Ubiquitous WBAN-based Electrocardiogram Monitoring System

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***Abstract*—This paper presents a remote patient monitoring system within the scope of Body Area Network standardization. In this regime, wireless sensor networks are used to continuously acquire the patient's Electrocardiogram signs and transmit data to the base station via IEEE.802.15. The personal Server (PS) which is responsible to provide real-time displaying, storing, and analyzing the patient's vital signs is developed in MATLAB. It also transfers ECG streams in real-time to a remote client such as a physician or medical center through internet. The PS has the potential to be integrated with home or hospital computer systems. A prototype of this system has been developed and implemented. The developed system takes advantage of two important features for healthcare monitoring: (i) ECG data acquisition using wearable sensors and (ii) real-time data remote through internet. The fact that our system is interacting with sensor network nodes using MATLAB makes it distinct from other previous works.**

***Index Terms*—eHealth, WBAN, ECG, mote, base station, TCP/IP, MATLAB, PS;**

I. Introduction

Sensor Networks, a new class of devices with wireless communication and processing capabilities, have shown potential application in improving eHealth services. Integration of low power wireless sensor network devices into medical environments raises Wireless Body Area Network (WBAN) for measuring and monitoring patient's vital signs. WBAN is a radio frequency based wireless networking technology that interconnects intelligent nodes capable of sensing, sampling, processing, and communicating of biological signals, attached on or around human body.

Several research groups and commercial vendors are already developing prototype system for transmitting the vital physiological data from a patient to a remote monitoring station using Wireless Sensor Network (WSN). CodeBlue [1] is one of the most comprehensive projects combining hardware and software sensor networks platform for Medical Care application. A multi-tier WBAN system prototype has been also proposed by researchers at [2]. Their system handles single-hop and slotted communication between the sensor and network nodes using ZigBee or Bluetooth. Moreover, the work carried out by researcher at [3] is similar to CodeBlue project. They have developed a system for detecting clinical deterioration using WSN based on real-time vital signs. In a recent project [4], a WSN based e-health system which estimates the location of targets without making any interference to their normal life has been developed. Despite the increased interest in the WSN areas, there are few studies on the system development with 'real-time' remote access to the vital signs via internet which is the other essential factor for Health monitoring. In terms of real-time data transmission through local network, majority of previous works focused on sending an alarm to the medical center in case of observing abnormalities while our system is completely adopted for real time data transmission. To the best of our knowledge, this is a first work which develops MATLAB based system for interaction with sensor network nodes. MATLAB contains advanced numerical computing ability, powerful libraries and elaborate toolboxes for plotting and analyzing data in real-time that eases data processing operations.

In this paper, we propose a secure WBAN for health monitoring which supports ECG wearable sensor and contains an online personal server for real-time data collection, visualization, memorizing, analyzing, and transmission to local Network and internet. The ultimate goal of this study is to design and implement a mobile system for patients' ECG monitoring in real-time while they are free to move. In Section II, we review the existing systems in the literature. The WBAN architecture that can meet the requirements for real-time ECG streaming and monitoring will be introduced in Section III. Section IV is devoted to the proposed system implementation and some practical results. Finally, Section V provides conclusion and our in progress works.

II. WBAN System Architecture

The proposed WBAN System for remote patient monitoring in real-time is illustrated in Fig. 1. The prototype system developed by our group can be functionally divided into two subsystems: (i) WBAN nodes, and (ii) Personal Server, being presented in the next paragraphs.

A. Development of the Wireless Body Area Network nodes

This subsection describes our experiences on developing a combined hardware and software platform for the Wireless Body Area Network nodes.

1) Hardware Design: The Vernier EKG [5] Sensor is the analog wearable sensor board we employed in our system to acquire ECG signals. It measures cardiac electrical potential waveforms for standard 3-lead ECG tracings. The IRIS mote developed by UC Berkeley and manufactured by Crossbow Technology [6] operates as a primary embedded platform for

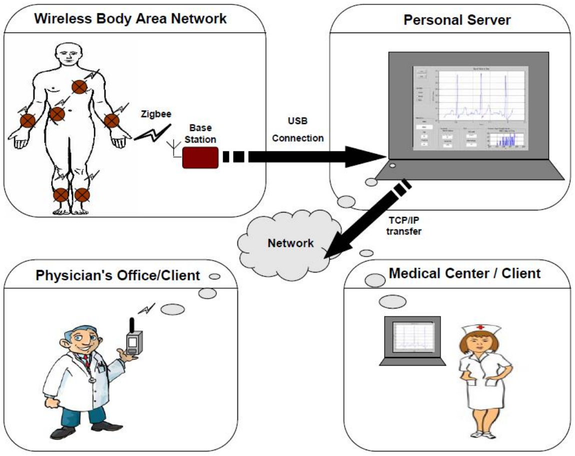

Fig. 1. WBAN System for real-time patient monitoring.

