Wireless Body Area Network (WBAN) for Medical Applications

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1. Introduction to WBAN

With the rapid advancements of wireless communication and semiconductor technologies the area of sensor network has grown significantly supporting a range of applications including medical and healthcare systems. A Wireless Body Area Network (WBAN) is a special purpose sensor network designed to operate autonomously to connect various medical sensors and appliances, located inside and outside of a human body. Introduction of a WBAN for medical monitoring and other applications will offer flexibilities and cost saving options to both health care professionals and patients. A WBAN system can offer two significant advantages compared to current electronic patient monitoring systems. The first advantage is the mobility of patients due to use of portable monitoring devices. Second advantage is the location independent monitoring facility. A WBAN node being an autonomous device can search and find a suitable communication network to transmit data to a remote database server for storage. It is also possible that a WBAN will connect it self to the internet to transmit data in a non-invasive manner.

The health care sector is increasingly looking for advanced ICT (Information & Communication Technology) systems to efficiently administer the healthcare delivery for a range of services. Advanced ICT systems will be able to deliver healthcare not only to patients in hospitals and medical centres; but also in their homes and workplaces thus offering cost savings, and improving the quality of life of patients. A WBAN will consist of a number of tiny sensor nodes and a Gateway node used to connect to the external database server. The Gateway node could connect the sensor node to a range of telecommunication networks. These communication networks could be either a standard telephone network, mobile phone network, a dedicated medical centre/hospital network or using public WLAN (Wireless Local Area Network) hotspots also known as WiFi. A WBAN can also take advantage of widely deployed mobile data networks such as the 3G/4G data networks to transmit patient data. A WBAN could allow a user to store its collected data on his/her PDA (Personal Digital Assistant) or iPod or any other portable devices and then transfer those information to a suitable computer. Future applications of WBAN introduce numerous possibilities to improve the health care and sports training facilities. The WBAN concept in

recent years has attracted attention of medical and ICT researchers. ICT systems are already in use in medical areas but their applications are limited. The main drawback of current systems is the location specific nature of the system due to the use of fixed/wired systems. There are many existing medical monitoring systems using specialised equipments which could send data using either standard telephone lines or specially designed network for medical applications. However, these systems are not location independent and in most cases they are clumsy in nature due to use of wired sensors. Use of a WBAN can introduce location independent monitoring systems. WBAN applications can also be extended to sports training areas where athletes or players can be monitored to find their deficiencies or to improve their skills.

This chapter presents the WBAN hardware and network design techniques. Section 2.0 presents medical applications scenarios by introducing the roles of different wireless networking standards. Section 3.0 presents hardware design techniques of WBAN nodes and networks. This section also discusses basic architecture of a WBAN node. Design of other nodes such as GATEWAY and CCU (Central Control Unit) is also presented in this section. Some basic performance result is also discussed in this section. Section 4 discusses WBAN network design technique. This section discusses several fundamental design techniques and introduces different MAC (Medium Access Control) protocols suitable for WBAN applications. Section 4 also discusses the link budget design issues. Section 5 presents a multi-patient monitoring system based on the WBAN architecture. This section also discusses various design features of a multi-patient monitoring system. Section 6 presents simulation results of the multi-patient WBAN system. Results presented in this section explain various operational features of the WBAN. Section 7 presents some future WBAN development issues. Summary of the chapter is presented in section 8.
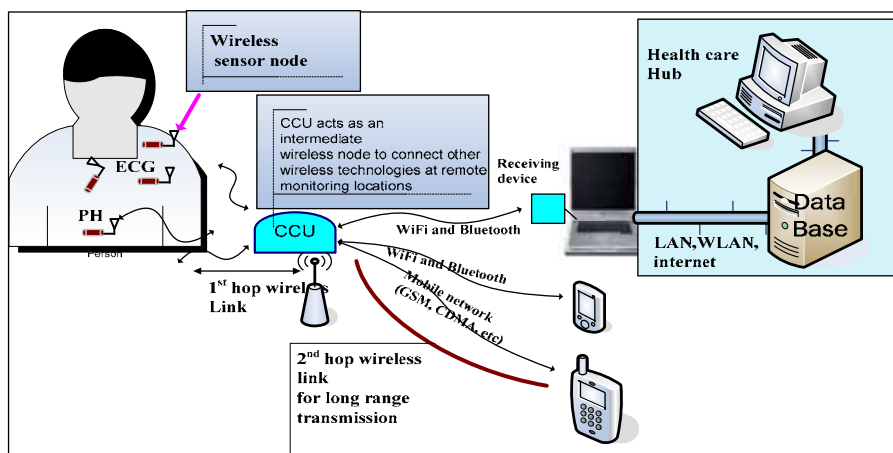

Fig. 1. A wireless body area network system. Collecting and monitoring data from individual wireless sensor nodes from a single human body via the gateway CCU.

2. Medical Application Scenarios

The application of Wireless Body Area Networks (WBAN) in medical environments may consist of sensor nodes attached to or implanted into a human body. These sensor nodes have wireless transmission capability and sense biological information from human body to transmit over a short distance to a control device worn on the body or placed at an accessible location. A sensor node electronics should be miniaturized, low-power and detect medical signals such as electrocardiogram (ECG), photoplethysmogram (PPG), electroencephalo-graphy (EEG), pulse rate, blood flow, pressure, and temperature. The collected data from the control devices are then transferred to remote destinations in a wireless body area network for diagnostic and therapeutic purposes incorporating another wireless network for a long range transmission (See Figure 1). There are a vast majority of monitoring systems developed and already being used in medical systems. Currently available systems are based on wired connection and their electronics are bulky, particularly when many sensors are wired to a wireless device. Any wire connection in a monitoring system becomes cumbersome and is not suitable to be worn by patients which could restrict their mobility. Thus WBAN requires individual wireless sensor node without any wire connections. Each individual sensor nodes will directly transfer the sensed physiological data to a control unit (CCU) and then to remote stations for diagnostic and health care purposes.

