Frequency Prioritised Queuing in Real-Time Electrocardiograph Systems

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***Abstract*—Real-time Electrocardiogram (ECG) telemonitoring is currently being envisaged to provide improved healthcare services for elderly and chronic care patients. A major challenge that arises in this situation is the need to reliably transmit ECG data over bandwidth constrained communications channels where congestion can lead to loss of ECG data. To overcome this problem, we propose a frequency prioritised transmission scheme which uses the sampling rate itself to separate out the ECG data into four frequency components, ranging from low to high frequency. We design a priority queuing system which gives highest priority to ECG packets containing low frequency components during transmission over a bandwidth constrained communications channel. The real-time performance of the proposed prioritisation algorithm is tested on a purposely built ECG machine. Our results show that the proposed scheme is robust and can withstand up to 65% of lost packets from a standard sampling rate of 320 Hz without any significant degradation in ECGs of healthy and arrhythmia sustained subjects.**

I. INTRODUCTION

Real-time Electrocardiogram (ECG) telemonitoring is currently being envisaged to provide improved healthcare services for elderly and chronic care patients [1]. Recently, there have been a number of publications addressing the design and system architecture aspects of large scale ECG telemonitoring systems, e.g. [2]–[4] provide a good illustration of the current research in this area. Research is also being conducted to reduce the invasiveness of ECG systems [2], [5]. With the current level of technology it is not difficult to design and build small ECG monitors that can be incorporated in phones and PDAs and interfaced with computers [4], [6]–[8]. The design of a low noise, non-contact sensors about the size of a US quarter dollar is described in [9]. ECG placement in smart clothing, where electrodes are built into a persons clothing, is also investigated in [10]. The major problem that arises in any real-time ECG monitoring system is that the bandwidth required to constantly transmit a large amount of ECG data (which can easily be of the order of a few gigabytes for single patient per day) is not guaranteed to be available at all times. In a bandwidth constrained communications channel, congestion can cause the loss of packets or the ECG signal leading to incorrect or missed diagnosis. Techniques to improve the performance of ECG telemonitoring in bandwidth constrained channels are, therefore, an important emerging area of research [11].

The use of compression techniques is one way of partially solving this problem by simply reducing the amount of ECG data that needs to be transmitted. Two distinct methods of compression are visible in literature. The first method exploits the mathematical properties of ECG waves directly by looking for inter-beat and intra-beat dependencies to develop a new type of compression specifically designed for ECG waves. Examples of this type of compression are SVD (Singular Value Decomposition) compression [12], and SPIHT (Set Partitioning In Hierarchical Trees) compression [13]–[15]. The second method proposes that an ECG can be viewed as a 2D image, and then compressed in the same way, e.g. using JPEG2000 to compress the ECG data [16]. In all cases, current compression algorithms suffer from the fact that they are effectively more complicated than the rest of the ECG machine. In addition, during periods of congestion compression may not help and compressed data can still get lost.

The problem of transmission of a large volume of ECG data over bandwidth constrained communications channels is addressed in [11]. The authors proposed a solution to the problem based on the principle that most of the data that a medical practitioner required when making a diagnosis was contained in the low frequency components of the ECG signal, e.g. ECG waves are made up of frequencies that at their highest are approximately 120 Hz, although most of the information used in diagnosis is less than 40 Hz [17]. The authors proposed that ECG data be decomposed using Wavelet Packet Decomposition, and then prioritised according to frequency, with low frequencies given the highest priorities. They evaluated the success of their algorithm using simulations based on packet response delay. However the performance was not demonstrated in a real-time ECG system. It must be noted that decomposition of ECG signal and subsequent prioritisation can be accomplished in other ways as well. For example, we can apply the principle of successive-refinement coding of information [18], [19], treating low-frequency components of the ECG signal as important information that must be decoded by the receiver and high-frequency components of the ECG signal as less important refinement information. However the resulting hardware implementation would be more complex.

