Modelling and analysis of energy efficient wireless body area networks

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Modelling and Analysis of Energy Efficient Wireless Body Area Networks

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Summary

This work is motivated by the challenges and shortcomings of the design and evaluation of wireless body area networks. Wireless body area network (WBAN) is an interesting application of sensor networks which can revolutionize our interaction with the outside world. Appealing applications of WBAN has attracted both academic and industrial attention. However there are some challenges that need to be addressed before such applications can come true.

One of the major challenges is the need for a general standard model of wave propagation around human body. Such model can be used for simulating and testing future devices which are to be used as a part of WBAN. Most of the efforts so far have been in static channel modeling. i.e. the channel is measured and modeled while the subject is not moving. However, most of our daily activities include some forms of motion. i.e. whole or some parts of our body has movements most of the time. Therefore, incorporating natural body movements in WBAN channel model is crucial. In this work, we address the dynamic nature of the channel around human body. This work provides a comprehensive mathematical channel model of surface to surface radio links around a moving human torso. Statistical analysis is performed on different parameters of the channel and typical values of parameters and their distributions are presented. In addition, an algorithm for reconstructing the samples of the channel response for different radio links over the body is provided.

The model is then verified by comparing the channel and system parameters and the estimated parameters from the real-time measured data. Finally, the dynamics of the channel model is incorporated to develop a power efficient routing algorithm. The channel model is then used to evaluate the performance of the algorithm in comparison with the existing routing schemes.

Another major challenge in the design of the body area networks is the scarce energy resources that could be carried by mobile computing devices including wearable and implantable devices in a body area network. In order to address this problem, two routing approaches are proposed and analyzed in this work. In the first approach, Coded Bit Modulation (CBM), a PHY layer modulation scheme for UWB impulse radio is introduced and analyzed in terms of bit error rate. Then, CBM is incorporated in a power efficient opportunistic routing scheme to decrease the energy consumption of the nodes in wireless body area networks while improving the packet error rate performance of the system. The performance of the CBM based routing scheme is compared with the existing routing schemes and is shown to outperform these methods in terms of energy consumption. In the second approach, an adaptive routing protocol is developed and analyzed which minimizes the energy cost per bit of information by using the channel information to choose the best strategy to route data. In this approach, the source node will switch between direct and relayed communication based on the quality of the link and will use the relay only if the channel quality is below a certain threshold. The mathematical model is then validated through simulations and used to confirm the advantage of the adaptive routing strategy to improve energy efficiency significantly compared with the existing methods.

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Abbreviations

WBAN Wireless Body Area Network

PDA Personal digital assistant

NC Network Coordinator

AES Advanced Encryption Standard

UWB Ultra-Wideband

FCC Federal Communications Commission

QoS Quality of Service

SNR Signal to Noise Ratio

TOA Time of Arrival

PDP Power Delay Profile

AIC Akaike Information Criterion

CBM Coded Bit Modulation

AWGN Additive White Gaussian Noise

PER Packet Error Rate

BER Bit Error Rate

PEP Packet Error Probability

BEP Bit Error Probability

RTS Request to Send

RTR Request to Relay

CTR Clear to Relay

CTS Clear to Send

ACK Acknowledge

ECG Electrocardiography

CDF Cumulative Distribution Function

IFI Inter-Frame Interference

PHY Physical Layer

LOS Line Of Site

TX Transmitter

RX Receiver

CIFS Contention Inter-Frame Spacing

SIFS Short Inter-Frame Spacing

PPDU Physical Layer Protocol Data Unit

PSDU Physical Layer Service Data Unit

Chapter 1

Introduction

1.1 Motivation

The notion of human computer interaction is evolving fast since the beginning of the computer era. For decades, computers were relatively large immobile devices and interacted with the user through screen and keyboard. Today, advances in nano-technology have enabled us to manufacture small hand-held devices capable of performing a variety of tasks. Ubiquitous computing is the result of the marriage of computing and wireless technologies. A user can use a pervasive computing infrastructure resource while moving in a building or between buildings without even noticing it. Such devices are being used in our everyday lives and a wide range of promising future applications has emerged in the literature [1–3]. Active Badge [1] is an example of such applications. In Active Badge network, each user is

Table 1.1: Specifications of some physiological sensors.

Physiological signal	Parameter range	Maximum Frequency (Hz)	Sample bits	Data rate (kbps)	Energy per bit (nJ)
Blood flow	1-1300 ml/s	20	12	0.48	16.65
ECG signal	0.5-4 mV	250	12	6	2.64
Blood pressure	10-100 mm Hg	50	12	1.2	6.60
Blood pH	6.8-7.8 pH units	2	12	0.048	170
Nerve potential	0.01-3 mV	10k	12	2400	3.7
Body temperature	32-40 °C	0.1	12	0.0024	3.5

equipped with a badge which transmits the person's location to a centralized system, enabling the calls or emails of the person to be forwarded to the correct location. Other examples on wearable computing could be found in [3].

Another major application of wearable computing systems is in health care systems. Thanks to the advances in nano-technology, a whole microcontroller unit, sensors and radio interface for data transmission, can be embedded in a single chip. The tiny dimensions of these chips make it feasible to integrate these communication units into wearable objects such as belt, wrist watch, head set, etc. These sensors are attached to or implanted inside the body to sense a vital sign, detect an abnormality or monitor a physiological parameter.

Table 1.1 provides parameters of some physiological sensors [4–7].

Such wearable sensors could benefit a majority of patients in need of constant monitoring and care. As the world is aging, the need for regular and long term vital sign monitoring of the elderly is on the rise. Until now, to monitor vital signs, the patients or the elderly had to stay in a dedicated room with measuring equipments at the hospital or a team of medical personnel had to monitor the patient at home. This would impose a huge cost on the patient and limitations in the daily activities

of the patient [8]. Currently, we are on the verge of the shift from these large scale costly monitoring to low cost micro scale wireless modules installed inside or on the body which are capable of collecting valuable information 24 hours a day without interrupting the daily activities of the user. Using such devices, data logs can be collected for days or months or even years as is necessary for chronic diseases or in case of a life threatening event. Along with these passive monitoring sensors, active modules can be used to deliver medicine based on information gathered by the sensors or command from medical health center. Another aspect of Wireless Body Area Network (WBAN) which makes it interesting is the emerging technologies which are becoming necessary in our daily life, such as mobile phones, music players, PDAs, etc. Connecting such devices wirelessly as in WBAN, paves the way for interesting applications in the future. Another interesting application of WBAN is in future computer gaming products. Gaming devices equipped with motion sensors and visual devices can revolutionize the gaming experience. Such devices would capture motions of the players through motion sensors and map the natural body movements into virtual world and interact with virtual objects.

A Wireless Body Area Network is defined as a network of implanted or on-body wireless modules performing a number of tasks. According to the IEEE report [9], an implanted node is a node placed immediately below the skin or deep inside the human tissue and an on-body node is a node placed on the skin surface or at most 2 cm apart. Unlike common wireless sensor networks, WBAN is a heterogenous network. i.e. nodes in a WBAN are not similar in general and perform different

tasks. In addition, the number of nodes is usually small in comparison with generic sensor networks.

A WBAN usually consist of a network coordinator (NC) and a number of implanted or on-body nodes. The NC is usually larger than the other nodes and is more powerful in terms of energy and computational resources. NC has the task of coordinating the whole network and keeping track of the nodes joining or leaving the network. In addition, NC acts as a gateway for communication to other networks. In other words, NC aggregates the data from nodes in the network and transmits to the other networks such as internet to be further processed. Furthermore, it receives and transfers commands from base station to the nodes. Nodes are usually consist of sensors to detect or measure a body parameter, a processor to perform simple or complex computational tasks and a transceiver to communicate with other nodes and NC. Depending on the functionality of the node, it may or may not have some of the mentioned components.

Due to the heterogeneity and diverse applications of WBAN, a range of different bit rates from few bits per second (temperature sensor in healthcare applications) to mega bits per second (video transfer in gaming applications) should be supported in a WBAN. Figure 1.1 shows the location of some sensing technologies which are developed or being developed for body area networks [10]. Electrocardiogram (ECG) is a continuous waveform showing the phases of cardiac cycles. Body temperature sensors measure the ability of body to generate and dissipate heat normally. Respiration rate sensor can detect abnormalities in respiration specially during sleep.

Figure 1.1: Typical WBAN.

Pulse oximeter sensor detects the amount of oxygen in the blood. Glucose meters measure the glucose level in the blood and could be used in combination with the insulin injection devices to deliver the exact amount of insulin to the blood. Electromyogram and electroencephalogram detect the muscle and brain activities respectively and accelerometers detect the movements of the body. Blood pressure sensor can constantly log the blood pressure of the patient throughout the day. Such logs can help in detecting long term and chronic diseases related to blood pressure.

Wearable health care devices have to satisfy very strict medical regulations while working under hardware resource constraints. These devices have to be very small and light while being able to work for a long period of time without changing the power source. In addition, radiation level of such devices should follow strict conditions imposed from both medical and technological regulatory agencies. Fur-

thermore, ergonomic and aesthetic aspects should be considered in the design of such devices to facilitate the use of the devices by the user. In addition to the above requirements, as mentioned before, WBAN is a heterogenous network. i.e. different nodes perform different task with different requirements such as bit rate, rate of transmission and size of the data they transmit. Hence, a candidate communication protocol has to be able to support all these requirements.

Communication in a WBAN could be divided into two parts, inter-communication between nodes of the WBAN and intra-communication between NC and an outside network such as internet. Due to the relatively small size of WBAN, the network is usually considered to have a classical star topology where all node communicate with the master device or NC. Communication to the other networks usually needs a higher data rate as aggregated data from nodes in WBAN have to be transmitted to the base station.

Existing communication protocols could be divided into two major categories. The first category encompass the conventional narrowband modulations. In narrowband modulation, a single carrier frequency is modulated in amplitude, phase or frequency to convey the information. The following wireless technologies fall in this category.

High rate communication technologies such as WiFi, GSM, WiMAX are suggested for communication between WBAN and outside networks. WiFi is a popular wireless technology working at 2.4 GHz band and supports up to 600 Mb/s at 32 m in indoor environments [8]. GSM is mainly designed to carry human voice over the telephone network. GSM has much lower data rates (between 30-200 Kb/s) for long distances

(400 m-3 km). WiMAX is designed to deliver high data rate (30-40 Mb/s) at long distance (9-16 km).

While these technologies provide reliable and fast data rates for external links, they are not the optimum way for communication between nodes in a WBAN. This is because these technologies are mainly designed for long range, between a few meters to several kilometers. Devices using these technologies usually need larger power resources and normally need to be recharged every day. Short range communication technologies such as, ZigBee, Bluetooth and UWB are suggested for inter-communication in WBAN [8,11].

Bluetooth is a short range wireless technology designed to connect fixed and mobile devices over short distances (5-100 m) and with data rates up to 3 Mb/s. The operating band for Bluetooth standard is the unlicensed ISM band at 2.4 GHz frequency. Bluetooth technology uses frequency hopping technique over 79 channels to avoid interference and fading in this high traffic band. The network configuration of Bluetooth standard is the star topology network, piconet, in which a master node can support up to seven slave nodes. In Bluetooth standard, communication is mostly between master and slave while a seldom used broadcast mode is also supported.

ZigBee standard [12] is another short range wireless technology with more emphasis on low power and low cost wireless networks. Nodes in ZigBee standard can work on single battery charge for months or even years. ZigBee devices operate in the ISM band at 2.4 GHz, same as Bluetooth, and can support up to 250 Kb/s and distances

up to 90 m. ZigBee protocol stack can support star, tree and mesh topologies. In addition, ZigBee supports advanced encryption standard (AES) with 128-bit keys which provides better security and integrity for the network data communication.

Another category of wireless technologies fall in the ultra-wideband (UWB) definition. According to Federal Communications Commission (FCC), a UWB device is any device that has fractional bandwidth over 0.25 or has a bandwidth greater than 500 MHz where fractional bandwidth is defined as,

$$r = 2 \frac{f_H - f_L}{f_H + f_L}. \quad (1.1)$$

where, f_L and f_H are the lower and upper -10dB cutoff frequencies respectively. UWB technology is relatively new compared to the above wireless standards. Under FCC ruling [13], 3.1-10.6 GHz band has been released for UWB device development. However, such devices have to follow a strict limit on radiated power in this band. The spectrum mask imposed in UWB band by FCC is shown in Figure 1.2. This unlicensed band could be utilized for short range communications in two ways, Orthogonal Frequency Division Multiplexing (OFDM) and impulse radio. In OFDM modulation, the channel is divided into several OFDM sub-channels with at least 500MHz bandwidth and is used as conventional OFDM. In UWB impulse radio (UWB-IR) modulation, a UWB pulse occupies the whole band while its spectral density is below the strict FCC spectral mask. In UWB impulse radio modulation,

a train of pulses convey the information where data is embedded in the position or amplitude of the pulses [14].

Figure 1.2: FCC spectrum mask.

Among the existing short range communications technologies ZigBee and UWB share the features that matches the requirements of the body area networks. Both technologies provide low cost and low energy connectivity between nodes in a BAN while their transceivers size is in the order of several millimeters to centimeters. Although these technologies are promising in the development of future body area networks, there are some challenges that need to be addressed before such applications materialize.

One of the major challenges in the development of BAN specially in healthcare applications is the life time of the individual nodes. As mentioned before, wearable computing devices have to be designed such that they impose the least interference with the daily activities of the user. For this reason and also aesthetical aspects,

such devices have to be as small as possible. Small dimensions imposes strict limitations on the energy resources of the nodes. Hence, the nodes have to use their valuable energy source efficiently to sense, process and transmit data. Receiving and transmitting data is one of the major sources of energy consumption in body sensor nodes [4]. Therefore, minimizing the data communication can significantly save the power source of the node and hence increase the life time of the system. This signifies the importance of a comprehensive protocol stack that is specifically designed for WBAN and covers the requirements of diverse applications of WBAN while maintaining a reasonable quality of service (QoS). Such protocol stack has to satisfy upper layer QoS criterions such as, latency, reliability, security, network and nodes life time, etc. and in the meantime overcome the lower layers challenges such as multiple access schemes, energy efficient routing, network topology changes and disconnections due to movements of human body.

While the design of a power efficient protocol for WBAN is of great importance, evaluating the performance of such protocols for different QoS merits is of equal importance. A prerequisite of an accurate WBAN system performance evaluation is a realistic radio channel model which is able to reproduce the real on-body channel characteristics closely and predict the performance of the network.

This research is motivated by the challenges and shortcomings of the system design and evaluation of wireless body area networks. In the first part of this research, the lack of a comprehensive channel model for dynamic radio links in a wireless body area network based on the natural dynamics of the human body is addressed.

In other words, a statistically accurate dynamic model based on comprehensive measurement campaign is provided for on-body radio links which can be used in designing and testing of on-body wireless networks. The surface to surface radio links categorized (CM3) in [9] are measured around a moving human torso using a real-time oscilloscope. The advantage of using the real-time oscilloscope is that it can capture the temporal features of the channel in real-time which give rise to a more accurate model when the channel is time varying as is the case in this research. In addition, power efficient opportunistic and adaptive routing protocols are proposed for dynamic body area networks and the performance of the system using these protocols is evaluated using the dynamic channel model.