So far there is no available standard for a wireless body area network specifically targeting healthcare applications. Most popular wireless technologies used for medical monitoring are ZigBee/IEEE892.15.4, WLAN, GSM (Global System for Mobile), Bluetooth (802.15.1) (Otto et.al., 2006, Soomro et.al., 2007, Anliker et.al., 2004, Proulx et.al., 2006). All these technologies are commercially available and optimized for short range communications except the GSM standard. These wireless standards are targeting general purpose sensor network applications and thus are not optimum solutions for medical environments. If these devices are used for wireless body area network applications, they should deal with the interference and coexistence issues (Howitt et.al., 2003, Sikora et.al., 2005). In addition to unlicensed ISM (Instrumentation Scientific and Medical) bands, there are other medical bands such as MICS (Medical Implant Communication Service) and WMTS (Wireless Medical Telemetry Service) that are specifically regulated for medical monitoring by communication commissions around the world (Yuce et.al., 2008). Recently developed short-range low data rate ultra-wideband (UWB) technology is another attractive technology that could be used for body area network applications due to its low transmitter power (Ho et.al., 2008).

In order to monitor medical implant devices and status of inner organs, a frequency around 400 MHz have been used as a popular transmission band in recent systems (Bradley 2007). The MICS is an ultra-low power, unlicensed, mobile radio service for transmitting data to support diagnostic or therapeutic functions associated with implanted medical devices. This frequency range can be used to enable the wireless communication of medical implant devices to deliver high level of comfort, mobility and better patient care (FCC, 2003). To treat a large number of patients wearing implanted systems in the same environment (e.g. hospital) require a reliable wireless networking in order to monitor and differentiate each individual implanted device and a patient. Thus implanted wireless nodes in a patient's body should form a wireless body area network so that one or more implanted devices

inserted in the bodies of a number of patients in a hospital environment can be controlled with minimum complexity. The system presented in (Bradley 2007) uses a RF (Radio Frequency) transceiver that is specifically designed to be used for in-body communication systems. The device uses the new medical band MICS together with the 433 MHz ISM band to form a medical sensor network of implant devices. More of such miniaturized low power RF transceivers should be designed in future in order to use in a medical sensor network as the MICS band is gaining more popularity. The successful implementation of a complete WBAN system will provide: wearable, wireless (no wire connections), easy to remove and attach sensor nodes, leading to increased mobility of patients and flexibility. A WBAN should operate and co-exists with other network devices operating in similar frequency bands. It is thus very important to ensure an interference-free, reliable wireless link from sensors that incorporates and interacts with the existing wireless technologies to form a heterogeneous networking environment.

One of the main applications of a WBAN is in medical care environment where conditions of a large number of patients could be continuously monitored. Figure 2 shows a WBAN based monitoring scenario applicable to a hospital environment. The figure represents several rooms at a single hospital floor. As can be seen, for a large scale deployment of WBANs, several controlled units (CCUs) are required to organize the collection of medical data from patients' body. Presence of several CCU is also useful for free movement of patients in hospitals. In fact monitoring many physiological signals from a large number of patients presents some challenges in both software and hardware designs. Some of those challenges are as follows: reliable communication by eliminating collisions of multi-patients' signals, and interference from other external wireless devices, low-cost, low power consumption, and providing flexibility to the patients so that patients can be relocated anytime (Yuce & Ho, 2008). Most of the existing schemes in the literature deal with a single patient monitoring or designed for monitoring one or few physiological signals.

The system in figure 2 includes individual wireless sensor nodes that can transfer a person's physiological data such as heart rate, blood pressure, ECG, EEG EMG via a wireless link, without the need of any wired connection. Each sensor will have wireless capability and its design will be optimized in terms of the physical characteristics of the physiological signal. The sensor nodes use a dedicated wireless link to eliminate the strong interference from other communication devices in a healthcare area; as reliable communication and accurate monitoring are very crucial for patients' safety. Hardware and software designs are being developed for a high performance and fault tolerant wireless communication and monitoring system.

Currently we are developing a complete wireless body area network that is based on different frequencies in order to eliminate interference issues as well as to apply different environments (Yuce & Ho, 2008). We use MICS, WMTS and 433 ISM bands to transmit signals from the sensors on the body. For the applications that require monitoring of many continuous signals such as ECG/EEG/EMG, we incorporate UWB (Ultra Wide Band) technology since a high data rate wireless link will be required (Ho et.al., 2008). The selection of wireless scheme for sensor nodes will depend on very much on the environment of the sensors nodes to be used and its signal characteristic. In addition, we also interfaced our devices with IEEE 802.15.4 (Zigbee) and WiFi links to cover a large area of a body area