In this paper, we propose a simple frequency prioritisation procedure to counteract the degradation of an ECG signal in a bandwidth constrained communications channel. Similar to [11], our approach relies on the fact that most of the important information in an ECG signal is contained in the lower frequency components. However, we show that robust

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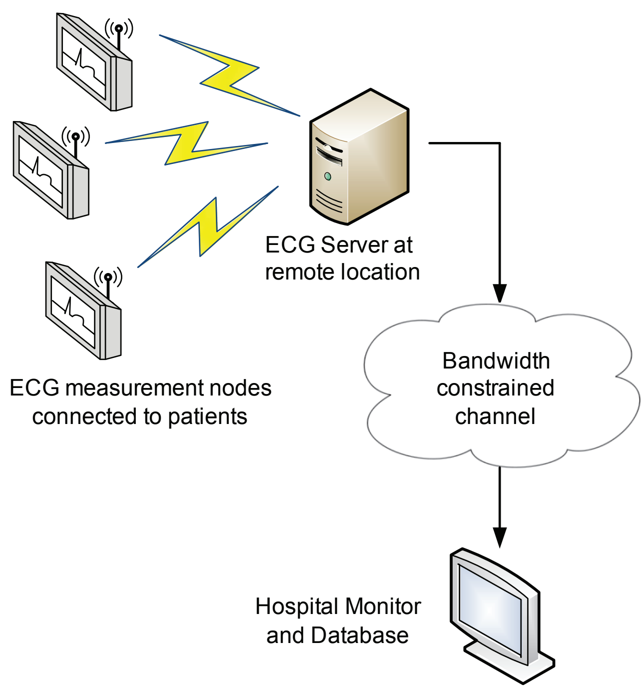

Fig. 1. Telemonitoring over a shared bandwidth constrained channel.

performance in congestion scenarios can be achieved without the need of using more complicated techniques such as Wavelet Packet Decomposition or successive-refinement coding of information. We test the performance on the proposed queuing scheme in real-time on a purpose built ECG hardware system. The major contributions of this paper in comparison to previous research are as follows:-

- We propose that frequency prioritisation of ECG signals can be achieved simply by giving samples required to reconstruct low frequency information a higher priority than those required for high frequency information. Such a frequency prioritisation scheme can be easily implemented in practical hardware systems due to its simplicity.
- We show that the proposed scheme delivers robust performance with increasing congestion in a bandwidth constrained channel and can withstand up to 65% of lost packets from a standard sampling rate of 320 Hz without any significant degradation in clinically important ECG features.

This paper is organised as follows. In Section II, we present the system model considered in this work. In Section III, we propose the new frequency prioritisation algorithm. The hardware system implementation is described in Section IV. The results are presented and discussed in Section V. Finally conclusions are drawn in Section VI.

II. System Model

The healthcare scenario considered in this work is illustrated in Fig. 1. The patients are connected to ECG machines in a nursing home and the acquired ECG data is transmitted (via wireless or wired connection) to an ECG server. The ECG server transmit the data to a centralized hospital database over a shared, bandwidth constrained channel. While the ECG system needs to constantly transmit real-time data the bandwidth over the shared channel at any given time cannot be guaranteed. On a commercial internet connection this could simply be caused by other users vying for the same channel.

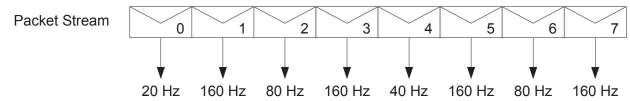

Fig. 2. Illustration of division of ECG packets into queues.

This paper addresses the bandwidth constrained link between the ECG server at the remote location and the hospital database. In the next section, we propose a frequency prioritisation algorithm that provides robust performance by dynamically adjusting to the actual bandwidth of the channel by discarding low priority packets.

III. Proposed Algorithm

In this Section, we present a frequency prioritised queuing system that provides robustness to the transmission of low frequency dominant ECG signals.

In an ECG transmission, lower frequencies are of a higher priority than higher frequencies. We propose to use the sampling rate itself to separate out the ECG frequency components. To illustrate this, consider an ECG signal sampled at 320 samples/sec. In this case, only 40 samples/sec are needed to ensure 20 Hz accuracy in the ECG. Thus in any one second of those 320 samples, 40 evenly timed samples can be selected and sent to a queue. This process can be repeated for any number of desired frequency queues.

In our implementation, four non-preemptive queues are chosen for implementation, a 20 Hz queue, a 40 Hz queue, an 80 Hz queue and a 160 Hz queue. This number of queues may not be optimum but is selected to keep the implementation simple. This process is illustrated in Fig. 2 which shows an incoming ECG packet stream at a sampling rate of 320 samples/sec. Every eighth sample is sent to the 20 Hz queue, every fourth to the 40 Hz, every remaining even sample to the 80 Hz queue, and every odd sample to the 160 Hz queue.