1.2 Objectives

The main objective of this research is to improve the performance of the wireless systems working under dynamic body environment. To fulfill the main objective, two primary challenges in the design and evaluation of wireless body area networks are identified and addressed. These challenges are described in detail in the following paragraphs.

Channel Model for Dynamic Surface to Surface Radio Links on Human Body

The current state of the art in radio channel model for human body is mostly based on static measurements in which the measurements are performed in stationary postures of the subject. On the other hand, dynamic nature of human body and daily activities, dictates the need for a comprehensive dynamic channel model. Therefore, this research is aimed to address the lack of such model which is crucial in testing and evaluating systems designed to work in an on-body wireless sensor network. The model is based on a comprehensive time domain measurements where the time varying features of the channel are captured and characterized in the model.

Adaptive Routing Protocol for Wireless Body Area Networks

Human body is a dynamic environment and the topology of the on-body sensor network is time varying. Hence, network protocols which are designed to work in WBAN have to accommodate changes in the network topology. This research is aimed to exploit the topology variations to enhance the performance of the system working in an on-body environment and optimize the energy consumption of the individual nodes as well as the whole network.

1.3 Contributions

In this research, a novel comprehensive channel model for dynamic radio links of wireless body area networks is provided. The model is based on measurements performed on different parts of the body and for several subjects. In addition, an adaptive routing protocol is developed for wireless body area networks. In this protocol, the source node decides on the routing scheme based on the channel information. The adaptive routing protocol is then evaluated using the dynamic channel model for WBAN. It is shown that, adaptive protocol can significantly reduce the energy consumption of the nodes and hence increase the lifetime of the network. In addition, results show that adaptive routing can significantly improve the packet delivery success rate of the source node while reducing the outage probability. The main contributions of this work are as follows:

Real-time Dynamic Channel Measurements on Human Body in Indoor Environment

A comprehensive measurements campaign was performed for on body radio channel in different postures. Static measurements were performed for standing, sitting and lying postures while walking as the most common daily activity was used for dynamic measurements. Measurements were performed using a real-time oscilloscope and in both narrow band and ultra-wideband.

Channel Model for Dynamic Surface to Surface Radio Links on Human Body

A novel channel model based on the real-time measurement of the dynamic radio channels in a body area network is provided. Statistical analysis is performed on different parameters of the channel and typical values of the parameters and their distributions are presented. In addition, an algorithm for reconstructing the samples of the channel response for different radio links over the body is provided. Finally, the performance of the model in predicting the channel and system parameters such as RMS delay spread and BER is evaluated and compared with the estimated parameters from the real-time measured data. The results show that the proposed model can closely predict the BER performance of a system designed to work in an on-body environment. The dynamic channel model around human body detailed in Chapter 4 has been accepted for publication as full paper in the Tier-1 International Journal IEEE Transactions in Microwave Theory and Techniques.

Coded Bit Modulation for UWB Impulse Radio

This research introduces Coded Bit Modulation (CBM), a new modulation for UWB impulse radio which is based on time-hopping binary phase-shift keying (TH-BPSK). In CBM, bit information is modulated in the spreading code associated with each symbol rather than the amplitude of the pulses. It is shown that this scheme enables the intermediate nodes to combine and transmit packets from other nodes together with their own packets without extra energy usage. This advantage can be utilized

in wireless sensor networks to increase the redundancy where a node can combine its data with a neighbor node's data in a single stream and transmit. Receiver design for CBM is presented and the BER performance is derived mathematically. Coded Bit Modulation detailed in Chapter 6 was presented in the 2013 IEEE 77th Vehicular Technology Conference (VTC), Dresden, Germany.

Opportunistic Routing in Wireless Body Area Networks

CBM modulation for UWB impulse radio is incorporated in an opportunistic routing protocol to improve the energy efficiency of the routing in WBANs. The cooperation between the nodes is extended to the case when some nodes are located on moving parts of the body such as hand. Then, using an opportunistic approach, the hand movements were exploited to preserve the energy of the relay node and hence increase the overall lifetime of the network. The opportunistic routing for wireless body area networks detailed in Chapter 6 is presented in the 2011 IEEE Consumer Communications and Networking Conference (CCNC), Las Vegas, USA.

Adaptive Routing in Wireless Body Area Networks

This work has three major contributions, First, an analytical model for the transmission energy cost per bit of information is developed based on the Markov chain of the process and the model is validated through simulations. Second, power efficient adaptive routing protocol is proposed and the performance of the protocol in terms of energy efficiency and outage is evaluated and compared with the standard

in system level through mathematical analysis and simulations. Third, a statistical model for the received power in a dynamic body area network is provided through real-time, time domain measurements.

Analysis based on the Markov model of the protocol shows that the adaptive routing can reduce the energy cost of information bit significantly. The adaptive routing protocol detailed in Chapter 7 is submitted for publication in the Tier-1 International Journal IEEE Journal of Biomedical and Health Informatics (J-BHI).

1.4 Organization

The rest of this thesis is organized as follows. Chapter 2 surveys the state of the art in channel modeling, principles of UWB-IR modulations and energy efficient routing in body area networks. Details of the measurement setup, location and equipments are provided in Chapter 3. Chapter 4 provides the comprehensive measurement results and channel parameters for different parts of the body. Then, the proposed dynamic channel model for body area networks is discussed and the parameters of the model are described in detail and estimated from measurements. Subsequently, an algorithm is provided to reconstruct the samples of the channel impulse response using the model. In Chapter 5, a mathematical model is provided and analyzed for single hop and two hop routing schemes in IEEE 802.15.6 standard [15]. Chapter 6 introduces Coded Bit Modulation (CBM) for UWB-IR and evaluates the performance of this modulation. Then, CBM is incorporated in an opportunistic routing

scheme to reduce the energy consumption of the nodes while maintaining the desired packet error rate. The performance of CBM is then compared with existing protocols using the dynamic body area network model in Chapter 4. Chapter 7 gives an adaptive routing protocol to decrease the energy consumption of the relay nodes using adaptive routing strategy based on the channel conditions. Finally, Chapter 8 summarizes the contributions of this work and provides recommendations for future works.

Chapter 2

Literature Review

2.1 Channel Model

Channel models have been proposed for radio links around human body. These models are based on analytical derivations, simulations and statistical analysis of the measurements. Mathematical analysis of the wave propagation around body yields insight to how waves behave around body. However, solving near field equations for wave propagation around human body is a cumbersome mathematical task. Therefore, analytical channel models are mostly based on simplifying assumptions to make mathematical equations computationally tractable. To overcome the difficulties of mathematical analysis, simulations are performed to obtain a mathematical model for wave propagation around human body. While models based on simulations give rise to more realistic scenarios, layered structure of human tissue

and complex shapes of different dielectric regions inside the body necessitates some simplifications in the simulation process. Another modeling approach which has been investigated in literature is the statistical modeling approach. In this method, parameters of the channel around human body is statistically analyzed and a statistical model based on these parameters is constructed.

Wave propagation around human body has been studied in the literature [16–25]. Initial measurements for path loss around human body is presented in [22] for $2.45GHz$. In [23], path loss measurements are performed for body area networks in UWB band ($3–6GHz$) and the path loss exponent (n) in log-distance path loss model (d^{-n}) for wave propagation through human body is given as $n \approx 4.1$. The effect of antenna is numerically investigated in UHF band in [26]. In [27], path loss exponent is measured through FDTD simulation around human body and log-normal distribution is suggested for multi-path components of the channel. S21-parameter is measured between two antenna placements around stationary human body for frequency range of $3 – 6GHz$ in [17]. The path loss exponent (n) is reported as $n \approx 7.2$ and log-normal distribution is suggested for the variations in the amplitude through Akaike Information Criterion (AIC). In [16], authors have provided analytical and numerical results for wave propagation around human body. To simplify the analysis, the straight on-body paths are approximated by a dielectric plane and curved paths are approximated by a dielectric cylinder. The authors have fitted the path loss model (d^{-n}) and found path loss exponent $n \approx 2.4 – 2.5$ for straight path and $n \approx 4.0 – 4.5$ for curved paths. In [18], human body is approximated by an in-

finite lossy cylinder and the scattered electromagnetic wave is obtained analytically for a point source close to the cylinder. The results show that the electromagnetic energy decays proportional to distance away from body (d^{-n}) where $n = 2$ in free space and $n \approx 3 - 3.5$ for straight body paths. The decay is exponential around body trunk ($e^{-\gamma d}$). In [19], exponential law is suggested for on-body power decay and γ is estimated through simulations. Body parts and trunk are simplified as cylinders and an analytical model of wave propagation around body is presented in [21]. Based on this study, energy decay behavior is proportional to $d^{-n}e^{-\gamma d}$.

In addition to the average received power, small scale variations of the amplitude have to be included in the model. Small scale variations are the result of the overlapping of multiple arrival of the signal due to the multi-path effect and also the received noise. In [17], the immediate channel around human torso is separated from reflections of the indoor objects. Distributions for both types of channels are obtained statistically from measured data. In [20], major parameters of the channel such as path loss exponent and RMS delay spread are estimated through measurements. Numerical models are used for different antenna positions and estimated parameters are compared with measurements. In [19], authors have used a tapped delay line channel model for on-body environment and parameters of the model are obtained from measurements. In [28], authors have adopted Saleh-Valenzuela indoor channel model [29] for body area network based on the measurements performed on stationary subjects in UWB band. Large scale statistics as well as small scale variation of the amplitude of the arrival rays are estimated from the mea-

surements. In [30] and [31], parameters of the channel are statistically estimated through measurements and BER performance of the UWB signalling schemes are compared.

Nevertheless, most of the efforts so far have been in static channel modeling. i.e. the channel is measured and modeled while the subject is not moving. On the other hand, most of the daily activities includes some forms of motion. i.e. whole or some parts of the body has movements most of the time. Therefore, incorporating natural body movements in WBAN channel model is crucial. A few works have been done in literature to address this problem [32–35]. In [32], human movements are simulated using numerical methods and polarization diversity is investigated for various movements. Channel impulse response is obtained using Vector Network Analyzer (VNA) during two activities, eating and walking in [33]. In [35], log-normal and Rician distributions are suggested for slow and fast fading of the channel gains respectively. Pseudo-dynamic measurements of various movements such as bending, leaning forward and rotation of torso and arms are performed using VNA in [34]. In these measurements, the subject has been asked to remain still while VNA sweeps the whole band and then the body would go to the next posture and the measurements is repeated. Mean delay spread is estimated from the measurement data and performance of a system working under Multi-band OFDM is investigated in terms of Bit Error Rate (BER). A summary of measurements and the resulting channel models for different scenarios applicable in body area network is available in IEEE P802.15-08-0780-09-0006 draft for channel models in body area networks [9].

In this work, we address the lack of a channel model around a moving human body which will be discussed in later chapters.

2.2 UWB Impulse Radio

Ultra-Wideband (UWB) impulse radio has long been under investigation in various applications due to its interesting properties. Having a simple radio and low cost design, robustness to the narrowband interference and multi-path fading, fine time resolution for accurate positioning and being carrier-less are some of the UWB impulse radio's (UWB-IR) fascinating properties.

Although early works on using UWB for communication dates back to the 1990's [36–38], the academic and industrial attention was drawn to this band after the Federal Communications Commission (FCC) released a large bandwidth for UWB communication system limited by a spectral mask [13, 39].

Various modulation types have been proposed for impulse radio communication [36–38, 40–49]. In [36], a UWB impulse based system for transmitting digital information is proposed. A multiuser extension of such system is presented in [37]. In this article, a pseudo-random time-hopping code is used to avoid catastrophic collision between users. The bit information is embedded in the position of the pulse (Pulse Position Modulation). Pulse Amplitude Modulation (PAM) is introduced in [50] for UWB impulse radio in which the information is embedded in the amplitude of the pulses in a single symbol. A variation of pulse amplitude modulation is Binary Phase

Shift Keying (BPSK) in which the data is modulated by the polarization of the pulses in a symbol. The repetition of the pulse in BPSK modulation types creates spikes in the frequency spectrum of the pulse and hence degrading the performance of the system in accordance with the FCC rules. To prevent the creation of these spikes in the spectrum, pulse amplitude and position randomization is used in BPSK modulation [43,44]. In this type of modulation, the pulse train amplitude is assigned a random polarity code. This pulse based polarity and position randomization conforms with FCC spectrum rules as it decreases the spectral spikes created by the pulse train [51]. In modulations where time hopping is applied, the symbol time T_s is divided into N_f frames with time duration of $T_f \leq T_s/N_f$. Likewise, each frame is divided into N_c time bins or chips with the duration of $T_c \leq T_f/N_c$. Thus, a symbol consists of $N_c N_f$ chips and there is a UWB pulse every N_c chips. We refer to this pulse position randomization as time-hopping (TH). Performance of modulation with pulse amplitude and position randomization is analyzed in [43,51–53]. The following subsections will described different types of UWB impulse radio modulations in more detail as the concepts will be used in later chapters.

2.2.1 Pulse Position Modulation (PPM)

The use of a random time hopping sequence in UWB-IR for multiple access is described in [37]. The symbol carrying each bit consists of a number of UWB pulses repeated at specific time instances. The data is modulated in the position of the pulses. The symbol format of the k^{th} user is

$$s_k(t) = \sum_{i=1}^{N_f} g(t - iT_f - c_i^k T_c - \delta d_{[i/N_f]}^k). \quad (2.1)$$

where $g(t)$ is the UWB pulse shape transmitted by user k and d_i s indicate that if the pulse is shifted by δ and depend on the data. Here, we assume that all users transmit the same pulse shape. We will later discuss the case when the pulse shapes differ for different users. As mentioned earlier, the symbol is divided into N_f time frames where each has time duration of T_f . Each frame contains one pulse and hence the whole symbol consists of N_f pulses. To avoid catastrophic collision between different transmitters, each user is assigned a random time hopping (TH) code (c_i^k) which shifts the pulse position of the corresponding transmitter within a frame. In fact, c_i^k is an integer within the range

$$0 \leq c_i^k \leq N_c \quad (2.2)$$

N_c is the number of time bins within a frame and is defined such that

$$N_c T_c \leq N_f \quad (2.3)$$

Data is modulated in the position of the N_f pulses belonging to the same symbol. This is shown in Equation 2.1 by δ which is a small time shift multiplied by the value of the corresponding symbol bit. If the bit is 0 no shift is incurred and if it is 1 all pulses will be shifted by δ in time.