network, as depicted in Figure 2. As these short ranges wireless standards are already available and in use for different applications in medical centers, incorporating a WBAN implementation with these standards will be an added advantage. As an example when installed in CCUs, these existing wireless standards can be used in a WBAN gateway to provide a networking between the CCUs and the remote stations.
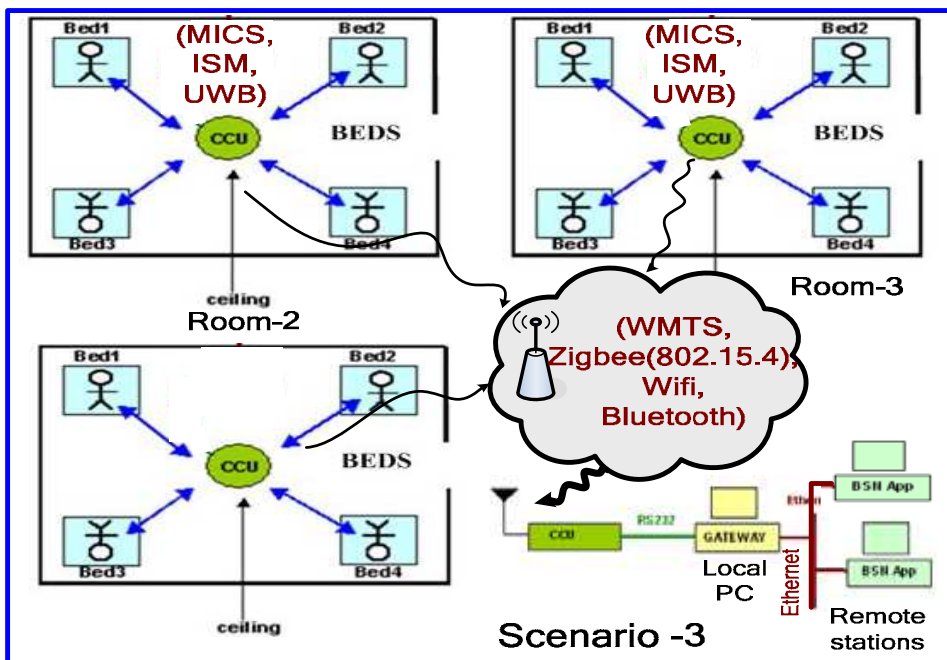

Fig. 2. A multi-patient monitoring scenario in a medical center, representing one room and one floor respectively.

In next section, we will describe a WBAN based medical monitoring prototyping system as a part of our wireless body area network project. The body area network prototyping system uses a multi-hopping structure to implement the scenario given in Figure 2.

3. Implementation of WBAN and Hardware Issues

A WBAN system that has been designed for healthcare applications is presented in this section. Hardware electronics and software programs are developed for the scenario presented in Fig. 2. In the implementation, one of the medical or ISM bands-MICS (Medical Implant Communication Service) or WMTS (Wireless Medical Telemetry Systems) or 433 ISM bands will be used between one CCU and its sensor nodes (the first wireless link). CCUs will interface with one of existing wireless standards such as Bluetooth, ZigBee, and WiFi for a remote monitoring system using a mobile network or the internet. Two pieces of software have been created in this project. The software residing at the local PC is named as

the GATEWAY. The job of GATEWAY is to gather data from the CCU through RS232/USB cable and forwards it to the remote PC using TCP/IP connections over an Ethernet network. The software residing at the Remote PC is named as BSN Application. The BSN Application will collate data from the local PC, convert and stores them onto the remote PC to be analyzed later by health professionals. The receiver station (i.e. the remote PC) is capable of displaying all the received data on a User Display Graphic (GUI) and is also capable of storing all the data in the database system of a medical center.

A hardware setup to realize the medical scenario presented in section 2 is depicted in Figure 3. Patients' physiological parameters are sent to intermediate CCUs and then to the base station. We are using a multi-hopping network technique that consists of three networking levels in the system. A network between sensors CCU, another network level is between CCUs-base station, and the last communication link is between base stations in the medical centers. The first wireless link is usually less than 10 meters. The second link targets a distance of more than 100 m. Distribution of data to remote destinations is sent via the internet. A CCU can be used for one individual in the medical center or can be used privately in a patient home. If more than one patient shares a CCU box, the CCU can either be connected to a local PC in the room or it can transmit data to another remote CCU box that is attached to a local PC via another wireless link using the WMTS (600 MHz) link as depicted in Figure 2.

The WBAN in Figure 3 is a multi-hopping wireless medical network that uses MICS band to obtain data from sensors placed on or in the body. The WMTS band is used in the intermediate node for a remote wireless communication link. The data is transferred to remote stations through the local area network or the internet already available in medical centers. Unlike the other medical sensor networks (usually operate at 2.4 GHz ISM band), we mainly use medical standards occupying the frequency bands that are usually assigned to medical applications. Both frequency bands are internationally available and are permitted for a remote monitoring of multiple patients simultaneously. The MICS band has a low emission power of 25 µW, comparable to the UWB. The lower power consumption feature is suitable for medical sensor nodes. Hardware and software designs are realized in the system to provide a multi-patient monitoring system with data transfer ability over a network or the internet to a remote computer. A media access layer (MAC) has been implemented on the developed hardware to support multi-patient monitoring facility.
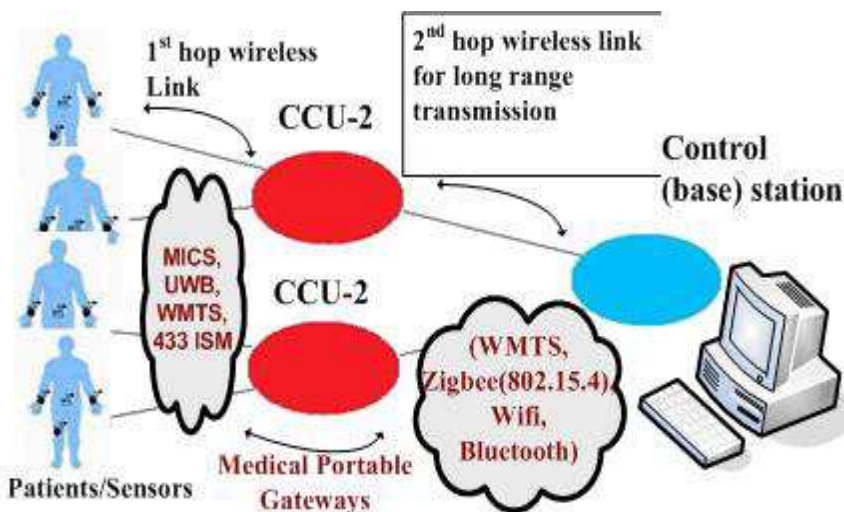
Fig. 3. Multi-hopping WBAN based multi-patient monitoring.

