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.
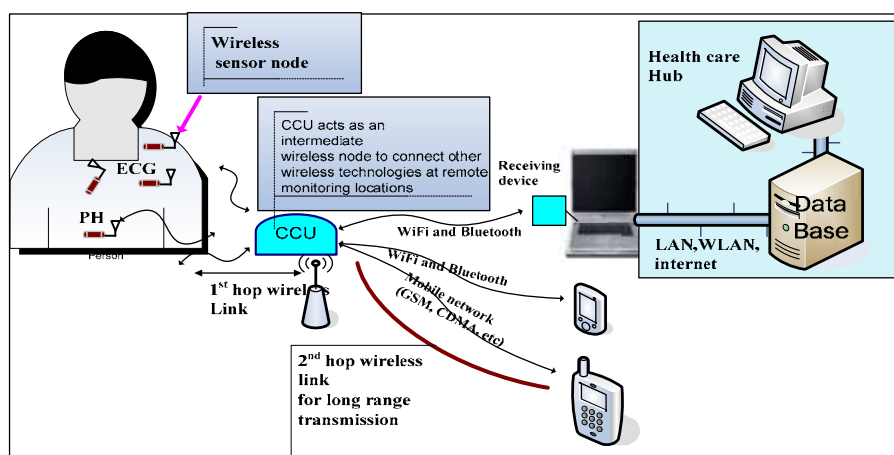

Fig. 1. A wireless body area network system. Collecting and monitoring data from individual wireless sensor nodes from a single human body via the gateway CCU.

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.
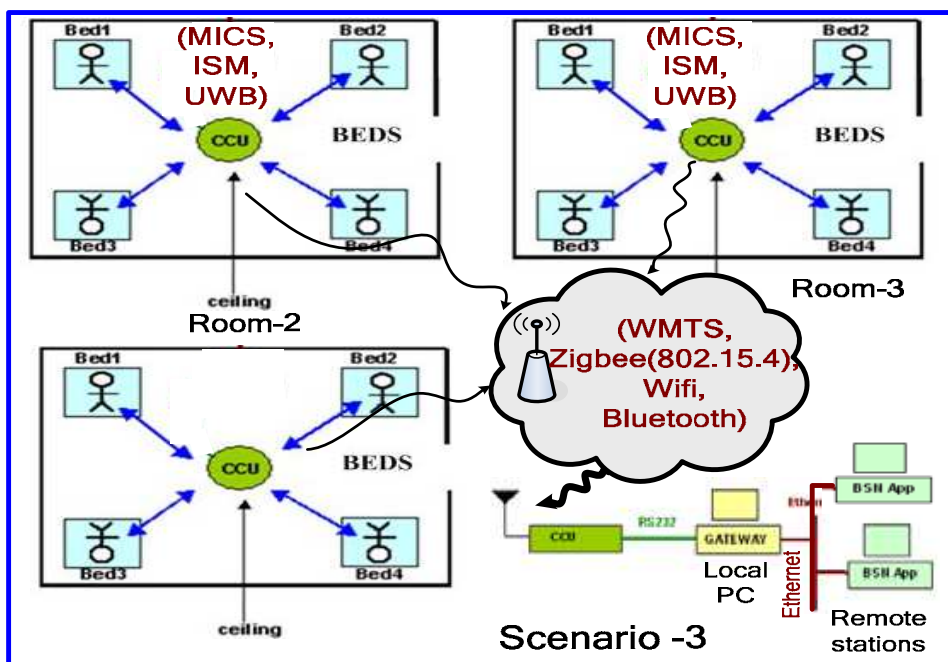

Fig. 2. A multi-patient monitoring scenario in a medical center, representing one room and one floor respectively.

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.
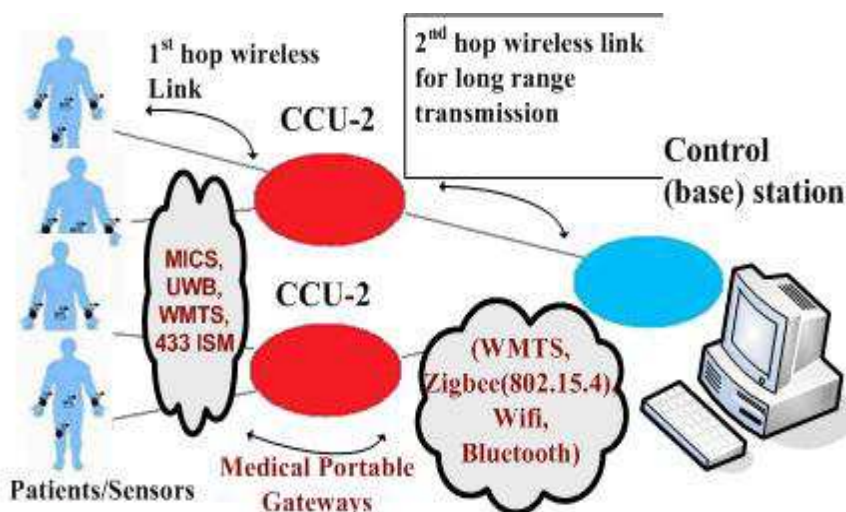
Fig. 3. Multi-hopping WBAN based multi-patient monitoring.

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.
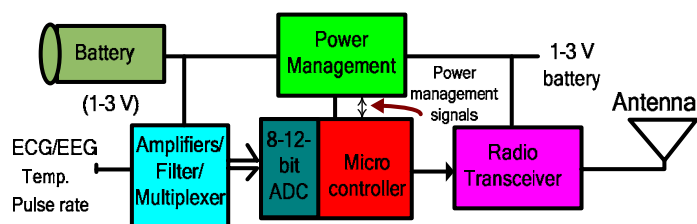

Fig 4. Block diagram of a wireless sensor node in a WBAN.

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.
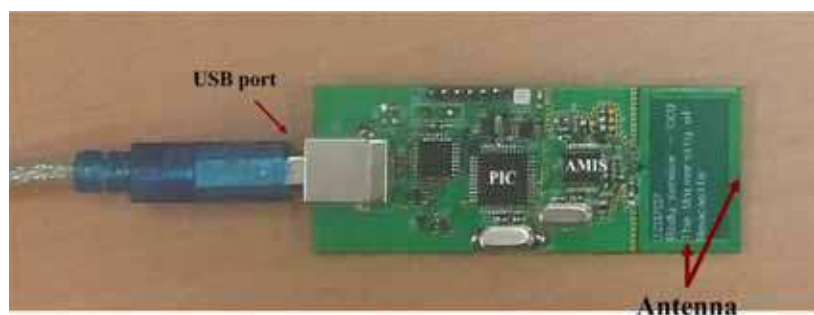

Fig. 6. CCU-1: a central control unit (CCU) used individually.

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.
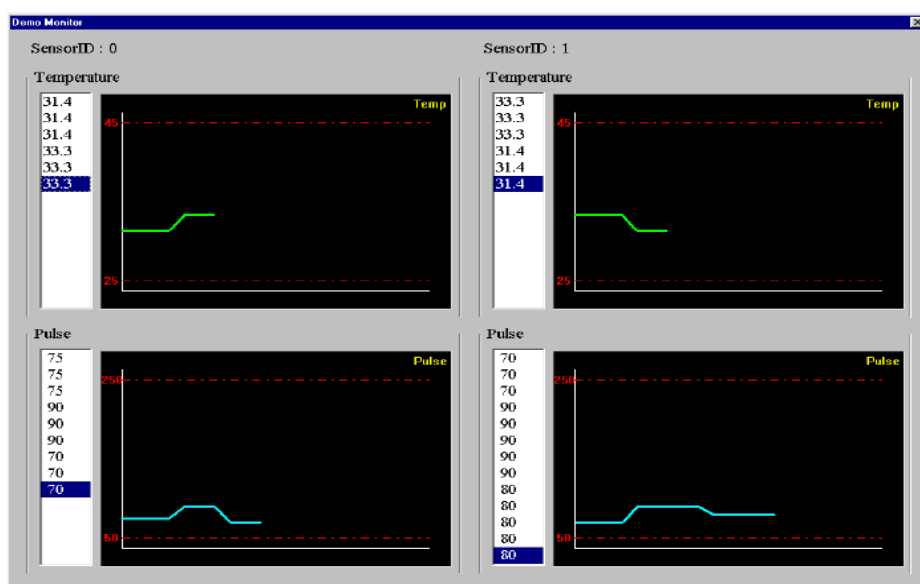

