Cardiac Signals Coding and Transmission in Real-Time Mobile Telecardiology Applications

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Abstract

Cardiac signals must be efficiently coded (in order to save channel bandwidth) and packetized using adapted application-level protocols (to guaranty monitoring quality) when transmitted in real-time operation. This paper shows an overview of different approaches for electrocardiogram (ECG) and echocardiogram (ECHO) coding and transmission over 3G networks. The described proposals permit the transmission of ECG and ECHO at rates of, respectively, 0.5 kbps per lead and 320 kbps for a medium-speed vehicle. The use of these methods enables to significantly reduce the demanded bandwidth guaranteeing signal quality in the receiver.

1. Introduction

A popular field in telecardiology deals with the transmission of cardiac signals over different kinds of communication networks. Wireless networks offer a wide range of scenarios and use cases for electrocardiogram (ECG) and echocardiogram (ECHO) transmission in telecardiology projects. Patient monitoring and early diagnosis in the area of emergency e-Health are usually carried out in ambulances and other mobile scenarios which require real-time operation through a wireless channel.

3G networks are widely used for wide-area wireless communications, implementing the Transmission Control Protocol/Internet Protocol (TCP/IP) stack to transmit the user data. Nevertheless efficient signal coding is still required especially when the bandwidth is shared by different applications and users. Since lossless compression does not achieve a sufficiently low transmission rate, lossy compression is often necessary and distortion is introduced. Therefore, much care must be taken in order to avoid distortion in the cardiac signals beyond a clinical usability threshold.

In addition to the application of compression methods that guarantee the clinical quality of the cardiac signals, it is essential to guarantee their integrity during transmission over the channel in order to provide an accurate diagnosis. Wireless channels are error prone compared with wired ones and therefore signals transmission can be more affected by erroneous bits which distort the reconstructed signals in reception.

Most works have studied the effects of both lossy compression and transmission errors in terms of distortion measured by using mathematical indexes (RMS, PRD, PSNR). The distortion introduced could affect the integrity of original ECGs and ECHOs inducing erroneous interpretations. Thus, this work presents some recommendations for coding and transmission taking into account the clinical point of view. A general procedure for a real-time telecardiology application is shown in Fig. 1, where Mean Opinion Scores (MOS) are considered to tune the parameters selected in the coding method and in the transmission protocol operation to guarantee clinical quality in reception. Following sections in the paper present various implementations of these blocks together with some results and recommendations obtained for mobile telecardiology applications.

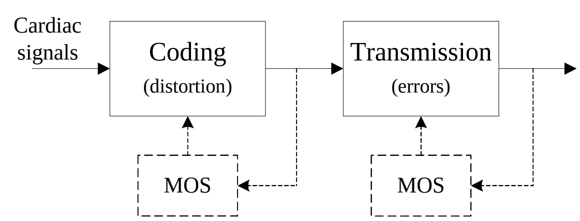

Figure 1. General procedure for coding and transmission.

2. Coding of cardiac signals

The Set Partitioning in Hierarchical Trees (SPIHT) has been considered for coding of both ECGs and ECHOs. SPIHT algorithm is used to code the signal in the wavelet domain. The principles of SPIHT are partial ordering by magnitude of the wavelet transform coefficients with a set partitioning sorting algorithm, ordered bit plane transmission, and exploitation of self-similarity across different layers. By following these rules, the encoder always transmits the most significant bit to the decoder. More details of SPIHT operation applied to ECG and ECHO can be found in [1, 2].

2.1. ECG coding

Regarding the ECG, a compression method based on the SPIHT 1D algorithm was developed and clinically validated through MOS tests. The ECG coding approach is based on noise estimation in the ECG signal that is used as an automatic compression threshold in the coding stage [3]. The proposed coding method consists of the following stages:

- preprocessing, including block division and baseline subtraction
- noise estimation, used as a distortion threshold in the coding stage
- wavelet transform (Coiflet C-12) and SPIHT algorithm application.

