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Multi-stage Real Time Health Monitoring via ZigBee in Smart Homes

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Abstract

We present a framework for a wireless health monitoring system within a smart home using ZigBee technology. Vital signals are collected and processed using a 3-tiered architecture. The first stage is the mobile device carried on the body that runs a number of wired and wireless probes. This device is also designed to perform some basic processing such as the heart rate and fatal failure detection. At the second stage, further processing is performed by a local server using the raw data transmitted by the mobile device continuously. The raw data is also stored at this server. The processed data as well as the outcomes of the analysis are then transmitted to the service provider center for expertsŕeview for diagnosis as well as storage. The main advantages of the proposed framework are (1) The ability to detect signals wirelessly within a Body Area Network (BAN) (2)Low-power and reliable data sensing through ZigBee network nodes and (3) Optimized analysis of data through an adaptive tiered architecture that maximizes the utility of processing and computational capacity at each of three stages. We are currently building a prototype of the proposed system using in-house ECG probes and ZigBee radio modules.

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Multi-stage Real Time Health Monitoring via ZigBee in Smart Homes

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***Abstract*— We present a framework for a wireless health monitoring system within a smort home using ZigBee technology. Vital signals are collected and processed using a 3-tiered architecture. The first stage is the mobile device carried on the body that runs a number of wired and wireless probes. This device is also designed to perform some basic processing such as the heart rate and fatal failure detection. At the second stage, further processing is performed by a local server using the raw data transmitted by the mobile device continuously. The raw data is also stored at this server. The processed data as well as the outcomes of the analyses are then transmitted to the service provider center for experts' review for diagnosis as well as storage. The main advantages of the proposed framework are (1) The ability to detect signals wirelessly within a Body Area Network (BAN) (2) Low-power and reliable data sensing through ZigBee network nodes and (3) Optimized analysis of data through an adaptive tiered architecture that maximizes the utility of processing and computational capacity at each of three stages. We are currently building a prototype of the proposed system using in-house ECG probes and ZigBee radio modules.**

***Index Terms*— Zigbee, electrocardiogram, health monitoring, smart homes.**

I. Introduction

As numerous wireless personal area networking (WPAN) technologies emerge, the interest for applications such as health care monitoring, smart homes and industrial control has grown significantly. ZigBee is the first industrial standard WPAN technology [2] that provides short range, low power and low data rate communication, and supports mesh networking and multi-hopping. While many smart-home application areas such as lighting, security and climate control have been suggested using the ZigBee standard, health-care applications have not received the attention they deserve despite their importance and high value added. Here, we present a prototype wireless system for realtime health monitoring in the smart home arena.

A number of systems have been reported for real-time patient monitoring. The UbiMon (Ubiquitous Monitoring Environment for Wearable and Implantable Sensors) project, aims to provide a continuous and unobtrusive monitoring system for patients in order to capture transient but life threatening events [5]. The CodeBlue project explores applications of wireless sensor network technology to a range of medical applications, including pre-hospital and in-hospital emergency care, disaster response, and stroke patient rehabilitation [6]. Most of the existing systems lack two key features: (1) Reliable wireless operation that conforms to standards (2) Compatibility with smart home systems.

Our ZigBee based architecture is based on the premise that the wireless technology combined with the widespread infrastructure smart homes can provide will be key to the effective use of medical monitoring systems. This is due to the fact that practicality of the sensing, transmission and processing steps is often the major obstacle against common use of such devices. Therefore, we believe that medical monitoring based on the emerging smart home wireless technology, ZigBee, has a great potential.

In addition, optimized processing of the collected data plays a key role. With optimization, we refer to the best use of computation and storage capacity at each of three different stages, namely the mobile device, home server and the central server. For example, the mobile device can play an important role in alerting the user in case of emergencies and therefore should be used for detecting the most urgent situations, especially at the absence of the wireless link. The home server typically has greater capacity and thus can perform much more complex tasks. In this paper, we provide the basic architecture of the system that we are currently developing and plan to implement in a pilot market in the next two years. The details of the algorithms as well as the results of the pilot project will be published as more progress is made.

The next section provides a brief overview of the ZigBee technology. Then, we present an introduction to ECG signals, which is the primary data we collect and process at the first stage of our development. The following section provides soem specific aspects fo our approach followed by some concluding remarks and discussion of the ongoing work.

