Scalable ECG Transmission to Improve the Diagnosability of Remote Patient

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***Abstract*—We present an adaptive framework for layered representation and transmission of electrocardiogram (ECG) data that can accommodate a time-varying wireless channel. The representation, combined with the layer-based earliest deadline first (LB-EDF) scheduler, ensures that the perceptual quality of the reconstructed ECG signal does not degrade abruptly under severe channel conditions and that the available bandwidth is utilized efficiently. Simulation shows that the proposed approach significantly improves the perceptual quality of the ECG signal reconstructed at the remote monitoring station.**

I. INTRODUCTION

In this paper, we present an adaptive framework to support high-quality remote electrocardiogram (ECG) monitoring over error-prone wireless networks. Our proposed adaptive framework consists of a layered representation of ECG data and an error control scheme based on automatic repeat request (ARQ) combined with a layer-based earliest deadline first (LB-EDF) scheduler.

The LB-EDF scheduling algorithm support the delivery of scalable ECG streaming over lossy channel in real-time. Scalable ECG streaming data have timing constraints because of their sensitivity to delay and jitter, and thus, the use of the EDF policy has the critical advantage of ensuring that higher (less important) enhancement layer(s) (EL(s)) can be discarded so that the base layer (BL) and the lower enhancement layers have a greater chance of arriving at the remote monitoring station (RMS) on time. Working in conjunction with the ARQ scheme, the proposed LB-EDF scheduler greatly improves the signal readability at the RMS by rescheduling the packets such that the more important lower-layer packets are transmitted first. This ensures *Graceful quality degradation* and efficient use of the bandwidth in a way that maximizes the perceptual quality and the resulting ECG readability, thus facilitating a correct diagnosis.

II. SYSTEM ARCHITECTURE

A wearable wireless ECG sensor (also called electrode) continuously measures the heart activity of a mobile patient. The resulting digital stream is grouped into packets that then transmitted wirelessly to remote healthcare professionals in real time through a nearby access point [1].

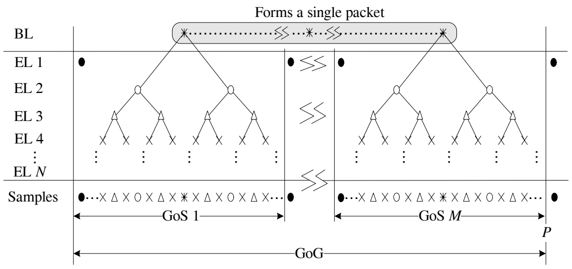

Fig. 1. Framework for layered temporal scalability, and packetization for transmission over the wireless channel.

III. REPRESENTATION OF ECG DATA

In general [2], an η-lead ECG is one in which η different electrical signals are recorded almost simultaneously, and it is often used as a one-off recording of an ECG. If η leads are recorded, and if the ECG output for each lead is digitized at a rate of R samples per second, each of which has a resolution of L_{smpl} bits, the resulting data-rate μ_{ecg} of the wireless ECG application is given as $\mu_{\text{ecg}} = \eta R L_{\text{smpl}}$. The digital stream is packetized and then sent to an RMS over a wireless channel.

It is clear from this definition that the quality of the obtained ECG signal improves with an increase in the sampling frequency. In a standard environment, scalability is achieved through a layered structure, where the ECG information is divided into two or more discrete bit streams corresponding to different layers, as shown in Fig. 1. The BL ECG stream contains fundamental ECG information that is periodically sampled at a low frequency. The EL contains ECG data sampled at higher frequencies in different time domains to produce the expected scalability.

Temporal scalability involves the partitioning of a group of samples (GoS) into a single BL and multiple ELs. Samples at the center of each GoS are packed into a single BL packet according to their sequence numbers; then this BL packet is transmitted with the highest priority. Assuming that the size of a packet and that of each ECG sample is L_{payload} and L_{smpl}, respectively, constructing a single BL packet requires $M = L_{\text{payload}}/L_{\text{smpl}}$ GoSs, and the interval of M GoSs is known as the period P. A layered structure for representing ECG data with N ELs is shown in Fig. 1.

Now, let S_0 and S_n $(1 \leq n \leq N)$ be a set that contains ECG samples corresponding to the BL and the nth EL, respectively; $\sigma_{i,j}$ is the ith ECG sample of the jth GoS. Then, S_1 includes

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the first ECG sample from each GoS; thus, it is defined as

$$S_1 = \{\sigma_{1,j} | j = 1, 2, 3 \ldots\}. \quad (1)$$

The BL sample in the jth GoS is located at $(\sigma_{1,j} + \sigma_{1,j+1})/2$. Next, the set S_2 contains two elements from each GoS, and it can be defined as follows:

$$S_2 = \left\{ \frac{\sigma_{1,j} + \frac{\sigma_{1,j}+\sigma_{1,j+1}}{2}}{2}, \frac{\sigma_{1,j+1} + \frac{\sigma_{1,j}+\sigma_{1,j+1}}{2}}{2} \right\}. \quad (2)$$