Fig. 8. Live monitoring of multi-patients (physiological data presented in a graphical form at the remote PC). SensorID is used to define each patient.
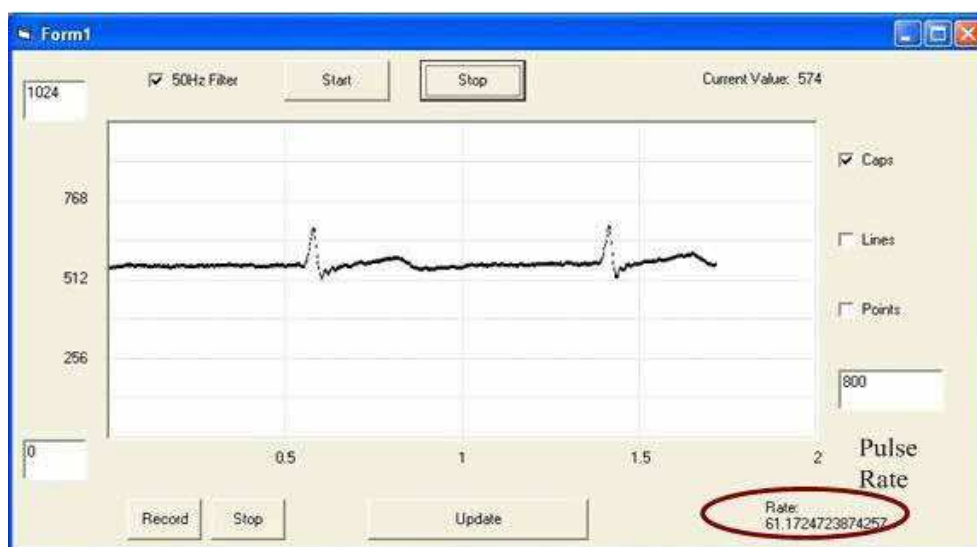
Fig. 9. A clean wireless ECG monitoring showing pulse rate is displayed.

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 ^{0}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.
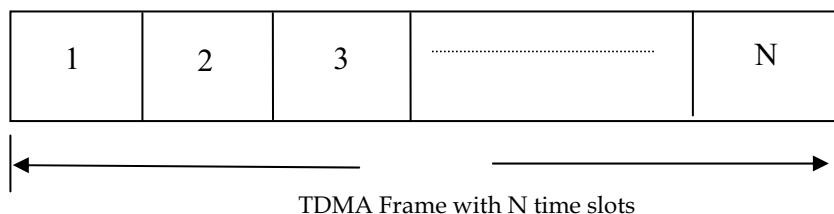

TDMA Frame with N time slots

Fig. 10. TDMA frame and slot structure.

A TDMA based WBAN can be made energy efficient where transmitter circuit of a sensor node is only activated in the specified slot. Also, a sensor node does not need to listen to the transmission channels all the time hence, energy consumptions for the communication circuits will be minimized. A fixed timer based sleep cycle control scheme can be used for a TDMA based system. However, a TDMA based WBAN has two major resource allocation problems. One of the main problems is supporting different sensors with different data inter-arrival time i.e. handling non-periodic data. In a TDMA based system generally a time slot will be allocated on a fixed basis to a particular sensor node and allow that node to transmit in the specified time slot without any possibility of collisions. As shown in the table 2 that a typical WBAN needs to cater for different sampling rates to gather various physiological data. Whereas in a TDMA system time slots are allocated on a fixed basis designed to handle synchronous information. For example, one can see from table 2 that for each blood flow sample a sensor node transmits 12 ECG samples. If these samples are generated from different nodes and they are allocated with separate time slots then the blood flow sensor node will not utilize transmission resources (time slots) efficiently. Resource utilization may not be a major problem for a WBAN because when sensor nodes are not transmitting any data, they will not utilize the transmission slot but will remain in the idle state to save energy. However, in this situation some system resources will be under utilized and the cost of a system may increase. The main problem of a TDMA based system is the scalability. The TDMA is a centralized protocol which requires changes in the central controller setup to accommodate any extra sensor node in a WBAN which could be the main drawback for a patient monitoring system; because the number of sensor nodes could vary depending on the condition of a patient. For example, should medical staff wants to add more monitoring devices on a patient body who is under observation then it will be necessary to modify the design of the TDMA time frame from the main controller. From a WBAN design point of view, a TDMA based system can be used to implement a patient monitoring system using a fixed number of nodes.

4.1.2 Polling MAC Protocol

Polling based MAC protocols are based on scheduled transmission technique utilizing the master slave architecture to transmit data. In a polling network, a central controller schedules all transmissions in the network thus avoiding any contention probability. Figure 11(a) shows a typical polling network architecture where all transmissions are controlled by the CCU. A polling network is more flexible than a fixed assignment based TDMA network where traffic sources with different interarrival rates can easily be accommodated. As shown in figure 11(a) the CCU will send polling messages to all nodes which in response to the poll can either transmit a message or can send a short NACK (Negative ACKnowledgement) when a node has no data to transmit. An ACK (Acknowledgement) for the previous transmission could be included in the polling message to improve data reliability. The polling frequency can be varied and optimized to support traffic sources of different information inter-arrival rate. Figure 11(b) shows the polling cycle and the polling sequence. It shows a round robin polling scheme where nodes are polled in a sequential manner. Figure also shows an additional polling slot is kept in at the end of the poll cycle which is used to support the scalability feature of the protocol. New nodes can either join or depart a network by simply sending a message to the central controller. Number of nodes in a network will vary the polling cycle time as well as the packet transmission delay. The

propagation delay is insignificant and can be ignored for a WBAN application. A polling network offers two main advantages. They are the deterministic and bounded transmission delay, and the scalable network architecture. When a new sensor node needs to be added in a WBAN, the new unregistered sensor node will send a JOIN message when the new poll slot appears in the polling cycle. When the controller receives the JOIN message then it creates a new polling slot and data slot for the new terminal. Similarly, when a node departs the network by sending a DEPART message the controller will remove the allocated poll and data slots. This simple process will allow a WBAN to accommodate variable number of sensor nodes. In a polling network the queuing and the packet transmission delay is largely determined by the traffic volume and the number of active nodes. When a new node joins a WBAN then the polling cycle length will increase thus increasing the packet delay by a fixed value (assuming fixed size slots are used). Power consumption of a polling network can be controlled by organizing the polling and data transmission sequences. For example, when a WBAN transmits data with different interarrival times then the polling sequence can be synchronized with the sampling rate. Similar to the TDMA MAC protocol, a node can wake up before its poll message then transmits or receives data in the specified time. The CCU could broadcast the polling and transmission schedules to maximize the node sleep time.
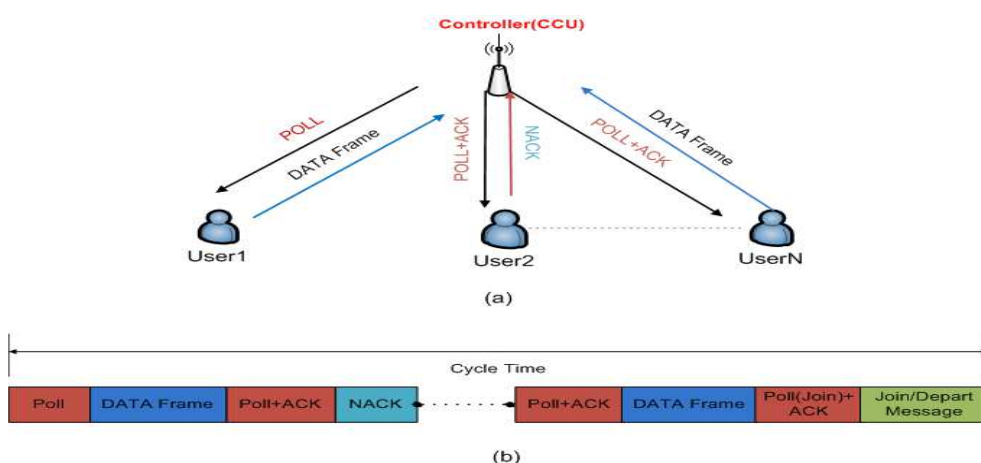

Fig. 11. A polling MAC based transmission sequence.