2.2. ECHO coding

Regarding the ECHO, the SPIHT algorithm is proposed for compression too. The compression method takes into account the particular characteristics of each visualization mode (see Fig. 2) and uses different compression techniques for each one:

- for 2D and Doppler modes, a SPIHT 3D video compression method based on regions of interest is applied. The proposed approach considers the properties of the different areas in the ultrasound video (data, black regions, etc.).
- for sweeping modes (M and pulsed/continuous Doppler), an encoder based on SPIHT 2D which operates slice-by-slice is applied. In these modes the image is displayed gradually and a new slice appears in each frame. Hence the new slice is only compressed for each frame.

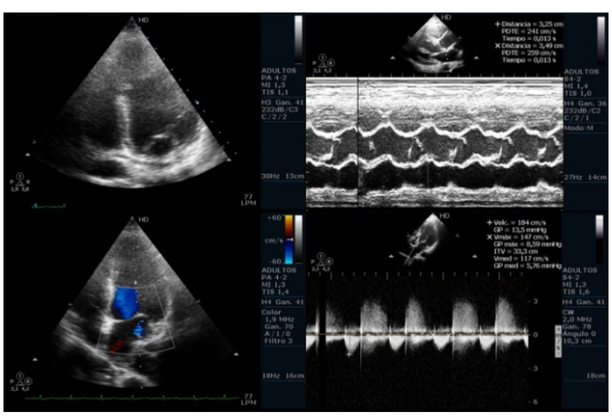

Figure 2. Different ECHO modes.

3. Clinical validation of coding

To obtain the cardiologists' opinions of the cardiac signals (ECG and ECHO) regarding compression, MOS tests have been designed in a collaborative process with cardiologists. Using these tests, the tolerance limits for compression can be quantified and a minimal transmission rate that guarantees an adequate diagnosis is defined. The proposed MOS tests consist of a blind and a semi-blind test. Results from both tests are combined into a unique measure, a weighted distortion index.

3.1. MOS for ECG

For the ECG, the aim of the blind test is to obtain the cardiologists evaluations in a blind condition, without knowing whether the ECG is compressed or not nor the compression ratio. Ten seconds of one lead are used in the evaluation, a value suggested by the cardiologists as commonly used in the clinical routine. A fragment of the blind test is shown in Table 1. On the other hand, the aim of the semiblind test is to obtain the cardiologists evaluation in direct comparison of the compressed ECG with the original. MOS is an index that reflects the distortion in the compressed ECG from cardiologists' point of view [3]. The higher the MOS, the higher the distortion introduced in the diagnostic content in the compressed signal. After MOS cardiologists' evaluation, a transmission rate threshold of 0.5 kbps per ECG lead was selected and hence 4 kbps for standard ECG.

Table 1. Fragment of the blind test for ECG (QRS wave).

		YES	NO
QRS	Normal	□	□
	IVCD	□	□
	LBBB	□	□
	RBBB	□	□
	Delta Wave	□	□
	Pacemaker	□	□

3.2. MOS for ECHO

For the ECHO, the aim of the blind test is to obtain the cardiologists' evaluations without knowing the compression rate used. It consists of a section about general video quality, a section to gather comments of the specialists, and a section presenting tables related to the features measured in a standard examination, which cardiologists have to fill in based on the structures and flows measured in the echocardiogram. A fragment of the blind test is shown in Table 2. The aim of the semi-blind test is to obtain the cardiologists' evaluations comparing directly the compressed video with the original. This test permits to measure the similarity between the compressed echocardiogram and the original one. The MOS index is calculated for each ultrasound mode taking into account the results obtained from the blind and semi-blind tests [4]. After MOS index evaluations, a minimum of

200 kbps and 40 kbps of transmission rate was required, respectively, to have suitable clinical quality in the compressed 2D modes and sweeping modes of echocardiogram video.

