Wireless Body Area Networks for Healthcare: A Feasibility Study

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ABSTRACT

The purpose of this feasibility study is to introduce wireless body area networks and also give an understanding of what possibilities and challenges there are when using short range wireless communications in this domain. We establish a prototype BAN system using Bluetooth technology and choose the Electrocardiogram (ECG) signal to test the data transmission performance over this system.

I. INTRODUCTION

Our era is witnessing an increasing pressure on quality and quantity of healthcare due to the increase of aging population, chronic diseases, and health consciousness of people. People put more attention in prevention and early risk detection. In US and European countries, retired parents usually do not live with their children. A system that can continuously monitor the health condition of elderly people and share information with remote care providers or hospitals will be in great demand.

As an effort of catching this trend, body area network (BAN) as an emerging technology for providing this kind of health information, has been attracting more and more attentions recently. IEEE has launched the IEEE 802.15 Task Group 6 (BAN) in November 2007 to develop a communication standard optimized for low power devices, and operating on, in or around the human body to serve a variety of applications including medical and consumer electronics [1]. In more common terms, a Body Area Network will be a network containing sensor nodes in close proximity to a person’s body monitoring vital signals of the human body and a more intelligent node capable of handle more advanced signal processing. Although the most obvious application of BAN is in the medical sector there are also more recreational uses to BAN. By this convenient means, elderly people can keep track of their health conditions without frequent visits to their doctors’ offices. Meanwhile, their doctors can still access the data and give their patients advices based on these data.

This feasibility study intends to shed some light upon the general questions arising in the BAN medical application. The rest of the report is organized as follows. Section II introduces the medical applications and requirements of BAN. In Section III, we propose a prototype system for BAN using Bluetooth transceivers. Comparisons and simulations are shown in Section IV and concluding remarks are given in Section V.

II. MEDICAL APPLICATIONS OF BAN

Medical applications of BAN cover continuous waveform sampling of biomedical signals, monitoring of vital signal information, and low rate remote control of medical devices [2]. They can be broadly classified into two categories depending on their operating environments [3]. One is the so-called wearable BAN, which is mainly operated on the surface or in the vicinity of body, such as medical monitoring. Another is the so-called implantable BAN, which is operated inside the human body, e.g. capsule endoscope and pacemaker.

II.A. Network architecture of medical BAN

In this study, the architecture under consideration is shown in Figure 1 [4]. This architecture consists of two main parts: multiple body sensor units and a body central unit. The body sensor units perform vital medical data acquisition, data (pre-)processing, actuator control, data transmission and provide some basic user feedback. The body central unit links multiple sensor units, performs data collection, data processing/compression, actuator control, basic event detection/management and provides external access together with a personalized user interface. In our study, we will use the ECG signal as an example to evaluate its performance in a healthcare environment.

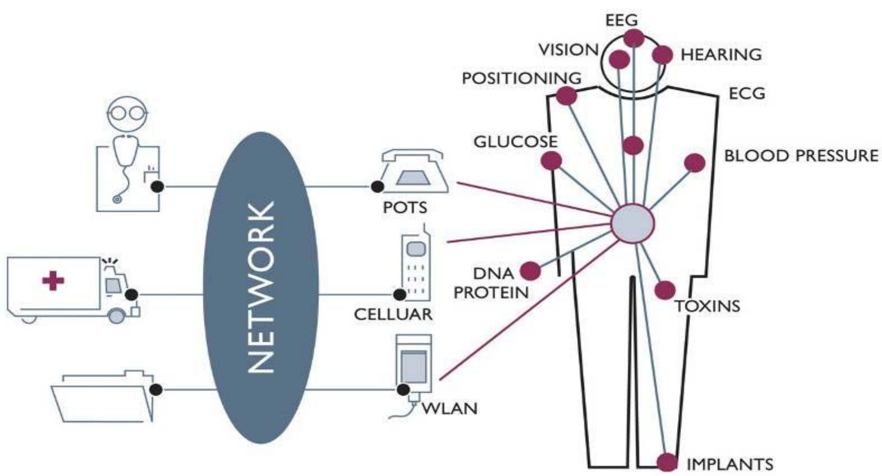

Figure 1: BAN architecture under consideration.