4.1.3 Random Access MAC Protocol

Random access protocols are commonly known as the ON DEMAND access protocol widely used in wireless local area and sensor networks designed for short range communications. These protocols are suitable for distributed systems with no or minimal control signaling. There are many random access protocols are in use among them the CSMA/CA (Collision Sense Multiple Access with Collision Avoidance) protocol is suitable for the short range wireless communication (Karl et.al., 2008). A CSMA/CA protocol based sensor accesses a transmission channel only when it needs to transmit any information. A node using the MAC protocol will check a transmission channel status only when it has data in its transmission buffer. If it finds a transmission channel to be free then the node initiates a packet transmission using a contention based procedure. Because of the contention nature of

the protocol a transmitted packet may collide and may require retransmission(s) to successfully transmit the packet. There are a number of advantages a random access protocol can offer for WBAN applications. Main advantages include lower signaling overhead, scalability, distributed control which allows the network to accommodate traffic sources with different interarrival rate and data rates. The CSMA/CA protocol also allows network to optimize power and transmission resources locally at each sensor node. For example, if a node generates any urgent data in a non-scheduled manner then a TDMA or a polling based system will have difficulties to transmit those data immediately. Whereas, as soon as the non-scheduled data is generated at a node the random access protocol based system can transmit the data provided the node have the necessary priority. However, the main disadvantage of a random access protocol could introduce a variable and longer delay if the traffic load is high. For a WBAN design it is not expected that the traffic load will be higher because of the system's transmission capacity. If the traffic load remains fairly stable and lower than about 70~80% of a network capacity then a random access based protocol offers reasonably lower delay. The average packet delay of a random access protocol based network is given by (1). Propagation delay is ignored in the equation. The first term of the right hand side of the equation represents the access delay (T_{access}) which is the time required by a CSMA/CA node to access the channel. Detail description of the CSMA/CA based channel access procedure can be found in the reference (Golmie et.al., 2006). The access delay depends on the traffic load of a network. The second terms represents the retransmission delay (T_{retry}). During the access phase if a packet experiences a collision then the transmitting node will backoff for a certain duration and then try to transmit the packet. The backoff period will be randomly distributed to minimize the collision probability. In case of a collision multiple retransmission attempts may be needed to resolve the collision. A packet could be dropped if the packet cannot be transmitted successfully after multiple collisions. The queuing delay (T_{queue}) represents the buffering delay at a node. The last term of the equation represents the packet transmission delay (T_{packet}) whose value depends on the packet size and the transmission data rate. From the discussion it is clear that the first three components could introduce delay jitter if the incoming traffic volume varies significantly over the time or the received signal to noise ratio (SNR) varies significantly over the time.

$$T_{d(random)} = T_{access} + T_{retry} + T_{queue} + T_{packet} \qquad (1)$$

To summarise the review of MAC protocols we compare the key features of three classes or protocols in Table 3. In the next section we examine the IEEE802.15.4 standard which defines the physical and MAC layers of the Zigbee standard. The Zigbee standard can be potentially applied for WBAN patient monitoring applications. The IEEE802.15.4 standard supports both random and schedules access protocols. Also, the IEEE802.1.5.6 working group is working on develops PHY and MAC layers with strong similarity with the IEEE802.15.4 standard (TG6). As mentioned earlier that a WBAN can be seen as a special purpose sensor network whose operational characteristics will be very similar to a wireless personal network (WPAN). The IEEE802.15.4 MAC protocol also supports the WPAN features using the star network topology.

MAC Features	Scheduled MAC: TDMA	Scheduled Mac: Poll	Random Access MAC: CSMA/CA
Packet Delay	Deterministic and fixed.	Deterministic, varies with the network traffic load (volume of data).	Variable, varies with network traffic load, priority and application type.
Packet Loss*	Deterministic and fixed.	Deterministic, varies with the network traffic load.	Variable, varies with the network traffic load and application type.
Traffic handling capability	Efficiently handle periodic traffic. For non-periodic traffic efficiency is lower due to variable delay.	Efficiently handle periodic traffic. Also, can handle non-periodic data by adjusting the polling cycle.	Can handle non-periodic traffic more efficiently than scheduled MAC protocols.
Energy Efficiency	Fixed transmission sequence can introduce fixed sleep cycle. However, energy efficiency could be low when handling non-periodic traffic.	Fixed transmission sequence can introduce fixed sleep cycle. Energy efficiency is better than the TDMA protocol where a node may wake up from sleep and send NACK to reduce the transmission cycle time.	Can offer much better energy efficiency compared to scheduled MAC protocols. Transmitting nodes remain in sleep mode until it is necessary to actually transmit data.
Transmission# efficiency	Very low or no overhead involve in this transmission.	High overhead due to the polling mechanism used. However, for WBAN applications the overhead is lower due to shorter propagation delay.	For WBAN applications the ratio of overhead to payload is normally high unless the aggregation technique is used.
Network Scalability	Poor scalability feature, particularly with non-periodic traffic.	Scalability property is good. Scalability margin is limited by the delay.	Scalability feature is good.

Table 3. Summary of yey features of WBAN MAC protocols.

*: Assuming a low BER channel and the effect of transmission errors are not considered.
#: Transmission efficiency is defined as the ratio of number of information bits transmitted to the total number of transmitted bits (data and overhead bits).

4.2 IEEE802.15.4 MAC Protocol

In this section we introduce the IEEE802.15.4 MAC standard which could be used to design first generation WBAN for medical and other health monitoring applications. The main objective of the IEEE802.15.4 standard is to provide a low-cost, reliable and low power wireless protocol to support a range of sensor networks and home networking solutions. The standard defines the lower two layers functionalities i.e. the PHY and MAC layer functionalities (Gutierrez et.al. 2001, Khan et.al., 2006). Both these layers have been designed to prolong the battery life requirement. Tables 4-(a) and 4-(b) lists the key PHY and MAC layers features of the IEEE802.15.4 standard respectively.

Frequency	868 – 868.6 MHz (Europe)	901 – 928 MHz (North America)	2.4 – 2.4835 GHz (World Wide)
Channel Bandwidth	0.3 MHz	0.6 MHz	2 MHz
No. of RF Channels	1	10 (separation 2 MHz)	16 (separation 5 MHz)
Maximum Data Rate	20 kbs	40 kbs	250 kbs
Modulation Technique	BPSK	BPSK	O-QPSK
Transmission Power	1 mw (min)	1 mw (min)	1 mw (min)
BER requirements	< 1%	< 1%	< 1%

Table 4-(a). Key PHY layer features of the IEEE802.15.4 standard.

Feature	Description
MAC Protocol	CSMA/CA (Carrier Sensing Multiple Access/Collision Avoidance)
Address	16 bit (short) or 64 bit (extended)
Transmission mode	Fully acknowledged mode
Energy Detection	Yes with the cooperation of the physical layer
Link Quality Indication	Yes with the cooperation of the physical layer

Table 4-(b). Key MAC layer features of the IEEE802.15.4 standard.

The standard supports two network topologies; these are star and peer-to-peer topologies as shown in the Figure 12. The star topology is a typical centralized architecture where a coordinator controls activities of various nodes. The star configuration will typically operate in a WPAN configuration. The peer-to-peer configuration can support a multi-hop network and the range can be extended by incorporating the mesh network architecture using the configuration. The IEEE802.15.4 standard divides transmission nodes in two categories, which determines the topology and the media access used by the network. One class of nodes are classified as a Full Functional Device (FFD) which can directly communicate with any other node and can act as a PAN coordinator as shown in Figure 13. The other class of node is known as a Reduced Function Devices (RFD) which can only communicate with FFDs.