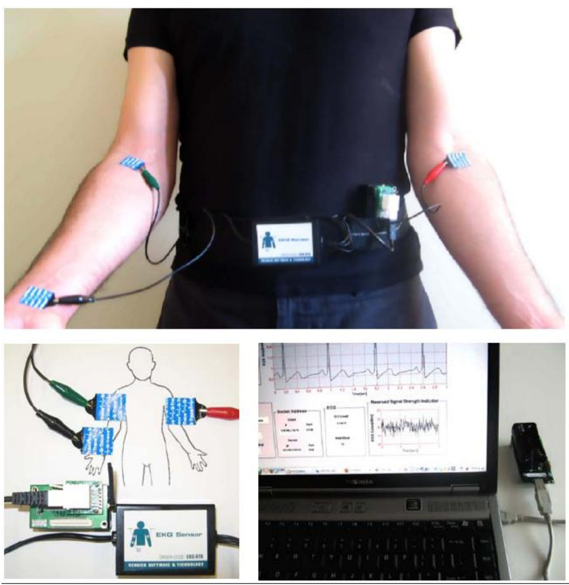

Fig. 2. The Vernier EKG sensor integrated to IRIS mote.

ECG sensor in our system. We choose to connect our ECG sensor to Crossbow's IRIS platform via the MDA100 [7] sensor board prototyping area which supports connection to all eight channels of the Mote's analog to digital converter (bottom-left in Fig. 2). On the patient body, the ECG sensor node is mounted on the waist and lets the subject feel freedom of movement (top in Fig. 2). The ECG signs are acquired by the sensor node and transmitted to the base station in real-time. The base station (bottom-right in Fig. 2), is composed of MIB520 [6] and is responsible for data collection, communication and in-system programming to PC.

2) Software Design: The TinyOS 2.0 operating system [8] was used for developing the Wireless ECG monitoring system. In this application, motes are programmed based on their functions and tasks. Hence, two types of motes are programmed: Mobile and Base. The Mobile IRIS mote that is connected to the ECG sensor runs an appropriate software

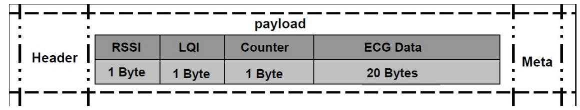

Fig. 3. Tinyos message fields and payload contents.

which uses the ADC to sample the analog ECG data from the sensor, constructs a message out of them, and sends it over IEEE 802.15.4 (ZigBee) to the IRIS mote connected to base station. The ADC channel continuously reads the ECG data and when enough ECG samples are collected in the message buffer, the application passes the message to the networking stack. ECG should be digitized at sampling frequency of 500-1000 Hz since fine temporal precision is needed with respect to expected variations in cardiac period. We faced with some challenges for determining this high sampling rate of the ECG signal. The first challenge was due to limitation of IRIS mote packet transmissions rate. IRIS mote can handle only 200 packet transmissions in a second which leads to a period interval of 5 ms for each packet. In order to satisfy desired sampling rate, each packet includes ten ECG data with a period interval of 1.4 ms. The other challenge is to find appropriate TinyOS Source and Sink Independent Driver (SID) interface compatible with ECG sampling rate. The application uses TimerMilliC which gives an independent millisecond granularity timer. On the IRIS motes, the 32 KHz external clock is divided by 32, so the best resolution we can get from that timer is 1 ms. To avoid timing issues with IRIS, a lower limit of 5 ms should be used. As a result, we have two options to get 1.4 ms sampling interval from Timer hardware in Atmega128: (i) using the Alarm interface which is asynchronous, and (ii) running the ADC module in streaming mode. As ECG provides a continuous stream of data, we programmed an IRIS to read data in block instead of individually by using ReadStream SID interface. Moreover, the motes are programmed to obtain link estimation metrics such as the received signal strength indicator (RSSI), packet error rate (PER), and sequence numbers. The packet number, showing the sequence number, is increased by one each time it is sent to the destination node. The sequence number is utilized to identify a packet within a burst. The received signal strength (RSSI) and link quality indicator (LQI) information are also requested for each packet by the receiver. All data (20 bytes for the ECG data, 1 byte for RSSI, 1 byte for LQI, and 1 byte for Counter (showing sequence numbers) are collected into one TinyOS message and then sent to the base station (see Fig. 3.). The full details on software design for the IRIS motes are reported in our application note [9] issued by CMC Microsystems.