II.B. System requirements and challenges

The medical BAN is supposed to support a low complexity, low cost, ultra-low power and highly reliable wireless communications for use in close proximity to, or inside, a human body to satisfy an evolutionary set of entertainment and healthcare products and services [2]. To dealing with a broad range of possible application, the key issue is the scalability in terms of data rates, power consumption, network size, and security. Figure 2 describes the ideal position for BAN in the power consumption versus data rate spectrum [3]. As we can see, the range of BAN devices can vary significantly in terms of the bandwidth and power consumption. In addition, medical signals are often life-critical, posing strict requirements in terms of accuracy, reliability and latency.

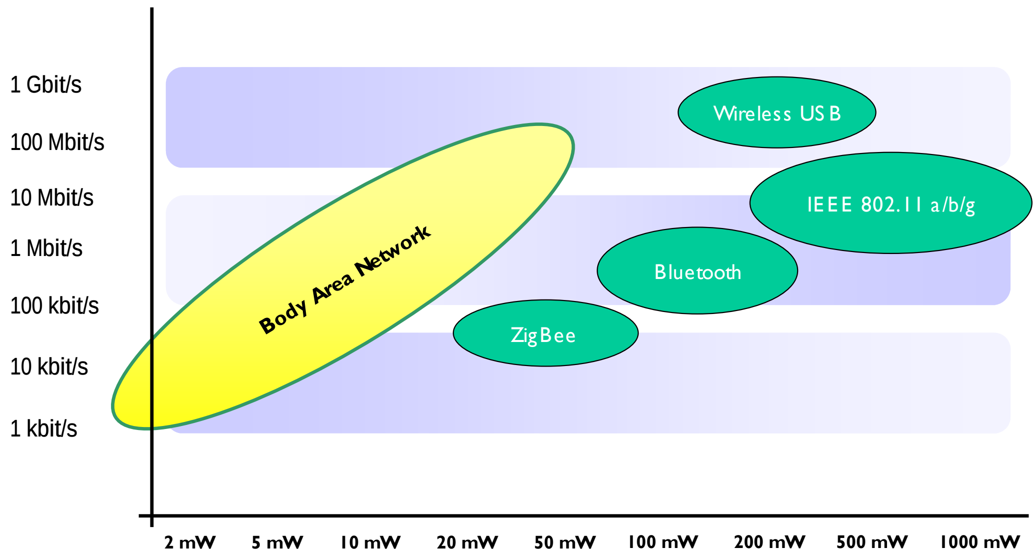

Figure 2: Data Rate versus Power Consumption.

III. A PROTOTYPE BAN SYSTEM WITH BLUETOOTH

From a general understanding of the BAN and the system requirements, it is evident that possible candidates in implementing BAN should be short range communication technologies.

IEEE 802.15.1 Bluetooth operates in the 2.4GHz ISM band, from 2400MHz to 2483.5MHz [5].The system employs a frequency-hopping multiple access schemes to combat interference and fading. The symbol rate is 1 Msymbol/s supporting a bit rate of 1 Mb/s. For example, ECG signal from each channel are digitized at 360 Hz with 11-bit resolution implying a data rate of 3.84 Kbps per channel, so all 12 channels of ECG data can potentially be transmitted using Bluetooth. In addition, forward error correction (FEC) and automatic repeat request (ARQ) for retransmission are used as authentication of reception to ensure reliable communication. Based on its suitability of BAN, we test a prototype system for BAN using Bluetooth technology. We will discuss the detailed system in the following.

III.A. System block diagram

The whole system block diagram is in Figure 3. First, the digitized ECG signals are passed through the data compression module in order to reduce the transmission requirement and the needed storage capacity. Then the compressed data are transmitted through the Bluetooth Radio System module. The details of these modules are described in the following sections. At the receiver, the inverse processes are performed to reconstruct the original signals.