When the bandwidth is insufficient to transmit all the packets, the higher priority packets are transmitted at the expense of low priority packets. The queue prioritisation process is illustrated in Fig. 3 and works without any sense of fairness. If there are any samples in the 20 Hz queue, they will be transmitted before the 40Hz queue, which in turn will be transmitted before the 80Hz queue. This means that the algorithm always chooses to transmit the lower frequency samples first - if there is not enough time to transmit all the samples, higher frequencies will be neglected.

On the receiver side it is necessary to reconstruct the signal from the received data. Packets that were not able to be transmitted in real time due to the low bandwidth of the

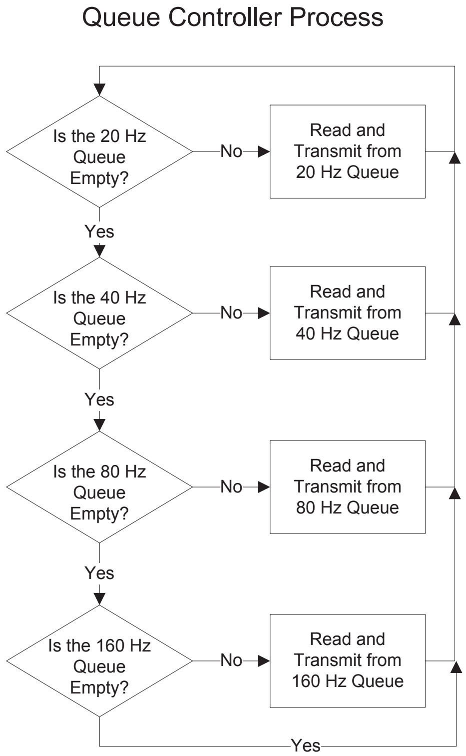

Fig. 3. Process flow of packet transmission.

channel are considered missing if they have not been received after a fixed time. It is not known what order packets will be received in excepting that high frequency samples are more likely to be lost than low frequencies. In order to facilitate this sorting a *packet number* indicating where each sample fits in the signal is prefixed to the sample. Together the packet number and sample are referred to as a packet, and provide the necessary information for the ECG signal to be reconstructed at the receiver.

IV. System Implementation

In order to test the performance of the proposed algorithm a prototype ECG machine was constructed. It is shown in Fig. 4. An ECG measurement unit using two Ambu M electrodes and an AD202 isolation amplifier was designed and implemented. An interface unit was also designed to accept recorded ECG signals from databases for testing. The acquired signal is sampled after having passed through 50 Hz analogue filters and passed to a Spartan 3E Field Programmable Gate Array (FPGA) [20]. The prioritised queuing algorithm is implemented in digital electronics on the FPGA. The queued ECG signal is transmitted across a controlled channel to a laptop running software that reconstructs the ECG, and uses linear interpolation to estimate any missing packets. For simplicity, the communications channel used in this project is a standard RS-232 Universal Asynchronous Receive Transmit (UART) channel. The congestion and resulting degradation of the

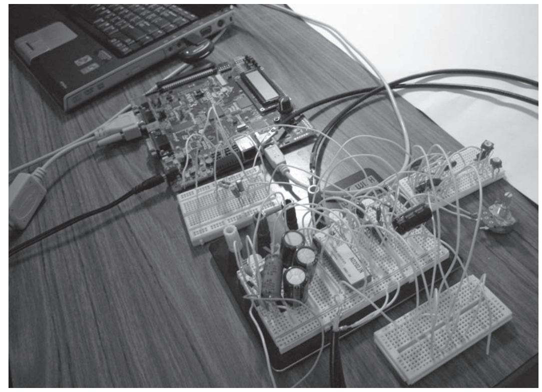

Fig. 4. Photo of prototype ECG Machine.

UART channel is simulated by altering the baud rate, and therefore the data rate. As the data rate is lowered a packet either will arrive, or it will not arrive. Note that the UART channel guarantees the order of arrival, i.e. the packets will arrive in the order in which they are sent.

V. Results

The testing was done for chosen ECG recordings from the MIT-BIH public domain database [21]. The particular records were chosen such that the first record corresponds to a healthy ECG signal (record aami3a from ANSI/AAMI EC13 Test Database), and the second record corresponds to an ECG of a subject with Atrial Fibrillation (record 08455 from MIT-BIH Atrial Fibrillation Database). Atrial Fibrillation is the most common sustained cardiac arrhythmia, increasing in prevalence with age, accounting for approximately one third of hospitalizations for cardiac rhythm disturbances [22]. It affects approximately 10% of the population over the age of 75 and is associated with an increased risk of stroke [22], [23], thus accurate remote monitoring will help fast diagnosis reducing the associated risks as well as being highly cost effective.