3.1 Sensor nodes Design

Sensor nodes are designed to collect raw signals from a human body. A sensor node undertakes three tasks: detecting signal via a front-end, digitizing/coding/controlling for a multi access communication and finally wireless transmission via a radio transceiver technology, as shown in Figure 4. In addition data acquisition and processing, the microcontroller maintains a power management scheme to control the distribution of the energy from battery in an optimized manner. It should be programmed to turn battery connections OFF for the blocks that are not functioning (i.e. during sleep mode). The signal from a human body is usually weak and coupled with noise. First, the signal should go through an amplification process to increase the signal strength. It then passes through a filtering stage to remove unwanted signals and noise. After which, it will go through an Analog to Digital conversion (ADC) stage to be converted into digital for digital processing. The digitized signal is then processed and stored in the microprocessor (i.e. microcontroller). The microcontroller will then pack those data and transmit over the air via a transceiver. Sensor nodes are designed to be small and power efficient so that their battery last for a long time. Figure 5 shows the hardware implementation of a sensor node containing all the blocks shown in Fig.4.
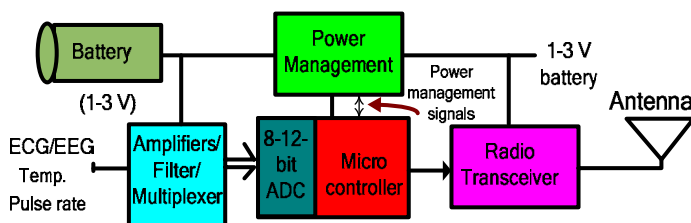

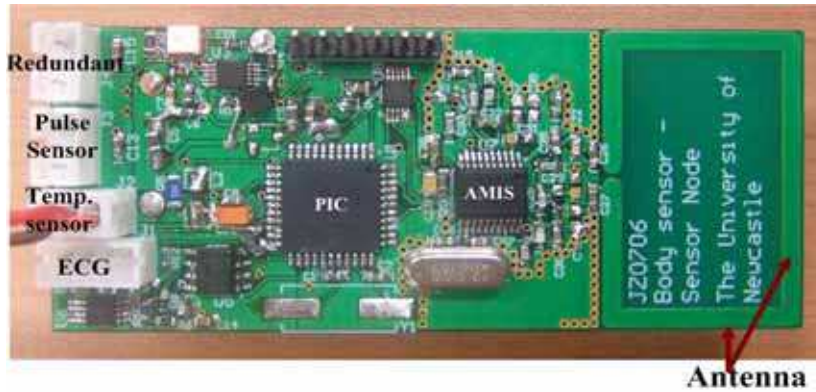Fig 4. Block diagram of a wireless sensor node in a WBAN.

Fig. 5. A 4-channel sensor node.

A sensor node electronics is designed to detect and transmit the physiological signals listed in Table 1. Characteristics of these physiological signals are obtained from the public domain available on the internet. Most physiological signals are low frequency in nature and occupy a small information bandwidth. At such low frequencies and low amplitudes, some problems inherent to circuits need additional attention. For reliable information transfer it is necessary that the interface electronics in the sensor nodes detect physiological signals in the presence of noise and increase the signal-to-noise ratio (SNR) of the detected signal for processing by the subsequent blocks of the sensor nodes. Considering the signal bandwidths given in Table 2, a sampling rate of around 200-400 Hz will be necessary for the analog-to-digital converter (ADC) in the microcontroller (the sampling rate should be at least twice the highest frequency of the signal that is digitized). The tradeoff between the reduction in sampling rate and the total power consumption of the ADC is determined by the choice of the specific physiological parameter used in the sensor node.

Parameter	Range of Parameter	Signal Frequency
ECG signal	0.5-4mV	0.01 – 250 Hz
Respiratory rate	2-50breaths/min	0.1 –10 Hz
Blood Pressure (BP)	10-400mm Hg	0-50 Hz
EEG	3μV-300μV	0.5-60 Hz
Body Temperature	32-40 ^{0}C	0 - 0.1Hz
EMG(Electromyogram)	10μV-15mV	10-5000 Hz
GSR(Galvanic Skin Reflex)	30μV-3mV	0.03-20 Hz

Table 1. Physiological parameter range and signal frequencies.

3.2 CCU and Gateway Design

The primary function of the CCU is to collect data from sensor nodes via the wireless MICS band link and forward these data to a local as well as to a remote PC for further analysis. As explained in the scenario given in Fig. 1, two CCU devices are needed in order to provide a complete WBAN transmission coverage in medical centers. One CCU is designed to be connected to a computer (Fig. 6) via the USB port while the other CCU is used to function as an intermediate device (Fig. 7) that presents a second wireless link for a longer range wireless sensor network. The latter case is more suitable for large medical centers and functions as an intermediate device. Although both CCUs can be used for multiple patients monitoring, the first CCU type (CCU-1) can also be useful for private usage at home or in a room of a hospital for a single patient monitoring.