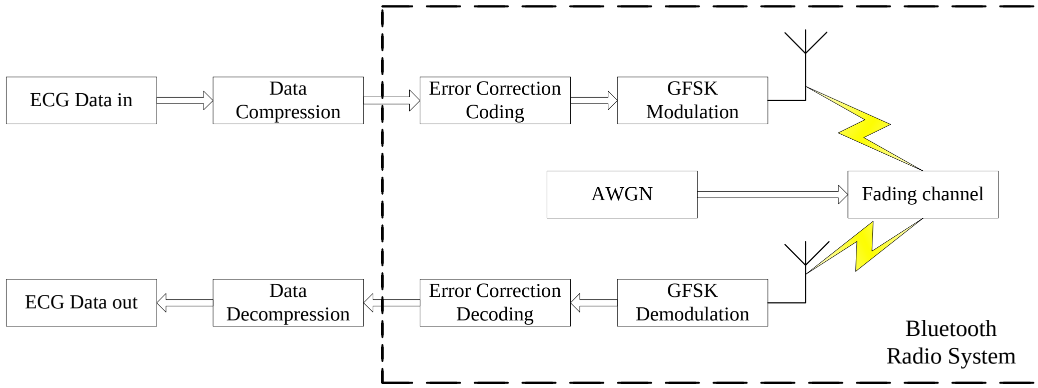

Figure 3: Whole system block diagram.

III.B. ECG data compression

By utilizing the ECG compression techniques, we expect to achieve the objective of reducing the amount of digitized ECG data as much as possible while preserving the diagnostic information in the reconstructed signal. The compression ratio (CR) is a measure of the compression performance, defined as the ratio between the number of bits needed to represent the original and the compressed signals. For the error criterion, the percentage root-mean-square difference (PRD) measure is employed [6]. However, the clinical acceptability of the reconstructed signal should always be determined through visual inspection by physicians.

Existing data compression techniques for ECG signals can be classified into three main categories: Direct data compression methods, transformation methods and parameter extraction methods [6]. Based on the ECG data characteristics and implementation complexity, we choose the following schemes:

1. Split the original signal into M successive blocks, each having N samples.
2. Transform each block using discrete cosine transform (DCT).
3. Quantize of DCT coefficients.
4. Encode the quantized DCT coefficients using LZW coding.

III.C. Bluetooth radio system

Modulation

The modulation is Gaussian frequency shift keying (GFSK) with a bandwidth-bit period product, also known as bandwidth (BT), of 0.5. The modulation index may vary between 0.28 and 0.35 [5]. A transmitted GFSK signal can be written as:

$$x(t) = \sqrt{\frac{2E}{T}} \cos\{ j2\pi \{ f_c t + h \int_{-\infty}^{t} g(\tau) d\tau \} \}$$

Where E is the energy per symbol, T is the symbol period, f_c is the carrier frequency, h is the modulation index and g(t) is the output of Gaussian low pass filter for the input data signal. The modulation index h is defined as:

$$h = 2 f_d T$$

where f_d is the frequency deviation, the maximum frequency shift with respect to the carrier frequency if a ‘0’ or ‘1’ is being transmitted.
The block diagram of the GFSK transmitter is shown in Figure4. First the bits are converted to NRZ signal elements. A ‘0’ is represented by a signal with value -1 and a ‘1’ by a signal with value 1, each with a duration of T seconds. The filter output is then connected to a Voltage Controlled Oscillator (VCO) that translates the amplitude of the filtered bits into a frequency shift.

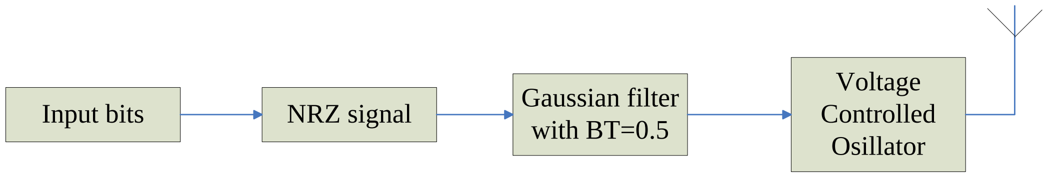

Figure 4: The block diagram of GFSK transmitter.

In Figure 5, the effect of the Gaussian filter is shown. The Gaussian filter reduces the bandwidth of the input signal of the VCO.