Table 2. Fragment of the blind test for ECHO (2D study)

		Normal	Abnormal
Valve morphology	Mitral (2D)	□	□
	Aortic (2D)	□	□
	Tricuspid (2D)	□	□

4. Transmission of cardiac signals

Conventional transport protocols used without introducing modifications may not be the most appropriate to send cardiac signals in real-time through wireless channels (for instance, TCP congestion-control mechanism is not recommendable for high BER values). Therefore new proposals for protocols adapted both to ECG and ECHO have been developed.

4.1. Reliable ECG transmission protocol

For the ECG, an application-level protocol was developed to perform the retransmissions of erroneous packets, introducing a monitoring buffer that mitigates negative effects in monitoring [5]. Reliable ECG Transmission Protocol (RETP) is a simple application-layer protocol developed specifically to be used in real-time ECG transmission. RETP is based on two protocol data units (PDU) types: one for ECG information transmission (INFO PDU) and the other for information acknowledgement (ACK PDU), which are encapsulated into a User Datagram Protocol (UDP) datagram. RETP PDUs are generated with a very low rate considering the following rules:

1) Each time an ECG block is coded, an INFO PDU is generated. INFO PDUs are stored in a retransmission buffer awaiting acknowledgment.

2) Each time an INFO PDU is sent, a retransmission timeout (RTO) timer is set. When an active RTO expires without acknowledgement, the corresponding INFO PDU is retransmitted and the RTO timer is reset.

3) Each time an INFO PDU is received in reception, an ACK PDU is created and immediately sent to the transmitter.

4) INFO PDUs received out-of-sequence are stored in a reception buffer and are not transferred to the monitoring buffer until the original sequence is recovered.

5) Each time an ACK PDU is received, the RTO timers associated to the acknowledged INFO PDUs are deactivated and INFO PDUs are removed from the retransmission buffer.

4.2. Reliable clinical video transmission protocol

For the ECHO, a protocol that incorporates the capabilities of retransmission and error correction techniques, which is able to adapt to the channel conditions has been tested and clinically validated [6]. Reliable Clinical Video Transmission Protocol (RCVTP) is an application-layer protocol based on User Datagram Protocol (UDP) developed to be used in real-time clinical video transmission. Two states are proposed in the protocol operation:

a) “good conditions” state, corresponding to few packet losses in the channel. In this state, the retransmissions mechanism is applied since the use of error correction codes under these channel conditions would require more amount of bits.

b) when more than a predefined percentage of blocks are not successfully received, the model turns into “bad conditions” state, in which both retransmissions and Reed-Solomon Forward Error Correction (FEC) codes are used. In this state, the error correction code and thus the extra amount of transmitted bits are appropriate.

Thus, retransmissions adapt the bits used to the amount needed and the FEC code provides extra protection. In order to decrease header overheads, reduce packet loss and increase security over noisy wireless links, RObust Header Compression (ROHC) has been used. This standard compresses IP and UDP headers to just 3 bytes, including the checksum field to discard erroneous packets. The redundancy introduced in the transmission is decreased allowing small packets to be transmitted and thus reducing the packet loss without excessive increase of transmitted bits.

5. Clinical validation of transmission

5.1. Channel model

A simple two-state Markov model has been proposed to simulate the 3G wireless channel and evaluate the protocols performance. This model simulates the transmission bit to bit. In the good state, the bit is transmitted unaltered, and in the bad state, the bit becomes erroneous. The probability of a bit being erroneous, i.e., the bit error rate (BER) is given by $BER = (1 - p)/(2 - p - q)$, and the average burst length (ABL) is given by $ABL = 1/(1 - q)$, where p and $1-q$ are, respectively, the probabilities of a successful transmission of bit n taking into account that the transmission of bit $n-1$ was successful and unsuccessful. A Rayleigh fading channel (flat in frequencies) is used to calculate the parameters of the two-state model, from the fading margin (F) and the Doppler frequency (f_d) wireless channel parameters.

