**Proceedings of the 28th IEEE
EMBS Annual International Conference
New York City, USA, Aug 30-Sept 3, 2006**

A Portable, Low-cost, Battery-powered Wireless Monitoring System for Obtaining Varying Physiologic Parameters from Multiple Subjects

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***Abstract*—A portable, low-cost, and battery-powered wireless monitoring system that is capable of measuring multiple physiologic parameters simultaneously from many subjects was developed. The wireless communication of data is based on a commercially-available mote known as *Tmote Sky*. The star network topology (SNT), is used to collect data from many patients via multiple motes. Application protocol software was developed to facilitate the communication link between the monitor terminal and multiple motes. Based on the standard specifications of the mote, the SNT strategy, and the application protocol software design, a single mote can support up to 5 electrocardiogram signals with a sampling rate of 200 Hz. This capability facilitates affordable wireless monitoring of multiple physiologic signals from many subjects; its application is especially attractive for monitoring subjects in nursing homes, battlefields, and disaster scenarios.**

I. INTRODUCTION

Growth in the elderly population of the United States continues to place increasing demands on heath care services. Telemedicine is growing in popularity, both among patients and at health insurance companies. Patients appreciate remaining independent within their communities. Medical insurers are supportive, as it reduces the incidence of costly admittance to hospitals. In-home health monitoring is rapidly emerging as a cost-effective mode of health care delivery for an elderly baby boomer population. Typically, in-home monitoring systems collect a variety of vital signs such as heart rate, blood pressure, oxygen saturation, body weight and temperature. These raw data are usually sent via phone lines to a central monitoring unit where a health professional reviews the information and responds appropriately. Currently, there is no cost-effective wireless in-home monitoring system, and thus, most monitoring companies rely on phone lines to transmit data, thus, the goal of constant monitoring is not completely accomplished. Furthermore, monitoring is mostly based on parameters other than the electrocardiogram (ECG) signal, since it requires a much greater sampling rate than parameters such as the respiration, blood pressure, and pulse oximeter signal, to name a few.

At present, a fully integrated wireless system that incorporates many essential physiological variables (e.g., ECG, respiration, blood pressure and pulse oximetry) does not exist. For example, most emergency medical centers as well as nursing homes still rely on individual devices that are all attached to patients via direct wires to collect data. A handful of emergency medical centers do employ wireless ECG monitors, but these are rife with technical problems such as having too many artifacts in the collected data (the signal-to-noise ratio is low), a limited range of transmission of data, and medical decision alerts that are prone to false alarms. Even at these hospitals, fully integrated wireless systems do not exist, due to both the high cost of deployment and immature technology.

Recent advances in wireless technologies have made some inroads in the aforementioned problems associated with a fully integrated wireless system becoming a reality. For example, Becker *et al*. demonstrated wireless transmission of a few vital physiological parameters using a Bluetooth protocol for a Personal Digital Assistant (PDA) device [1]. In other works, a cell phone has been used to transmit biomedical signals [2-4]. More recently, Rasid and Woodward have developed a Bluetooth telemedicine processor for a multichannel biomedical signal transmission via mobile cellular networks[4]. Specifically, their system utilizes the newly-developed cellular protocol known as general packet radio service (GPRS), which has much higher data transmission rates than the global system (GS protocol) for mobile communications. In another study, Hung et al. utilized a wireless application protocol for telemetry application of biomedical signals [3]. However, because this system uses an analog wireless transmission module, the data are more sensitive to noise contamination. The common feature among all of the aforementioned systems is that they are all limited to data collection from a single or at most a few subjects.

To this end, a wireless system that is capable of transmitting simultaneous multiple parameters from many subjects was developed. This system is based on a low cost commercially-available wireless transmission mote known as *Tmote Sky*. This system features ultra-low power consumption, relatively long range of radio transmission (50m indoor and 125m outdoor), and great mobility due to its small size. Another salient feature of this system is that a single mote receiver supports data collection from multiple patients with multiple physiologic parameters, making it suitable for scenarios as diverse as battlefields, emergency rooms, and nursing homes.