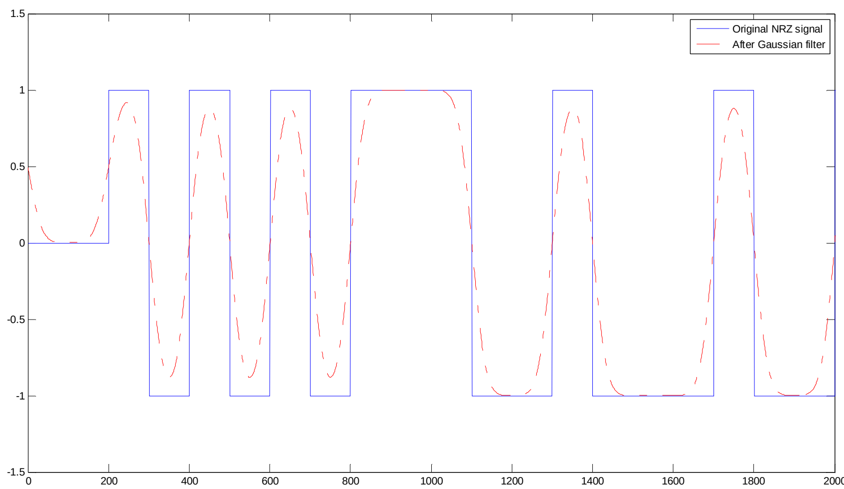

Figure 5: NRZ signal before and after the Gaussian filter.

Statistical Channel Model

The channel model we adopt is the exponential channel model [7], which provides a good compromise between simplicity and reality. The taps are complex, zero mean Gaussian random variables with variances that decay exponentially. The taps can be written as:

$$h_k = N(0,\frac{1}{2}\sigma_k^2) + j \cdot N(0,\frac{1}{2}\sigma_k^2) \quad \text{for } k = 0,1,\ldots,k_{\max}$$

and

$$
\begin{aligned}
k_{\max} &= \lceil 10 \cdot \tau_{rms} / \mathrm{T_s} \rceil \\
\beta &@ e^{-\mathrm{T_s}/\tau_{rms}} \\
\sigma_k^2 &= \sigma_0^2 \ \beta^k \\
\sigma_0^2 &= {1-\beta} \Big/ {1-\beta^{k_{\max}+1}}
\end{aligned}
$$

where τ_{rms} is the root mean square delay spread, $\mathrm{T_s}$ is the sampling period which is the space between the taps, σ_0^2 is the normalization factor which ensures that the sum of the average power profile is one. Theoretically, there are an infinite number of taps in the exponential model; however, the magnitude of the taps decays rapidly. Therefore, it is reasonable to truncate the taps at some point which is given by $k_{\max}$.

An example of the impulse response of the channel is shown in Figure 6.