The performance of the proposed prioritised scheme is compared to the transmission with no prioritisation against following three criteria in order to demonstrate the ability of the proposed algorithm to accurately transmit ECGs preserving physiologically important features.

1) Correlation: Correlation coefficient was calculated as the cross-correlation between original and received ECGs normalised to the auto-correlation of individual signals. It provides information on how important features of the original ECG are accurately transmitted via the channel during loss of packets.
2) RR intervals: Ventricular contractions or the R-peaks were identified from the ECG using a threshold based peak detection algorithm. Time differences between consecutive R-peaks (RR intervals) provide important information on autonomic nervous system modulation on heart beats, and can be further utilised in heart rate variability analysis [24]. We compared the RR intervals of the received ECG to the original transmitted ECG.

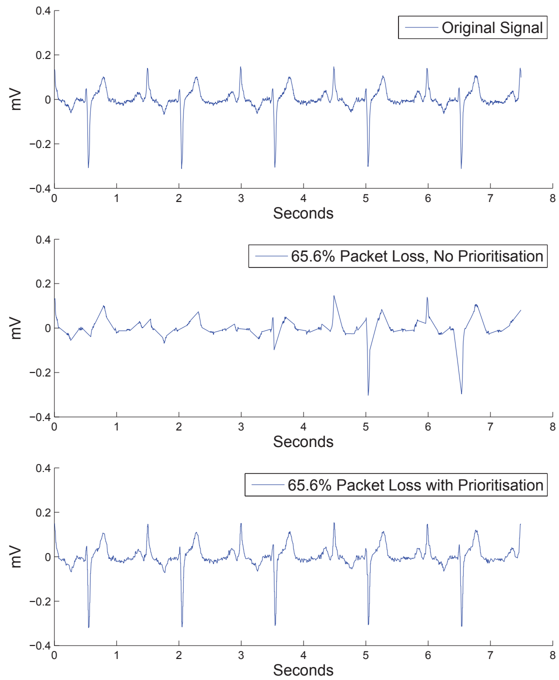

Fig. 5. Transmission of a healthy ECG signal: original transmitted ECG (top), received ECG without prioritisation scheme (middle), and received ECG with proposed prioritisation scheme (bottom) at 65.6% packet loss.

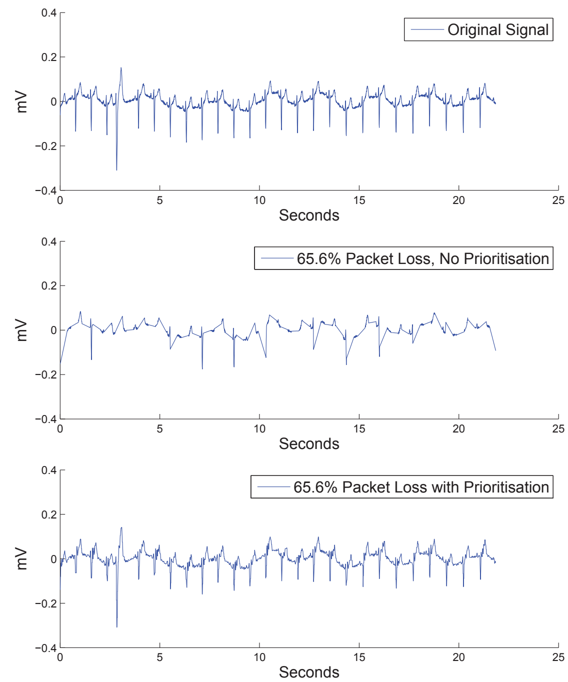

Fig. 6. Transmission of an Atrial Fibrillation ECG signal: original transmitted ECG (top), received ECG without prioritisation scheme (middle), and received ECG with proposed prioritisation scheme (bottom) at 65.6% packet loss.

3) QT intervals: The QT interval was measured as the time between the starting point of the Q-wave and the ending point of the T-wave on the ECG, and represents electrical depolarization phase of the ventricles. It provides useful information on cardiac conduction system, and we estimated and compared the QT intervals of the received ECG and the original transmitted ECG.