The sensor nodes/CCU hardware requires a microcontroller and a wireless transceiver to coordinate all activities. The CCU-1/sensor nodes consist of the wireless link (AMI52100 IC) from AMI semiconductor used for the MICS band generation (we also used CC1000 in some sensor nodes to generate 433 MHz ISM and WMTS bands for sensors-CCU wireless connection) and the microcontroller PIC16F87. In addition to these chips, we use another transceiver the CC1010 chip from Chipcon (this chip contains CC1000 and a microcontroller built in) on the intermediate CCU (CCU-2) board to develop a wireless transmission and networking with the WMTS band. The CC1010 and CC1000 transceiver chips have the capability to transmit anywhere within 300 and 1000MHz (It was tuned to WMTS band in our prototype system). The wireless chips AMI52100 IC (Integrated Circuit) and CC1000 family are selected in the project for following reasons: overall cost saving, low-power consumption, size, and the suitability of operating at the MICS, WMTS, and 433 MHZ ISM bands. The AMIS IC has a data rate capability of 19 kbps while CC1010 provides 76 kbps. The CCU-2 device in a WBAN can be comprised of the standards such Zigbee and the 802.11 Wi-Fi standards to accommodate and interface with different wireless platforms and to connect to internet for remote monitoring.
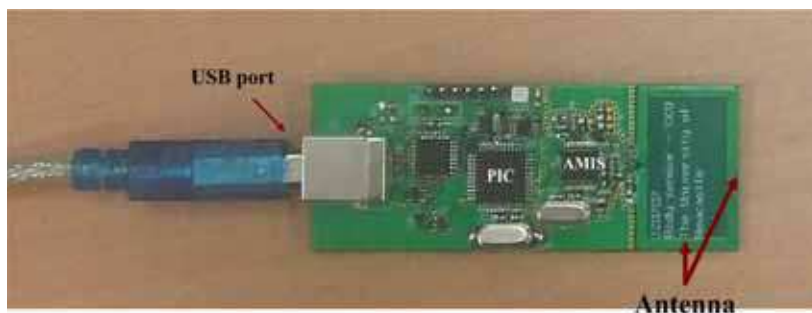

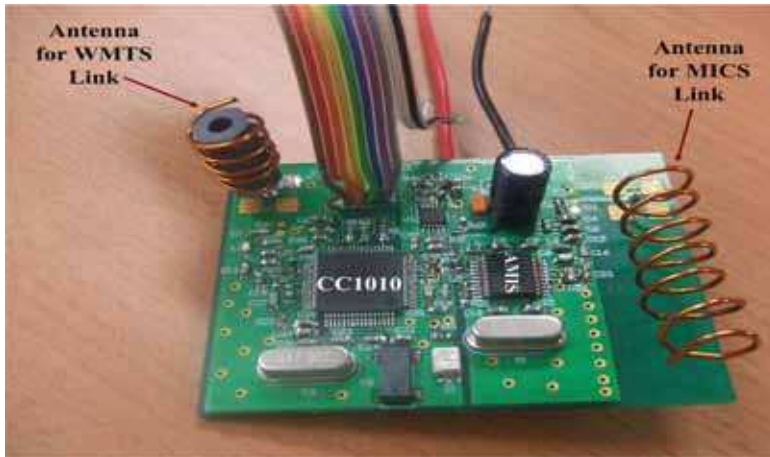Fig. 6. CCU-1: a central control unit (CCU) used individually.

Fig. 7. CCU-2: Intermediate Central Control Unit (CCU). This device is shared by more than one patient and portable. It contains a dual wireless transceiver to support two directional wireless links.

3.3 Medium Access Control Protocol (MAC) and Monitoring

A number of MAC protocols have been proposed for medical sensor networks. Main requirements of a MAC protocol of a medical wireless sensor network are reliability, flexible transmission mechanism and high channel efficiency. Mainly three classes of MAC protocols have been considered for medical applications. They are TDMA (Time Division Multiple Access), polling protocol, and the contention based protocol also known as the random access protocol (Yuce et.al., 2008).

The contention based protocols such as ALOHA and CSMA have been proposed and used for many low power sensor network applications. A combination of a polling protocol and CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) MAC protocol to transmit the sensor data from multiple sensors to the CCU could be a good mechanism for both power saving as well as for reliable communication of critical medical data. The CSMA/CA MAC protocol is used by the IEEE802.11 WLAN (Wireless Local Area Network) based WiFi and the IEEE802.15.4 based WPAN (Wireless Personal Area Network) standards. The CSMA/CA protocol is a contention based protocol which could offer lower delay and reliable transmission of packets in small size networks like a wireless medical network.

The signals in Table 1 are grouped by the CCU into critical data and non-critical data during the transmission. The wireless protocol will be designed such that the priority will be given to critical data. A critical data packet (such as ECG, it could change according to status of a patient) in a CSMA/CA based sensor network can be immediately transmitted without waiting for its turn. Thus such a mechanism will allow the sensor nodes collecting crucial physiological data (i.e. ECG) to CCU without any collision, loss and delay. For non critical data like temperature, the polling network will be used for the node so that the information

will be sent whenever it is needed. A polling structure can be very power efficient and is utilized for the sensor nodes in the WBAN where the data collection is not necessary all the time. By using a polling structure, we can keep the power consumption of the sensor nodes significantly low so that a battery can last several years.

The CCU will collect information and control its flow using the developed communication protocols. The mode of information transmission of a sensor node will depend on the application and the signal type. The sensor nodes in polling scheme will sleep most of the time and wake up for a duration required for a reliable data transfer. Sleep and wake up patterns can be controlled by the acquired signal and by the application. Wake up pattern could be periodic or it can be demand driven. Only the ASIC processor in the microcontroller, which operates with a very low clock rate, always stays awake in the system and will trigger the awakening process. As a result of this process, significant power saving is achieved hence, the battery life is extended. Sensor nodes that are configured in a polling scheme will enter CSMA/CA communication scheme during data transmission so that it will not affect the transmission of the critical data. One of the main objectives is to conserve power within each node and to keep active power to a minimum level so that smaller batteries can be utilized in sensor nodes. Since the time spent in sleep mode is very long compared to the active period, keeping the power consumption as low as possible will greatly increase the battery life of each node.