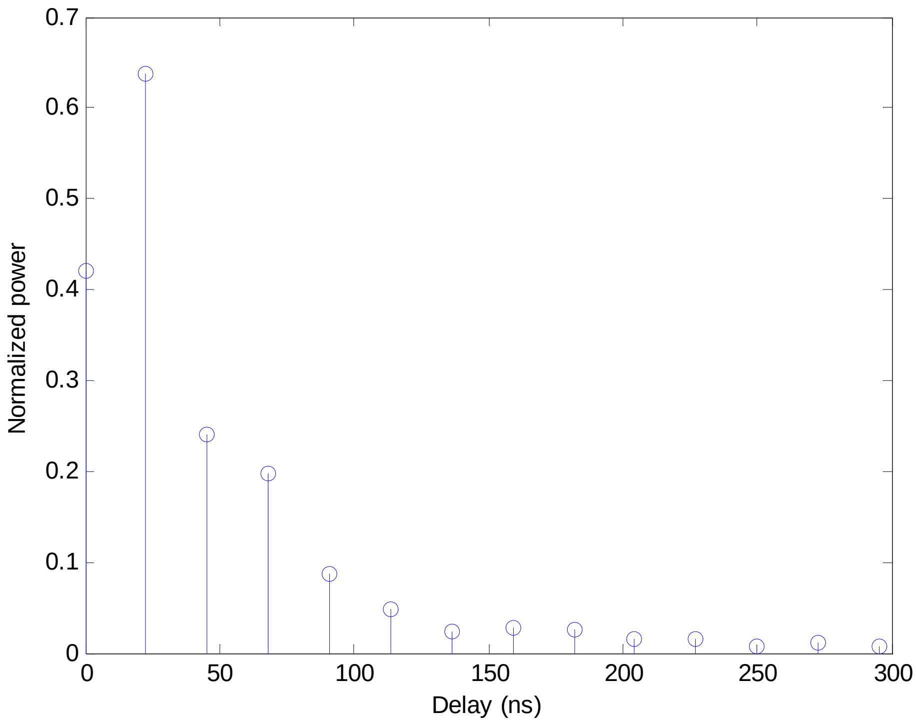

Figure 6: Example plot of the impulse response of the channel.

Demodulation

At the receiver, we use a simple differential demodulator. The complex base-band signal was sampled and multiplied by its complex conjugate that was delayed by a symbol period. The resulting differential phases of the symbols, $\Phi_n - \Phi_{n-1}$ are detected and decided that '1' was sent if $\Phi_n - \Phi_{n-1}$ was greater than or equal to zero and ‘0’ was sent if $\Phi_n - \Phi_{n-1}$ was negative. The block diagram of the demodulator is shown in Figure 7.

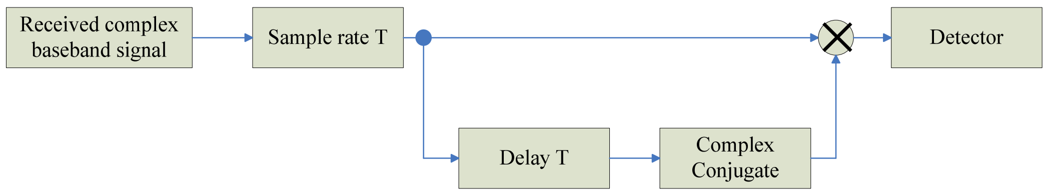

Figure 7: The block diagram of differential demodulator.

IV. SIMULATIONS

The MIT-BIH Arrhythmia database was used to evaluate the proposed data compression and modulation schemes. In this standard database, the ECG signals were digitized through sampling at 360 Hz with 11-bit resolution. The first 10000 samples of 10 MIT-BIH records have been tested.

IV.A. ECG data compression performance

For the data record 100, 101, 102, 103, 104, 105, 106, 107, 108, and 109, table 1 gives the simulation results on CR and PRD. As shown in the table, we can achieve a CR of 6:1 to 14.5:1 with the PRD of about 5. The distortion is mainly due to the quantization process in the compression. With the optimization for the quantization, we expect to reduce the distortion and achieve a PRD of about 1 or less.

Table 1: Results of CR and PRD on the standard records.

Record	CR	PRD (%)
100	8.2	4.9
101	9.0	5.3
102	8.3	6.4
103	9.0	5.4
104	8.5	7.8
105	11.0	5.3
106	6.1	4.1
107	14.5	8.7
108	13.6	6.1
109	11.6	4.0

Figure 8 shows the original and reconstructed signal of MIT-BIH record 109 (CR = 11.6, PRD = 4.0). We can see in the figure, the reconstructed signal in Figure 8 (a) generally preserves the important information and features of the original signal in Figure 8 (b).

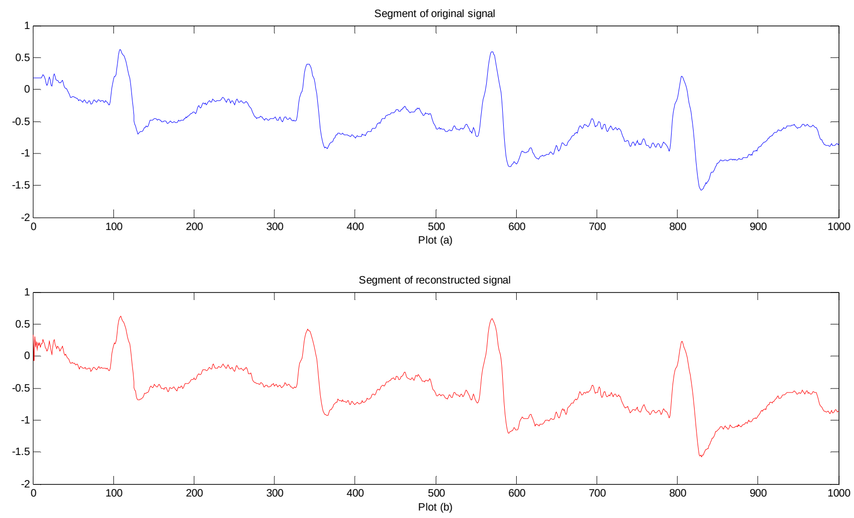

Figure 8: Record 109 compression results. (a) Original signal; (b) reconstructed signal