Assuming that N_u users are using the medium simultaneously, the received signal at the receiver is

$$r(t) = \sum_{k=1}^{N_u} A_k s_k(t - \tau_k) + n(t). \quad (2.4)$$

in which A_k is the mutual channel attenuation between receiver 1 and transmitter k and $n(t)$ is the channel noise. τ_k is the asynchronization between the receiver and transmitter. Here we assume that the receiver can synchronize with the desired transmitter using a synchronization algorithm. The objective of the receiver is to determine if the pulses are shifted where bit value is 1 or the pulses are not shifted indicating a bit value of 0. Assuming that only one user is transmitting, by knowing which pseudo-random code is being used by the user, the receiver has a template of the j^{th} transmitted symbol available given by

$$s_{temp}(t) = \sum_{i=jN_f}^{(j+1)N_f-1} g(t - iT_f - c_i T_c). \quad (2.5)$$

The received sequence of the symbols represented in terms of the receiver's template is given by

$$r(t) = \sum_m A_m s_{temp}(t - mT_s - \delta d_m - \tau_m) + n(t). \quad (2.6)$$

where T_s is the symbol period. The optimal receiver for this signal in additive white gaussian noise is a correlation receiver. Assuming synchronization, we have

$$I = \int_{jT_s \leq t \leq (j+1)T_s} r(t)v(t)dt. \quad (2.7)$$

where

$$v(t) = s_{temp}(t) - s_{temp}(t - \delta). \quad (2.8)$$

I would be positive over a symbol period if 0 is sent and negative if 1. A block diagram of such receiver is shown in Figure 2.1.

The received signal goes through a Low Noise Amplifier (LNA) and then is multiplied by two template of the replica of the original transmitted pulse, one positive and

Figure 2.1: Receiver Structure

one negative, provided by template pulse generator at the appropriate times. The timing is provided by the delay time controller according to the chosen pseudo-random code. The result is integrated and the output of the integrator is positive or negative according to the bit value. Decision making circuit generates the bit information based on the output of the integrator. The probability of the error for such correlation receiver in AWGN is,

$$P_e = Q\left(\sqrt{\frac{E_b}{\sigma_n^2}}\right). \quad (2.9)$$

where E_b is the energy of a bit and σ_n^2 is the variance of the noise.

2.2.2 Pulse Amplitude Modulation (PAM)

In PAM, the bit data is embedded in the symbol pulse train amplitude rather than the pulse positions [50]. The symbol structure of PAM is mathematically expressed as,

$$s_k(t) = \sum_{i=1}^{N_f} d_{[i/N_f]} g(t - iT_f - c_i^k T_c). \quad (2.10)$$

where d_i s are levels of amplitude of the pulses corresponding to the bit values. i.e. strings of bits are mapped to a specific level, d , and transmitted. Applying randomly chosen time slots within a frame guarantees non-catastrophic collision between users in time hopping PAM. It has been shown in [50] that PAM and PPM have the same Bit Error Probability (BEP). Both PPM and PAM modulations just described use the same polarity for the pulses within a symbol although the polarity may change for another symbol as is the case for PAM. However, repetition of a number of similar pulses with the same polarity causes spikes in the spectrum of the signal. The distance between these spikes is a multiple of the inverse of the pulse repetition rate. Figure 2.2.a shows a sample of the spectrum of a PPM modulated signal. Existence of such spikes can degrade the performance of the system to comply with the FCC spectrum regulations regarding UWB band.

2.2.3 Time Hopping Binary Phase Shift Keying (TH-BPSK)

A variation of PAM is proposed in [44] in which the pulse polarization changes randomly within a symbol. The symbol structure for this type of modulation is

$$s_k(t) = \sum_{i=1}^{N_f} b_{[i/N_f]} a_i^k g(t - iT_f - c_i^k T_c). \quad (2.11)$$

in which a_i^k randomly assumes ± 1 . $b_{[i/N_f]}$ conveys the bit information and remains the same during a symbol. It has been shown in [51] that this variation can improve the spectrum of the signal significantly. Spectrum of a TH-BPSK signal with and without pulse based polarity randomization is compared in Figure 2.2

(a) PAM spectrum without pulse based randomization

(b) PAM spectrum with pulse based randomization

Figure 2.2: Spectrum of a PAM signal without (Top) and with (Bottom) pulse based polarity randomization

2.2.4 Pulse Shape Modulation

The use of orthogonal hermite pulse shapes for multiple access is investigated in [54]. In this method, modified hermite pulse shapes are assigned to different users. The receiver can distinguish and extract the data from different users by correlating the received signal with the pulse shape of each user. In this way, the signal from the desired user gives rise to a non-zero output. This type of modulation can mitigate the effect of multiple access interference but it has no effect on intersymbol interference.

Modified hermite pulse shapes are given by,

$$h_n(t) = (-1)^n e^{-\frac{t^2}{4}} \frac{d^n}{dt^n} (e^{-\frac{t^2}{4}}). \quad (2.12)$$

Figure 2.3 shows the modified hermite pulse shapes for different values of n .

Figure 2.3: Orthogonal modified hermite pulse shapes.

2.3 Routing in WBAN

Body area network is a network of several heterogeneous on-body sensors with different functionalities and resources and a network coordinator (NC) which is the most powerful node in terms of energy and computational resources [8, 10, 55]. Network coordinator aggregates data from sensors in the network and transmits the data to a data processing center over an external link.

Routing data in body area network has been investigated in literature. Design of a personal gateway for communication with outside networks is investigated in [56]. Narrowband radio is compared with FM-UWB for connecting the sensor nodes in an on-body network in [57]. Results show that FM-UWB outperforms the narrowband radio in terms of energy consumption. In [58], communication between an implanted sensor node and an outside base station is investigated. A MAC layer protocol is

provided for a star topology of WBAN which uses a flexible bandwidth allocation to reduce the energy consumption of the nodes in [59]. In [60], cooperation between nodes in a multi-BAN network to route data to a sink node belonging to one BAN is studied. A stochastic route selection mechanism based on the maximum perceived outage probability, maximum queue utilization factor and the remaining battery power information is provided. The performance of the proposed scheme is assessed through system level simulation and has been shown to outperform random and best route selection schemes.

In general, existing routing protocols for WBAN could be assorted into three categories. Some protocols use a star topology. Star topology is the most simple network topology for BAN. In this configuration, communication between sensor nodes and network coordinator (NC) is direct or single hop. Direct communication between nodes and network coordinator simplifies the network protocol and reduces packet delivery delay when the link quality is high enough to satisfy the quality of service merit. However, as mentioned above, human body is a dynamic environment. As a result, the topology of the BAN can change drastically by time. Such variations in the network topology can cause high path loss between the source node and the network coordinator even though the nodes might be very close to each other. Thus, to compensate for the severe attenuation of the signal, transmission power has to be increased proportionally so that the signal reaches the destination with the desired SNR. Nevertheless, increasing transmit power severely affects the energy resources of the nodes and reduces the life time of the network. The reason is that, unlike

a generic sensor network where nodes are usually similar and can undertake each other's task in case one of them runs out of energy or fails, in a body area network, each node has a specific task which is different from other nodes. Hence, if a node fails the whole network might malfunction. To avoid increasing transmission power proportional to the path loss, cooperative communication is suggested for WBANs. In this type of protocols, each node is assigned to a higher level node. Network coordinator has the highest level. To reach NC, source node transmits its packets to higher level nodes in a multi-hop scheme until it reaches NC. Based on the number of nodes and network topology, the number of hops can vary between two to several hops. Multi-hop communication is investigated for routing data in BAN [61–64]. In [61], using extra nodes and cooperation between nodes to relay information to the base is compared with the single hop scheme. The simulation results show that the relay network can greatly improve the life time of the network. Network life time is defined as the time interval between the time network starts working to the time in which the first node dies in the network. It has been shown that in the single hop scheme the nodes with highest distance from the sink will be drained out of energy and die faster while in the multi-hop case the relay nodes closer to the sink have much higher energy consumption due to the traffic they carry. In [64], performance of non-cooperative communication is compared with cooperative communication in body area network environment. It is shown that cooperation can reduce energy consumption in higher path loss environment while direct transmission is preferred in lower path loss environment. In addition, it is suggested that prior knowledge of the body posture can improve the energy efficiency. While such

protocols provide higher packet delivery success rates and reduce outage probability, they severely increase energy usage of the nodes due to excessive and unnecessary packet retransmissions. Opportunistic routing is suggested and analyzed for BAN in [65–68]. In opportunistic routing, each node is assigned to a pre-defined node. During the packet transmission, the relay node assigned to the source node tries to pick up the packet. If the relay receives the packet successfully it would forward it to the destination node (NC) at another session. It has been shown that opportunistic routing can improve packet delivery success rate while reducing the outage probability in comparison with direct and multi-hop routing protocols.

Although routing has been investigated in WBAN, there is still a need for routing schemes that can accommodate for the specific conditions of a body area network. As mentioned in the Introduction on WBAN, sensor nodes in a body area network have to be small and ergonomic. The small dimensions means small antenna size which in turn translates to higher frequency bands usage. On the other hand, human body is considered a hostile environment in terms of electromagnetic propagation for higher frequencies (microwave and above). This is because higher frequencies are greatly attenuated inside and in the close vicinity of human body. This means that two on-body nodes may experience very weak connectivity even though they are located in very close proximity. To make everything worse, human body is a dynamic environment. This means that the on-body network topology is changing drastically by time. Such changes could be quite abrupt and can affect the channel severely even between two nearby nodes. Hence, there is a great need for a routing

protocol specifically designed for body area networks which includes all these considerations. In the following chapters, we exploit the dynamic nature of the on-body network to use energy of the nodes in the network efficiently. The proposed protocol can adaptively choose the best scheme to route data and hence reduce the energy consumption of the nodes compared to existing routing schemes.

2.4 Summary

Channel models have been proposed for radio links around human body. These models are based on analytical derivations, simulations and statistical analysis of the measurements. Analytical channel models are mostly based on the simplifying assumptions to make near field equations tractable. To overcome the difficulties of mathematical analysis, simulations are performed to obtain a mathematical model for wave propagation around human body. Another modeling approach is to model the channel around body statistically. Models developed so far are mostly based on static postures of the body. Considering the dynamic nature of human body there is still a need for a mathematical model for the channel around a moving body which is addressed in this thesis.

Existing routing protocols are mostly based on static channel models. However, channel around human body is a dynamic channel with specific properties. Hence, there is still a need for a routing scheme that can accommodate for the hostile and time varying environment in a body area network while using the energy resources

of the nodes efficiently. The new dynamic channel model presented in this thesis is then used to develop an energy efficient adaptive routing protocol.

Chapter 3

Measurement Setup and Equipments

Measurements were performed in Nanyang Technological University. Figure 3.1 shows the map of the rooms and the furniture and equipments arrangements. The locations of the measurements are shown by circles. The main area's dimensions are 20×16.5 m and is equipped with cubicles, tables, chairs, and PCs. Cubicles walls are 1.65m high and have a table and a PC each. Measurements are performed in the main area as well as two rooms inside the main area. People are randomly moving about during measurements in the main area. Room 1 is 5×3 m and is equipped with a table, two PCs, two chairs and a sofa. Room 2 is 5×2 m and is used as a storage room. It contains equipments such as pulse generators, oscilloscopes, etc. positioned on a table. The room is equipped with a desk, a PC and a chair as well. Figure 3.2 shows a view of the experiment room.

Figure 3.1: Schematic of the experiment room and location of the equipments.

Figure 3.2: View of the experiment room 1.

The following equipments are used in the measurements.

3.1 Digital Storage Oscilloscope

An Agilent DSO80804B 80000B Series Infiniium real-time oscilloscope was used to receive the transmitted signal and also to transfer data to the PC. The oscilloscope has 4 input channels with a bandwidth of 8 GHz and is able to sample up to 40 GSamples/s. The noise floor of the oscilloscope at 5 mV/div is 294 μ V and the trigger time jitter is less than 500 fs (rms). The inputs are equipped with 4 BNC-compatible connectors. Figure 3.3 shows a view of the front panel of the oscilloscope.

Figure 3.3: Front panel of the oscilloscope.

Figure 3.4: Front panel of the impulse generator.

3.2 UWB Pulse Generator

A PicoSecond impulse generator (Model 3500D) was used to generate the required UWB pulse. The generated pulse has fine time resolution with a full width at half maximum (FWHM) of 75 ps and peak amplitude of 8 V with a selectable positive or negative polarization. Pulse repetition rates up to 1 MHz is supported via an SMA-compatible output port. Two microwave quality attenuators provide the desired attenuation at the output port. Figure 3.4 shows the front panel of the pulse generator. In Figure 3.5.a the UWB pulse generated by impulse generator is shown. Frequency spectrum of the pulse is shown in Figure 3.5.b.

3.3 Analog Signal Generator

Agilent PSG Analog Signal Generator E8257D was used to provide carrier frequencies for narrowband measurements. The signal generator is capable of producing carrier signals in the range of 250 KHz-20 GHz and output power up to 26 dBm at 20 GHz. The signal generator supports AM, FM and Phase modulations and has a built in sweep function. The front panel of the signal generator is shown in

(a) UWB pulse generated by impulse generator.

(b) Spectrum of the impulse.

Figure 3.5: The impulse generated by impulse generator in time and frequency domains.

Figure 3.6: Front panel of the analog signal generator.

Figure 3.7: Power splitter.

Figure 3.6.

3.4 Broadband Power Splitter

Mini-Circuits ZFSC-2-10G wideband low loss power splitter was used to provide the trigger signal for the oscilloscope. The power splitter has a bandwidth of 8 GHz and loss of 0.5 dB in the frequency range of 2-100 GHz. The maximum input power is 1 W and the input and output ports are SMA-compatible. Power splitter is shown in Figure 3.7.

3.5 UWB Omni-Directional Antenna

SkyCross Omni-directional antennas (SMT-3TO10M-A) were used to transmit and receive signals. SkyCross antennas have a bandwidth of 3.1-10 GHz and peak gain of 4.4 dBi at 4.5 GHz. Radiation pattern is omni-directional in azimuth plane and the feed impedance is $50\ \Omega$. The dimensions of the assembly PCB area of the antenna are " $26.2 \times 18.5 \times 1$ " and the antenna element dimensions are " $13.6 \times 16 \times 3$ ". Figure 3.8 shows the antenna. The radiation pattern of the antenna is shown in three planes in Figure 3.9 [69].

Figure 3.8: Antenna.

3.6 Experiment Setup

Measurement setup was performed by connecting the signal generator output to the transmitter antenna using coaxial cables. The signal was received by the receiver

Figure 3.9: Radiation pattern of the antenna.

Figure 3.10: Block diagram of the experiment setup.

antennas which were attached to the input ports of the oscilloscope. The oscilloscope was triggered through "AUX" input by the trigger output of the impulse generator. The antennas were fixed against the subject body using plastic material with dielectric values similar to air to prevent unwanted reflections. The oscilloscope connects to the PC using GPIB interface. MATLAB was used to receive and process the signals. Figure 3.10 shows the block diagram of the experiment setup and the equipments.

Chapter 4

Channel Model for Dynamic Radio Links in WBAN

This chapter provides a model for dynamic body radio channel. First, the measurements results of the different parameters of the channel are provided and discussed. Then, a channel model is provided based on the statistical analysis of the measurements. Subsequently, an algorithm is provided to create samples of the channel response based on the model. Finally, system level evaluation of the model is compared with independent measurements.

4.1 Average Received Power and Path Loss Model

In this work, to determine which model better explains the wave propagation behavior, Akaike Information Criterion (AIC) is used as the comparison criterion. It

is noteworthy to mention that AIC only provides a measure of how good a model fits to the data among several candidate models but is unable to suggest the best model for the data.