A Personal Area Network (PAN) structure as shown in Figure 13 is controlled by the PAN coordinator. In a WBAN design the CCU can take the role of a PAN coordinator. The coordinator periodically sends beacon signals that identify the PAN. The PAN is identified by a 16 bit PAN identifier. The beacon frame also contains information such as a list of outstanding frames, and other system related parameters. The time interval between these beacon signals is constant and users can select a value which is a multiple of 15.38 ms. The maximum beacon interval time could go up to 252 ms. Two consecutive beacon signals forms a *superframe* separated by 16 equally sized time slots as shown in the Figure 13. The superframe is subdivided into active and inactive periods. All nodes including the coordinator can turn off its transceivers and go into a sleep state during the inactive period of a superframe. The active period which consists of 16 timeslots, where each timeslot is divided into two groups. One set of slots forms the *contention access period* **(CAP)** and the rest of the slots become part of the *Guaranteed Time Slots* **(GTS)**. The length of the active and inactive periods is configurable hence, allowing system design flexibility to accommodate different types of applications. The CAP slots can be accessed using the standard CSMA/CA procedure whereas the GTS slots are allocated by the coordinator when a request is made by a node. The flag in the request packet indicates whether the slot will be used to transmit or to receive. Upon receiving a slot request the coordinator will allocate a GTS slot when appropriate resources are available. When GTS slots are used for transmission a node can schedule its sleep cycle and wakes up just before the time slot starts and sends the packet. On the other hand when a CAP slot is used then the node must wake up in advance and perform carrier sensing or other collision avoidance procedures before it can initiate a transmission. The CAP slots can be used to support both periodic and non-periodic data sources such as irregular heart beat or pulses. Whereas the GTS slots can be used to transmit high priority information from critical patients to guarantee data transfer. Both access modes can be configured to support acknowledgement based connections to improve the reliability. From the MAC architecture point of view it can be seen that the 802.15.4 standard is well suited for a WBAN applications.
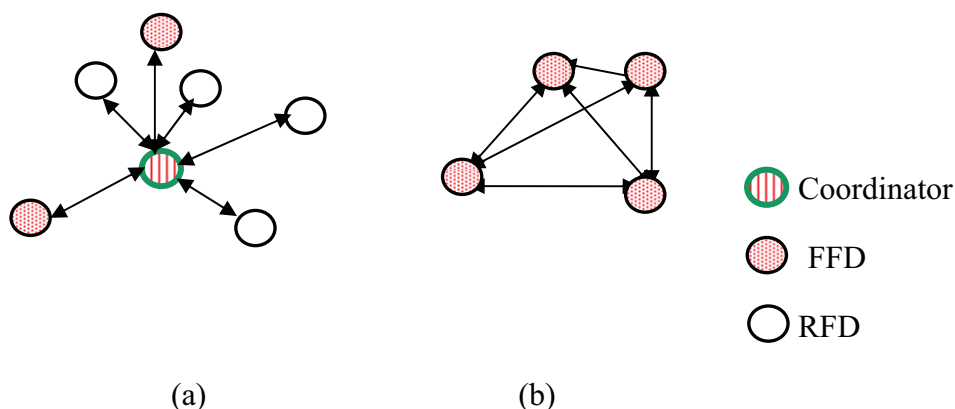
(a)   (b)

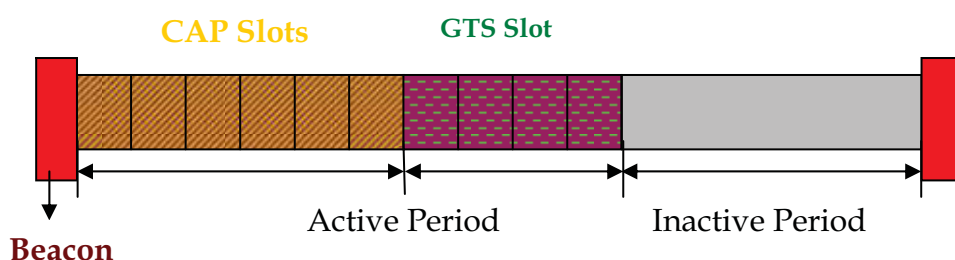Fig. 12. Network topologies. (a) star topology, (b) peer to peer topology.

Fig. 13. Super frame structure of the IEEE802.15.4.

4.3 Basics of Link Budget Calculation

For every wireless network it is important to properly design the wireless link in order to maximize the packet transmission success rate and to minimize the energy consumption of nodes. The link budget of a WBAN will depend on the radio propagation conditions and packet transmission techniques used in a WBAN. The packet transmission issue has already been discussed in the previous sections. The radio propagation condition is dictated by the path loss and fading processes. Fading can be classified as a large scale and small scale fading. Small scale fading occurs due to the relative position of a transmitter and a receiver, whereas the large scale fading is attributed to the mobility of a node which is not very relevant for a WBAN node. The path loss in a WBAN environment will depend on the location of a node. An implanted node will experience a different path loss value compared to an external node for the same transmitter receiver separation distance due to the presence of various body tissues and fluids. A transmitter's energy requirements will be directly influenced by the path loss environment of a node. The task force TG6 of the IEEE802.15.6 work group has extensively studied the channel modeling issues for the WBAN (Yazdandoost et.al., 2009). The work divided WBAN nodes in three different categories:

Implant node, body surface node and the external node. An implant node could reside immediately under the skin or deep inside a body surrounded by various tissues. A body surface node is placed on the surface of human skin with a maximum permissible distance of 2 cm from the body. An external node will be generally away from the body upto a distance of 5 meters. The standards committee also considered that an implant device will operate in the MICS band only. The body surface and external nodes are allowed to use a range of frequencies available for WBAN applications.

The maximum power limitation of a medical devices decided by various regulatory bodies. The ETSI (European Telecommunication Standards Institute) set the maximum to 25 µwatt ERP (Equivalent Radiated Power), whereas FCC (Federal Communication Commission) and the ITU-R (International Telecommunications Union – Radio) set the maximum power to 25 µwatt EIRP (Equivalent Radiated Isotropic Power) which is 2.2 dB lower than the ETSI value. With this limitation it is very important to design nodes and place them strategically to obtain physiological information from various part of the body. The power budget of a WBAN node is also affected by the selection of antenna used on these nodes. In a WBAN two types of antenna's could be used; one is the dipole antenna and the other type is the loop antenna. The radiation patterns of these antennas will also influence a link delay budget. The total path loss between a WBAN implant transmitter and a receiver can be calculated by the equation 2. The path loss for a body surface node can be approximated by using the free space path loss model for a short link distance.

$$PL(d) = PL(d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right) + S$$
$$S \alpha N(0, \sigma_s)$$

(2)

Where $PL(d_0)$ is the measured path loss at a reference distance d_0 from the transmitter, d is the distance in meter, n is the path loss exponent, and S is the loss due to the shadow fading which is normally distributed with a zero mean value with a standard deviation of σ_s. One of TG6 groups established test beds using a multi-thread loop antenna to measure various loss components of (1) for implant to implant and implant to body surface transmissions. Measured values of various loss components are listed in Table 5. A number of other research groups have measured different path loss components for different operating environments. More detail information can be obtained from following references (Yazdandoost et.al., 2009).

Communication Environment	PL(d_0) dB		n		σ_s dB	
	Implant to Implant	Implant to Body Node	Implant to Implant	Implant to Body Node	Implant to Body Node	Implant to Body Node
Deep tissue	35.04	47.14	6.26	4.26	8.18	7.85
Near Surface	40.94	49.81	4.99	4.22	9.05	6.81

Table 5. Measured values of path loss components (Yazdandoost et.al., 2009).