IV.B. Bit Error Rates performance

Figure 9 shows the plot of BER vs. SNR in the presence of additive white Gaussian noise (AWGN) and the effect of the multipath channel. As we can see in the figures, it takes more than 30 dB SNR to achieve an acceptable BER of the order of 10^{-3} in the fading channel. This can be potentially improved by designing more optimal and sophisticated receiver schemes.

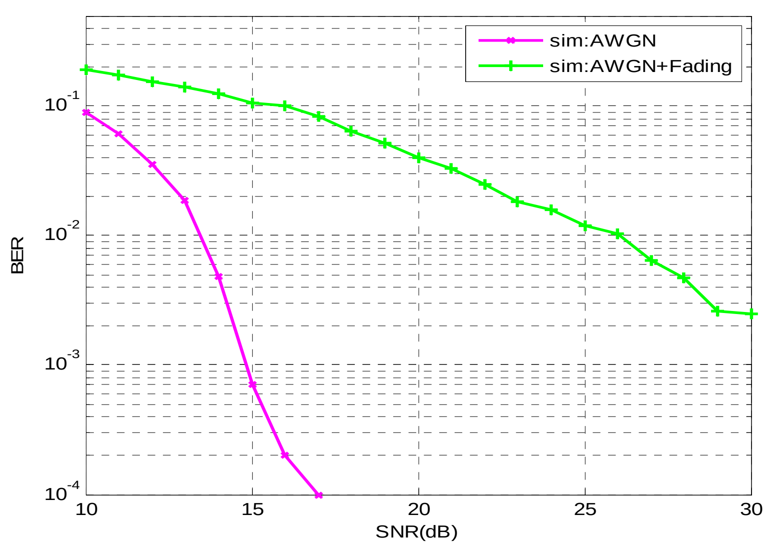

Figure 9: BER vs. SNR

IV.C. Overall system performance

Figures 10 and 11 show the overall system performance with SNR equals to 29dB and 30dB, respectively. Plot (a) in both figures is a segment of the original ECG signal and plot (b) is a segment of reconstructed ECG signal. As we can see, when SNR equals 29dB, the reconstructed signal exhibits severe distortion. When SNR equals 30dB, the calculated PRD is about 95, but the reconstructed signal seems to retain the basic shape and clinical features of the original signal in this case. We can take a close look at one period of the ECG waveform as shown in Figure 12, the PRD is relatively high because there are many subtle differences between the original and reconstructed signal, which does not seem to influence the peaks of the general waveform.

Therefore, in order to keep the fidelity of the original ECG signal, it appears that the signal to noise ratio must be at least 30 dB, which is fairly high. This will increase the emission power and power consumption and not feasible to BAN with ultra-low power requirement for BAN. A possible solution to this problem is to design more sophisticated demodulation schemes for GFSK modulation in fading channels.