4.1.1 Akaike Model Selection Criterion

AIC is defined as follows [70]:

$$AIC_c = -2\log_e(l(\theta|y)) + 2k + \frac{2k(k+1)}{s-k-1} \quad (4.1)$$

where the first expression on the right side of the equation is the logarithm of the maximum likelihood function obtained from sample space $\{y \in Y\}$; k is the number of estimated parameters and s is the sample size. The second and third terms penalize the AIC score against the number of parameters used in the model and sample size. The model with the least AIC score is the best model describing the available data. Note that AIC score is only interpreted relatively and its absolute value is data dependant.

4.1.2 Path Loss Model

Path loss model reflects the large scale variations in the channel gain. When propagating away from the objects, radiated electromagnetic energy decays proportional to d^{-n} , where d is the distance between the source node and the receiver node and

n is the path loss exponent. n is 2 for free space propagation environments and is shown to be between 1.6 – 3.5 for indoor communication [71]. However, such models are mostly valid with the far field assumption. In the near field area, where waves are guided by boundaries such as waveguides or other objects, the energy decay can follow other functions [72].

As mentioned in Section 2.1, due to the complexity of the near field wave propagation, the exact analytical solution could not be obtained without simplifying assumptions. On the other hand, a reliable model has to be based on the empirical data rather than simplified analytical results. In this section, the two major models, log-distance decay model (d^{-n}) vs. exponential decay model ($e^{-\gamma d}$) for straight and curved body paths are compared based on AIC to determine which model best fits empirical measurements.

To determine which model best fits the path loss on different on-body paths, received power was measured in time domain using the UWB pulse generator and the oscilloscope. Path loss was obtained by dividing the received power with the transmitted power from the pulse generator. To estimate parameters of the two models (n, γ), received power in dB was fitted to a degree one polynomial as follows,

$$\begin{aligned} PL_{dB} &= -10n \log(d) + C_1, & \text{log-distance model;} \\ PL_{dB} &= -10 \log_{10}(e) \gamma d + C_2, & \text{exponential model;} \end{aligned} \quad (4.2)$$

Table 4.1: Height and weight of the subjects

	Height(m)	Weight(Kg)
Subject1 (Male)	1.77	76
Subject2 (Male)	1.79	87
Subject3 (Female)	1.60	48
Subject4 (Male)	1.77	67
Subject5 (Female)	1.56	44
Subject6 (Male)	1.87	88

where C_1 and C_2 are constants that account for the system and cable losses. C_1 and C_2 are eliminated when n and γ are calculated,

$$\begin{aligned}
 n &= \frac{-1}{10} \frac{PL_1 - PL_2}{\log(d_1) - \log(d_2)}, \\
 \gamma &= \frac{-1}{4.34} \frac{PL_1 - PL_2}{d_1 - d_2}.
 \end{aligned} \tag{4.3}$$

where PL_1 and PL_2 are path loss values in dB measured at the distances d_1 and d_2 from the transmitter. Figure 4.1 shows a sample of the curve fitting.

The experiments were performed on 6 subjects, two of which were females. Heights and weights of the subjects are given in Table 4.1.

To determine the best model for the path loss, curved and straight on-body radio links were measured. Measurements were performed around waist (C1), leg (C2), arm (C3) and along arm (S1), leg (S2), along body from waist to chest (S3), wrist to lap (S4), left wrist to left lap (S4), left wrist to right side of the waist (S5) and waist to head (S6) as shown in Figure 4.2 where 'C' denotes curved paths and 'S' denotes straight paths. Every 16 acquired signals were averaged to improve the signal to

(a) Log-distance

(b) Exponential

Figure 4.1: Samples of curve fitting to the log-distance and exponential models.

Figure 4.2: Links measured for path loss exponent: 'S' indicates straight path and 'C' indicates curved path.

noise ratio.

Placement of the antennas are shown in Figure 4.3.

According to Equation 4.1, Akaike score for the two models are obtained using the following equations,

$$\begin{aligned} AIC_{\log\text{-distance}} &= 2n\log(d) + 2, \quad \log\text{-distance model;} \\ AIC_{\text{exponential}} &= 2\gamma d + 2, \quad \text{exponential model;} \end{aligned} \quad (4.4)$$

Normalized Akaike score for the subjects are given in Table 4.2,

Akaike score for measurement data of all paths, both curved and straight, shows that

Figure 4.3: Placement of the antennas.

Table 4.2: Akaike score data

	AIC	Subject 1	Subject 2	Subject 3	Subject 4
C1	Poly	0.13	0.02	0.20	0.22
	Exp	0.36	0.11	0.28	0.24
C2	Poly	0.07	0.20	0.13	0.28
	Exp	0.18	0.22	0.28	0.32
C3	Poly	0.79	0.96	0.92	0.64
	Exp	0.84	1.00	0.93	0.73
S1	Poly	0.38	0.23	0.26	0.45
	Exp	0.47	0.29	0.33	0.49
S2	Poly	0.20	0.53	0.20	0.26
	Exp	0.31	0.57	0.36	0.34
S3	Poly	0.31	0.23	0.20	0.42
	Exp	0.44	0.30	0.29	0.46
S4	Poly	0.51	0.47	0.31	0.48
	Exp	0.63	0.59	0.45	0.60
S5	Poly	0.24	0.18	0.12	0.21
	Exp	0.38	0.25	0.16	0.22
S6	Poly	0.12	0.08	0.13	0.21
	Exp	0.27	0.15	0.18	0.28

polynomial (log-distance) decay path loss model (d^{-n}) has a better fit to the data than its exponential counterpart ($e^{-\gamma d}$). Figure 4.4 shows the normalized Akaike scores for the two models, subjects 1 to 4 and different on-body paths. The same trend is observed in all subjects.

Path loss exponent was estimated for different points along the measurement path and the values are given in Table 4.3. As seen in the table, path loss values are larger for curved paths than straight paths. This is expected as the links with curved paths receive energy mostly via diffraction around the body parts and hence suffer more attenuation than a direct path.

This is consistent with the energy decay model near non-conductive objects. As the human body has small conductivity compared to metallic objects and wave-guides, it is expected that the energy decay model near human body to be the same as the energy decay model near non-conductive surfaces.

Figure 4.4: Normalized Akaike scores for log-distance(d^{-n}) and exponential($e^{-\gamma d}$) models for 4 test subjects

Table 4.3: Path loss exponent for different on-body links

Path	n	γ
S1	2.59	50.61
S2	2.77	52.36
S3	3.744	70.12
S4	2.15	41.56
S5	2.03	40.32
S6	2.05	40.44
C1	4.40	75.32
C2	3.77	70.15
C3	3.67	69.10

4.1.3 Path loss at 400MHz

Path loss exponent was estimated for different points along the measurement path and the values are given in Table 4.4.

Table 4.4: Path loss exponent for different on-body links

Path	n
S1	3.02
S2	2.42
S3	2.85
S4	2.03
S5	2.09
S6	2.14
C1	2.72
C2	3.48
C3	2.95

4.2 Distribution of the Received Power Variations

UWB channel is different from its narrowband counterpart where in UWB channel, the reflections arrive in different resolvable time bins and do not overlap.

To model the channel gain in UWB band at different on-body nodes, the received power was divided by the transmitted power from the pulse generator. Then, AIC score was obtained for the candidate models as described in the previous section, Log-normal, Rayleigh and Rician. Based on AIC, log-normal distribution is the best fit for the variations of the channel gain in this band. Figures A.8-A.14 in Appendix A show the variations of the channel gain vs. time and its distribution in this band. Parameters of the log-normal distribution in this band is given in

Table 4.5.

Table 4.5: Parameters of the log-normal distribution of the channel gain variations of the first arriving ray in UWB band.

	μ	σ		μ	σ
L_{10}	-13.61	1.93	L_{01}	-13.36	1.07
L_{12}	-13.13	0.77	L_{02}	-15.10	0.57
L_{13}	-12.94	0.61	L_{03}	-16.72	1.33
L_{14}	-14.05	0.41	L_{04}	-13.48	0.42
L_{15}	-15.77	1.53	L_{05}	-13.10	0.25
L_{16}	-16.88	0.97	L_{06}	-17.42	0.96
L_{17}	-16.79	0.95	L_{07}	-16.13	0.32

4.3 Power Delay Profile Measurements

To model the small scale variations and ray arrival times, a set of measurements was performed using the same equipments and pulse specifications as given in Chapter 3. In this set of experiments, a grid of 4 receiver nodes with 1 cm separation were installed at four on-body locations with possible future applications interest. The antenna installation map is shown in Figure 4.5. Calibration was performed to compensate for cable loss, connection mismatch and other imperfections in the signal path from the antenna to the oscilloscope. To calibrate different input ports, all receivers were placed at a known distance (0.5 m) and the signals were compensated to be the same as channel 1 in peak amplitude. As the cable length and antenna

Figure 4.5: On-body links used for modeling.

characteristics remain constant during the movements, the compensation factor is assumed constant throughout the measurements.

Receiver grid 1 was positioned on the chest of the subjects and at the center. Chest is a candidate location for ECG sensor in medical and recreational applications. Receiver grid 2 was positioned on the wrist where sensors such as blood pressure and pulse measurement sensors can be installed. Receiver grid 3 was placed on the head over the left ear. This is where EEG sensor, hearing assistant devices and mobile phone headsets are installed. Receiver grid 4 was placed on the ankle. This position is mostly used by motion sensors, pace meters etc. The transmitter was placed on the waist. This is where larger devices with more resources (memory, energy source etc.) such as PDA and mobile phones are usually placed. Hence, this node can be considered as the candidate location for the NC which can organize the network and communicate with the outside world.

To characterize the effect of movements on the on-body radio channel, about 64 seconds of natural movements were captured where each acquisition took about 0.08 seconds to complete such that normal walking movements of the body do not affect the measurements. After 64 seconds, about 200 acquisitions of the real-time channel impulse responses were available for each receiver of the grid i.e. 800 signals for each location. During the measurements, the subjects were asked to imitate walking for about 20 seconds, then bend, pick up an object and put it on a table or sit on a chair, stand up and then continue walking [34,73,74]. Meanwhile, the oscilloscope acquired time domain impulse responses of the channel. Each acquisition is the average of 16 real-time recorded signals to improve the signal to noise ratio and to compensate for pulse amplitude fluctuations. In total, 3200 signals with approximately 1300 data points were collected for 4 on-body paths. Measurements were performed on 6 subjects at various locations in the 3 rooms as shown in Figure 3.1. A total of 28800 samples of the channel responses were collected and analyzed. Measurements from Subjects 1-4 were used to create the model while Subjects 5-6 measurements were used to compare and validate the model. Samples of the power delay profile captured at the middle receiver of the grids 1-4 from Subject 1 are shown in Figures B.1-B.4 in Appendix B.

4.4 RMS delay spread

Placement of the on-body gateway is of great importance. This is because the gateway has the task of transmitting the data gathered from nodes in the network to the base station, receiving and transferring commands from the control center to the nodes in the network. Hence, the gateway has to have an unobstructed link most of the time. On the other hand, due to the movements of the body parts, the connection of the gateway and the base station might be obstructed in case the gateway is not placed appropriately. Our observation shows that, placing the gateway in locations where it can receive several copies of the transmitted pulse through multi-path reflections can reduce the probability of disconnection and improve the signal to noise ratio (SNR). When the channel between two on-body nodes has less obstruction from body parts, delay spread of the channel would be large in indoor environment. This is because, nodes with longer delay spread can receive reflections from surrounding objects as they are not severely obstructed by the body parts. Hence, placing the gateway in places with longer delay spreads decreases the probability of outage.

Mean delay spread and RMS delay spread are two metrics usually used to characterize the delay spread of the channel. Mean delay and RMS delay spread are defined as follows [71]:

$$\begin{aligned}\bar{\tau} &= \frac{\int_0^{\infty} \tau A_c(\tau) d\tau}{\int_0^{\infty} A_c(\tau) d\tau} \\ \tau_{rms} &= \sqrt{\frac{\int_0^{\infty} (\tau - \bar{\tau})^2 A_c(\tau) d\tau}{\int_0^{\infty} A_c(\tau) d\tau}}\end{aligned}\quad (4.5)$$

where $A_c(\tau)$ is the power delay profile of the channel and τ is the time interval relative to the first arriving ray.

To find the best on-body locations for placing the gateway, mean and RMS delay spread of the channel at the candidate on-body locations were obtained through measurements at standing, sitting and lying postures. The location of the transmitter and receivers for this measurement setup are shown in Figure 4.5.

In the standing posture, the subject was standing with hands relaxed at the sides of the waist and at the center of the room. In sitting scenario, the subject was asked to sit on a chair with both hands positioned on the lap. To measure delay spread in the lying state, the subject was asked to lie supine on a sofa with hands relaxed at the sides. Head was slightly raised by a pillow to mimic a natural sleeping state.

The mean value of the RMS delay spread in the different scenarios are shown in Figures 4.6-4.8.

As seen in the figures, the receiver on the head has the largest RMS delay spread value. This is because this receiver can receive the surrounding reflections from a wider range of angles compared to the other receivers which are blocked by body

Figure 4.6: Average RMS delay spread for standing posture at different on-body locations.

Figure 4.7: Average RMS delay spread for sitting posture at different on-body locations.

Figure 4.8: Average RMS delay spread for lying posture at different on-body locations.

parts. Ankle and wrist have approximately the same RMS value and chest has the least. This is because, the chest receiver is blocked by body trunk from one side and only receives the rays arriving in front of the body. This weakens the late arriving rays as these are the combination of the energy reflected by far objects. Blocking parts of these rays will decrease the energy received in late time and hence reduces the RMS delay spread value compared to the other receivers.

In sitting posture, hands were placed on the lap and hence both wrist and chest receivers are shadowed by the body trunk from the rays coming from objects located behind the body and hence have similar RMS delay spread values.

In lying posture, the subject was lying supine on a sofa with hands at the sides of the body. The sofa is covered by dielectric material although it has a metallic skeleton. Hence, body could be considered floating in the air from the electromagnetic point

of view. In this posture, head, wrist and ankle receivers are approximately at the same level and hence have similar RMS delay spread values. However, chest has smaller RMS delay spread value as it is blocked by body trunk and does not receive the ray coming from the ground and other objects under the body trunk.

In conclusion, head and wrist have the longest delay spread compared to the other nodes and hence are more accessible from an outside network. This makes these two nodes a better option for placing the gateway. Depending on the application, priority might be given to either of these nodes.

To compare the effect of movements on the connection with outside networks, delay spread variations were obtained during the walking activity and are compared with the standing posture. Figure 4.9 compares the average value of RMS delay spread of standing vs. walking measurements. As observed, the mean value of RMS delay spread does not show significant change for standing and walking measurements.

On the other hand, moving parts of the body show the highest variations in the delay spread than less moving body parts. This is reflected in Figure 4.10. In the figure, variance of the time variations in RMS delay spread is shown for different nodes. As expected, wrist has the largest variations in RMS delay spread and these variations are periodic. As the wrist is moving from the front part of the body towards the back, it loses line of sight with the transmitter and other parts of the body such as the opposite hand, chest and front parts of the leg and hence cannot receive reflection from these parts. When the wrist is at the back, the most contributing signal is the diffracted wave around torso which arrives at the receiver on the wrist.

Figure 4.9: Comparison of average RMS delay spread for standing and walking.

When the wrist gains line of sight position with the body parts, the RMS delay spread value re-correlates with the previous values.