For a WBAN design it is very important to calculate the path loss and fading values to determine the minimum transmission power of a node. Minimum transmission power of a node can be approximately determined by(3)

$$P_{Tx}(\min) = P_L(total) + P_{Rx}(\min) \tag{3}$$

Where P_L(total) represents total power loss between a transmitter and a receiver, P_{Rx} represents the minimum power required by a receiver in to order to receive a packet successfully. The minimum received power value will depend on the receiver's sensitivity which is largely determined by the SNR/BER (Signal to Noise Ratio/Bit Error Rate) profile of the modulator/demodulator used. In some cases instead of measuring SNR values, the SNIR (Signal to Noise Interference Ratio) is used which takes care of the interference generated by other transmitters in the vicinity. Interference could be generated by other wireless devices operating in the same or adjacent frequency bands. For example, for the 2.4 GHz operation there could be potentially many interfering sources in hospital environment. Figure 14 shows the BER profile of different modulation techniques which could be used in a WBAN node. Simpler modulation technique which supports moderate data rate offers reasonable BER value when the SNR value is above 7 dB. The effective BER measured at the MAC layer could be reduced by using appropriate FEC technique. For a high quality medical monitoring system it is necessary to maintain the packet error rate (PER) close to zero. Packet error rate of a link can be derived using (4).

$$PER = 1 - (1 - p)^L \tag{4}$$

Where p is the bit error probability and L is the packet length expressed in bits. As shown in (4) that PER value depends on the transmission link condition and the packet length selection. For example, a packet size of 100 bits will introduce a PER value of 9.5% when the BER is 10^{-3} which is a typical transmission channel condition, whereas the PER value drops to zero if the channel BER is 10^{-5}. For a BPSK modulator for a change of 3 dB SNR could result in such a significant improvement of PER values. Hence it is important to notice that the selection of physical layer parameters and link budget value will significantly influences the quality of a WBAN monitoring system.
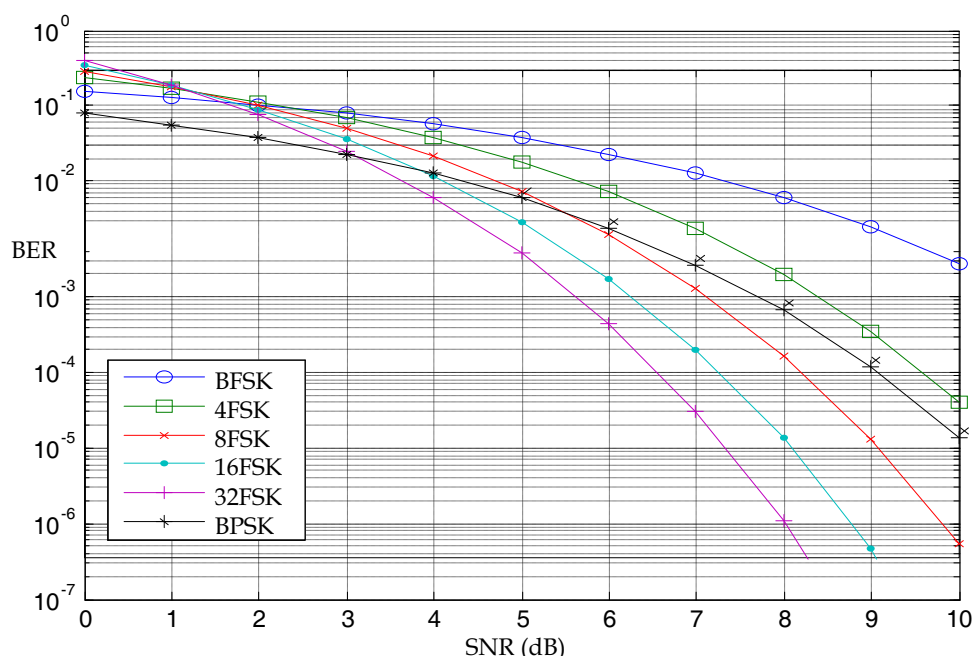
Fig. 14. BER profile of different modulation scheme using coherent receivers (Doong-Sun et.al., 2009).

In the next section we examine a ZigBee based patient monitoring system which can be configured to support single or multi-patient monitoring applications. The ZigBee standard is based on the IEEE802.15.4 PHY and MAC layers (Zigbee).

5. A WBAN Based Patient Monitoring System

In this section we present a ZigBee based muti-hop patient monitoring system which illustrates a WBAN network architecture is proposed in Figure 15 where multiple sensors are placed on each patient. The data from sensors are transmitted to the PCU (Patient Coordinator Unit-A wearable device that can be carried or wearable by the patient). The PCU aggregates sensor data and transmit them to the CCU (Central Coordination Unit). The CCU acts as an intermediate network device that forward the collected medical data to a patient database (DB) where remote monitoring devices can retrieve patients' data for healthcare professions. Each patient body forms a PAN (Personal Area Network) where PCU acts as the PAN coordinator. Similarly the CCU acts as the PAN coordinator for all PCUs which can be considered as a second tier network. All nodes in each PAN will synchronize with their PAN coordinators. In case of signaling failure, a coordinator may not be able to form a PAN in time resulting in transmission failures. The network operates in a multi-hop fashion where each link transmits data using the CSMA/CA protocol. Relay nodes such as the PCU and the CCU can be configured in two ways. One of the

configurations is that these nodes simply act as forwarding node i.e. it receives a packet and simply forwards the packet to the next link. Other configuration is that these nodes receive multiple packets from sensor nodes, and then encapsulates multiple packets and forward a larger packet. The former approach can be implemented with nodes with low processing capability whereas later approach reduces the number of transmission access on the forward link thus reducing probability of collisions for a ZigBee based system.

Fig. 15. A WBAN based multi-hop patient monitoring system. Each patient's body forms a PAN and consists of sensor nodes and the PCU.

In a Zigbee based system it will be necessary to reduce the number of packets transmitted from sensor nodes to reduce the contention level in a network. To achieve that, the sensor nodes may aggregate multiple physiological data and transmit in a single packet. As seen from Table-2 that data sample sizes are quite small only 12 bits/sample which is much smaller than the minimum 802.15.4 packet header length. Sending each sample separately will increase the contention level significantly, which will result in an increase in the packet loss and delay. In order to reduce the contention level it will be prudent to opportunistically combine multiple samples and transmit these samples in a single packet. Later in the performance analysis section, the effectiveness of data aggregation technique will be further discussed. The multi-hop network shown in the Figure 15 may have interference problem when the CSMA/CA protocol is used. A transmission on a path can interfere another

transmission on a different path. For example, a sensor node to PCU transmission can interfere with the transmission between the CCU to DB. To avoid this problem, it is necessary to control power levels of each transmission and in addition, some form of loose scheduling is necessary to avoid or to reduce collision levels. Also, the relay configuration could reduce the problem. Figure 16 shows the IEEE802.15.4 sensor node transmit profile. The power profile of the sensor node was generated using the path loss model only, fading effects were not considered in this calculation. Based on the power-distance relationship, sensor nodes on the body will transmit at an appropriate power level depending on the proximity of receivers and transmitters.
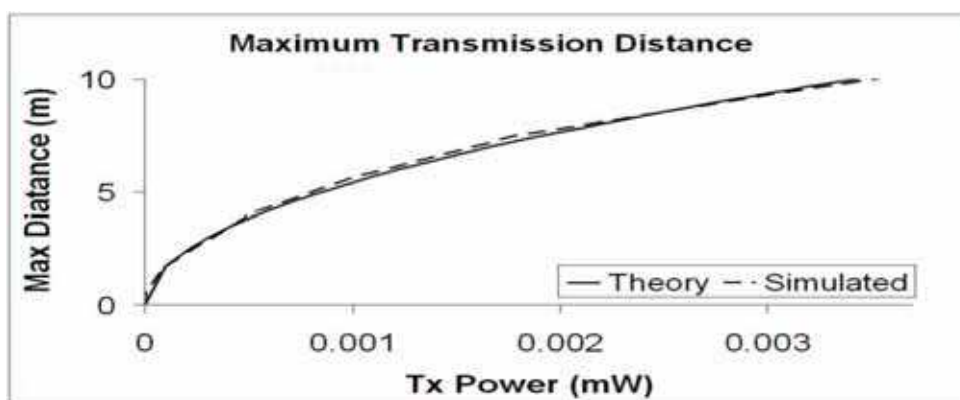
Fig. 16. IEEE802.15.4 Sensor node power transmission profile.

6. Performance Analysis of WBAN

In this section we analyze the performance of the proposed WBAN for patient monitoring applications using a simulation model (Bulger, 2008). We use this model to analyze the performance of a multi-hop network where patient data is transmitted from sensors to the data base (DB) using the PCU and the CCU as relay nodes. In the body area network model, we simulated all sensors but the nerve potential traffic generators listed in Table 2. In the initial simulation model all sensors are connected using individual ZigBee transmitters. When the aggregate data model was used then a number of sensors are connected to a single transmitter. In the later section we discuss the effect of data aggregation on the WBAN performance. Figure 17 shows the packet structure used in the simulation.

