The Effects of Transmission Errors in ECG Real-Time Wavelet Compression Codecs

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Abstract

This paper discusses the error effects in wavelet compression codecs for real-time ECG monitoring in a wireless telecardiology application. Two different strategies for ECG coding are presented and the error effects in the received ECG signals are discussed. Both quantitative (RMS error index) and qualitative (cardiologist opinions) are presented in order to decide if it is useful to monitor retrieved information from ECG packets received with errors or erroneous packets should be discarded. Although RMS index suggests that it would be recommendable to show them, cardiologists conditioned their preference to the number of erroneous blocks in the monitoring process: few number of errors, monitoring no information; high number of errors, monitoring erroneous information.

1. Introduction

Telecardiology is one of the most mature and successful areas in telemedicine. The most popular field in telecardiology deals with the transmission of electrocardiographic (ECG) signals over different kinds of communications networks. It is well known that ECG transmission can be carried out in two different ways: pre-recorded (store-and-forward) and real-time. Although pre-recorded transmission is often a wider-used solution due to its simplicity, there are special scenarios where real-time ECG transmission is necessary. Emergency telemedicine is one of them. Continuous ECG monitoring is required to evaluate and supervise the patient health status. This monitoring is normally carried out in an ambulance, where the ECG is transmitted to a hospital for specialist supervision [1]. In this case, the only way to communicate an ambulance with a hospital is through a wireless channel.

Working in real-time telecardiology, when the conditions of the channel are poor the number of packets suffering transmission errors will be large. Retransmitting the information could not be a solution because the retransmitted information could be received with error continuously. In this case, trying to recover some information from the corrupted packets could be considered instead of retransmission.

In recent years, the application of wavelet transform (WT) for ECG compression has drawn major attention within the biomedical and e-Health research. There have been several proposals for ECG real-time transmission [2] but none of them took care about the effects of transmission errors introduced in the ECG signal.

The aim of this paper is two fold. Firstly, we present two ECG WT coding strategies suitable for real-time telecardiology applications based on the transmission of the most significant WT coefficients of every segmented ECG block. Secondly, errors introduced in the ECG during transmission (using a simulated UMTS channel) are analyzed using both quantitative and qualitative criteria.

2. Real-time wavelet ECG coding

In this section we present the wavelet ECG coding method. It is based on the coding of the ECG WT coefficients. Compression is achieved by selecting a subset of the most relevant coefficients which afterwards are efficiently coded.

To achieve real-time functionality requirements, the ECG signal is segmented into blocks whose coding results are then packetized for transmission. In our approach, the ECG coding method is divided into the following stages, illustrated in the block diagram in Fig. 1:

i) Pre-processing.
ii) Wavelet transform computation and coefficients selection.
iii) Coefficients coding.
iv) Packetization.

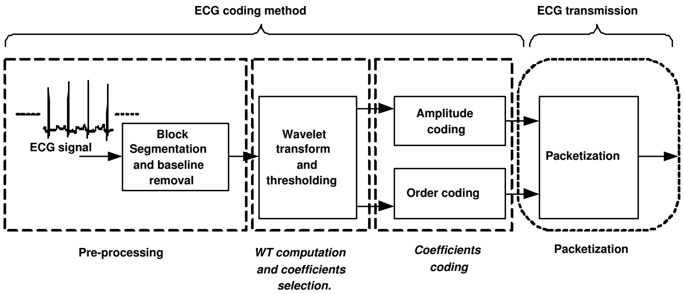

Figure 1. Block diagram of the ECG coding scheme.

2.1. Pre-processing

The ECG data stream is divided into fixed length blocks and every block is coded as an independent entity. Each lead in the block is treated independently through all the coding process. Then the baseline of the acquired ECG signal is removed. As real-time operation is required, a simple baseline estimation method is used: a third-order Butterworth low-pass filter (cut-off frequency equal to 0.5 Hz) used in forward/backward directions to avoid phase distortion. After the estimation, baseline is subtracted from the signal.

2.2. Wavelet transform computation and coefficients selection

After baseline wandering subtraction, the WT is applied to each available ECG block. A Coiflet wavelet was used as mother function due to its good performance on ECG compression. The WT coefficients are sorted by decreasing energy and the number of coefficients to be transmitted is selected according to a threshold. In this implementation, the threshold in selected to fulfil a desired transmission bit rate considering different bit allocation strategies, defined in the next section. In this way, the codec works in a constant bit rate (CBR) operational mode.

2.3. Coefficients coding

After threshold operation, a subset of WT coefficients is preserved for transmission. Since the selected coefficients may be different in each block, both order and amplitude must be coded for every block. Two different coding strategies are proposed for order and amplitude information in the next sub-sections.