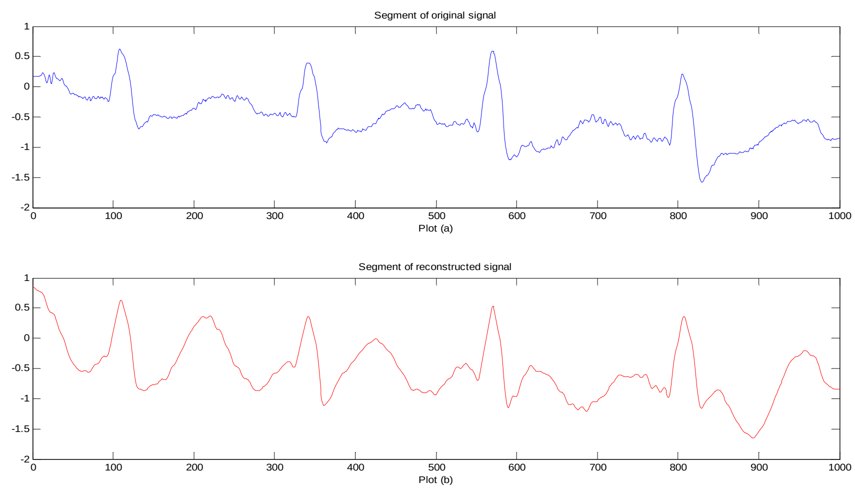

Figure 10: Original and reconstructed signal with SNR = 29dB. (a) Original signal; (b) reconstructed signal.

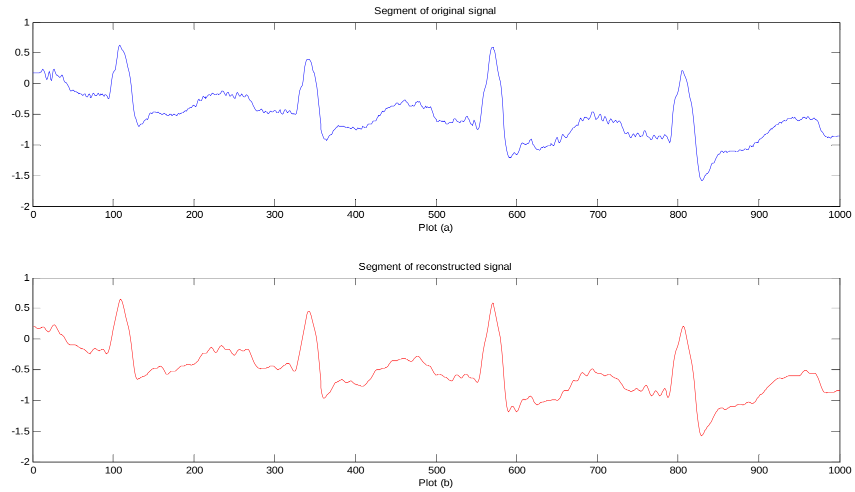

Figure 11: Original and reconstructed signal with SNR = 30dB. (a) Original signal; (b) reconstructed signal.

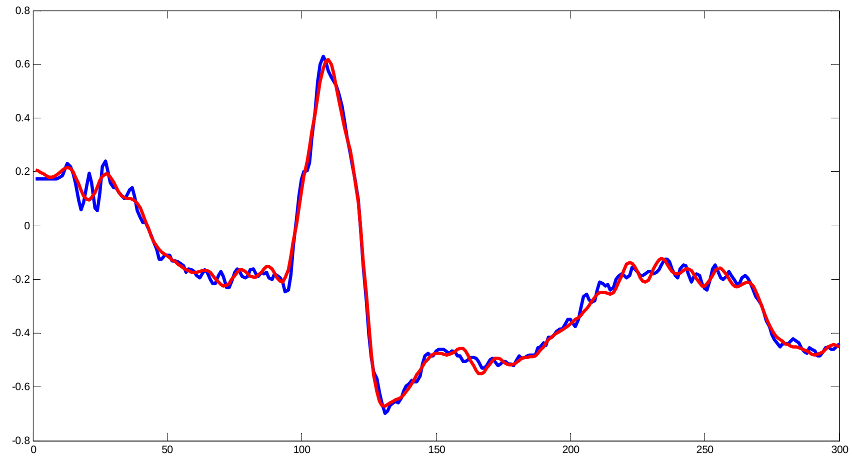

Figure 12: One period Original and reconstructed waveform with SNR = 30dB.

V. SUMMARY

This report has introduced the IEEE 802.15 TG-BAN and presented the performance simulation and analysis of ECG data transmission in a wireless body area network using Bluetooth technology. The result shows that the raw ECG data can be greatly compressed while keeping the fidelity of the original signal to reduce the transmission overhead and storage capacity. The SNR needed to achieve an acceptable BER (10^{-3}) in Bluetooth is fairly high. The system performance can be further improved by optimizing the quantization in the ECG compression process, and designing of more sophisticated receivers for the GFSK modulation in fading channels.

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