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II. System Design

A. System Description

The system is constructed based on the Personal Area Network (PAN) protocol as specified by the IEEE 802.15.4 standard [5]. The system consists of three parts: transmitter and receiver, which are both comprised of motes, and a display terminal, as shown in Fig. 1. A transmitter mote includes a wireless transmission circuit (*Tmote Sky*) and other analog or digital physiologic parameter acquisition modules such as the ECG or pulse oxymeter sensors. A receiver mote is also based on the *Tmote Sky* wireless circuit, but it is programmed to receive data from many individual transmitter motes. Furthermore, a receiver mote's function is to transfer the data to the display terminal as well as to receive commands from the display terminal and pass them on to the appropriate motes. The display terminal can be a personal computer, PDA, or a packaged mote with an incorporated digital signal processor and liquid crystal display.

Tmote Sky is a wireless transmitter/receiver circuit originally developed by UC Berkeley. Its main component is the wireless dual-purpose transmitter and receiver CC2420, manufactured by the Chipcon company. The CC2420 integrated circuit is IEEE 802.15.4 compliant with a radio frequency (2.4 GHz) transceiver designed for low-power and low-voltage wireless applications [6]. Some of the unique features of the CC2420 are its low current consumption and programmable output power. The range of radio transmission based of the CC2420 is up to 50m indoors and 125m for outdoors. The CC2420 is controlled by a low-power consumption microcontroller, the MSP430 circuit, which was developed by Texas Instruments. Another salient feature of the MSP430 is the integrated 8 channel, 12-bit analog-digital-converters (ADC) [7]. Furthermore, the MSP430 can be programmed to sample the analog signals at varying sampling rates and has the capacity to store a small amount of data. These temporary stored data can be sent to a receiver mote when the MSP430 receives a command to transmit the data. The time delay between transmissions of data is approximately less than approximately 125 milliseconds for a single mote, but this delay becomes variable when many motes are simultaneously active. Finally, the MSP430 can be programmed to transfer data to CC2420 or USB port using two universal synchronous/asynchronous receiver/transmitters (USART): USART0 and USART1. In the *Tmote Sky*, USART1 is used to control the USB port and USART0 is used to control the CC2420 for wireless transmission. Wireless transmission is only available when the CC2420 is active. In our system, the CC2420 was programmed to periodically turn on and off according to the commands sent by the receiver mote. This allows USART0 to be available most of the time to obtain data from the data acquisition modules that have digital output.

The display terminal is responsible for providing real-time display of raw data as well as processed data. The mote has a reasonably fast microprocessor for real-time implementation of the fast Fourier transform routine.

Communication between the transmitter and receiver mote was based on the star network topology (SNT), as shown in Fig. 1. Simply, the SNT involves data transmission from individual motes to the receiver mote only when the consent command is given by the receiver mote. Specifically, the receiver mote queues each available mote sequentially at a given time interval. During each queue, the receiver mote sends a command to a particular transmitter mote to send data. The transmitter mote needs to send the requested data before the Guaranteed Time Slot (GTS) expires. When the transmission of data is completed, the mote becomes inactive and yields the radio channel to other available motes for subsequent data transfer. This data transfer scheme precludes transmitter motes from sending data at the same time. Therefore, data loss is minimal with this SNT scheme.

B. Software Development

The software used for communication between the transmitter and receiver motes was based on the NesC language, running on the tiny operating system (TinyOS). TinyOS is an open-source operating system designed for wireless embedded sensor networks that have very limited resources [8]. It features a component-based architecture and event-driven execution model. NesC is an extension of the C language, designed to embody the structuring concepts and execution model of TinyOS [9]. Specific details concerning communication protocols using TinyOS are described in proceeding paragraphs.