2.3.1. Huffman code for jumps and APCM for amplitudes (Coding strategy A)

Relevant wavelet coefficients on each ECG block appear very close in the order sequence inside clusters (this effect is produced by the low-pass shape ECG power spectral distribution). To take advantage of the dominant coefficients order proximity, selected coefficients are sorted by order and the first difference of the orders sequence for the preserved coefficients is calculated (these difference values are denoted as jumps between the selected orders). The result is that most of the probability is concentrated in small jump values [3]. Such a priori information is used to design an efficient coefficient order coding. In this way, a Huffman code can be implemented with a symbol probability that reflects the observed jumps probability characteristics. Both the coder and the decoder know the Huffman code used. When the data is transmitted through a noisy channel, an error introduced in a jump codeword is fatal for this implementation. For instance, an error in a single bit would yield to a completely erroneous decoding of the following jumps. Hence, a de-synchronization would be produced in the decoder which propagates its effects through the complete data stream making the ECG block useless.

For amplitude coding, an Adaptive Pulse Code Modulation (APCM) coder is used. The number of bits is selected to assure a fixed quantization noise level for the amplitudes coefficients coding and varies block-to-block depending on the coefficients maximum amplitude [3].

2.3.2. PCM for orders and decreasing APCM for amplitudes (Coding strategy B)

If the coefficients are sorted by amplitude in absolute value, advantage can be taken from the fact that the absolute amplitude decreases fast from the highest coefficient to the lowest. In this way, an Adaptive Pulse Code Modulation (APCM) that uses different number of bits for coefficient coding as the amplitude decreases can be used. This coding approach will be called decreasing APCM. For each block, subsets of coefficients could be defined as a function of the number of bits they need to be coded. Note that the coding scheme is adaptive because for each ECG block the number of bits used in the coder is adapted to cope with the maximum amplitude found in the WT coefficients of the block. This coding strategy has a clear advantage over a Huffman code in error-prone environments. There is no risk of de-synchronization in the decoder because the number of bits of each coefficient order and amplitude are a priori known. Thus, an error either in the amplitude or in the order does not affect the subsequent data in the packet.

For order coding, a simple PCM coder is used since after ordering the coefficients by amplitude, no special arrangement of orders that could be used for a more efficient coding is found.

2.4. Packetization

Each ECG block is coded and then packetized in a Protocol Data Unit (PDU) for the transmission into the data field of the transport layer protocol. Information that needs to be packetized is: number of leads, number of selected WT coefficients per lead and coefficients orders and amplitudes. A CRC is introduced to cover the PDU. Thus, it is possible to know if a PDU is arriving with errors at reception.

3. Results and discussion

A subset of records (100, 101, 102, 103, 107, 109, 111, 115, 117, 118 and 119) from MIT-BIH Arrhythmia database [4] has been selected for performance evaluation of the proposed coding strategies. The sampling rate of the two-lead ECG recordings is 360 Hz and the resolution 11 bits per sample. In Fig. 2 the rate-distorion (RD) curves for strategies A and B are shown when both are working in an error-free environment with an ECG block length of 512 samples. RD curves were obtained averaging results obtained using 10 minutes of lead 1 from the subset. RMS distortion index has been used as error measure.

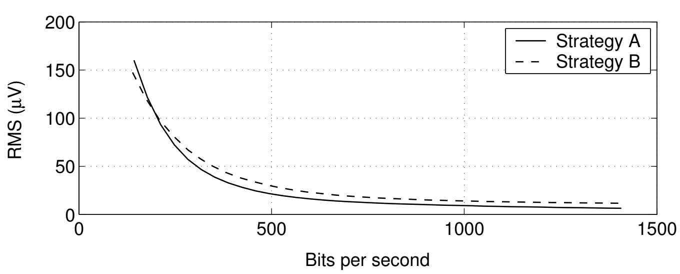

Figure 2. RD curves for Strategies A and B.

Strategy A presents a better performance than strategy B except for very low transmission rates. The real fact is that these very low transmission rates are never used in practice because they provide very poor reconstructed signals, useless from a clinical point of view. Consulted cardiologist have pointed out that a transmission rate greater than 500 bits per second (bps) per lead for our coding strategies leads to a reconstructed ECG signal suitable for diagnosis.

In order to compare the possible gain of letting pass information, we also considered the case where all packets received with error are dropped. To differentiate from their counterpart strategies, they are denoted as strategy A* and strategy B*. To compute the RMS error in reception for strategies A and B, blocks where no information can be extracted are discarded and replaced by a constant zero value. In strategies A* and B* all packets with errors are dropped and replaced by zero, as previously explained.

Tab. 1 shows the error measured in reception in the received signal for different bit error rate (BER) values. The first minute, lead 1 (ECG block of 512 samples) of each record was passed through a UMTS simulator [5] 90 times for each channel condition. Averages of the obtained values for all the subset are given for performance analysis. Transmission rate in the simulation was 500 bps.

Table 1. RMS error (μV) in received ECG

BER	0	$2.5 \cdot 10^{-3}$	$1.2 \cdot 10^{-2}$
Strategy A	21	43	104
Strategy A*	21	49	115
Strategy B	30	42	78
Strategy B*	30	58	122

It can be noted that as the BER increases, strategies A and B outperform their counterpart strategies (A* and B* respectively) from the RMS value point of view. An interesting fact is that as the BER increases, strategy B performs better than strategy A, suggesting, taking into account only this error measurement, that strategy B is more error resilient than strategy A.