4.5 Power Delay Profile Model

The tap delay line model better suits the dense environment around human body in terms of multi-path components [19], and is expressed mathematically as follows:

$$C(t) = \sum_i h_i \delta(t - \tau_i). \quad (4.6)$$

Figure 4.10: Variance of RMS delay spread for walking.

where, i is the ray (multi-path) number, h_i and τ_i are channel gains and delay associated with each arriving ray and δ is the Dirac impulse function. In the rest of this chapter, we characterize the parameters of this model based on the measurement data.

4.6 Average Amplitude Model

To obtain the distributions of h_i and τ_i , first, the time axis was divided into bins slightly larger than the pulse width. Then, arrived replicas of the transmitted pulse in each bin were deconvolved from each recorded sample of the channel impulse response using CLEAN algorithm [75, 76]. The output of the CLEAN algorithm is

a set of times and amplitudes corresponding to each multi-path where each multi-path can be a combination of several overlapping pulses. Deconvolution process was continued until the energy of the detected pulse fell below the received noise energy. As we observed, pulses arrive in random polarity (± 1) with uniform distribution. Hence, from now on, the absolute value of the amplitude will be modeled. The random polarity of the pulses will later be incorporated into the model when reconstructing the impulse response based on the model. In the next step, the average amplitude pattern of the received multi-path rays were investigated to find a trend. We observed that the average as a function of multi-path (ray) number give rise to an interesting pattern in time. Observations show that the average of the amplitude fits well to a truncated Gaussian curve as a function of multi-path number where multi-paths are ranked according to their time of arrival. Using multi-path number is appropriate considering the dynamic nature of the channel. i.e. the same set of rays might arrive in different time bins due to the relative movements of the transmitter and receiver.

Figure 4.11 shows samples of the average pattern for four on-body paths. As seen in the figures, the number of significant arriving rays is larger for wrist and head. This is because at these locations the receiver is able to collect more rays reflected from surrounding objects, walls and ceiling. On the other hand, the receiver on chest is blocked by body from one side and receives less energy from surrounding objects. This can help on making decision on positioning the nodes. For example, if high bit rates are required, the node has to be positioned to minimize the number of

(a) Waist to Chest

(b) Waist to Wrist

(c) Waist to Head

(d) Waist to Ankle

Figure 4.11: Samples of average amplitude pattern vs. ray number for 4 on-body paths

Table 4.6: Estimated parameters of the average model for 4 on-body paths

Receiver location	α	λ	δ
Chest	0.21	6.29	3.55
Wrist	0.11	2.40	4.02
Head	0.18	3.75	2.98
Ankle	0.10	1.80	3.27

arriving rays and hence delay spread to prevent inter-symbol interference. On the other hand, if connectivity is the main concern, the nodes have to be positioned to receive the maximum number of rays.

Mathematical model used for the average amplitude of arrival rays is as follows:

$$a(i) = \alpha e^{-\frac{(i-\lambda)^2}{2\delta^2}}. \quad (4.7)$$

where $a(i)$ is the mean of the i^{th} multi-path coefficient of the channel and α , λ , δ are the model parameters which depend on the body shape, location of the receiver and environment. α is a measure of the received energy and is inversely related to the path loss gain as will be discussed later. δ indicates the dispersion of the rays through time axis while λ is related to the ray numbers with the highest energy. Table 4.6 gives the estimated parameters of the average model. The values are averaged over the grid points, subjects and rooms.

4.7 Distribution of the Multi-Path Channel Gain Variations

To model the small scale variations of the amplitude of the rays, the average is deducted from the amplitude of the rays and variations distribution is compared to several candidate distributions. Akaike Information Criterion (AIC) was used to determine which model is the best among the candidate distributions. Normal, Rayleigh, Rician, Nakagami, Log-normal, Exponential and Weibull were scored to find the best fit distribution. Among all, zero mean normal distribution gives the best fit based on the Akaike criterion. Figure 4.12 shows a sample of the histogram of the small scale variations of the channel gain against the prediction of normal distribution for waist to chest link. This is due to the dense multi-path environment at the proximity of the human body and surrounding objects. That is, for a UWB pulse propagating in the immediate proximity of body, distances of different body parts are comparable with the pulse width. As a result, several pulses reflected from body parts will overlap in the same time bin and give rise to a normal distribution based on central limit theorem. In addition, the surrounding objects in the close proximity of the body contribute to the energy arrived in each time bin. We also observed that the variance of the Gaussian distribution decays exponentially as a function of multi-path number. i.e. later arrival rays have smaller amplitude variations than those arrived earlier. This is because late arrival rays are reflected from far objects and hence suffer a large path-loss decay. Hence, they have much

Figure 4.12: Distribution of amplitude variations against normal distribution.

smaller variations compared to the early rays. To capture this effect, the following model is used for variance changes:

$$\sigma(i) = \sigma_0 e^{-\zeta i}. \quad (4.8)$$

where $\sigma(i)$ is the variance of i^{th} multi-path coefficient. σ_0 is the variance of the first coefficient and ζ is the decay factor. Estimated values for parameters in Equation 4.8 are given in Table 4.7.

4.8 Distribution of the Time of Arrival

Table 4.7: Variance model parameters

	σ_0	ζ
Chest	0.02	0.20
Wrist	0.04	0.24
Head	0.02	0.09
Ankle	0.01	0.16

To model the random arrival times of the rays, the time intervals between the rays were compared based on the Akaike Information Criterion. Three candidate distributions, Exponential, Gamma and Weibull were compared for the best fit. Based on AIC, Gamma distribution shows the best fit to the distribution of interval between arrival times. Parameters of the Gamma distribution is given for 4 on-body paths in Table 4.8. The values are averaged over grid points.

Time of arrival distribution for L_1 link of subject 1 is shown against the Gamma distribution in Figure 4.13.

4.9 Distribution of the Total Ray Number

Poisson distribution has been shown to be the best fit for the number of arrival rays in UWB channel models [19]. Our observation shows that, based on AIC, Poisson distribution is a better fit over Geometric distribution for the total number

Table 4.8: Gamma distribution parameters

Receiver location	k	$\theta(ns)$
Chest	0.75	0.56
Wrist	0.62	1.14
Head	1.46	0.56
Ankle	0.75	1.32

Figure 4.13: Distribution of time of arrival against gamma distribution.

Table 4.9: Poisson distribution parameter (ρ)

Receiver location	Chest	Wrist	Head	Ankle
Parameter Value	12	6.90	7.29	5.62

of multi-path rays which is in accordance with the results reported in [19]. Poisson parameter for different body paths are averaged over the subjects and the results is given in Table 4.9. The distribution fitting for the total ray number of $L1$ of subject 1 is shown in Figure 4.14.

Figure 4.14: Poisson distribution fitting to the total number of arrived rays.

4.10 Channel Reconstruction Using the Model

In this section, an algorithm is provided to reconstruct the channel as given in Equation 4.6.

1) As a first step, the number of the arrival rays has to be determined using Poisson distribution. To do this, a random number L is extracted from Poisson distribution with parameter corresponding to the placement of the receiver.

Samples of randomly drawn values of L for different on-body paths are given in Table 4.10.

2) Next, the parameters of the average model given in Equation 4.7 has to be

Table 4.10: Sample values of L

Channel	Chest	Wrist	Head	Ankle
L	15	11	7	5

estimated. As mentioned before, Equation 4.7 gives the average values of the gain of each multi-path component (h_i) of the tap delay line channel model given in Equation 4.6. α , λ , δ in the model are dependant on the body shape and the location of the receiver on body and hence have to be determined empirically for different subjects.

The average values of the channel multi-path gains ($E\{h_i\}$) could be obtained using Equation 4.7 and L .

3) Small scale fading could be added to the model using Gaussian distributions with zero mean and variances for L taps given in Table 4.7. Let the L random numbers be $\{s_1 \dots s_L\}$. Channel gains ($h_1 \dots h_L$) could be obtained as,

$$h_i = P(i)(\alpha e^{-\frac{(i-\lambda)^2}{2\delta^2}} + s_i). \quad (4.9)$$

where $P(i) = \pm 1$ is the random polarity of the i^{th} multi-path with uniform distribution.

4) Next, random arrival times of the rays should be determined. The time intervals between ray arrivals can be drawn from the Gamma distribution with parameters presented in Table 4.8. Assuming that the first arrival time is zero, the subsequent time of arrivals are determined by adding the next time delay until all L multi-path

arrival times are determined.

4.11 System Level Evaluation of the Model

Frequency selective fading or multi-path fading is caused by multi-path delay spread and can severely degrade the performance of a communication system when the bandwidth of the signal is much larger than the coherence bandwidth of the channel. Inter Symbol Interference (ISI) caused by multi-path arrivals is a limiting factor in bit rate of the system.

RMS delay spread is a metric usually used to characterize the delay spread of the channel. RMS delay spread is defined in Equation 4.5. RMS delay spread can be used to estimate the maximum achievable bit rate with no ISI.

To evaluate the accuracy of the model, delay spread CDF obtained from the model is compared with the values estimated from measurements. CDF of the delay spread is defined,

$$F = \int_0^{\tau} f_{\tau}(x)dx. \quad (4.10)$$

where, τ is the RMS delay spread and $f_{\tau}(x)$ is the distribution of the RMS delay spread. Figure 4.15 shows the comparison of the CDF obtained through the model and measurements. As seen in the figure, the model closely follows the estimated

Figure 4.15: Delay spread CDF comparison.

values from the measurements.

To further evaluate the performance of the model in predicting the parameters of the system, BER performance was compared for the real-time measurements of the radio channel and the model. A simplified block diagram of the system used for BER simulation is shown in Figure 4.16. To capture the properties of UWB channel, BPSK UWB-IR modulation with the second derivative of Gaussian pulse with pulse width of 0.16 ns was used to obtain BER performance of the model. The Gaussian pulse was convolved with the impulse response of the channel and then Gaussian noise was added to the signal. As the aim of the simulations was to evaluate the performance of the model, no coding was applied on the input data.

Figure 4.16: System model

Table 4.11: Communication System Parameters

Frequency Band	3.1-10 GHz
Symbol Rate	200 MSymb/Sec
Modulation	TH-BPSK UWB-IR
Receiver	Coherent Receiver
Sampling Rate	20 GS/s

At the receiver, the received signal was multiplied with an unmodulated template of the symbol and the result was integrated over a symbol time. Synchronization was assumed between transmitter and receiver in all simulations. Parameters of this system is given in Table 4.11.

In Figure 4.17, BER performance of the system using stationary model in [9] is compared with the results obtained from dynamic measurements of the channel. As expected, the BER performance of the system is better in stationary setting than dynamic. In addition, the figure shows that the stationary model could not be used for performance evaluation in dynamic settings.

To evaluate the performance of the model in predicting the parameters of the system, the average BER obtained from on-body links of the dynamic model is compared with the BER from measurements as shown in Figures 4.18a-4.18d. The average BER is obtained by averaging the BER simulations of 40 randomly chosen realiza-

Figure 4.17: BER performance comparison using stationary model and dynamic measurements.

tions of the channel. As the figures show, results obtained from the model closely follow the values estimated from measurement data from all channels. In fact, simulation results shows that the model can approximate the BER of the system working under a dynamic body channel with 92% accuracy.

Lognormal and Rician distributions are suggested for slow and fast fading respectively for walking in indoor environment and in UWB frequencies in [35]. The statistics of the channel gains are provided for hip to chest, wrist and foot. Average BER obtained from these links are compared with the present model for similar paths in Figures 4.18a-4.18d. As seen in the figures, average BER is lower for lognormal-Rician model. The reason is that the time of arrival of the rays are not incorporated in the lognormal-Rician model and hence there is no inter-symbol interference. On the other hand, in our model, inter-symbol interference contributes to the higher BER values especially in higher SNRs.

Both modulation type and channel condition can affect the BER of the system. In general, the BER for the common modulations can generally be written as,

$$BER = Q\left(\sqrt{\beta \frac{\alpha E_s}{N_0}}\right). \quad (4.11)$$

where β is a constant related to the modulation type and α is the channel gain. E_s and N_0 are the transmission energy per symbol and the power spectral density of the noise respectively. Channel models, such as log-normal, Rayleigh, and Rician

affect the BER through α while the modulation type would affect BER through β as shown in Equation 4.11.

(a) L1

(b) L2

(c) L3

(d) L4

Figure 4.18: BER comparison: Model vs. Measurement for (L1 to L4 paths); E_b is the energy of one bit and N_0 is the noise power spectral density.

4.12 Summary

In this chapter, a comprehensive model for dynamic channel around human body is provided. Such model can be used to evaluate systems designed to work in a body area network. Measurements were performed on different on-body radio links simultaneously using real-time oscilloscope while the subjects were imitating natural movements of the human body. Log-distance model was selected for the wave power decay around human body based on Akaike information criterion and path-loss exponents are obtained for different body parts. Subsequently, large scale and small scale variations of the channel are analyzed and a statistical model of the dynamic channel based on the measured data is provided. Model is evaluated in terms of RMS delay spread and BER against the estimated values from measured data. Simulation results show that the model can closely predict the parameters of a system working in a dynamic body area channel.

Chapter 5

Mathematical Analysis of IEEE 802.15.6 Standard

In this chapter, a mathematical model is provided and analyzed for the single hop and two hop routing schemes in IEEE 802.15.6 standard [15]. This analysis will be extended to the opportunistic and adaptive routing schemes in Chapters 6 and 7 respectively.

Here, we assume that RTS/CTS scheme specified in [77] is used to reserve the medium for data frame exchange as it is shown that RTS/CTS scheme can greatly reduce collision time when the payload size is large [78]. To exchange a data frame with the hub (H) directly, the source node (S) initializes a back-off counter with a random integer number between 1 and w_k after sensing the medium is idle for a contention inter-frame spacing ($CIFS$) time interval. k in w_k indicates the number

of previous unsuccessful retransmissions of the same frame. w_k is an integer starting from w_0 , doubling every even k and saturates at w_m where $\{w_0, w_m\}$ depend on the user priority of the source node. The counter freezes if the medium is sensed busy during the count down until the end of the current on-going session. If the medium is idle and the back-off counter reaches zero, the source node transmits a request to send (*RTS*) frame and waits for a clear to send (*CTS*) frame. If an *RTS* frame arrives after a short inter-frame spacing (*SIFS*) interval, source node will transmit its data with another *SIFS* delay and waits for the acknowledgment frame (*ACK*) from the hub. *SIFS* is shorter than *CIFS* to ensure completion of the current session before other nodes start their transmission. As mentioned earlier, if an expected frame (*CTS* or *ACK*) is not received from the hub after an $SIFS + TO$, where TO is the time out interval, the frame is considered lost. In this case, w_k is doubled if the number of retries is even and remains unchanged if it is odd or maximum window size, w_m , is reached.

We assume that the nodes adjust their transmission power when transmitting the frame payload to maintain a specific BER, e_b , required by upper layers. The preamble of the frames is transmitted with a constant predefined power P_{tx0} . Hence, the packet error probability of a data frame is,

$$p_d = 1 - (1 - e_b)^{N_b}. \quad (5.1)$$

where N_b is the number of bits in the frame.