II. ZigBee for Wireless Sensing and Transmission of Medical Data

Many medical applications would benefit from standards-based wireless technology that is reliable, secure, and runs on low power. Established standards for wireless applications, such as Bluetooth and IEEE 802.11, allow high transmission rates, but at the expense of high power consumption, application complexity, and cost. ZigBee networks on the other hand, are primarily intended for low duty-cycle sensors, those active for less than 1% of the time. For instance, an off-line node can connect to a network in about 30 ms. Waking up a sleeping node takes about 15 ms, as does accessing a channel and transmitting data. Applications such as reading the pressure in an oxygen tank can send the reading once per hour from a sensor which would then return to sleep. The low-power demand extends battery life in remote sensors. The network name comes from the zigzagging path a bee (a data packet) takes to get from flower to flower (or node to node)[3].

ZigBee is best described by referring to the 7-layer OSI model for layered communication systems. The Alliance specifies the bottom three layers (Physical, Data Link, and Network), as well an Application Programming Interface (API) that allows end-developers the ability to design custom applications that use the services provided by the lower layers. Figure-1 shows the layered protocol architecture adopted by the alliance. It should be noted that the ZigBee Alliance chose to use an already existing data link and physical layers specification. These are the recently published IEEE 802.15.4 standards for low-rate personal area networks. We describe the key features of each layer in the following. Complete descriptions of the protocols used in ZigBee can be found in [1],[2].

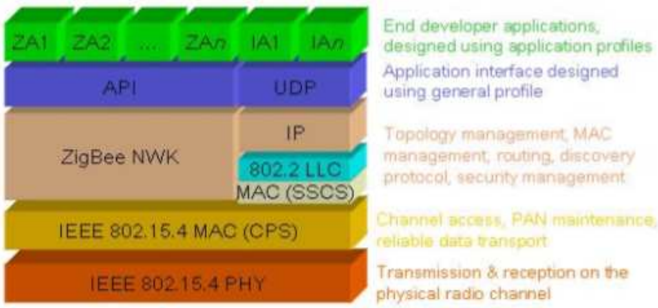

Fig. 1. Illustration of ZigBee stack

A. PHY Layer Features

The IEEE 802.15.4 standard [1]defines three frequency bands of operation: 868MHz, 916MHz and the 2.4GHZ bands. We will focus on the 2.4GHz bands as these are the most commonly available products at the moment and in addition this band offers the highest achievable data rate of 250Kbps at the physical layer.

B. Data Link Layer Features

The IEEE 802.15.4 is a light-weight simple protocol that is based on CSMA (Channel Sense Multiple Access). Its responsibilities may also include transmitting beacon frames, synchronization and providing a reliable transmission mechanism. A key aspect of the data link layer is that individual packets are each acknowledged thus providing link level delivery guarantees. However, there are no quality of service guarantees or support for priority levels of network traffic. Essentially, ZigBee offers only best effort end-to-end delivery of individual packets.

C. Network Layer Features

The majority of the new technology development that has occurred within the ZigBee Alliance has been in the creation of the network layer. The responsibilities of the ZigBee network layer includes mechanisms used to join and leave a network, and to route frames to their intended destinations. The routing of course may involve using multiple intermediate relay devices within the network. In addition, the discovery and maintenance of routes between devices devolve to the network layer. Also the discovery of one-hop neighbors and the storing of pertinent neighbor information are done at the network layer.

III. ECG Basics

The electrocardiogram is primarily a tool for evaluating the electrical events within the heart. The action potentials of cardiac muscle cells can be viewed as batteries that cause charge to move through the body fluids. These moving charges can be detected by recording electrodes at the skin surface. Figure 2 illustrates the typical lead II ECG where the active electrodes are placed on the right arm and left leg.