5.2. Quality parameters and monitoring process

In order to measure the visual quality of ECGs and ECHOs from a clinical perspective, an application that creates a video reproducing the real monitoring process using the reception data obtained in the different simulations has been developed. To obtain the cardiologists' opinions of the cardiac signals monitoring quality, simple MOS tests have been developed to rate the clinical quality of the monitoring process and to find out whether the monitoring is suitable or not for real-time application. Using these tests, the tolerance limits for the monitoring process and the channel conditions can be quantified. To estimate the quality of the received signals and videos some quality parameters were analyzed:

- Bandwidth (BW) used in the communication in bps (to measure the efficiency of RETP and RCVTP protocols).
- Number of stops per time unit, when the ECG monitoring buffer runs out of samples.
- Mean duration of the stops during the ECG monitoring process.
- Percentage of time with the ECG monitoring stopped, derived from number of stops and their duration.
- Percentage of time with guaranteed ECHO clinical quality, when the video is visualized with the minimal bandwidth required.
- Monitoring delay, defined as the time from signal acquisition until shown in the monitoring process.

6. Results and discussion

OPNET was the network simulator used to implement the 3G wireless model and the application protocols described above. In the wireless network, f_d values were simulated ranging from 20 Hz (low-speed vehicle) to 100 Hz (high-speed vehicle) and fading margin values ranging from -5 dB to -30 dB. A summary of the main results obtained for both ECG and ECHO (only results corresponding to 2D modes are shown since they require more network resources) are presented in Tab. 3 for the BER and speed values indicated (medium-speed vehicle). In order to have suitable clinical quality for the compressed ECG and ECHO, transmission rates of 0.5 kbps per lead and 320 kbps (including retransmissions and correction codes extra load), respectively, are required. Monitoring delay and percentage of time with the monitoring process stopped and with guaranteed quality are also shown in the table. As general comments, an increase in BER produces an increase in the BW used and a degradation of the monitoring process.

Table 3. ECG and ECHO (2D modes) summary results.

Parameter	ECG	ECHO
BW (kbps)	0.5	320
Delay (s)	2	2.2
% time	15% (stopped)	95% (guaranteed)
BER	10^{-1}	0.031
v (kmh^{-1})	60	60

7. Conclusions

Special characteristics of cardiac signals should be taken into account to optimize methods and protocols used in conventional applications. Cardiologists' evaluation has to be considered in the development of these particularized methods. Coding and transmission approaches presented permit the transmission of ECG and ECHO at rates that significantly reduce the demanded bandwidth guaranteeing signal quality in the receiver.

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References

[1] Lu Z, Kim DY and Pearlman W. Wavelet compression of ECG signals by the set partitioning in hierarchical trees algorithm. IEEE Trans. Biomed. Eng. 2000; 47(7):849–56.

[2] Kim BJ, Xiong Z and Pearlman W. Low bit-rate scalable video coding with 3-D set partitioning in hierarchical trees (3-D SPIHT). IEEE Trans. Circuits Syst. Video Technol. 2000; 10:1374–87.

[3] Alesanco A and García J. Automatic Real-Time ECG Coding Methodology Guaranteeing Signal Interpretation Quality. IEEE Trans. Biomed. Eng. 2008; 55:2519–27.

[4] Alesanco A, Hernández C, Portolés A, Ramos L, Aured C, García M, Serrano P and García J. A clinical distortion index for compressed echocardiogram evaluation: recommendations for Xvid codec. Physiol. Meas. 2009; 30:429-440.

[5] Alesanco A and García J. Clinical assessment of wireless ECG transmission in real-time cardiac telemonitoring. IEEE T. Inf. Technol. Biomed. 2010: 14(5):1144-52.

[6] Cavero E, Alesanco A and García J. Enhanced protocol for real time transmission of echocardiograms over wireless channels. IEEE Trans. Biomed. Eng. 2012. DOI 10.1109/TBME.2012.2207720.

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