The Columns Of The Scanned Matrix

Patient Number	Number of Columns of Scanned Matrix			
	1 Column	2 Column	3 Column	4 Column
104	33.9306	38.4941	38.2311	36.9982
105	31.8687	34.9922	34.2399	32.5761
116	36.1336	40.9819	40.8402	38.7792
150	33.3871	37.6635	36.8876	35.6914
169	27.9330	30.6409	30.3529	29.1404

As demonstrated in Table 4, although the difference between 2 and 3 columns for the scanned matrix is small, for all ECGs, the best CR will be obtained if two columns in the matrix are chosen. However, considering one column in the matrix corresponds to a lot of row numbers and causes a reduction in the CR. Also the probability of having a lot of rows with four or even more zeros consecutively is low; therefore, taking 4 or more columns for the matrix will decrease the CR. Fig. 3 displays increasing CR versus PRD by changing the threshold for the patient number 150. It is obvious that increasing the CR causes more distortions and increasing the PRD as well.

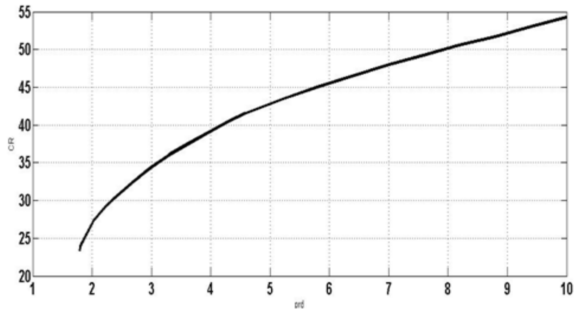

Figure 3. Increasing CR versus PRD.

Figure 4 shows the best (minimum) CR verses different the PRD values. It is obtained by applying the multiobjective PSO (MOPSO) algorithm for finding different thresholds for each detail and approximation.

As shown in Table 2, the best compression is achieved when the biortogonal 3.3 wavelet with seven level of decomposition is applied. Thus, the optimization algorithm should find seven theresholds for each seven detail coefficients and one for the approximation coefficients. After finding the best thresholds, the corresponding inverse CR (vertical axes) and PRD (horizontal axes) are pointed in the figure. This algorithm is executed for 25 iterations with repositorty of size 100 and the population size was 100.

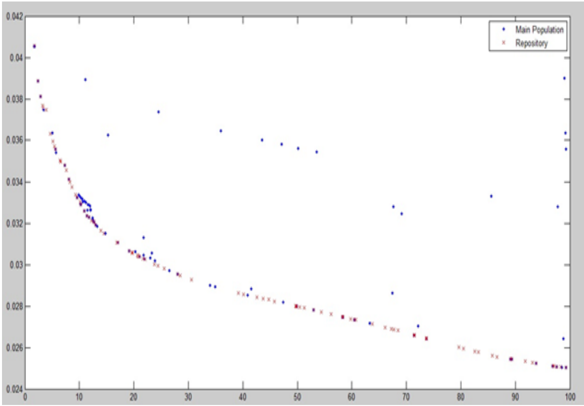

Figure 4. Finding the optimum thresholds(7 level) which miximize the PRD and minimize the CR

We found the best results achieved for each patient for PRD almost 5%, by using the optimization algorithms with 8 specific thresholds for each eight parts of coefficient. These best results are shown in table 5.

Table 5. Best Results After Applying Optimization Algorithms

Patient Number	Best Results after applying optimization algorithms	
	CR	***PRD***
104	51.5231	5.0431
105	40.6708	5.0092
116	62.0257	4.9670
150	51.6549	5.1085
169	39.5224	5.1091
234	39.0713	5.2987
241	56.7608	56.7608
242	38.0986	38.0986
243	55.3174	55.3174
244	33.9854	33.9854

For describing the effect of the lossless encoder, Table 6 shows the obtained results of compressing the scanned matrix for patient number 104 by different 7zip algorithms. The output of scanned matrix is saved with two formats, .mat and .ascii. Then the obtained files are compressed by 7zip software. As shown in Table 6, if the output data is saved with .ascii format, the lossless encoder will be more effective. Therefore, the proposed algorithm is able to compress the size of input files about 300 times which means a huge reduction. Compared to the reported methods in [13] and [14], the proposed method provides much higher compression.

Table 6. Effect Of Diferrent Compression Algorithms Of 7zip

Proposed Method	*CR*		*PRD*
Principal Component Analysis [13]	20		5%
Wavelet-based with genetic algorithm [14]	20		Below 10 %
On Low_Complexity Joint Coding Scheme [15]	3.41		0
ASCII Character Encoding [16]	15.72		7.89
The proposed method without 7zip	Average 45.87		5%
The proposed method with 7zip algorithms	CR for mat File	CR for ascii File	5%
LZMA	259.8985	324.6404	
LZMA2	259.8863	324.6023	
PPMD	258.3382	308.3477	
BZIP2	256.1779	280.5907	

Fig. 5 presents a fragment of the original signal ECG for the patient number104 and the decompressed ECG of channel II for the proposed technique. In this case, PRD for 8 base channels was 4.2% and PRD for 12 channels jointly was 3.17%. Also the PRD for each channel separately was less than 6.5%.