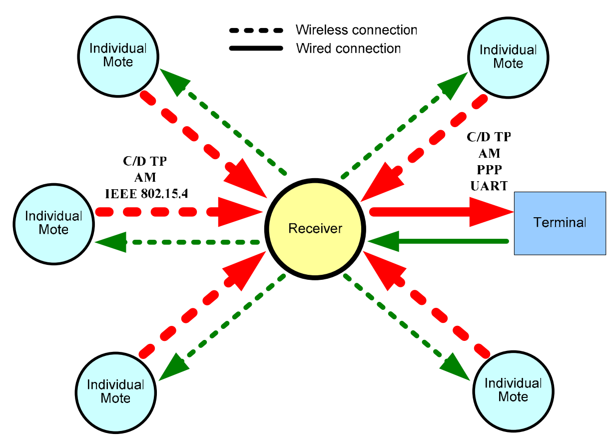


Fig. 1. System architecture of the Star Network Topology

III. Communication Protocols

A. IEEE 802.15.4 Standard

Tmote Sky is compliant with the IEEE 802.15.4 wireless standard. This standard encompasses the Medium Access Control (MAC) and Physical Layer (PHY) Specifications for the Low-Rate Wireless Personal Area Networks (LR-WPANs). The CC2420 of the *Tmote Sky* fully supports the PHY requirement but has only limited support for the MAC layer. Consequently, the application software we have developed implements the MAC layer.

B. Universal Asynchronous Receive/Transmit (UART)

In the current version of our system, the display terminal (personal computer) and the receiver mote are connected via a USB port. The USB driver maps the USB port to a virtual serial communication port (COM port) so that data can be exchanged between a computer and the receiver mote via the standard UART link. To establish correct UART communications, the following three parameters need to be specified: the baud rate, byte size and stop bit. We configured the baud rate to be 262,144 bps, which is the highest value supported by *Tmote Sky*. The byte size and stop bit were configured to be 8 bits/byte and 1 bit without parity check, respectively.

C. Command/Data Transmission Protocol (C/D TP)

The C/D TP was developed specifically for our system. While it is designed for the application-layer protocol, it is also used in the MAC layer. The C/D TP consists of the REQUEST-RESPONSE in transmitting commands or physical data. A REQUEST C/D TP message requires a mandatory RESPONSE from the targeted recipient to ensure a successful communication link between the transmitter and receiver motes. The structure of a typical C/D TP message with an arbitrary selected data field is provided in Fig. 2 (a). The last two bytes in a C/D TP message represent the Channel Selection Word (CSW). As shown in Table 1, specific bits are assigned to different channels, which can represent different physiological parameters to be collected. In the current system, C/D TP supports up to 15 channels. However, given the presence of a "reserved bit" (bit 15) in CSW, it can be easily extended to more than 30 channels, if necessary. C/D TP also provides the capability to obtain variable sampling rates for different physiologic parameters.

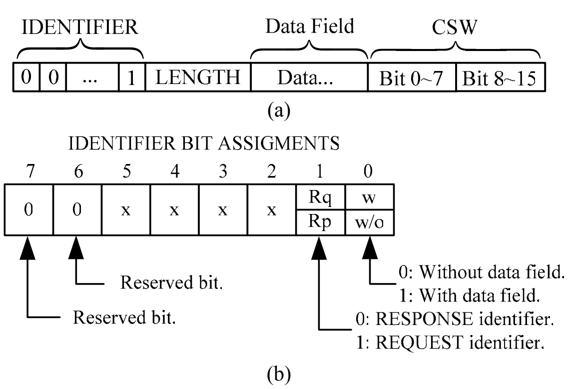


Fig. 2. Structure of a C/D TP message with data field. (a) Frame structure of C/D TP message; (b) Bit assignments of the IDENTIFIER filed.