5.1 Markov Model

A Markov model for IEEE 802.11 DCF function is proposed and analyzed in [78]. This model is extended in [79] to include the freezing of back-off counter due to an on-going communication. The Markov model in these works is analyzed under a perfect channel. In this work, we modify the Markov model in [79] to accommodate for the differences in IEEE 802.15.6 MAC layer and variations in the channel quality. Similar to 802.11 DCF function, the maximum back-off number is doubled with failure in the packet delivery. However, this increase occurs every even failed attempt in IEEE 802.15.6. Applications are prioritized in IEEE 802.15.6 to support different delay and throughput requirements. However, the on-body sensor nodes for biomedical applications which is the focus of the thesis have the same priority. Hence, we assume that all nodes have the same priority level. In addition, we assume that the error probability of short control frames are negligible compared to the lengthy data frames. To achieve lower packet error rate for control frames, an error correction code may be implemented in the payload section of the frames.

Markov model of the protocol is shown in Figure 5.1. Rows in Figure 5.1 show the back-off stages where w_i indicates the maximum back off number in i^{th} stage and m is maximum number of back off stages. m is always an odd number as if m were even, $w_{m+1} = w_m$ and thus $m + 1$ would be the maximum stage. p_b and

Figure 5.1: Markov model of the protocol.

p_f are the probabilities of a busy medium and a failed transmission respectively. Similarly as assumed in [78], p_b is not a function of back off stage of the node and thus is constant. p_b is also the probability of collision. p_f is related to p_b and p_d and depends on the routing scheme used by the source node. Hence,

$$p_f = \begin{cases} p_b + (1 - p_b)p_d, & \text{Single hop;} \\ p_b + (1 - p_b)p_d, & \text{Two hop;} \end{cases} \quad (5.2)$$

In single hop communication, a transmission session fails either because of collision or error in data packet. In two hop communication, communication between the source node and the hub is only through a relay node and hence transmission fails due to collision or when packet is received with error by the relay.

The following equations hold for the steady state of the Markov model in Figure 5.1 where all nodes have a packet to transmit immediately after their packet is successfully transmitted or dropped when maximum number of retries is reached. Assume that $b_{i,k}$ is the steady state probability of the node being in $(i, k)^{th}$ state. Then,

$$\begin{aligned} b_{i,0} &= p_f b_{i-1,0} \Rightarrow b_{i,0} = p_f^i b_{0,0}. \\ b_{m,0} &= p_f b_{m,0} + p_f b_{m-1,0} \Rightarrow b_{m,0} = \frac{p_f}{1 - p_f} b_{m-1,0} \\ \Rightarrow b_{m,0} &= \frac{p_f^m}{1 - p_f} b_{0,0}. \end{aligned} \quad (5.3)$$

Using the above equations and the Markov model,

$$b_{i,k} = \frac{w_i - k}{1 - p_b} \begin{cases} \frac{1-p_f}{w_i} \sum_{j=0}^m b_{j,0}, & i = 0; \\ p_f b_{i-1,0}, & 0 < i < m; \\ p_f (b_{m-1,0} + b_{m,0}), & i = m. \end{cases} \quad (5.4)$$

Hence,

$$b_{i,k} = \frac{w_i - k}{w_i(1 - p_b)} b_{i,0} \quad 0 \leq i \leq m. \quad (5.5)$$

Normalization condition requires,

$$\sum_{i=0}^m \sum_{k=0}^{w_i-1} b_{i,k} = 1 \quad (5.6)$$

Therefore,

$$\sum_{i=0}^m \frac{b_{i,0}}{1 - p_b} \underbrace{\sum_{k=0}^{w_i-1} \frac{w_i - k}{w_i}}_{\frac{w_i+1}{2}} = 1. \quad (5.7)$$

Using (5.3) in (5.7) we obtain,

$$\begin{aligned} & \sum_{i=0}^{m-1} \left(\frac{w_i + 1}{2} \frac{b_{i,0}}{1 - p_b} \right) + \frac{w_m + 1}{2} \frac{p_f^m}{1 - p_f} \frac{b_{0,0}}{1 - p_b} = 1; \\ \Rightarrow & \frac{b_{0,0}}{2(1 - p_b)} \left[\underbrace{\sum_{i=0}^{m-1} (p_f^i w_i + p_f^i)}_{S_1} + \frac{p_f^m}{1 - p_f} (w_m + 1) \right] = 1. \end{aligned} \quad (5.8)$$

Using the fact that $w_{2i} = 2^i w_0$ and $w_{2i+1} = 2^i w_0$ for $i = 0, \dots, (m-1)/2$, we can rewrite S_1 in the above equation,

$$S_1 = \sum_{i=0}^{(m-1)/2} (p_f^{2i+1} w_{2i+1} + p_f^{2i+1} + p_f^{2i} w_{2i} + p_f^{2i}) \quad (5.9)$$

$$= (1 + p_f) \left(w_0 \frac{1 - (\sqrt{2} p_f)^{m+1}}{1 - 2p_f^2} + \frac{1 - p_f^{m+1}}{1 - p_f^2} \right). \quad (5.10)$$

Substituting (5.9) in (5.8) results in,

$$b_{0,0} = \frac{2(1 - p_b)}{(1 + p_f) \left(w_0 \frac{1 - (\sqrt{2} p_f)^{m+1}}{1 - 2p_f^2} + \frac{1 - p_f^{m+1}}{1 - p_f^2} \right) + \frac{p_f^m}{1 - p_f} \left(2^{\frac{m-1}{2}} w_0 + 1 \right)}. \quad (5.11)$$

A node will transmit if its counter reaches zero and hence probability of transmission

τ is,

$$\tau = \sum_{i=0}^m b_{i,0} = \frac{2(1-p_b)}{(1-p_f^2)w_0 \frac{1-(\sqrt{2}p_f)^{m+1}}{1-2p_f^2} + 1 - p_f^{m+1} + p_f^m(1+p_f) \left(2^{\frac{m-1}{2}}w_0 + 1\right)}. \quad (5.12)$$

5.2 Energy Consumption Analytical Model

To operate in CSMA/CA mode of IEEE 802.15.6, all nodes must sense the medium at all times and postpone their transmission based on the expected transmission duration of the current frame exchange based on the information provided in the control section of the frames. Thus, the nodes are either listening to the medium or transmitting a frame. Electronics power consumptions is assumed to be included in the corresponding transmit and receive power values. To perform the back off procedure, every node spends some time in the back off states. Assuming a limited number of unsuccessful retries r_m after which the packet is dropped, the average number of slots spent in the back off procedure before a packet is successfully transmitted or dropped is given by

$$\begin{aligned} \bar{n} = & \sum_{r=0}^{m-1} p_f^r (1-p_f) \sum_{k=0}^r \underbrace{\sum_{i=0}^{w_k-1} \frac{1}{w_k} i}_{\frac{w_k-1}{2}} \\ & + \sum_{r=m}^{r_m} p_f^r (1-p_f) \sum_{k=0}^m \sum_{i=0}^{w_k-1} \frac{1}{w_k} i + p_f^{r_m} \sum_{k=0}^m \sum_{i=0}^{w_k-1} \frac{1}{w_k} i \end{aligned}$$

If $m \leq r_m$,

$$\bar{n} = \sum_{r=0}^{r_m-1} p_f^r (1 - p_f) \sum_{k=0}^r \frac{w_k - 1}{2} + p_f^{r_m} \sum_{k=0}^{r_m} \frac{w_k - 1}{2} \quad (5.13)$$

The average energy consumed by the nodes while performing the back off procedure is,

$$\bar{E}_{bo} = \bar{n} \beta P_{rx}. \quad (5.14)$$

where, β and P_{rx} are the slot time and the power consumed by the node to receive and overhear the frames on air respectively.

The average number of times the channel is sensed busy at each back off state is

$$\bar{s} = \sum_{i=0}^{\infty} (1 - p_b) p_b^i = \frac{p_b}{1 - p_b}. \quad (5.15)$$

Hence, the total number of times the channel is sensed busy by a node during the back off procedure is

$$\bar{n}_b = \bar{n} \bar{s}. \quad (5.16)$$

5.2.1 Source Node

The energy consumed by the source node while overhearing the on-going transmission depends on whether a collision occurs or not. In the case where no collision occurs, the packet transmission might be successful or with errors. The average energy of consumption due to overhearing on-going packets during back off procedure is calculated as,

$$\bar{E}_o^S = \bar{n}_b \left[\frac{p_b}{p_{tx}} \bar{E}_{oc} + \left(1 - \frac{p_b}{p_{tx}}\right) ((1 - p_d) \bar{E}_{os} + p_d \bar{E}_{of}) \right]. \quad (5.17)$$

where, p_{tx} is the probability that at least one node is transmitting given by

$$p_{tx} = 1 - (1 - \tau)^{N_n}. \quad (5.18)$$

where N_n is the total number of nodes in the network. $\bar{E}_{oc}$, $\bar{E}_{os}$, $\bar{E}_{of}$ are the energy consumed by a node to overhear a collision, successful data transmission and failed data transmission by other nodes respectively and are calculated as follows,

$$\begin{aligned}
 \bar{E}_{oc} &= (T_{RTS} + TO + SIFS + CIFS)P_{rx}, \\
 \bar{E}_{os} &= (T_{RTS} + T_{CTS} + T_D + T_{ACK} + 3SIFS + CIFS)P_{rx}, \\
 \bar{E}_{of} &= (T_{RTS} + T_{CTS} + T_D + TO + 3SIFS + CIFS)P_{rx}.
 \end{aligned} \tag{5.19}$$

where, T_{RTS} , T_{CTS} , T_{ACK} and T_D are duration of RTS , CTS , ACK and data frames respectively including PHY and MAC layer headers.

The average number of retries before a packet is successfully transmitted or dropped is,

$$\begin{aligned}
 \bar{r} &= \sum_{r=0}^{r_m-1} r p_f^r (1 - p_f) + p_f^{r_m} r_m \\
 &= p_f \frac{1 - r_m p_f^{r_m-1} + (r_m - 1) p_f^{r_m}}{1 - p_f} + p_f^{r_m} r_m.
 \end{aligned} \tag{5.20}$$

The average energy consumed during retransmission is,

$$\bar{E}_r^S = \bar{r} \left[\frac{p_b}{p_f} \bar{E}_{txc}^S + \left(1 - \frac{p_b}{p_f}\right) \bar{E}_{txf}^S \right] \tag{5.21}$$

$\bar{E}_{txc}^S$ and $\bar{E}_{txf}^S$ are the transmission energy consumed during a collision and failed

direct data exchange respectively and are obtained as follows,

$$\begin{aligned}\bar{E}_{txc}^S &= T_{RTS} \bar{P}_{tx}^{SX} + (TO + SIFS + CIFS) P_{rx}, \\ \bar{E}_{txf}^S &= (T_{RTS} + T_D) \bar{P}_{tx}^{SX} + (T_{CTS} + TO + 3SIFS + CIFS) P_{rx}.\end{aligned}\quad (5.22)$$

$\bar{P}_{tx}^{SX}$ is the average transmission power used by S to maintain the desired BER at the destination $X \in \{H, R\}$ while transmitting directly,

$$\bar{P}_{tx}^{SX} = \int_0^1 f_{SX}(\alpha) P_{tx}^{SX}(\alpha) d\alpha. \quad (5.23)$$

where $f_{SX}(\alpha)$ is the distribution of the channel gain between S and X .

The probability that a packet is dropped is,

$$p_w = 1 - \sum_{r=1}^{r_m} (1 - p_f) p_f^{r-1} = p_f^{r_m}. \quad (5.24)$$

and hence a packet is successfully transmitted with probability,

$$p_s = 1 - p_f^m. \quad (5.25)$$

The average energy consumed to transmit a packet successfully is,

$$\bar{E}_s^S = p_s \bar{E}_{txs}^{SX}. \quad (5.26)$$

where $\bar{E}_{txs}^{SX}$ is the energy consumed during a successful direct transmission to node X and is obtained through the following equation,

$$\bar{E}_{txs}^{SX} = (T_{RTS} + T_D) \bar{P}_{tx}^{SX} + (T_{CTS} + T_{ACK} + 3SIFS + CIFS) P_{rx}. \quad (5.27)$$

The average total energy consumed by the source node per data bit is,

$$\bar{E}_b^S = \frac{\bar{E}_{bo} + \bar{E}_o^S + \bar{E}_r^S + \bar{E}_s^S}{L}. \quad (5.28)$$

where L is the payload size.

5.2.2 Relay Node

In two hop scheme, relay node sends the packet received from S in single hop scheme.

The average energy consumed by the relay R_i to receive a packet from S is,

$$\bar{E}_{rx}^{R_i} = (1 - p_d)\bar{E}_{RXs}^{R_i} + p_d\bar{E}_{RXf}^{R_i}. \quad (5.29)$$

where, $\bar{E}_{RXs}^{R_i}$ and $\bar{E}_{RXf}^{R_i}$ are energy consumption for receiving a successful or failed data packet and are obtained as,

$$\begin{aligned} \bar{E}_{RXs}^{R_i} &= (T_{CTS} + T_{ACK})\bar{P}_{tx}^{R_iS} + (T_{RTS} + T_D + T_{ACK} + 4SIFS + CIFS)P_{rx} \\ \bar{E}_{RXf}^{R_i} &= T_{CTS}\bar{P}_{tx}^{R_iS} + (T_{RTS} + T_D + TO + 3SIFS + CIFS)P_{rx}. \end{aligned} \quad (5.30)$$

where, $\bar{P}_{tx}^{R_iS}$ is the average transmission power of R_i used to transmit to S .

The average energy consumed by R_i to overhear an on-going communications is,

$$\bar{E}_o^{R_i} = \bar{n}_b \left[\frac{p_b}{p_{tx}} \bar{E}_{oc} + \left(1 - \frac{p_b}{p_{tx}}\right) ((1 - p_d)\bar{E}_{os} + p_d\bar{E}_{of}) \right]. \quad (5.31)$$

The average energy consumed during retransmissions is,

$$\bar{E}_r^{R_i} = \bar{r} \left[\frac{p_b}{p_f} \bar{E}_{txc}^{R_i} + \left(1 - \frac{p_b}{p_f}\right) \bar{E}_{txf}^{R_i} \right]. \quad (5.32)$$

$\bar{E}_{txc}^S$ and $\bar{E}_{txf}^S$ are the transmission energy consumed during a collision and failed data exchange respectively and are obtained as follows,

$$\begin{aligned} \bar{E}_{txc}^{R_i} &= T_{RTS} \bar{P}_{tx}^{R_i H} + (TO + SIFS + CIFS) P_{rx}, \\ \bar{E}_{txf}^{R_i} &= (T_{RTS} + T_D) \bar{P}_{tx}^{R_i H} + (T_{CTS} + TO + 3SIFS + CIFS) P_{rx}, \end{aligned} \quad (5.33)$$

where, $\bar{P}_{tx}^{R_i H}$ is the average transmission power of R_i used to transmit to H .