The physical layer generates the packet by encapsulating the MPDU (MAC Protocol Data Unit) with the physical layer overheads. The minimum header length is 18 bytes long. Considering the transmission efficiency, such a large overhead introduces a design constraint for the WBAN. As discussed before that each physiological signal sample is only 12 bits long hence, it will be inefficient to transmit a single sample in a packet. Sending a short payload not only reduces the transmission efficiencies but also increases the probability of collisions consequently increasing packet delay and losses. Increasing contention level in a random access network has further consequences on the power

consumption of sensor nodes. Higher contention level in a CSMA network introduces more collisions and retransmissions. When packets are retransmitted more frequently, then a node consumes higher power level thus decreasing the battery life. During retransmission, the energy consumption increases because same information is transmitted multiple times before a packet is successfully received. Most of the ZigBee Integrated Circuits (IC)'s will consume highest power when the device is transmitting data (Khan et.al., 2006). So, it is necessary to optimize the number of transmission and retransmission of packets to reduce the packet delay and loss as well as to reduce the power consumption requirements of sensor nodes. As discussed, minimizing energy consumption of a WBAN is one primary objective of the MAC design process hence, it is necessary to design packet transmission process taking into account of energy consumption issues. Although the CSMA/CA protocol introduces the contention/collisions in a network which may results in packet losses or delay but this protocol handles both periodic and non-periodic data with equal efficiencies. Later we will show that by appropriately selecting parameters and traffic levels the QoS parameters of patient monitoring system can be improved.
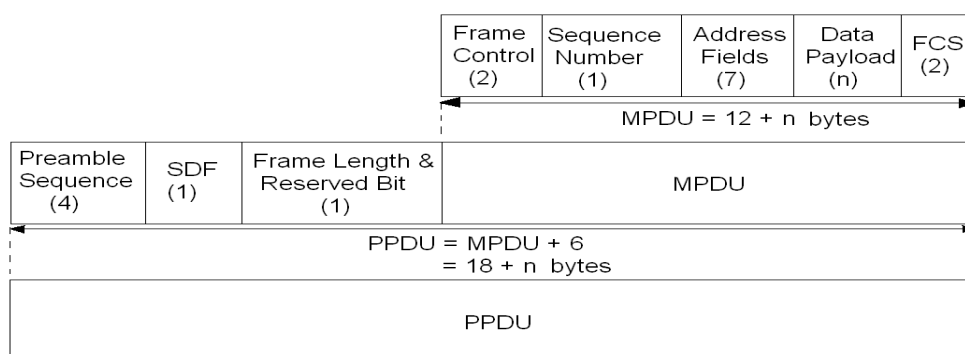
Fig. 17. Zigbee packet structure used in the simulation model. The MPDU represents MAC protocol data unit and PPDU represents the physical layer protocol data unit.

Multiple useful simulation results are obtained using the developed simulation model. In this simulation a single CCU is used which connects a number of sensor nodes. Both the CCU and sensor nodes are implemented using the Zigbee Standard. Figure 18 shows the packet loss and packet generation rate of the simulated WBAN for different payload sizes. Result shows that with the increasing payload size the throughput of WBAN increases due to fewer transmission attempts. The figure shows that with single sample/payload the network only manages to successfully transmit 120 packets offering a success rate of 40%. When the average payload size is increased to 120 bits/packet then the number of transmission attempts is dropped to 50 packets/sec offering 100% throughput in the network. The improvement in the efficiency can be achieved due to lower contention level in the network which resulted fewer packet losses due to the packet dropping threshold. In this simulation, we used five retransmission attempts as the packet dropping threshold, which means if a packet is unable to successfully transmit a packet in five successive attempts then the packet is dropped from the transmission queue.
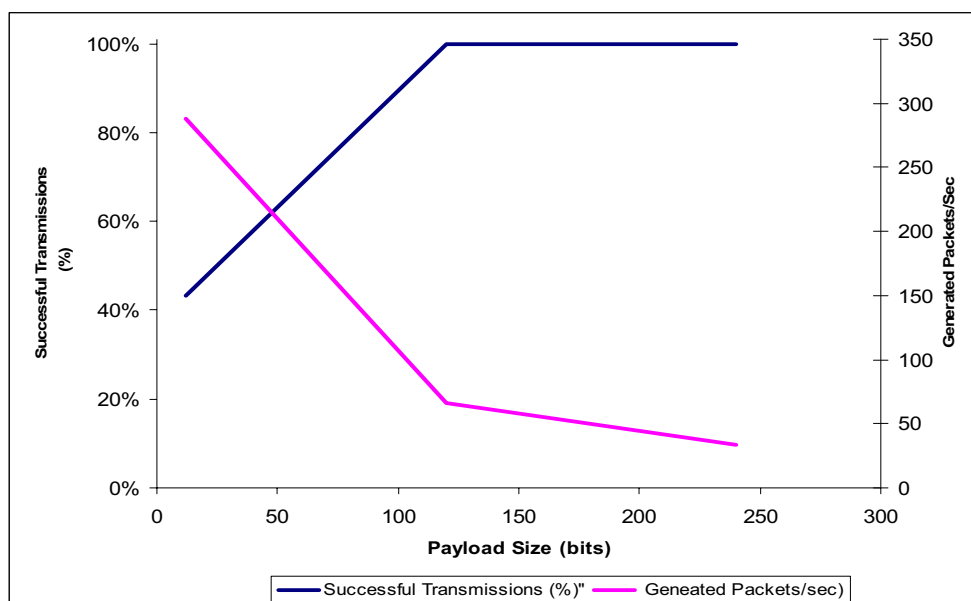
Fig. 18. WBAN packet loss and packet generation rate for different data aggregation rate/payload size.

The delay profile of the WBAN for different payload sizes is investigated and presented in Figure 19. The plot shows that the average packet delay decreases with the increasing payload size. Both results (Figure 18 & 19) show the same trend. The delay profile shows that delay decreases more sharply when the payload size is between 12 to 120 bits. This characteristic can be explained using the equation (1). As shown in the equation the end-to-end delay has four major components. The first three delay components T_{access}, T_{retry} and T_{queue} are contention level dependent. For a smaller payload the contention level increases due to the frequent network access causes significant rise in all these delay components. As the payload size exceeds the total header size the packet transmission delay T_{packet} becomes the dominant component of the overall delay. During the simulation it was observed that when single sample is used as the payload per packet some of the ECG sensor nodes are not able to get any access to the network. From Table 1 it can be seen that the ECG node is a demanding node in terms of transmission access. It requires the transmission channel access after every 2 ms with a data rate requirement of 6 kbs. However, when the overhead bits of a packet is considered the actual data rate for the ECG links become 72 kbs. One can see from these results that the selection of packet size and frequency of packets transmissions in a WBAN is very important from the reliability and QoS point of view.
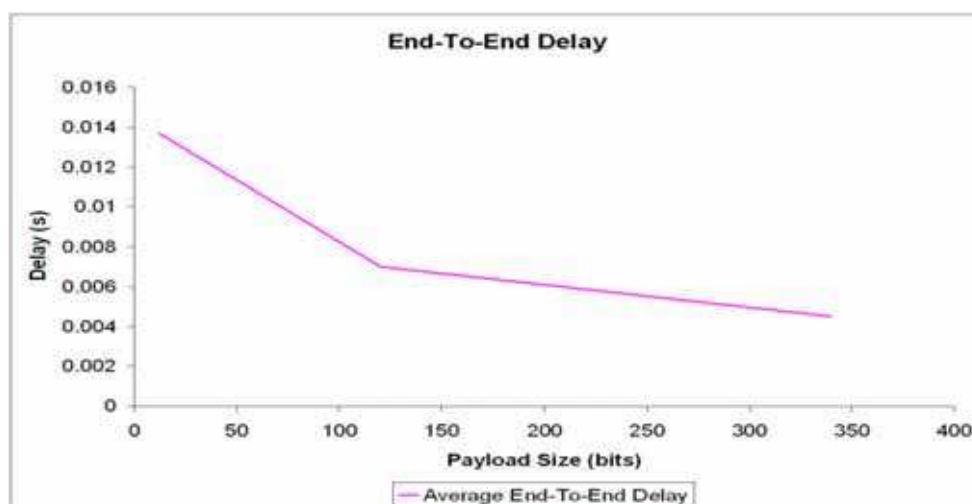
Fig. 19. WBAN delay profile for different payload sizes.