A very important procedure when evaluating error effects for biomedical signals in general and for ECG in particular is to evaluate them from a clinical point of view. When using strategies A and B, ECG blocks with errors would be presented to cardiologists. On the other hand, when working with strategies A* and B*, no errors would be shown but a zero constant signal instead.

Fig. 3 shows some possible transmission error effects in the monitoring. Fig. 3(a) shows an excerpt of 5 blocks from an original ECG (512 samples per block, from record 100). In Fig. 3(b) the previous ECG compressed at a rate of 500 bps with a reconstruction error of 13 μV is shown. This signal would be received if no transmission errors were produced. In Fig. 3(c) possible effects of transmission errors in strategies A and B are shown. Finally, in Fig. 3(d) the signal received considering strategies A* and B* is presented. Due to the ECG PDU has a CRC code, both in Fig. 3(c) and (d) a warning is included over the block indicating that the block being monitored comes from an erroneous packet.

Error effects in strategies A and B on the one hand and A* and B* on the other were shown to cardiologists and they were asked about what do they prefer to view in a monitor. They agree in pointing out that the preference would be conditioned to the number and frequency of erroneous blocks. If there are not many erroneous blocks (low BER) in the monitoring process and these erroneous blocks

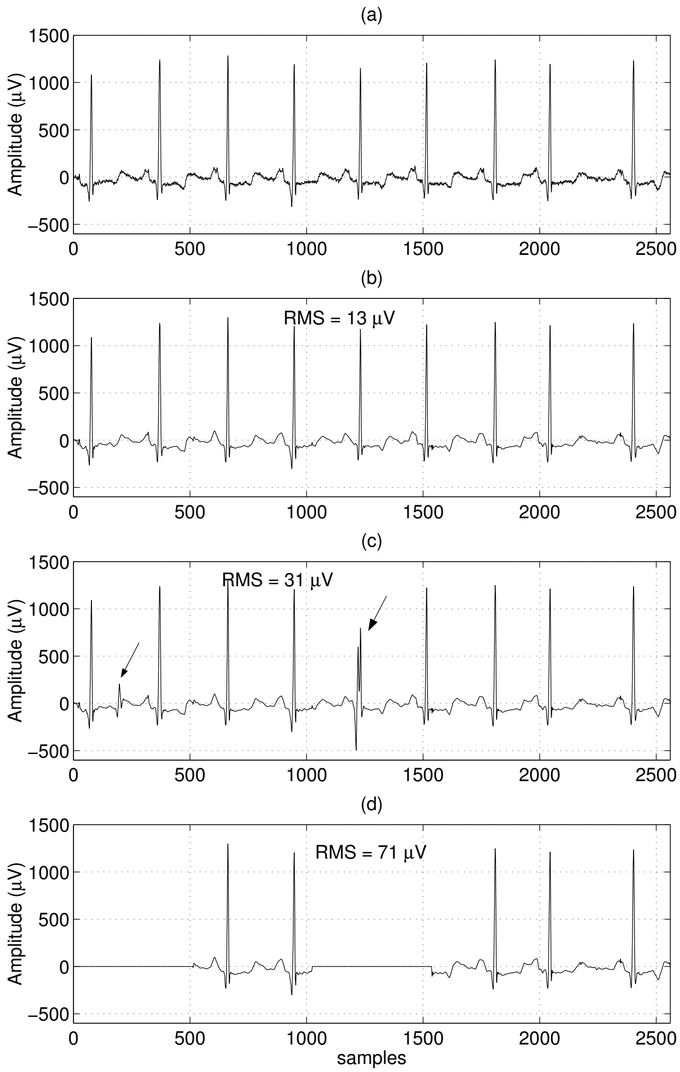

Figure 3. Received ECG signal (5 blocks) for different cases. (a) Original Signal. (b) Received signal without errors. (c) Possible error effects for strategies A or B (arrows). (d) Error effect for strategies A* or B*.

are not consecutive, they would prefer to monitor no ECG information rather than erroneous information because a large quantity of non erroneous information is available. On the other hand, if the errors are frequent (high BER), they would prefer to monitor the erroneous packets since sometimes introduced artifacts could be correctly identified and the signal would be still useful to make same measurements such as heart rate.

Taking into account only the RMS error, it may be said that strategy B outperforms A as the BER increases and strategies A* and B* performs worse than A and B also as the BER increases. The real fact is that from the cardiologist point of view, the preference is conditioned by the frequency of errors. In this way, it is clear that quantitative measurements would lead us to uncomplete conclusions compared with the complete view that cardiologists provide us about reconstructed signal quality and their appropriateness for a real-time monitoring process.

4. Conclusions

Two different coding strategies for ECG compression have been presented based on the WT. They have been discussed using both quantitative (RMS) and qualitative (cardiologist opinion) criteria. Strategy A presents better performance than B in an error-free environment. Although quantitative results show that strategy B performs better than A, and both outperforms A* and B* respectively as the BER increases, cardiologist that monitored the reconstructed signals with transmission errors conditioned their preference to the number of erroneous blocks: few number of errors, strategies A* and B*; high number of errors, strategies A and B.

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