B. Development of Personal Server

The personal server (PS) which is the core processing element has the potential to be implemented on home or hospital computers. The multithreading PS application runs on MATLAB environment and supports different services in

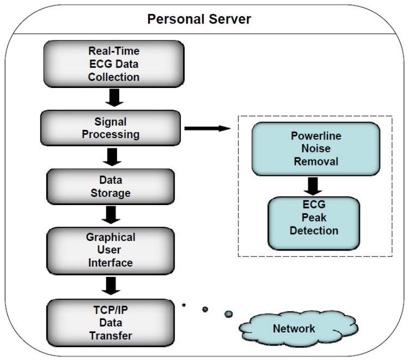

Fig. 4. Functional architecture of Personal Server services.

real-time to the users: (i) continually receiving data from the wireless sensor network and storing it in a database, (ii) applying an efficient signal processing analysis on ECG data for calculating heartbeats, (iii) establishing a Web Application Server for different users such as physicians and medical centers to have real-time and continues access to patients' vital sign through internet, and (iv) providing a graphical user interface for real-time visualization of patients' vital signs. Functional architecture of PS services is shown in Fig. 4. The PS communicates to the base station using serial port interface provided by MATLAB Instrument Control Toolbox [10]. PS deploys dedicated threads with framework of callbacks and events to process the incoming TinyOS 802.15.4 frames containing ECG data samples. In this regard, an event occurs after a packet is received and consequences in associated callbacks. Callback functions are responsible for reading, parsing, verifying, and managing incoming packets. In addition to reading, the data payload such as ECG, RSSI, LQI, and Counter values will be extracted for further processing. LQI and Counter values are utilized for tracking lost packets. A buffer is assigned for storing packet's contents (a FIFO-first in first out) which isolates the processes of reception and storing. Signal processing (ECG peak extraction) and TCP/IP algorithms are executed in their own callbacks and applied to all packets saved in FIFO buffer in real-time.

1) Heart beat calculation using Discrete Wavelet Transform (DWT): We have developed a powerful algorithm in order to calculate the heartbeat based on DWT. We decompose the ECG signal into 3 levels by applying DWT and rebuild the Level 3 approximation (A3) (Fig. 5b) and detail (D3) (Fig. 5c). The low frequency ECG will be reconstructed from the Level 3 approximation (A3) and detail (D3). In order to remove baseline wandering, this regenerated ECG (Fig. 5d) will be subtracted from original ECG. The de-trended ECG (Figure 5e) contains high amplitudes spikes which are R-waves. A threshold level is set up based on the average amplitudes of the R-waves. All the spikes in the remaining signal exceeding the threshold level are considered as R-waves if the slope of the signal is positive before the spike, and the slope is negative after that. After determining R-wave, the R-R intervals are detected, a percentage of the shortest and longest intervals are

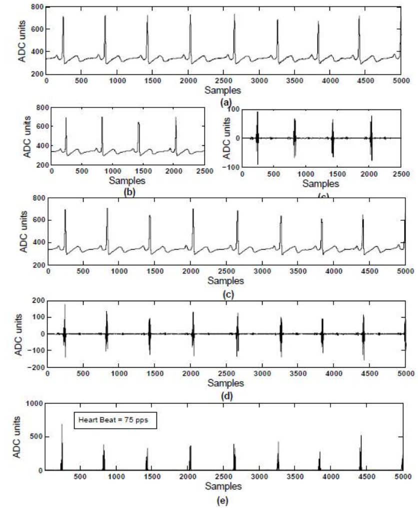

Fig. 5. (a) Original Signal. (b) The Level 3 approximation (A3). (c) The Level 3 detail (D3). (d) Low level ECG. (e) De-trended ECG. (f) R-detected ECG.

discarded, and the remaining intervals are averaged to arrive at the patient's heart rate.

2) TCP/IP Data Transfer: Once three cycles of ECG are stored in the FIFO buffer, the assigned callbacks responsible for establishing TCP/IP transfer will be called and executed. Consequently, a persistent connection will be launched. Compare to usual connection, this persistent connection lies in fewer TCP connection meaning lower responses latency, less overhead on the underlying networks, less memory used for buffers, and less CPU time. In this case, instead of using a TCP connection per packet transfer, the client leaves the connection in place after opening a TCP connection to a particular server. In each transmission, three cycles of ECG stream will be written on connection buffer. When either a client or server is ready to close the connection, it informs the other side and the connection is closed.