It is important to investigate the performance of an in interconnected WBAN to analyze the performance of a multi-patient monitoring system. In the proposed scenario, it is assumed that all patients' sensor nodes transmit their data via the PCU and CCU to the DB. As discussed earlier that in this model PCUs and CCUs are simply acting as a relay node and forwarding those data to the DB. In order to minimize the number of packets we use the data aggregation technique at the source node. In this simulation we connect all sensors to two sensor nodes which transmits data using the data aggregation technique. One of the sensor nodes (sensor 1) aggregates ECG, body temperature and blood pH data and transmits these data after every 145 ms generating 7 packets/sec. The other sensor node (sensor 2) aggregates data from the blood flow, blood pressure and respiratory rate sensor and transmit these data after every 485 ms generating 3 packets/sec. This aggregated packet structure allows 73 data samples with a payload size of 880 bits/packet. Using the aggregating technique each PAN now generates only 10 packets/sec. The effective data rate requirement of sensor 1 and sensor 2 becomes 6.05 kbs and 1.92 kbs respectively.

The delay profile for a multipatient networking scenario is depicted in Figure 20. The plot shows the average end-to-end delay which is the total delay over 3 hops (sensor→PCU, PCU→CCU and CCU→DB). It is observed that the delay increases with increasing number of patients. In this case the main reason for the increase in delay is caused by the contention or interference from different PANs. For an operating ZigBee network, sensor nodes on each patient's body forms a working PAN with the PCU as the coordinator. In a multi-hop networking, collisions can happen either within a PAN or between PANs when simultaneous transmission goes on in different PANs. Also, transmission from the PCU to CCU or from the CCU to DB transmissions can be interfered by the transmissions from other PANs if the IEEE802.15.4 MAC is used on all the links. In our simulation all the wireless links used the CSMA/CA protocol. Figure 20 shows the end-to-end delay which the sum of the all hop delays is as represented in (5). The delay plot shows that the delay

profile for up to 6 patients is quite acceptable where the average packet delay is about 170 ms. Within this 170 ms the monitoring system will be able to transmit large number of samples due to the aggregation technique used.

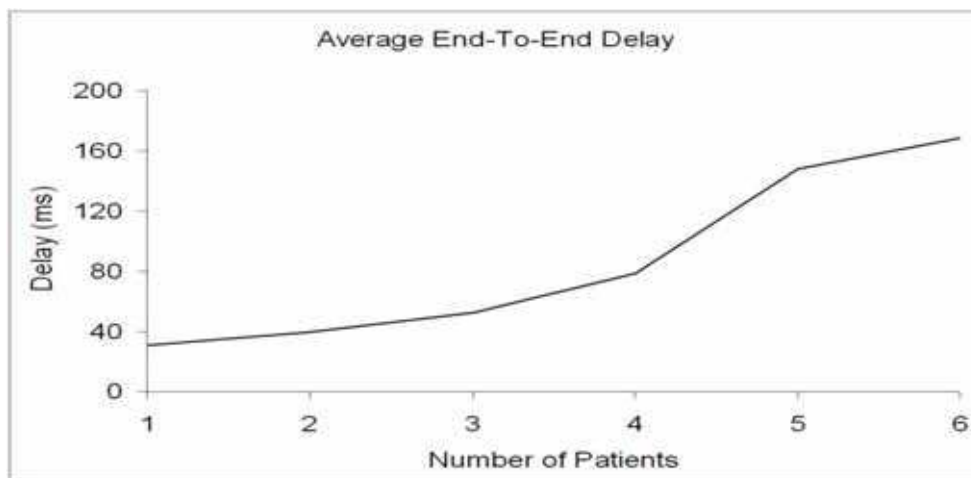$$T_{ee} = \sum_{i=1}^{N} T_{d(random)i} \qquad (5)$$

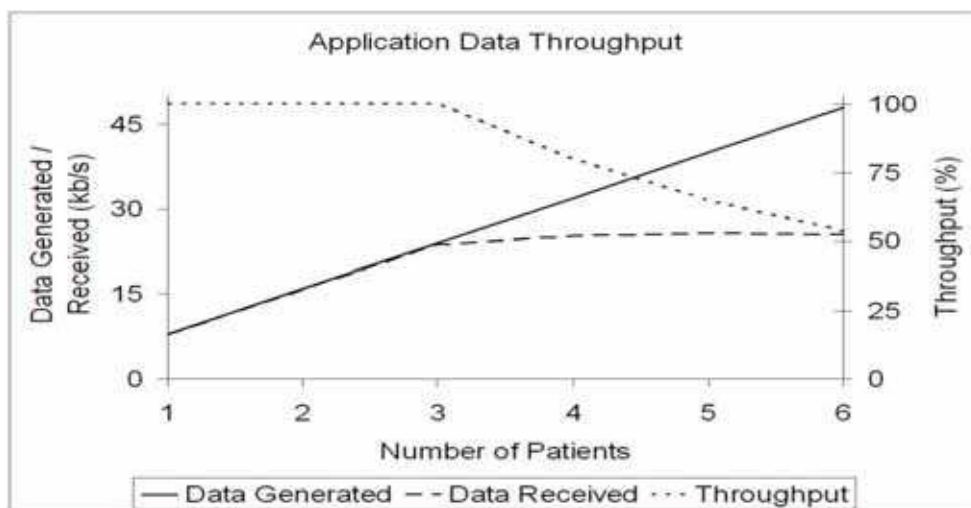Fig. 20. Delay profile of the multi-patient monitoring system.

Fig. 21. Data generation and application throughput profile in a multi-patient monitoring system.

The application throughput profile of the monitoring system which is presented in Figure 21 was obtained using the simulation model presented in figure 15. Figure 21 shows that the application throughput remains 100% for upto three patients. The application throughput starts to drop due higher end to end delay and the contention level. In this network each packet crosses three links and these packets may experience collisions on all links depending on the transmission status of other networks. Application throughput can be increased if higher end-to-end delay is tolerated. Both the application throughput and delay can be tuned by controlling the backoff parameters and the number of allowable retransmission attempts used to resolve collisions. For a WBAN based system design one needs to tune the traffic and MAC protocol parameters to compromise between the delay and the throughput. When contention level increases, packets are lost due to two main reasons; one is expiry of packet lifetime due to fixed number of retransmission attempts, and secondly due to the PAN formation error as depicted in Figure 22. If sensor nodes are unable to communicate with its PAN coordinator then a PAN formation error occurs. When the PAN formation error occurs then sensor nodes in that PAN can not transmit any packets. A PAN error can occurs due to the failure of signaling packet transmission which can be caused by the collisions or interference from other PANs or links in a multi-hop network.

Figure 22 shows that the PAN formation error starts to appear when the number of patients exceeds three. To minimize the effect of collision and interference on other links in this simulation we incorporated variable transmission power technique as shown in Table 6. The table shows that the PCU and CCU are transmitting at higher levels than the sensor nodes because CCU and PCU will need to cover longer distances. Higher transmission power of CCU and PCU is mainly responsible for interfering with other PAN transmissions. A suggested method for a ZigBee based design approach would be to use the GTS slots for PCU and CCU transmissions and use the CAP slots for the sensor nodes. This means that higher power nodes will not interfere with the sensor nodes and hence the contention levels will significantly drop.

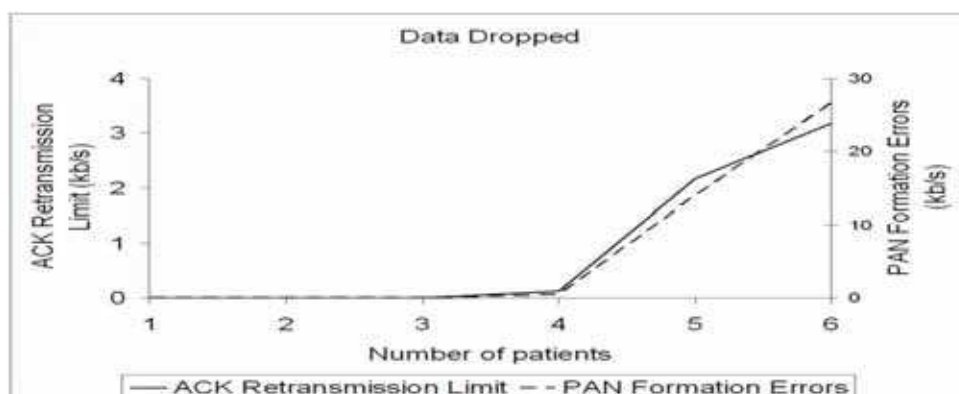| Node Type	Maximum Transmission Distance (m)	Power Constraint	Transmit Power (dBm)
Sensor	0.5	High	-50
PCU	8	Medium	-26.6
CCU	8	Low	0
DB	10	Low	0

Table 6. Node transmission power.