The average energy consumed to transmit a packet successfully is,

$$\bar{E}_s^{R_i} = p_s \bar{E}_{txs}^{R_i}. \quad (5.34)$$

where $\bar{E}_{txs}^{R_i}$ is the energy consumed during a successful transmission and is obtained through the following equation,

$$\bar{E}_{txs}^{R_i} = (T_{RTS} + T_D)\bar{P}_{tx}^{R_iH} + (T_{CTS} + T_{ACK} + 3SIFS + CIFS)P_{rx}, \quad (5.35)$$

The average total energy consumed by the relay node per data bit is,

$$\bar{E}_b^{R_i} = \frac{\bar{E}_{rx}^{R_i} + (1 - p_d)(\bar{E}_{bo} + \bar{E}_o^{R_i} + \bar{E}_r^{R_i} + \bar{E}_s^{R_i})}{L}. \quad (5.36)$$

As a result, the average total energy consumed on a payload bit for single hop and two hop are,

$$\bar{E}_{bSHop} = \bar{E}_b^S, \quad (5.37)$$

$$\bar{E}_{bTHop}^i = \bar{E}_b^S + p_{R_i}\bar{E}_b^{R_i}. \quad (5.38)$$

To obtain a measure of the reliability of the network, we define the outage as the probability that a data packet transmission is unsuccessful and is dropped by the transmitter after maximum number of retries is reached. The outage probabilities of single hop and two hop are as follows,

$$p_o = \begin{cases} p_f^{r_m}, & \text{Single hop} \\ p_f^{r_m} + (1 - p_f^{r_m})p_f^{r_m}, & \text{Two hop} \end{cases} \quad (5.39)$$

In a two hop communication, outage as defined above occurs either when the source node drops the data after reaching maximum retries or when the packet is successfully transmitted to the relay but is later dropped by the relay.

Chapter 6

Opportunistic Routing Using CBM

A WBAN can be used in a patient monitoring system. In this system, patients are equipped with a number of on-body sensors gathering physiological information of patients 24-hours a day. The data collected by the sensors are collected by the hub which is a wearable dedicated device aggregating data from on-body sensors and retransmitting to central data unit where data from all patients are logged. Every patient has its own WBAN with a hub. Central data unit coordinates hubs which are in its vicinity. In such applications, patient can move freely in the coverage area of the central data unit while their physiological data are being monitored. As an example application, assume that a wireless device (S) is attached to the left wrist which has high mobility. It can be pulse monitoring device sensing and transmitting pulse rate, a blood pressure sensor or a motion sensor with clinical or recreational

applications. The device is sending packets to the hub (H) on the right side of the waist which is usually larger and has more power and computational resources to be logged or re-transmitted to a data center or clinic. H can be a mobile phone, PDA or a dedicated device. This configuration is a typical example of the futuristic applications of an on-body network where wireless modules could be embedded in devices used in everyday life such as wrist watch and mobile phones. An important challenge in such system is the lifetime of the sensors and the network. It is crucial for the WBAN to work for months and in the case of implanted sensors even for years. This shows the significance of preserving the energy in these networks. Chapters 6 and 7 address this problem and provide methods to improve the energy efficiency of the network.

In this chapter, Coded Bit Modulation (CBM), a PHY layer modulation scheme for UWB-IR is introduced and analysed in terms of BER. Then, CBM is incorporated in a power efficient routing scheme to decrease the energy consumption of the nodes in WBAN. The performance of the routing scheme is compared with existing routing schemes described in Chapter 2 and using the channel model provided in Chapter 4.

6.1 Introduction

Carrier-less nature of UWB-IR modulation provides interesting features such as low energy consumption and small transceiver size which are appealing in energy constraint networks such as Wireless Sensor Network (WSN). Energy is a limited

resource in a WSN [80, 81]. This signifies the need for a network protocol stack which minimizes the energy usage of the nodes while maintaining acceptable quality of service. Cooperation between nodes in both large and small scale WSNs can improve the overall network performance [82–84]. However, this comes at the cost of increased energy usage of the nodes cooperating in routing their neighbour's data. The following section will introduce Coded Bit Modulation (CBM), a modulation scheme for UWB-IR. It is shown that, using CBM, relay nodes can provide redundancy for their neighbour nodes without increasing their energy consumption.

6.2 Coded Bit Modulation (CBM)

Define $\mathcal{V}$ as the vector space containing all possible combination of vectors associated with the elements of the random time hopping code space as described in Section 2.2.1. The vector corresponding to the symbol S_k is represented as $\bar{v}_k$. Hence,

$$\mathcal{V} = \{\bar{v}_1, \dots, \bar{v}_M \mid M = (2N_c)^{N_f}\} \quad (6.1)$$

where N_f is the number of frames in a symbol.

In BPSK modulation, the vector $\bar{v}_i$ is modulated as $b\bar{v}_i$ to convey the bit information where $b \in \{-1, 1\}$ is the bit information. The symbol structure and the

Figure 6.1: Symbol structure and the corresponding vector $\bar{v}_i$

corresponding vector are shown in Figure 6.1. Detection process can be represented as the inner product of the code vector with an unmodulated vector of the same code multiplied by the energy of the pulse E_p . The inner product of the code vector is defined as,

$$A = \bar{v}_i \cdot \bar{v}_j = \sum_{k=1}^{N_f} v_{ik} v_{jk}. \quad (6.2)$$

where v_{ik} is the k^{th} element of the i^{th} code vector $\bar{v}_i$. As an example, assume that a symbol has three frames and each frame contains two time bins. Two random code vectors corresponding to this symbol structure are,

$$\begin{aligned} \bar{v}_1 &= [0, -1, 10, 01], \\ \bar{v}_2 &= [10, 10, 10]. \end{aligned} \quad (6.3)$$

The inner product of v_1 and v_2 is,

$$\bar{v}_i \cdot \bar{v}_j = 1. \quad (6.4)$$

Hence,

$$E_s = E_p(b\bar{v}_i) \cdot (\bar{v}_i) = bE_p(\bar{v}_i \cdot \bar{v}_i) = bE_p N_f. \quad (6.5)$$

where E_s is the symbol energy. Information is extracted by finding the sign of the output which is a function of b .

Now we introduce Coded Bit Modulation (CBM) to encode N -bits of data in one symbol. The idea is to encode the N -bit blocks of information with 2^N different vectors, chosen from the vector space $\mathcal{V}$. In other word, strings of length N -bits are mapped to 2^N vectors chosen from the vector space $\mathcal{V}$. N -bit sequences of data are then transmitted by sending corresponding symbol associated with the vector representing this specific N -bit combination. At the other end, the receiver detects the transmitted vector and decodes the data. Therefore, by sending the same symbol format as conventional TH-BPSK and hence the same amount of energy, N -bits of information is transmitted instead of just one bit. Nevertheless, this comes at the expense of degraded BER performance of the modulation which will be discussed in later sections. To optimize the detection process, vectors must be chosen to maximize the distance between vectors. The distance between vectors is defined as,

$$d(\bar{v}_i, \bar{v}_j) = \left\| \bar{v}_i - \bar{v}_j \right\|, \quad \forall \bar{v}_i, \bar{v}_j \in \mathcal{V}, i \neq j. \quad (6.6)$$

where

$$\left\| \bar{v}_k \right\| = \bar{v}_k \cdot \bar{v}_k. \quad (6.7)$$

Hence, the set of vectors that maximize the following sum are the optimum choice of vectors,

$$\mathcal{X} = \arg \max_{\bar{v}_i, \bar{v}_j} \left\{ \sum_{i,j} d_{\bar{v}_i, \bar{v}_j} \right\}. \quad i, j = 1, \dots, 2^N. \quad (6.8)$$

Now the problem is to find $\bar{v}_i$ s which maximize the above expression. Define A as the inner product of two randomly chosen $\bar{v}_i$ and $\bar{v}_j$ from $\mathcal{V}$,

$$A = \bar{v}_j \cdot \bar{v}_i, \quad i, j = 1, \dots, M. \quad (6.9)$$

Assuming no time drift between the receiver and transmitter, A is an integer value

in the interval $[-N_f, \dots, N_f]$. The maximum (N_f) , occurs when $\bar{v}_i$ is multiplied by itself and minimum $(-N_f)$ occurs when $\bar{v}_i$ is multiplied by $-\bar{v}_i$. To find the members of $\mathcal{X}$, we start with a randomly chosen vector $\bar{v}_1$ from the vector space $\mathcal{V}$. According to Equation 6.6, distance between $-\bar{v}_1$ and $\bar{v}_1$ is $2N_f$ which is the maximum possible distance and hence, $-\bar{v}_1$ is also chosen as a member of $\mathcal{X}$. The next candidate has to be the farthest from both $\bar{v}_1$ and $-\bar{v}_1$ and hence must be orthogonal to $\bar{v}_1$. Therefore $\bar{v}_2$ is chosen from the space orthogonal to the space spanned by $\bar{v}_1$. For the same reason as above, $-\bar{v}_2$ is also chosen as a member of $\mathcal{X}$. This process is continued until all 2^N members of $\mathcal{X}$ are chosen. The number of bits that can be transmitted simultaneously is limited by the size of the vector space,

$$N \leq \log_2(M) = N_f(1 + \log_2(N_c)). \quad (6.10)$$

in which M is the size of the vector space. However, if N exceeds $1 + \log_2(v)$ where v is the dimension of vector space $\mathcal{V}$, vectors will no longer be orthogonal and the BER efficiency of the system would be severely degraded. This is because, the constellation points get too close to each other and the probability of error increases at the receiver.

Assuming block size $N = 2$, number of frames $N_f = 4$ and number of chips per frame $N_c = 3$, the symbol has 12 chips with one pulse in every 3 chips. A vector of 12 elements defines the location and polarization of the pulses within the symbol.

To encode 2 bits we would need $2^2 = 4$ vectors. Following the above procedure, we choose the following vectors:

$$\begin{aligned}
 \bar{v}_1 &= [001, 0-10, 001, -100]^T. \\
 \bar{v}_2 &= -\bar{v}_1 = [00-1, 010, 00-1, 100]^T. \\
 \bar{v}_3 &= [100, 001, -100, 0-10]^T. \\
 \bar{v}_4 &= -\bar{v}_3 = [-100, 00-1, 100, 010]^T.
 \end{aligned} \tag{6.11}$$

where $\bar{v}_1, \bar{v}_3$ form the basis of the vector space. Note that as mentioned earlier, orthogonality is not a necessary condition. However, non-orthogonal basis increases the probability of error in the detection process. Thus, the transmitter can encode and transmit 2-bits blocks of data according to Table 6.1. To minimize the probability of error, codes with highest distance are assigned to the bit sequence with highest bit difference. For example, 00 and 11 have two different bits and hence are assigned to $\bar{v}_1$ and $\bar{v}_2$ which have the largest distance ($2N_f$).

Table 6.1: Bit sequence mapping.

bit sequence	Vector
(0, 0)	$\bar{v}_1$
(1, 1)	$\bar{v}_2$
(0, 1)	$\bar{v}_3$
(1, 0)	$\bar{v}_4$

Figure 6.2: Schematic of the receiver structure

6.3 Maximum Likelihood Receiver Structure

The receiver design for CBM differs from the receivers used for TH-BPSK modulation. In TH-BPSK, information is modulated in the amplitude of the pulses. Hence, the received signal is correlated with a non-modulated replica of the same code and by finding the sign of the resulting signal, the bit information is obtained [49, 85]. On the other hand, in CBM, the receiver extracts the information through detecting the code that has been sent. Receiver structure for CBM is shown in Figure 6.2. To detect the transmitted code, the received signal is correlated with the basis vectors of $\mathcal{X}$. The code with the highest correlation is chosen and based on the sign of the correlation the corresponding N -bit combination is sent to the output.

The BER of this receiver is,

$$BER = \sum_i p_i P(\mathbf{E} | s_i). \quad (6.12)$$

where, p_i is the probability of sending s_i ($i \in \{1, \dots, 4\}$) and $P(\mathbf{E} \mid s_i)$ is the probability of error in case s_i is sent and is defined,

$$P(\mathbf{E} \mid s_i) = \frac{1}{2} \left[\int_{-1}^1 P_Z(Z) dZ + 2Q\left(\sqrt{\frac{2E_s}{N_0}}\right) \left(1 - \int_{-1}^1 P_Z(Z) dZ\right) \right]. \quad (6.13)$$

$P_Z(Z)$ in Equation 6.13 is,

$$P_Z(Z) = \frac{\sqrt{SNR}}{\sqrt{2\pi}} \frac{Z e^{-\frac{1}{2} \frac{SNR}{Z^2+1}}}{(Z^2+1)^{\frac{3}{2}}} \left[1 - 2Q\left(\sqrt{SNR} \frac{Z}{\sqrt{Z^2+1}}\right) \right] + \frac{1}{\pi(Z^2+1)} e^{-\frac{1}{2} SNR}. \quad (6.14)$$

where,

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2} du, \quad SNR = \frac{E_s}{N_0 B/2}. \quad (6.15)$$

E_s , N_0 and B are the transmission energy of a symbol, noise power spectral density and the bandwidth of the system respectively. Details of the BER analysis of the

Figure 6.3: BER performance of CBM compared for different number of combined bits.

above receiver is given in Appendix C.

The BER of this receiver is compared in Figure 6.3 for different number of combined bits using the channel provided in Chapter 4 by simulations. To obtain the BER, samples of the channel are reconstructed as described in Section 4.10. The modulated symbol is filtered with the channel impulse response and the bit information is decoded using the receiver structure discussed above. The received bit is compared with the transmitted bit and the number of errors are counted for each modulation. As seen in the Figure 6.3, there is trade-off between the number of encoded bits and the BER performance of the system.

6.4 Opportunistic Routing Using CBM

The location of the sensor nodes in BAN is usually defined by the application and the task the sensor is performing. On the other hand, relays and NC locations are usually defined based on the requirements of system and resources. For example, NC collects the data from all over the network and acts as the hub to communicate with the outside network. Wrist and waist are candidate locations for placement of hub. While placing the hub on the wrist can provide better connectivity with the outside networks, waist node has more connectivity with the nodes placed in frontal section of the body.

Assume that a wireless device (S) is on the left wrist which has high mobility. The device is sending packets to the hub (H) on the right side of the waist which is usually larger and has more power and computational resources. H can be a mobile phone, PDA or a dedicated device. This configuration is a typical example of a futuristic applications of an on-body network where wireless modules could be embedded in devices used in everyday life such as wrist watch and mobile phones. A relay node (R) on the left shoulder provides relay service for the source node. The network configuration is shown in Figure 6.4.

In CBM-opportunistic routing, the source node initiates a session according to the procedures described in Chapter 5 and sends its data packet to the hub. Simultaneously, the relay node will listen to the packet from S . In case the packet is received by hub successfully, it will acknowledge the reception of the packet by sending an

Figure 6.4: Network configuration

ACK frame which causes the source node to proceed to the next frame and the relay node to discard the packet received from the source node. On the other hand, if no *ACK* is received from the hub after a time out period, the relay will acknowledge the reception of data and combines the packet with its own data using CBM modulation as described in Section 6.2 and re-transmits to *H*. This way, *S* receives two copies of the packet from *H* without any extra energy usage by the relay node.

6.5 Performance Evaluation and Comparison

As discussed in Chapter 5, two types of routing schemes are defined in IEEE 802.15.6 standard. In this section, the proposed opportunistic routing is compared with the single hop and two hop schemes in the IEEE 802.15.6 standard.