In order to monitor data, several computer programs have been developed in this project. The necessary software programs have been identified in Figure 2. The software called GATEWAY is developed at the monitoring PC to control the communication with the CCU to get readings from sensors and then forward them through the network/internet to an application on a remote PC. While performing this task, the GATEWAY also verifies the data integrity and schedules retransmission if required. Another software was developed at the remote PC (called BSN) that collects readings from GATEWAY via the network/internet. These readings are stored in the remote PC for analysis. The BSN application can collect and store readings automatically so that no manual intervention is required. It can undertake the administration of patients' particulars such as assigning new sensor ID to patients, segregating sensor readings from different patients and storing them into the data base. The GUI also allows the medical personnel to enter the patient's information.

A graphical user interface (GUI) at the local PC as well as at remote PCs is also designed to display medical data. Both the data received from the CCU and the data sent to the BSN can also be displayed by the GUI in a text or graphical formats. The physiological signals of patients can be accessed by medical staff anywhere in the medical center as long as their computers are connected to the local area network in the building. An example of live monitoring from two patients scenario is shown in Figure 8. It displays temperature and pulse rate information of two patients at the same time. The graph allows up to 20 readings to be displayed. Every sensor device has a unique Sensor ID and must be registered under a patient name before they are used (Yuce et.al., 2008). In the event that an unregistered sensor node is used, all its readings received will be discarded by the BSN application.

The monitoring of the continuous signal like ECG, EMG and EEG is more complicated compared to parameters such as pulse rate and temperature signals. Unlike temperature

and pulse rate, the information sent to the CCU requires a continual and undisturbed sampling period as high as 400 samples per second, each sample of size 10 bits will require a connection speed of 4000 bps. To allow for MAC overhead and packet retransmission, the baud rate (i.e. data rate) for the RF link should be at least twice this rate. The use of Manchester encoding is advisable to help maintain data integrity and a stable connection, which halves the data rate of the link. As shown in Table 1 amplitude and frequency information of the continuous physiological signals are similar and thus the same analog front end is used to detect these signals with similar signal amplification and filtering. Typically ECG and EEG signal has amplitude of less than 500µV with frequency less than 100 Hz. The front-end of the sensor node (.e. interface electronics) uses an instrumental amplifier (INA321) and an active low pass filter (LTC6081) (TI 2009). When operating in shut down mode it consumes less than 3µA. Figure 9 is an ECG signal obtained from our set up. Each sensor node representing only one patient can only have one ECG. In order to eliminate the DC noise (50 Hz/60 Hz interference) a recursive filter has been implemented at the PC to obtain an accurate ECG signal. Shown in Figure 9, by clicking on 50 Hz filter, the recursive notch filter operates on the received ECG signal.
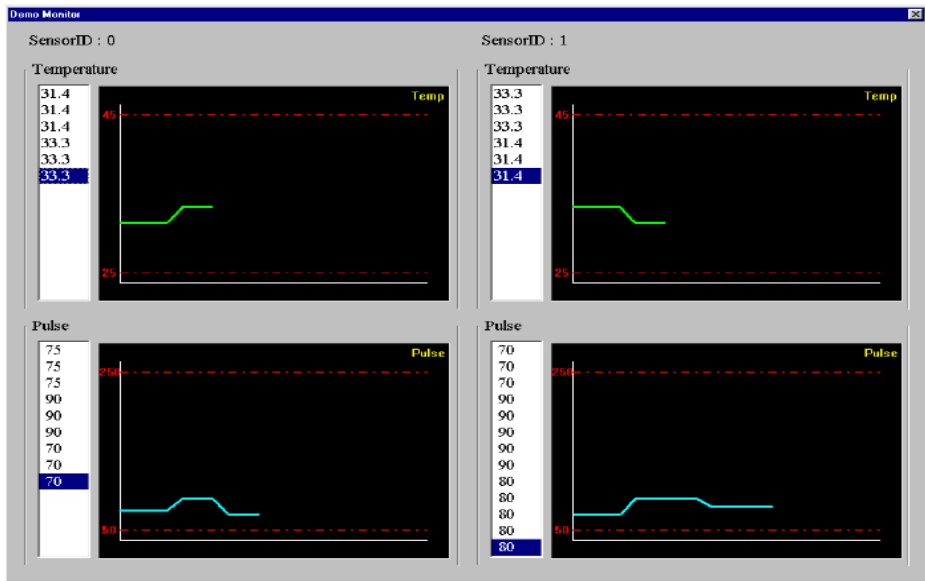

Fig. 8. Live monitoring of multi-patients (physiological data presented in a graphical form at the remote PC). SensorID is used to define each patient.
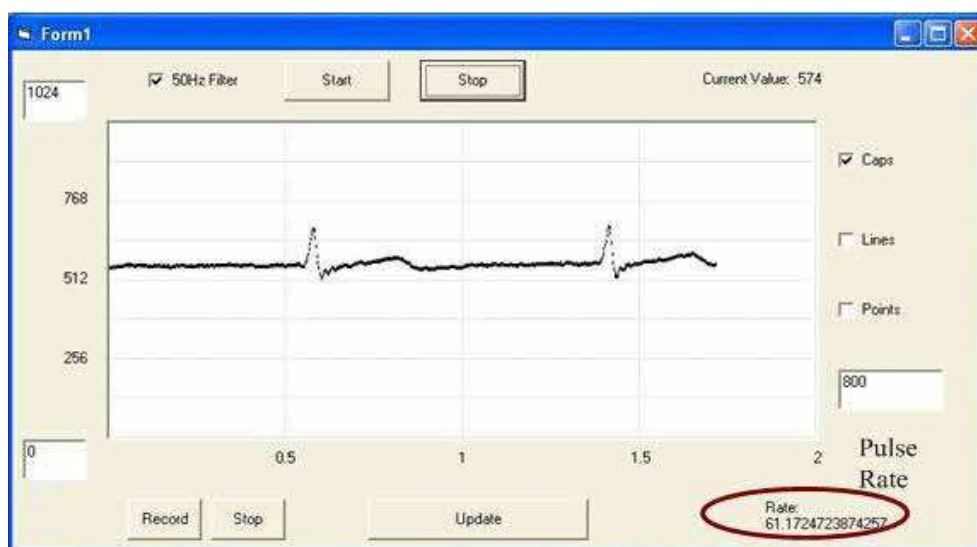
Fig. 9. A clean wireless ECG monitoring showing pulse rate is displayed.