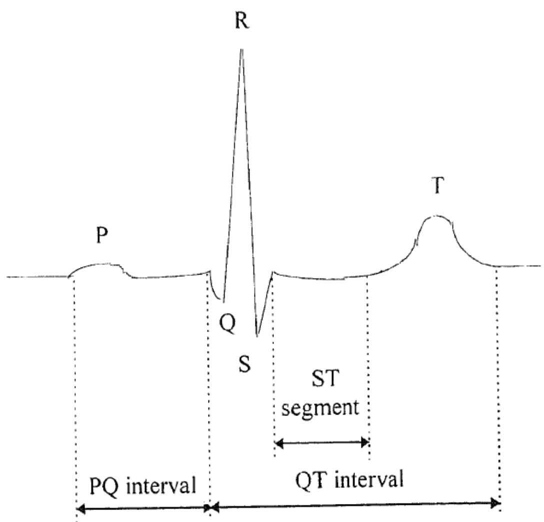

Fig. 2. Illustration of the key ECG features

The first deflection, the P wave, corresponds to a current flow during atrial depolarization. Normal P waves have various shapes, from flat to sharply-peaked with amplitudes ranging from 0 to 0.3mv. The PQ interval, extending from the beginning of the P wave to the first component of the QRS complex, corresponds to the depolarization of the atria, AV node, AV bundle and its branches, and the Purkinje system. The second deflection, the QRS complex, is due to ventricular depolarization. The final deflection, the T wave, is the result of ventricular repolarization. Atrial repolarization is usually not evident on the ECG, because it occurs at the same time as the QRS complex.

IV. Mobile ECG Sensing and Algorithms

The proposed platform operates in two different modes. In the first mode, it measures the raw ECG signal from up to three electrodes, and locally analyzes heart rate variability. If an arrhythmia risk is detected, an alert is transferred to the home server over the ZigBee network controller. In the second mode, the raw ECG is measured and transmitted continuously to the home server, and then the home server analyzes the

ECG records. If any anomaly is detected, patient's doctor is contacted. The ZigBee protocol does not have any transport layer functionality. Continuous transmission of the ECG data requires support for segmentation and reassembly, which is not offered by the current version of the ZigBee standard. We have implemented these functionalities at the application layer.

A. Sensing and Transporting ECG Data

We have built a hardware platform for sensing and processing ECG signals. Key steps consist of low noise amplification, quantization, digital filters and feature detection algorithms. The processed digital data is then sent to a local server over the ZigBee network.

Typical ECG signal level on the human body surface is around 2mV. The AD converter used in our setup accepts voltages from 0 to 3V. Therefore, we first add 1.5V offset to center the ECG waveform prior to amplification. The amplified signal is then quantized to 8 bits by the ADC within the M16C micro-controller. The discrete waveform is passed through a differentiator and low-pass filter as shown in Fig4, where $E(k)$ represents the quantized ECG signal. The sampling rate in our implementation is 320Hz. The filter transfer functions are as follows:

$$G_1(z) = 1 - z^{-1} \quad (1)$$

$G_1(z)$ is a differentiator filter; and it is used to obtain slope of the QRS complex. $G_2(z)$ is a low-pass filter to avoid residual noise and intrinsic differentiation noise. Overall filter response maximizes the energy of the QRS complex and improves detection of R wave peaks.

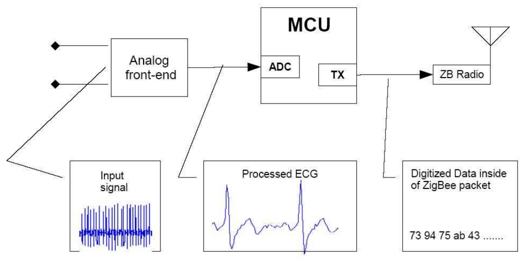

Fig. 3. Block diagram of the ECG measurement platform

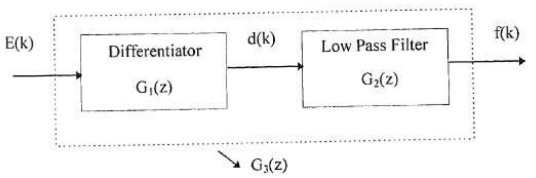

Fig. 4. Filters for ECG signal conditioning

B. Detection of QRS Peaks

Adaptive threshold setting similar to that in [7] is used to detect QRS peaks. Note that due to severe baseline drifting and movement of patients, an ECG signal waveform may vary drastically from a heart beat to the next. With adaptive threshold, probability of missing a *QRS* peak can be decreased.

In our platform, the first five seconds of the absolute value of the low pass filtered digitized ECG data, $f(n)$, is searched for its highest peak. Let us denote the magnitude of this peak as $p[0]$. Then, the threshold τ is initialized to $\tau[0] = \alpha p[0]$, where $\alpha < 1$. In our implementation, we set $\alpha = 0.65$.