A. Performance with and without prioritisation

Figs. 5 and 6 show the original ECG signal (for reference) and received signals without and with prioritisation after passing through a bandwidth constrained channel with 65.6% packet loss for healthy and Atrial Fibrillation ECG signals respectively. It can be clearly seen that without the proposed algorithm the received ECG signal is completely distorted, and can not be used for medical diagnosis purposes. In contrast, the prioritisation algorithm is able to withstand 65.6% packet loss and the received ECG signals are visually similar to the original ECG signals and contain the important diagnostic information. This comparison illustrates and confirms the effectiveness of the proposed algorithm.

B. Correlation performance

Table I illustrates the performance of the proposed algorithm for different packets loss. It can be seen that even without any packet loss, the electronic noise has a slight effect on the received signal and consequently the correlation is not perfectly 1 for 0% packets loss case. Correlation drops below 0.9 for healthy ECG transmission when the packets loss is more than 29.6%, where as proposed method is robust to higher packets loss and can achieve a correlation of 0.97 even at a 83.6% packets loss. In the case of Atrial Fibrillation ECG, correlation drops significantly lower (below 0.5 at 65.6%) without the prioritisation algorithm, where as proposed method can achieve a correlation of 0.89 for the same baud rate. It is also evident that the ECG from a healthy patient only contains low frequencies and therefore the algorithm performs better compared to the case of atrial fibrillation ECG which contains slightly higher frequencies as well.

C. RR and QT intervals

We demonstrate the ability of the proposed method to preserve physiologically important ECG parameters by comparing RR and QT timings of the received ECG with the original ECG. Fig. 7 shows the estimated RR and QT intervals from original Atrial Fibrillation ECG and corresponding received ECG with the prioritisation scheme for first 26 cardiac cycles. Timings of the received signal closely matches with the original, and rms errors were as low as 0.017s and 0.021s for RR and QT intervals respectively. Note that errors were even smaller for the case of healthy ECG due to the higher correlation. On the other hand, only few R-peaks are detectable when transmitted without the prioritisation in both healthy and Atrial Fibrillation cases as can be seen in Figs. 5 and 6. Also Q and T points can not be identified due to the highly distorted waveforms. Thus, meaningful results for RR and QT timings will not be possible without applying the proposed frequency prioritisation algorithm.

TABLE I
CORRELATION COEFFICIENTS AT DIFFERENT BAUD RATES FOR HEALTHY AND ATRIAL FIBRILLATION ECG WITH AND WITHOUT PRIORITISATION SCHEMES

Baud rate	Packets lost	Healthy ECG		Atrial Fibrillation ECG	
		without prioritisation	with prioritisation	without prioritisation	with prioritisation
9600	0%	0.99	0.99	0.92	0.95
4800	29.6%	0.90	0.99	0.83	0.93
2400	65.6%	0.71	0.97	0.49	0.89
1200	83.6%	0.56	0.97	0.48	0.80

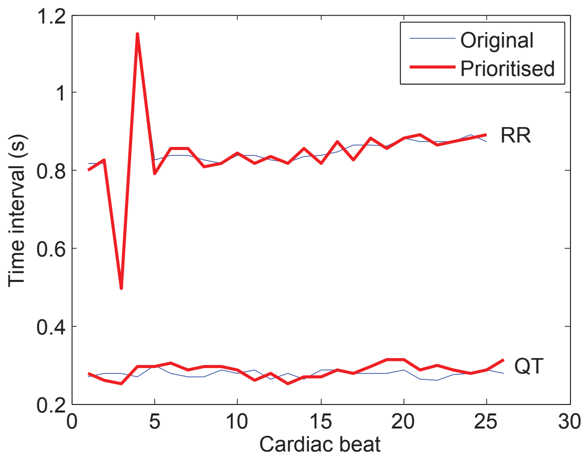

Fig. 7. Estimation of RR and QT intervals in the original Atrial Fibrillation ECG (thin line) and received ECG at 65.6% packet loss using proposed prioritised method (bold line).

VI. CONCLUSIONS

One of the major problems in real-time ECG telemonitoring is that changes in the available bandwidth can cause the loss of packets or the ECG signal. In this paper, a simple frequency prioritisation scheme has been presented, which uses the sampling rate itself to separate out the ECG data into four frequency components, ranging from low to high frequency. The performance of the proposed algorithm has been demonstrated using a prototype hardware ECG machine. It has been shown that the system can withstand a loss of up to 65% of packets while preserving clinically important ECG features by using the proposed priority queuing scheme.

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