3.4 Ultra Wideband Based WBAN

We design sensor node electronics using the low data rate ultra wideband (UWB) wireless transmission for wireless body area network (UWB-WBAN) (Ho & Yuce, 2008). The UWB is a narrow pulse based transmission system whose spectrum is spread across a wide range of frequencies. Low data rate UWB is suitable for vital signs monitoring system as it transmission power is lower than WLAN, Bluetooth and Zigbee systems, which is less likely to affect human tissue and causes interference to other medical equipments. Furthermore, it is able to transmit at higher data rate which is suitable for real time continuous monitoring of many physiological signals. In this part of the project, we developed the sensor node electronics using the low data rate UWB transmission technique and investigate its characteristics when operating in or around the human body. The ultimate goal is to integrate UWB sensor nodes together with our narrow band medical based sensor nodes to form a wireless body area network application for healthcare systems.

4. WBAN Network Design Techniques

A WBAN which could collect critical and non-critical data from different parts of a patient body needs to be designed considering a number of important issues. In a patient monitoring system data transmission reliability and latency is extremely important. Reliability and latency of a WBAN will depend on the design of physical and MAC (Medium Access Control) layers. Design of these layers determines the power consumption profile of a WBAN which is an important design issue. The MAC layer also plays an important role to determine network efficiency and resource utilization issues which ultimately determine a system and operating costs of a WBAN. At the same time the PHY (Physical) layer also determines reliability of a WBAN. A PHY layer could select appropriate

modulation and coding techniques to combat against transmission channel variability. Performance of a WBAN can be defined in terms of reliability, power efficiency and scalability. Section 6 presented a particular implementation of a MAC protocol for a WBAN. This section presents a more general MAC design approach and design rules.

Reliability:

Reliability of a WBAN is directly related to the packet loss probability and the packet transmission delay. Packet loss probability is influenced by the BER (Bit Error Rate) of a channel and the MAC layer transmission procedures. The PHY layer of a WBAN can reduce the effective bit error rate of a transmission link by using adaptive modulation and coding techniques to suit the transmission channel conditions. Details on the BER values for various modulation techniques can be found in references (Mark et.al., 2003). Use of forward correction error (FEC) technique can reduce the effective bit error rate however, the use of a FEC technique requires transmission of additional redundant bits which could increase the power budget of a WBAN node due to transmission of additional bits. Careful design of modulation and coding techniques is essential for the optimum operation of a WBAN. The MAC layer has also important role for the reliability of a WBAN related to the channel access technique, packet size selection and packet retransmission strategy used in a WBAN. The reliability and power budget of a WBAN also depends on the interference situation of a network. If the interference and noise floor of a network is high, in order to successfully transmit packets, a node needs to transmit at a higher transmitter power level. MAC layer design techniques are further discussed in section 9.

Power Efficiency:

Power management in a WBAN is a very important operational issue. Power usage can be minimized by optimizing the PHY and MAC layer processes. A PHY layer can increase the probability of successful transmissions by selecting appropriate modulation and coding techniques. Higher packet transmission success probability reduces the end-to-end packet delay as well as the power budget of a WBAN node. Power budget of a node could be optimized by increasing successful packet transmission probability. Power optimization scope at the PHY layer is generally limited and fixed. On the other hand a MAC layer can introduce much higher level of power savings by using a range of techniques including packet transmission scheduling and channel access techniques, use of optimal packet structure, and intelligent signaling techniques. Since a WBAN will be operating in a shared communication environment it is necessary to minimize the contentions and interference.

Scalability:

A WBAN needs to be scalable which is essential for a patient monitoring system. For patient monitoring it is quite often necessary to change the number of WBAN nodes to collect various physiological data from a patient. A scalable WBAN will allow health care professionals to easily reconfigure a WBAN by either adding or removing nodes without affecting the operation of the WBAN. Scalability will largely depend on the MAC protocol design.

In an installed WBAN generally PHY layers are fixed hence, the MAC layer can take a major role to maintain QoS (Quality of Service) and reliability under variable transmission and traffic conditions. In this chapter we examine the MAC protocol design issues for a WBAN based patient monitoring system. Before moving into the discussion of network and MAC design issues first we examine the network and MAC protocol design requirements. Some of the main requirements of a WBAN design are listed below.

- A WBAN should be able to support a range of medical applications including acquiring periodic and non-periodic data sources, and transmitting to a service node (figure 1) in a multihop network within a maximum fixed delay without any loss of critical information (Golmie et.al., 2006). At the same time a WBAN should be able to support exchange of non-medical and control information to remotely supervise various appliances when operating in a remote patient monitoring environment.

- A WBAN should be able to operate in a power constrained environment where power sources such as battery could last for a reasonably longer period of time. Power optimization for the implantable nodes is more critical than other nodes. Power savings can be achieved by combining appropriate PHY and MAC layer procedures.

- A WBAN should be self healing, secure and reliable which may include implantable and external nodes.

- A WBAN should support data rates between few tens of kbs to several Mbs to host a range of applications such as images and video clips.