Let $p[i]$ denote the first local peak of $f(n)$ after a threshold crossing. After determining the slopes on both sides of $p[i]$, the zero crossing between $p[i]$ and the peak of the highest slope is chosen as the i^{th} *R* wave peak location. The next threshold is set as

$$\tau[i] = \alpha\tau[i-1] + (1-\alpha)p[i-1] \quad (2)$$

If an R-to-R interval turns out to be β times longer than the previous interval, where $\beta > 1$, only within that section of the ECG a search is repeated with a lower threshold to detect a possibly missed heart beat. We set β to 1.5.

The inverse of the interval between two consecutive *R* wave peaks gives the instantaneous heart rate. Their sequence shows how heart rate varies.

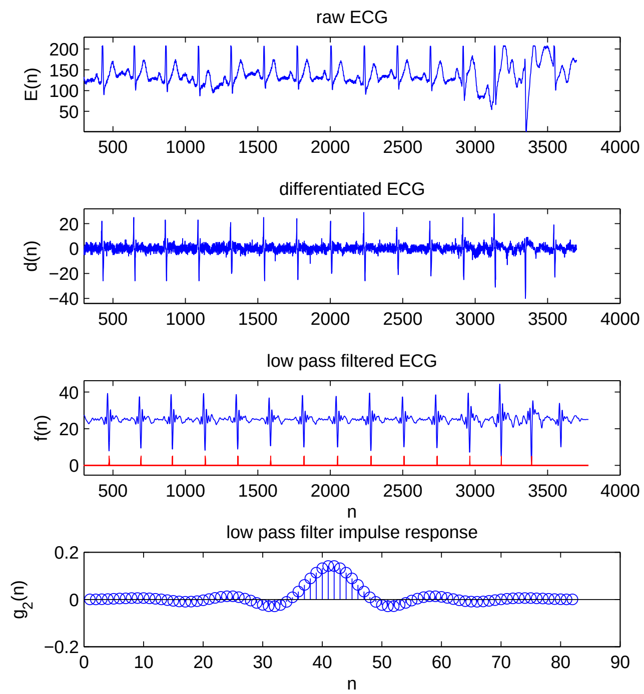

Fig. 5. a) raw measured ECG signal b) ECG signal $d(n)$ after the differentiator c) ECG signal $f(n)$ after low pass filtering. The detected R peaks are overlaid on the plot d) impulse response of the low pass filter, $g_2(n)$

In Fig.5, a raw ECG trace and the output of the implemented R peak detector is shown. It is robust against baseline drifting caused by patient movements.

C. ZigBee Network Configuration

In the current implementation ZigBee network is configured in such a way that it uses one PAN per unit being monitored i.e. apartment, hospital section. Every device is configured as a ZigBee End-device. Several devices may coexist and report data simultaneously. In order to completely cover the monitored area, several additional ZigBee routers may be required. Current version of the ZigBee standard does not provide any solution for mobile nodes such as handover or roaming. When ZigBee device moves between coverage areas of different routers the transmission will be interrupted until the node finds new route to the controller. At the initial configuration every router device discovers the route to the controller (PAN Coordinator in our case) than later it can respond to the route discovery request from the ECG device and does not need to rediscover the enire route.

The application software running on ZigBee devices is responsible for the creation of proper payload that carries corresponding commands, responses and data. Once the payload is created, it is passed to the ZigBee APS layer for the transmission over the air using API provided by ZigBee stack manufacturer. Application endpoint has one incoming cluster and two outgoing. Incoming cluster is used for command and control messages, one of the outgoing clusters is used to send response to control messages and the other to send raw ECG data. Node can receive command messages such as "start", "stop" to control transmission, "setFQ" to set sample frequency and others may be defined in the future. At 320 Hz sample rate device produces 4 data packet per second. Depending on the hardware configuration (RAM available) some amount of data can be stored locally in case of temporarily network failures.

ZigBee device endpoint consists of 2 incoming and 1 outgoing clusters. Outgoing cluster is for command and control interface. Incoming clusters receive command responses and ECG data. Upon receiving the data, ZigBee coordinator passes it to the server for further processing and analysis.