Table 1 CSW (Channel Selection Word) Bit Map

Bit	Channel	Bit	Channel
0	Not mapped	8	Not mapped
1	ECG	9	Not mapped
2	SpO2	10	Not mapped
3	Blood pressure	11	Not mapped
4	Respiratory	12	Not mapped
5	Glucose	13	Not mapped
6	Temperature	14	Not mapped
7	Not mapped	15	Reserved

The identifier shown in Fig. 2(a) is further detailed in Fig. 2(b). As shown in Fig. 2(b), bit0 indicates if the message contains a data field; bit1 distinguishes the REQUEST message from the RESPONSE message; bit2 to bit5 define the operation of the message; and bit6 and bit7 are not used but are available for future use, if necessary. Based on the above bit assignments, the identifier space is divided into the following four subspaces:

REQUEST with data field: $4\times n + 3$

REQUEST without data field: $4\times n + 2$

RESPONSE with data field: $4\times n + 1$

RESPONSE without data field: $4\times n$

($n = 0, 1, 2, \ldots, 15$)

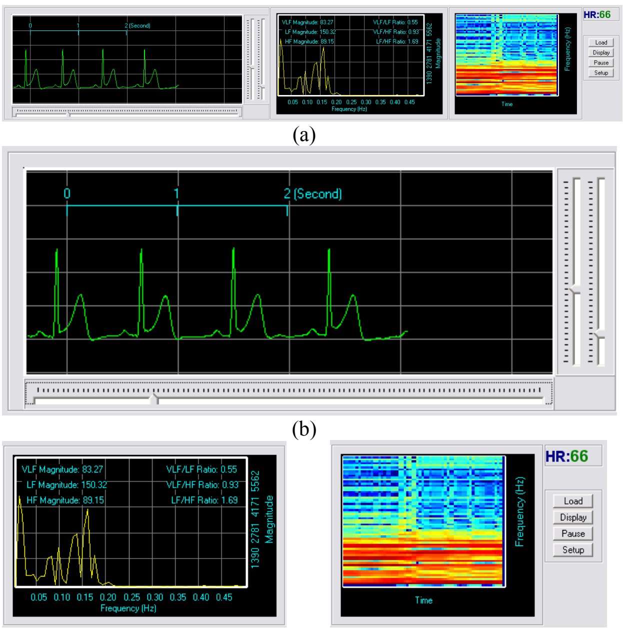
We have developed C/D TP to simplify the establishment of the PAN, to organize the MAC, and to obtain efficient data transmission processes. In our system, each individual mote is pre-programmed with pre-determined specific transmission times and loads. As a consequence, data communication between many transmission motes and the receiver mote are highly organized, devoid of congestion, and utilize the full radio bandwidth. For the transmitter mote, the GTS was set to 25 milliseconds. However, this value is flexible and can be changed by sending a C/D TP REQUEST message from the display terminal to the receiver mote.

Fig. 3. A single transmission mote and a single receiver mote for wireless ECG data collection.

IV. Results

A sample of our system, consisting of a single transmission mote and a single receiver mote for wireless ECG data collection at a sampling rate of 200 Hz, is shown in Fig. 3. Currently, one receiver mote is able to receive wireless data from 5 transmitter motes at a sampling rate of 200 Hz. Although the accuracy of the system based on 5 transmitter motes has not been thoroughly tested, visual examination reveals that each mote is successful in transmitting beat-to-beat ECG signals without any loss of data. Furthermore, due to sufficiently high sampling rate, the ECG data obtained from each mote contain accurate morphology of the ECG waveforms.

Fig. 4 shows the main interface of the display software we have developed. Some of the features include instantaneous calculation of the power spectral density, time-frequency analysis, instantaneous heart rate, and their time- and frequency-domain statistics.



(a)

(b)

(c) (d)

Fig. 4. Terminal display software: (a) display window of a single mote; (b) ECG data display window of a single mote; (c) instantaneous power spectrum of heart rate and the resultant statistics shown at the top of the figure; (d) online time-frequency spectra analysis together with instantaneous heart rate display. The time-frequency spectrum is updated every second.

V. Conclusion

We have successfully designed a wireless health monitoring system that is capable of collecting data simultaneously from 5 different subjects at a sampling rate of 200 Hz. With further optimization schemes, the system will be able to collect data from 10 different subjects at the same time at a sampling rate of 200 Hz. Furthermore, the system can be expanded to include obtaining data from other physiologic parameters. These additional capabilities are currently under progress in our laboratory.

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