3) Graphical User Interface: A graphical user interface (GUI) is embedded into PS which enables users to perform multiple interactive tasks. The GUI shown in Fig. 6, allows users to switch between three different options; Monitor, Record, and Send. In this Scenario, the users can visualize collected and transmitted ECG data in real-time by choosing the Monitor option. The Record option stores all the ECG data received from base station and lets the users to save all the important information including name, age, and weight into the specified database. The data transmission to clients over the internet occurs when the users select Send option. In addition to transferring data, the socket addresses of both Server and Client will be shown in Socket Address panel. The Start and Stop push buttons are responsible for opening and closing the Serial port Connection. The ECG signal is plotted on an axis located on the upper right of GUI. The RSSI value of each received packets will be plotted on the axis in the lower right which can be used for estimating the location of the subjects.

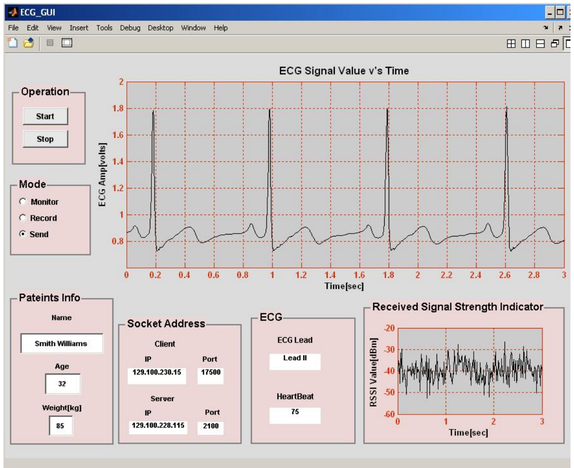

Fig. 6. The graphical user interface developed in MATLAB for providing real-time monitoring of the vital sign information, definition, and configuration of the system's overall behavior.

III. Implementation and Verification

To evaluate the performance of our developed system in a real practice, the system has been tested on a real subject, and all important steps comprising real-time ECG acquisition, peak detection, data storage and transmission via TCP/IP through internet have been assessed. The ECG wireless sensor node was placed on the subject's waist and three electrode tabs were attached to his arms. The ECG data were successfully collected, sampled at 740 Hz frequency by IRIS mote and transmitted over sensor network to the base station in real-time. In the first test, subject's heart beat has been calculated by ECG peak detection using DWT and compared to the simultaneous results obtained by high accurate digital wrist heart beat meter; the results were well matched. The next step was assessment of data transfer between two computers, server and client, via TCP/IP; the monitoring of received ECG data on the client system was successfully and precisely performed with 5 seconds delay. Finally, the impact of mobility on networking performance was evaluated through several experiments carried out in different locations inside our lab. The measurements were conducted for series of packets sent from the sensor node in different power settings to the base station (see Fig. 7). From the figure we see that with power settings more than 0 dBm, even for large distances, the packet reception rate is above 0.90 which indicates link stability. On the other hand, for the minimum power setting (-3 dBm), even for short distances, the communication link is not stable enough.

IV. Future work and Conclusion

This paper presents a system prototype of wireless sensors for medical care within the framework of Body Area Network standardization. Our experiences on developing a combined hardware and software platform for the WBAN nodes were described and discussed. In addition to developing WBAN nodes, the personal server interfacing between the WBAN

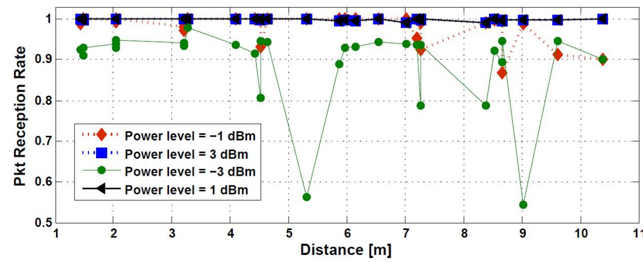

Fig. 7. The packet reception rate for different power settings and distances between IRIS motes

sensor nodes and Wide Area Network was implemented on PC. The PS was responsible for providing multiple functionalities such as real-time visualization, memorizing, analyzing and communication with clients requesting connection over internet. The developed system takes advantage of interaction with sensor network nodes using MATLAB. Several test has been performed to assure the feasibility and accuracy of the system. Moreover, the impact of mobility on networking performance was evaluated by recording the packet reception rate for different power settings and distances between nodes. These tests confirm the reliability of prototype system while the subject moves to different locations.

We are currently working on developing a smartphone-based platform for client remote visualization. This client program runs on BlackBerry smartphone as it offers unique features for developing Java application. The BlackBerry communicates with Personal Server using TCP/IP connection.

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