D. Data Processing at the Home-Server

Digitized ECG data is continuously transmitted to the Home-Server via the ZigBee network. Additionally, results of the analyses at the mobile device are sent to the server and stored here for future reference. The goal is to provide a repository for more detailed analysis of the data by medical professionals or detection algorithms. In addition, the stored data is processed for more detailed and accurate analysis of ECG signals for detections such as Q-T interval and T wave detection.

The main responsibilities of the home server are: (1) Coordinate the ZigBee in-home wireless network (2) Store incoming data (3) Conduct accurate and detailed anaylsis of the data and (4) Communicate with the central service provider for transmission of the data and notifications for detected anomalies. We are currently developing a Linux-based architecture housed on a PC-platform that allows remote access through a web-based interface. The server also is connected to the ZigBee network through a Coordinator module connected via USB or serial port. Routers on the smart home network will be continuously powered and distributed throughout the home, possibly one for each room. An existing ZigBee network normally used for lighting or security can be used for this purpose as well. The data repository is made available for future use by service provider as well as the user and is backed-up against losses through a data warehousing service.

E. Data Processing at the Central Server

Continuous recording and analysis of ECG data provides an excellent basis for automated detection as well as professional diagnosis of many cardiological symptoms. According to our model, the last and the third piece is the central data processing center where servers as well as medical personnel can provide a variety of services such as storage, early diagnosis and in-home care. The home server transmits periodic reports and makes stored data available to the central server.

A key point for the central server processing is the optimization of the use of resources at the home server resources and the central server. As the number of users increase, the central server can allocate only a limited amount of computational capacity to each user. Therefore, data analysis is performed at the home server ass much as possible.

The central server also functions as an entry point for the professional staff to monitor the data and reports generated by the home server. In addition, the alerts initiated by the mobile device are transmitted to the central server through the home server. The central server also keeps records of all transactions through an event management system.

V. Discussion and Future Directions

The system briefly descried above is currently being developed at all three stages of (1) Mobile device, (2) Home Server and (3) Central Server in our labs. We are implementing relevant algorithms for detection of certain anomalies and building the rest of the infrastructure at home and central servers. There are several open questions that we currently face. These are briefly discussed below:

A. Sensing: Wireless or wired?

A common need of medical monitoring systems is the minimal interference with the daily life of the monitored persons. The widespread use of such devices can only be possible with non-invasive and comfortable sensors. The low-power nature of ZigBee nodes can offer great potential in creating a local wireless network within the proximity of human body for data collection within the body area. On the other hand, some wired solutions exist that can provide great reliability and eliminate the need for even infrequent battery replacement or recharge. This is one of the issues for further research and trials.

B. ZigBee platforms: Power or power?

There is an inevitable compromise between computational power and power consumption of several possible embedded platforms available in the ZigBee market today. Our goal is to use the best performing microcomputer device while maintaining an acceptable power usage. This is directly related to the choice and optimization of the algorithms used on the mobile device, therefore leads to a complicated decision making process.

C. Service Provider Models

There are several questions that must be made from a service providers' perspective for the system to function effectively. The channels for alert notification system, access rights and privacy concerns, scalability with respect to the number of systems and users are among some important issues that face the service provider models. Our approach aims to build a flexible, extensible architecture at the central server in order to answer as many of these questions as possible.

REFERENCES

[1] IEEE Standard for Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) specifications for Low Rate Wireless Personal Area Networks (LR-WPANs), 2003.

[2] ZigBee Alliance Document 02130: Network Layer Specification, July 2004.

[3] ZigBee Networks Open the Door to More Wireless Medical Devices, Medical Design, April 2005.

[4] J. Morganroth, F. V. Brozovich, J. Mc Donald, R. A. Jacobs, "Variability of the QT measurement in healthy men, with implications for selection of an abnormal QT value to predict drug toxicity and proarrhythmia," The American J. Cardiology, v.67, pp.774-776, 1991

[5] Benny P L Lo and Guang-Zhong Yang, "Implementations of Body Sensor Networks, Sensor Networks (BSN 2005), April 2005

[6] CodeBlue project, http://www.eecs.harvard.edu/ mdw/proj/codeblue/

[7] Z. Sahinoglu, 'Analysis of Multi-lead QT Dispersion by Means of an Algorithm Implemented on LabView,' MSc. Thesis, NJIT, January 1998