- A WBAN should support QoS management features to offer priority services. Particularly when a critical patient is monitored, the system must guarantee delivery of critical physiological data to a service node. For medical data the main QoS features will be the transmission delay and the packet loss.

- A WBAN should operate and co-exists with other network devices operating in similar frequency bands. Also, a WBAN should be able to operate in a heterogeneous networking environment where different wireless networks can co-exist and may offer similar or different services.

There are a number of classes of MAC protocols exist which are used for different networking applications (Golmie et.al., 2006). MAC protocols are mainly classified into two categories; scheduled and random access protocols. The scheduled access protocols offer deterministic packet delay and packet loss thus offering higher quality of service (QoS). On the other hand the random access protocols are dynamic in nature where transmission resources are allocated to the communication nodes only when a node has any information to transmit. A random access protocol introduces variable delay and sometime packet losses. However, the delay and packet loss figures depend on the traffic volume and application scenarios. For a low traffic volume such as the WBAN scenario a random access protocol may offer pseudo deterministic performance which will be similar to scheduled access protocols. Another main advantage of a random access protocol is the ability to use of adaptive sleep cycle control and resource management techniques which reduce power consumption of sensor nodes (Omeni et.al., 2008).

4.1 MAC Protocols for Wireless Body Area Networks

Wireless Body Area Network is a special purpose wireless sensor network with several specific requirements as mentioned in previous sections. A short range wireless system such as the body area network can be developed using either a scheduled or a random medium access control protocol. In a WBAN, the MAC protocol determines the packet or information delivery schedule as well as the packet loss probability. These two QoS factors are also influenced by the transmission channel and traffic/data characteristics in a network. Figure 1 showed a typical WBAN with multiple sensor nodes and a single Central Coordinator Unit (CCU) which collects data from all sensor nodes as well as controls the operation of these sensor nodes. In order to transmit information among these nodes and to coordinate these transmissions, it is necessary to develop a suitable MAC protocol. This particular WBAN shown in figure 1 is operating in a star configuration where all the sensor nodes are connected to the CCU by using a single hop connection. A star configuration allows all sensor nodes to directly transmit data to the CCU.

Sensors on the body will collect different physiological data where the data sampling rate and data sample size will vary. Table-2 lists the characteristics of physiological data. The table shows that the data rate and data generation times of different physiological signals are quite variable. Generally these signals are periodic in nature but their rate could vary based on the physiological condition of a patient. Some of the signals ideally appears to be periodic but may turn into a non-periodic or a random signal based on a patient condition. For example, if a patient develops an abnormal heart condition then the heartbeat sensor could generate an aperiodic or a random signal. A MAC protocol of a WBAN should be able to efficiently handle these variations. Also, a body sensor node generally have very limited storage capacity, hence it will be necessary to transmit data within a specified time delay to avoid any data loss due to the buffer overflow. Time delay constraint will also be determined by the priority status of a data stream. For example, if a critical patient is monitored then some of the physiological data could be more important than other data and hence, the high priority data stream requires a quick channel access. To support information transmission within a WBAN it is necessary to develop a dynamic MAC protocol which not only transmit information reliably but also the protocol needs to be energy efficient and scalable. Next section we review three classes of protocols such are scheduled TDMA (Time Division Multiple Access), polling and random access protocols. Beside these three protocols another class of protocols known as the reservation protocol is also used in the sensor networking applications however, this class of protocol is not well suited for WBAN applications due to higher signaling requirements. Additional signaling traffic not only consumes extra bandwidth but also consumes significant amount of energy. Below we briefly discuss the scheduled and random access protocol features for WBAN applications.

Physiological Signal	Parameter range	Maximum Frequency (Hz)	Sample Interarrival time (sec)	Payload /sample(bits)	Required data rate (kbs)
Blood flow	1-300ml/s	20	0.025	12	0.48
ECG signal	0.5-4mV	250	0.002	12	6.0
Respiratory rate	2-50breaths/min	10	0.05	12	0.24
Blood Pressure (Direct Arterial)	10-400mm Hg	50	0.01	12	1.2
Blood pH	6.8-7.8pH units	2	0.25	12	.048
Nerve Potentials	0.01-3mV	10,000	5E-06	12	2400
Body Temperature	32-40 °C	0.1	5	12	.0024

Table 2. Physiological data characteristics.

4.1.1 Scheduled TDMA MAC Protocol

A scheduled MAC protocol can offer deterministic delay and no packet loss due to absence of any transmission channel contention. The Time Division Multiple Access (TDMA) is a scheduled multiple access technique where transmission of packets are managed in the form of time frame and slots. A time slot can be seen as a dedicated transmission resource used to carry patient data with minimum or no overhead. A central controller which is the CCU in case of a WBAN will allocate time slots to each sensor nodes to transmit data. Figure 10 shows a typical TDMA frame and slot structure. Slots could be allocated on a permanent basis to each sensor node to transmit information from a sensor node to the CCU. When time slots are allocated by the CCU then packet overhead of the information transfer can be eliminated resulting fewer bits to transmit. A TDMA based MAC protocol could be suitable for a small WBAN with a limited number of sensors generating data at a fixed rate and transmitting fixed block of data.
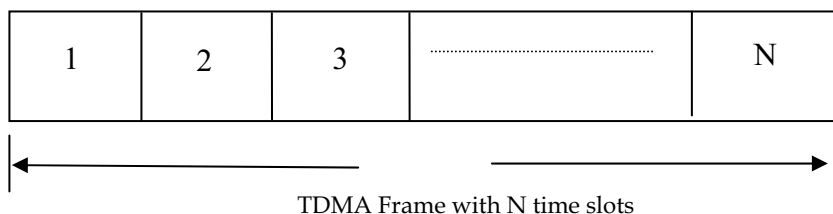

Fig. 10. TDMA frame and slot structure.

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