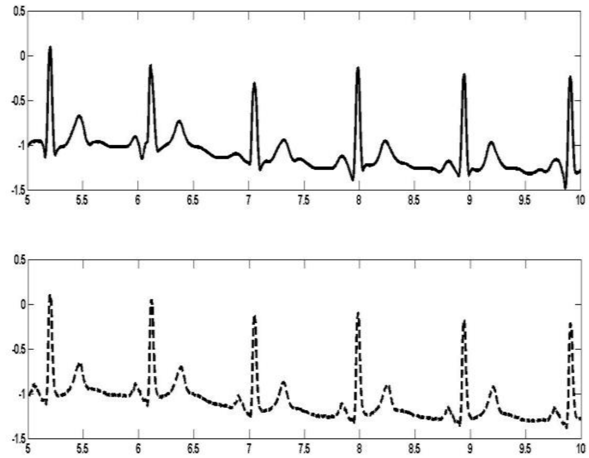

Figure 5. Original and reconstructed signal of lead II.

CONCLUSION

In this paper, we proposed a novel approach for lossy compression of multichannel ECG signals. The proposed method is based on implementing one dimensional wavelet transform to exploit inter-channel correlations. Also optimum thresholds are searched via optimization algorithms to maximize the CR and minimize the PRD. We emphasized on the results with PRD almost 5%. In addition, a new method of scanning the wavelet coefficients was introduced.

It is demonstrated that the use of the proposed method can lead to a considerable compression ratio compared to the reported methods. The CR will be more than 250 for a PRD of less than 5%.

REFERENCES

[1] Jalaleddine S. M. S., Hutchens C. G., Stattan R. D., and Coberly W. A., 1990, ECG data compression techniques – a unified approach, IEEE Trans. Biomed. Eng., 37: 329-343.

[2] Abenstein J. P., and Tompkins W. J., 1982, New data-reduction algorithm for real time ECG analysis, IEEE Trans. Biomed. Eng., BME-29: 43-48.

[3] Cox J., Noelle F., Fozzard H., and Oliver G., 1968, AZTEC: a preprocessing program for real time ECG rhythm analysis, IEEE Trans. Biomed. Eng., BME-15: 128-129.

[4] Bendifallah A., Benzid R., and Boulemden M., 2011, Improved ECG compression method using discrete cosine transform, Electronics Letters, 47: 87-89.

[5] Lukin V., Zriakhov M., Zelensky A. A., Egiazarian K., Varri A., 2008, Lossy compression of multichannel ECG based on 2-D DCT and pre-processing, Proceedings of Internatinal Conference Modern Problems of Radio Engineering Telecommunications and Computer Science, 159-162.

[6] Sharifahmadian E., 2006, Wavelet compression of multichannel ECG data by enhanced set partitioning in huerarchical trees algorithm, 28th Annual International Conf. of the IEEE Eng. in Medicine and Biology Society, 5238-5243.

[7] Kumari R. S. S., and Sadasivam V., 2007, A novel algorithm for wavelet based ECG signal coding, International journal of Computers and Electrical Eng., 33: 186-194.

[8] Rajoub B. A., 2002, An efficient coding algorithm for the compression of ECG signals using the wavelet transform, IEEE Trans. Biomed. Eng., 49: 355-362.

[9] Mukhopadhyay S. K., Mitra M., and Mitra S., 2011, An ECG data compression method via R-peak detection and ASCII character encoding, ICCCET 2011, 136-141.

[10] Zeybek E. H., Nait-Ali A., Oliver C., and Ouled-Zaid A., 2007, A novel scheme for joint multichannel ECG ultrasound image compression, 29th Annual Internatinal Conference of the IEEE, Engineering in Medicine and Biology Society, 713-716.

[11] Sgouros N. P., Constantinou I. P., Loudos G. K., and Kossida S. A., 2007, Use of the MPEG-4 ALS architecture and inter-channel prediction for multi-channel ECG coding, IEEE Internatinal Symposium of Signal Processing and Informatin Technology, 754-759.

[12] Kamamoto Y., Harada N., Moriya T., Ito N., Ono N., Nishimoto T.,and Sagayama S., 2009, An efficient lossless compression of multichannel time-series signals by MPEG-4 ALS, IEEE 13th International Symposium Consumer Electronics, 159-163.

[13] Jain R., 2015, 12 Lead ECG Data Compression Using Principal Component Analysis, International Journal of Emerging Trends & Technology in Computer Science (IJETTCS), 4: 34-39.

[14] Wu T. C., Hung K. C., Liu J. H., Liu T. K., 2013,Wavelet-based ECG data compression optimization with genetic algorithm, Journal of Biomedical Science and Engineering (JBiSE), 6:746-753.

[15] Kim D. S. and Kwon J. S., 2014, A Lossless Multichannel Bio-Signal Compression Based on Low-Complexity Joint Coding Scheme for Portable Medical Devices, Sensors, 14:17516-17529.

[16] Mukhopadhyay S.K., Mitra M., and Mitra S., 2012, ECG Compression Technique Using ASCII Character Encoding and Transmission Using GSM Transmitter, International Journal of Electrical, Electronics and Computer Engineering, 1: 77-82.