Fig. 22. Packet dropping profile in a multi-patient monitoring system. Figure shows packet dropping rate due to expiry of retransmission threshold and the PAN formation error.

7. Future Application Prospects and Development for WBAN

Future WBAN designs should concentrate a number of areas including the hardware and protocols design. The hardware development area should focus on design of very small and miniaturized wireless sensor nodes so that they can be used as a wearable device or could be implanted in the body. The hardware design should also concentrate on the development low power sensor nodes possibly by harvesting energy from body movements or using some other intelligent technique to generate its own power. The sensor nodes should be able to transmit the medical data in a reliable and secure method. A sensor node should also be able to incorporate with other wireless systems such as Bluetooth, WiFi and short-range wireless sensor networks such as Zigbee. Seamless interconnection feature of WBAN means the protocol stack should be developed intelligently so that a WBAN node can adapt itself in any operating environment. Developing an interference free wireless medical network for monitoring physiological parameters is one of the most important issues for a WBAN application. A future WBAN system should incorporate the following enhanced features:

- Low cost and tiny sensor node electronics design with wireless capability.
- A dedicated wireless transmission standard to eliminate possible interference issues.
- **Wireless Security-**Key software components should be developed to accommodate secure and effective wireless transmission. Medical data should only be accessible by authorized medical professionals without any possibility of eves dropping on the radio link.
- A WBAN should include alarm mechanism to define critical level of physiological signals monitored and can interact with other medical instrument.
- A dedicated adaptive wireless protocol should be designed for WBANs to accommodate critical and non critical data in the same platform with a low latency and information loss probability.

The selected wireless technologies and the frequency for transmission are very critical for future implementation of WBAN systems. Some of the recommendations made in this

section are also being investigated by the IEEE802.15.6 working group (TG6). The group started their work in December 2007 and expected to produce a draft ready standard for sponsor ballot in December 2009. It is expected that the development of an unified IEEE standard could lead to many commercial development and deployment of WBANs in many healthcare and aged care applications.

8. Summary

This chapter has introduced the WBAN technology as well as main concepts and relevant design techniques. To develop an efficient WBAN system it is necessary to use advanced design concepts to develop its hardware and protocols. Hardware and protocol design techniques presented in this chapter can be used to develop an efficient WBAN system. The performance analysis section presented some results which will give an idea to researchers and system developers how a WBAN will perform in a multi-patient monitoring environment. Further work will be necessary in future to develop fully autonomous, long life, multimedia WBAN systems which could be used to support advance medical diagnostic systems.

Acknowledgements

9. References

Anliker, U. *et al*. (2004) AMON: a wearable multiparameter medical monitoring and alert system. *IEEE Trans. Information Tech. In Biomedicine*, December 2004, vol. 8, no: 4, pp.415-427, ISSN: 1089-7771

Bradley PD. (2007) Implantable ultralow-power radio chip facilitates in-body communications. (Zarlink semiconductor) RF Dessign 2007; 20-24, Zarlink

Bugler G. and Yuce M. R. "Communication protocols for a multi-hoping wireless body sensor network," Technical Document, University of Newcastle, November, 2008

Dong-Sun, K., et.al, (2009) Block Based PHY and Packet transmission for low data rate in-body WBAN, IEEE802.15.6 group working document: IEEE802.15-09-0317-0006, May 2009.

FCC, (2003) FCC Rules and Regulations, "MICS Band Plan," Table of Frequency Allocations, Part 95, Jan. 2003

Golmie, N., Cypher, D. & Rebala, O. (2006), Performance analysis for low rate wireless technologies for medical applications, *Computer Communications*, vol:28, no: , pp. 1266-1275, ISSN: 0140-3664

Gutierrez, G. A., et.al, (2001) IEEE802.15.4: a developing standard for low-power low-cost wireless personal area networks, *IEEE Network*, Sept/Oct-2001, vol: 15, issue: 5, pp: 12-19, ISSN: 0890-8044

Ho C. K. and M. R. Yuce, (2008) Low Data Rate Ultra Wideband ECG Monitoring System, *Proceedings of the IEEE Engineering in Medicine and Biology Society Conference* (*IEEE EMBC08*), pp. 3413-3416, August 2008, IEEE, Vancouver, British Columbia, Canada

Howitt, I.; Gutierrez, J. A. (2003) IEEE 802.15.4 low rate - wireless personal area network coexistence issues. *IEEE Wireless Commun. and Networking Conf. (WCNC)*, 2003, pp. 1481-1486, IEEE, New Orleans, Louisiana, USA

Karl, H. and Willig, B.T., (2008) Dynamic Duty Cycle Adaptation to Real-Time Data in IEEE802.1.5.4 based WSN, *Proceedings of the 5th IEEE Conference on Consumer Communications & Networking Conference,* pp. 353-357, IEEE, Las Vegas, Nevada, USA

Khan, J.Y., Hall, D.F. and Turner, P. D. (2006) Development of a Wireless Sensor Network System for Power Constrained Applications", *IEEE Asia Pacific Conferences on Circuits and Systems*, 2006, pp. 147-150, IEEE, Singapore

Mark, J.W. & Zhuang W. (2003). Wireless Communications and Networking, pp. 63-116, Prentice Hall, 0-13-040905-7, USA.

Omeni, O., Wong, A. C. W, Burdott A. J. & Toumazou, C. (2008) Energy Efficient Medium Access Protocol for Wireless Medical Body Area Sensor Networks, *IEEE Transactions on Biomedical Circuits and Systems*, vol:2, no:4, December 2008, pp. 251-258, ISSN: 1932-4545

Otto, C. A., Jovanov, E., and Milenkovic, E., (2006) A WBAN-based system for health monitoring at home. *Proceedings of the 3rd IEEE/EMBS Int. Summer School, Medical Devices and Biosensors*. Sept, 20-23, 2006, IEEE, Cambridge, MA, USA.

Proulx, J.; Clifford, R.; Sorensen, S.; Lee, D. J.; Archibald, J. (2006) Development and evaluation of a bluetooth EKG monitoring system. *Proceedings of the 19th IEEE Symposium on Computer-Based Medical Systems*, 2006, pp. 507 – 511, IEEE, Salt Lake city, Utah, USA.

Sikora A.; Groza V. F. (2005) Coexistence of IEEE802. 15.4 with other Systems in the 2.4 GHz-ISM-Band. *Proceedings of IEEE Instrumentation and Measurement,* May 2005, pages 1776-1791, IEEE, Ottawa, Ontario, Canada

Soomro, A; Cavalcanti, D. (2007) Opportunities and Challenges in Using WPAN and WLAN Technologies in Medical Environments. *IEEE Communications Magazine*, February 2007, vol:45, no:2, pp. 114-122, ISSN:0163-6804

TG6, http://www.ieee802.org/15/pub/TG6.html, IEEE

TI, http://focus.ti.com/lit/ds/sbos168d/sbos168d.pdf pg 14. 2009.

Yazdandoost, K. Y. & Sayrafian-Pour, K. (2009) Channel Model for Body Area Network, IEEE802.15.6 group working document: IEEEP802.15-08-0780-09-006, April 2009

Yuce M.R.; Ho C. K. (2008) Implementation of Body Area Networks Based on MICS/WMTS Medical Bands for Healthcare Systems. *IEEE Engineering in Medicine and Biology Society Conference (IEEE EMBC08)*, August 2008, page(s): 3417-3421, IEEE, Vancouver, British Columbia, Canada

Yuce, M. R.; Ng, P. C.; Khan, J. Y. (2008) Monitoring of physiological parameters from multiple patients using wireless sensor network. *Journal of Medical Systems,* 2008, vol. 32 , pp. 433-441, ISSN: 0148-5598

Zigbee, http://www.zigbee.org, Zigbee

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