The first element of the set S_1 and S_n $(n \geq 2)$ corresponds to the ($2^{(N-n)}$+1)th ECG sample and the first ECG sample, respectively, whereas the interval between two consecutive elements of S_n is 2^{N-n+1}. Therefore, set S_n can generally be defined as follows when n is greater than one:

$$S_n = \{\sigma_{2^{(N-n)}+1,1} + 2^{N-n+1}k | k = 1, 2, 3 \ldots\}. \quad (3)$$

The number of samples in the BL $|S_0^g|$ and in the nth EL $|S_n^g|$ $(n \geq 1)$ in a period P is respectively defined as follows:

$$|S_0^g| = M, \; |S_n^g| = 2^{n-1}M \;\; (n \geq 1). \quad (4)$$

Now, the total number of samples R_g in a period P is

$$R_g = M \sum_{n=0}^{N} |S_n^g| = 2^N M. \quad (5)$$

As a result, the sampling frequency in the BL and in the nth EL is $R_B = M/P$ and $R_E^n = 2^{n-1}M/P$, respectively, where $R = R_B + \sum_{n=1}^{N} R_E^n$ and $P = R_g/R$.

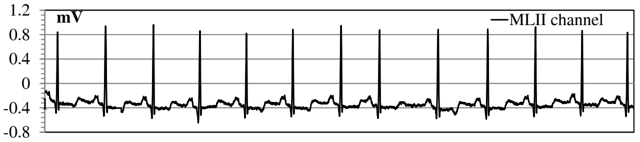
IV. ARQ-BASED ERROR CONTROL USING LB-EDF

Owing to the proposed layered representation of ECG data, it is intuitive to consider relative "importance" of the data in the scalable ECG stream in order to avoid an abrupt degradation in the quality of the ECG signal. The loss of consecutive ECG symbols has a greater effect on the ECG signal than the loss of a few random symbols. Therefore, it is desirable to prioritize the delivery of packets in the BL or lower ELs, even under severe channel conditions. For this purpose, we assign higher priority to packets in the lower layer, these can then be transmitted earlier, with a greater opportunity for retransmission in the case of loss. Packets in the same layer are served according to EDF policy. The scheme improves bandwidth utilization and the readability of the ECG signal in the case of some data loss via the prioritization of the low-frequency data in the BL or lower ELs.

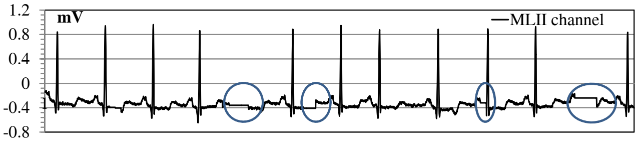
V. PERFORMANCE OF WIRELESS ECG TRANSMISSION

In the simulation, we set the packet size to 512 bits; each packet contains a maximum payload of 490 bits and a packet header of 22 bits. The fundamental timing unit for packet transmission is set to 1.67 ms, as per the CDMA2000 1xEV-DO Revision A standard [3]. The transmission of a packet requires one time-slot, and the resulting reference channel data-rate is 307.2 kb/s.

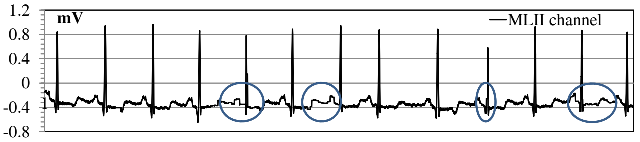
The relative advantage of our framework can clearly be seen in Fig. 2, which depicts a snapshot of the original ECG signal obtained from patient and that of the corresponding signal reconstructed in the RMS when the channel error rate is 0.1 and the patient moves at 2 km/h (channel errors were modeled using the threshold model suggested by Zorzi et al. [4]). It is observed that compared to the original ECG signal in Fig. 2(a), the ECG signal reconstructed with conventional transmission framework (CTF), which serially packetizes consecutive symbols in order, frequently omits important ECG information; this might lead a physician to misinterpret a patient's condition. However, for the same pattern of error in the wireless channel, the perceived quality of the reconstructed signal degrades very gracefully in our framework, as shown in Fig. 2(c), with the help of layered representation and by selectively recovering packets with higher priority. *This provides the physician with a better chance of arriving at an accurate diagnosis.*



(a) Original signal



(b) Reconstructed signal at the RMS using conventional framework



(c) Reconstructed signal at the RMS using the proposed framework

Fig. 2. Snapshot of ECG signal fluctuations for MLII channel when the channel error rate is 0.1 and the patient moves at 2 km/h.

VI. CONCLUSIONS

The proposed adaptive framework can effectively limit the effect of error bursts that are commonly occur in a wireless channel, hence ensures that the *perceptual quality degrades gracefully under severe channel conditions.*

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