In [53], a closed form expression for the BER of TH-BPSK as a function of E_b is given where E_b is the transmit energy of a bit,

$$P_e \approx Q\left(\frac{\sqrt{E_b} \sum_{l=1}^{L_f} \alpha_l \beta_l}{\sqrt{\frac{E_b}{NN_c} \sigma_{IFI,1}^2 + \frac{E_b}{N} \sigma_{IFI,2}^2 + \sigma_n^2 \sum_{l=1}^L \beta_l^2}}\right) \quad (6.16)$$

where α_l s are the channel multi-path coefficients, β_l s is the rake receiver fingers coefficients, L_f is the total number of the rake receiver fingers, $N = N_c N_f$ is the total processing gain of the system and σ_n^2 is the noise variance. $\sigma_{IFI,1}^2$ and $\sigma_{IFI,2}^2$ are the variances of the interference caused by the multi-path reflections of the pulses belonging to the two previous frames or inter-frame interference (IFI). Here

Table 6.2: System Parameters.

Parameter	Value [15, 86]
Frequency Band.	3.1 – 10GHz
Modulation	TH-BPSK
Symbol Rate	3.9Mb/sec
<i>SIFS</i>	75μsec
<i>CIFS</i>	100μsec
<i>TO</i>	30μsec
β	292μsec
N_n	10
N_r	1
w_0	8
w_m	32
m	5
r_m	5
e_b	10^{-6}
P_{rx}	16μW
L	1024 bits

we assume that the receiver has only one finger and hence $L = 1$. The BER analysis of the CBM modulation is given in Appendix C.

The energy performance of the opportunistic routing is compared with the single hop and two hop schemes using the channel model in Chapter 4 through simulations (indicated by markers in the figures) and compared with the mathematical model (solid lines) in Chapter 5. Simulations are implemented in MATLAB following the medium access rules specified in the standard. Parameters of the system are given in Table 6.2.

Assume that the quality of service of the upper layers of the system specifies the BER requirement. Figure 6.5 shows the energy consumption per bit of information for different schemes. As seen in the figure, the energy consumption of the opportunistic scheme is lower than the other two schemes. In addition, the figure shows that as

Figure 6.5: Energy consumption per packet vs. desired BER.

the BER requirement relaxes, less energy is consumed per bit of information due to the lower transmission power.

6.6 Summary

The limited number of sensors in a WBAN makes the network vulnerable to the malfunction of individual nodes. Preserving the energy of the nodes translate directly to the increased network lifetime. In addition, increasing the battery life of the node in WBAN leads to more comfort for the patient or even a necessity in the case of implanted sensors where changing the energy resource is invasive. In this work, we exploit the motion of the body parts to improve the energy efficiency of

the nodes and hence increase the lifetime of the network. Coded Bit Modulation is introduced which is a coding scheme to combine multiple bits of information into one symbol without increasing the symbol energy. CBM is then incorporated in an opportunistic scheme to reduce the energy consumption of the nodes. To evaluate the performance of the proposed scheme, the energy consumption per bit in CBM-opportunistic is compared with the existing schemes.

Chapter 7

Adaptive Routing in Dynamic Body Area Networks

This chapter introduces a power efficient adaptive routing protocol based on the channel information at the receiver.

General format of a physical-layer protocol data unit (PPDU) is shown in Figure 7.1. The size of each section is shown above the section in bits. PHY layer adds a preamble and its own header to the physical-layer data unit (PSDU) which is delivered by MAC layer. PHY header contains transmission information including, data rate and length of the data. PSDU is the MAC layer frame and consists of 6 sections as shown in Figure 7.1. Frame control section contains information about the frame including the frame type and sequence number of the frame. Recipient ID, sender ID and BAN ID fields contains the abbreviated address of the intended recipient

of the frame, sender of the frame and the network respectively. MAC frame body contains the payload information and is not present in the control frame types. The length of MAC frame body varies between 1 and L_{max} . Frame check sequence (FCS) contains the binary coefficients of a cyclic redundancy check (CRC) polynomial of degree 15. Details of the frame format and fields are available in [15].

Figure 7.1: General format of a physical-layer protocol data unit (PPDU) and physical-layer data unit (PSDU).

7.1 Adaptive Routing

To accommodate for the best transmission scheme selection, CSMA/CA mode of multiple access protocol in IEEE 802.15.6 [15] is extended as described in details in the rest of this section.

In adaptive routing, source node obtains the instantaneous channel information through preamble of the *RTS* frame received from the hub. If the instantaneous channel gain (α) is higher than a threshold (α_0), S uses a direct communication scheme as described in Chapter 5. On the other hand, if the reception is below the threshold, S transmits a request to relay (*RTR*) frame after an *SIFS*. *RTR* is an

RTS frame with relay field in frame control header set to 1 and recipient address set to multi-cast address of the group of the relay nodes. Relays will respond by a clear to relay (*CTR*) after an *SIFS* and according to their predefined order number. After receiving the expected number of *CTR* frames, *S* transmits its encapsulated data frame with recipient ID set as the ID of the relay node with the best link quality and relay field of the header set to 1 to indicate that the final destination is *H*. If the hub and the chosen relay node (R_i) receive the frame correctly, they will transmit acknowledgment after an *SIFS* and $2SIFS + T_{ACK}$ respectively, where, T_{ACK} is the duration of the acknowledgment frame. If the relay receives the *ACK* from the hub, it discards the frame. Otherwise, it transmits the data frame to *H* in a contended session. If *S* receives an *ACK* from either *H* or R_i or both, it proceeds to the next frame, otherwise, the frame is considered lost and it tries to retransmit the frame until retry number of the frame reaches maximum or the frame is sent successfully. Figure 7.2 shows successful and unsuccessful data transmission sessions with and without a relay.

We assume that the nodes adjust their transmission power when transmitting the payload to maintain a specific BER, e_b , required by upper layers. The preamble of the frames is transmitted with a constant predefined power P_{tx0} .

In adaptive routing, the probability of a failed transmission depends on whether the source node decides to send the packet directly or through a relay. As both the relay and the hub listen for the packet when relay is used, packet delivery fails only if both the relay and the hub receive the packet with error. Hence,

Figure 7.2: Sessions corresponding to the data frame transmission in adaptive routing.

$$p_f = p_b + (1 - p_b)p_d(p_R p_a + (1 - p_R)). \quad (7.1)$$

where, p_a is the average packet error probability of the direct transmission link between the source node and the hub during a relayed transmission and approximates the instantaneous packet error probability. p_R is the probability that the source node decides to use relay for data transmission,

$$p_R = \int_0^{\alpha_0} f_{SH}(\alpha) d\alpha. \quad (7.2)$$

in which $f_{SH}(\alpha)$ is the distribution of the channel gain between S and H .

7.2 Energy Consumption Model

The energy consumed by the source node during the back off process and overhearing the on-going transmissions in adaptive scheme is similar to the single hop and multi hop and are given in (5.14) and (5.17).

The average number of retries before a packet is successfully transmitted or dropped is,

$$\bar{r} = \sum_{r=0}^{r_m-1} r p_f^r (1 - p_f) + p_f^{r_m} r_m = p_f \frac{1 - r_m p_f^{r_m-1} + (r_m - 1) p_f^{r_m}}{1 - p_f} + p_f^{r_m} r_m. \quad (7.3)$$

The average energy consumed during retransmission is,

$$\bar{E}_r^S = \bar{r} \left[\frac{p_b}{p_f} \bar{E}_{txc}^S + \left(1 - \frac{p_b}{p_f}\right) (p_R \bar{E}_{txfR}^S + (1 - p_R) \bar{E}_{txf}^S) \right] \quad (7.4)$$

$\bar{E}_{txc}^S$, $\bar{E}_{txf}^S$ and $\bar{E}_{txfR}^S$ are the transmission energy consumed during a collision, failed direct data exchange and failed relayed data frame exchange respectively and are obtained as follows,

$$\begin{aligned} \bar{E}_{txc}^S &= T_{RTS} \bar{P}_{tx}^{SH} + (TO + SIFS + CIFS) P_{rx}, \\ \bar{E}_{txf}^S &= (T_{RTS} + T_D) \bar{P}_{tx}^{SH} + (T_{CTS} + TO + 3SIFS + CIFS) P_{rx}, \\ \bar{E}_{txfR}^S &= (T_{RTS} + T_{RTR}) \bar{P}_{tx}^{SH} + T_D \bar{P}_{tx}^{SR} + (T_{CTS} + T_{ACK} + v T_{CTR} + (5 + v) SIFS + CIFS) P_{rx}. \end{aligned} \quad (7.5)$$

where T_{RTR} is the duration of RTR frame. $\bar{P}_{TX}^{SH}$ and $\bar{P}_{TX}^{SR}$ are the average transmission power used by S to maintain the desired BER at H and R respectively while transmitting directly,

$$\bar{P}_{tx}^{SH} = \int_{\alpha_0}^1 f_{SH}(\alpha) P_{tx}^{SH}(\alpha) d\alpha. \quad (7.6)$$

where P_{TX}^{SH} is the instantaneous power used by S to maintain the desired BER at H and,

$$\bar{P}_{tx}^{SR} = \sum_{i=1}^v p_{R_i} \int_0^1 f_{SR_i}(\alpha) P_{tx}^{SR_i}(\alpha) d\alpha. \quad (7.7)$$

where p_{R_i} is the probability that R_i is chosen by S over the other relays and is defined as follows,

$$p_{R_i} = p(\alpha_{SR_i} > \alpha_{SR_j}), \quad 1 \leq j \leq N_r, j \neq i. \quad (7.8)$$

where α_{SR_i} and α_{SR_j} are the gain of the channel between S and i^{th} and j^{th} relay respectively. N_r is the number of the relays. The probability that a packet is dropped is,

$$p_w = 1 - \sum_{r=1}^{r_m} (1 - p_f) p_f^{r-1} = p_f^{r_m}. \quad (7.9)$$

and hence a packet is successfully transmitted with probability,

$$p_s = 1 - p_f^{r_m}. \quad (7.10)$$

The average energy consumed to transmit a packet successfully is,

$$\bar{E}_s^S = p_s (p_R \bar{E}_{txsR}^S + (1 - p_R) \bar{E}_{txs}^S). \quad (7.11)$$

where $\bar{E}_{txs}^S$ and $\bar{E}_{txsR}^S$ are the energy consumed during a successful transmission to the hub and the relay respectively and are obtained through the following equations,

$$\begin{aligned} \bar{E}_{txs}^S &= (T_{RTS} + T_D) \bar{P}_{tx}^{SH} + (T_{CTS} + T_{ACK} + 3SIFS + CIFS) P_{rx}, \\ \bar{E}_{txsR}^S &= (T_{RTS} + T_{RTR}) \bar{P}_{tx}^{SH} + T_D \bar{P}_{tx}^{SR} + (T_{CTS} + vT_{CTR} + 2T_{ACK} + (5 + v)SIFS + CIFS) P_{rx}. \end{aligned} \quad (7.12)$$

The average total energy consumed by the source node per data bit is,

$$\bar{E}_b^S = \frac{\bar{E}_{bo} + \bar{E}_o^S + \bar{E}_r^S + \bar{E}_s^S}{L}. \quad (7.13)$$

where L is the payload size.

Relay Node

Relay node sends the packet received from S in single hop scheme. The average energy consumed by the relay R_i to receive a packet from S is,

$$\bar{E}_{rx}^{R_i} = (1 - p_d) \bar{E}_{rxs}^{R_i} + p_d \bar{E}_{rxf}^{R_i}. \quad (7.14)$$

where $\bar{E}_{rxs}^{R_i}$ and $\bar{E}_{rxf}^{R_i}$ are the energy consumptions for receiving a successful or failed data packet and are obtained as,

$$\begin{aligned} \bar{E}_{rxs}^{R_i} &= (T_{CTR} + T_{ACK}) \bar{P}_{tx}^{R_i S} + (T_{RTR} + (v-1)T_{CTR} + T_D + T_{ACK} + (4+v)SIFS + CIFS) P_{rx} \\ \bar{E}_{rxf}^{R_i} &= T_{CTR} \bar{P}_{tx}^{R_i S} + (T_{RTR} + (v-1)T_{CTR} + T_D + TO + (v+3)SIFS + CIFS) P_{rx}. \end{aligned} \quad (7.15)$$

where $\bar{P}_{tx}^{R_i S}$ is the average transmission power of R_i used to transmit to S .

The average energy consumed by R_i to overhear an on-going communications is,

$$\bar{E}_o^{R_i} = \bar{n}_b \left[\frac{p_b}{p_{tx}} \bar{E}_{oc} + \left(1 - \frac{p_b}{p_{tx}}\right) ((1 - p_d) \bar{E}_{os} + p_d \bar{E}_{of}) \right]. \quad (7.16)$$

The average energy consumed during retransmissions is,

$$\bar{E}_r^{R_i} = \bar{r} \left[\frac{p_b}{p_f} \bar{E}_{txc}^{R_i} + \left(1 - \frac{p_b}{p_f}\right) \bar{E}_{txf}^{R_i} \right]. \quad (7.17)$$

$\bar{E}_{txc}^S$ and $\bar{E}_{txf}^S$ are the transmission energy consumed during a collision and failed data exchange respectively and are obtained as follows,

$$\begin{aligned} \bar{E}_{txc}^{R_i} &= T_{RTS} \bar{P}_{tx}^{R_i H} + (TO + SIFS + CIFS) P_{rx}, \\ \bar{E}_{txf}^{R_i} &= (T_{RTS} + T_D) \bar{P}_{tx}^{R_i H} + (T_{CTS} + TO + 3SIFS + CIFS) P_{rx}. \end{aligned} \quad (7.18)$$

where $\bar{P}_{tx}^{R_i H}$ is the average transmission power of R_i used to transmit to H .

The average energy consumed to transmit a packet successfully is,

$$\bar{E}_s^{R_i} = p_s \bar{E}_{txs}^{R_i}. \quad (7.19)$$

where $\bar{E}_{txs}^{R_i}$ is the energy consumed during a successful transmission and is obtained through the following equation,

$$\bar{E}_{txs}^{R_i} = (T_{RTS} + T_D)\bar{P}_{tx}^{R_iH} + (T_{CTS} + T_{ACK} + 3SIFS + CIFS)P_{rx}, \quad (7.20)$$

The average total energy consumed by the relay node per data bit is,

$$\bar{E}_b^{R_i} = \frac{\bar{E}_{rx}^{R_i} + (1 - p_d)(\bar{E}_{bo} + \bar{E}_o^{R_i} + \bar{E}_r^{R_i} + \bar{E}_s^{R_i})}{L}. \quad (7.21)$$

As a result, the average total energy consumed on a payload bit is,

$$\bar{E}_{bAdaptive}^T = \bar{E}_b^S + p_R \sum_{i=1}^v p_{R_i} \bar{E}_b^{R_i}. \quad (7.22)$$

The outage probability of the adaptive scheme as defined in Chapter 5 is,

$$p_o^{Adaptive} = p_{fs}^{rm} + (1 - p_{fs}^{rm})p_R p_a p_{fr}^{rm}. \quad (7.23)$$

where p_{fs} and p_{fr} are the probability of a failed transmission by the source node using adaptive routing and the relay node using single hop scheme respectively as given in Equation 7.1. In adaptive routing, outage occurs when neither relay nor the hub receive the data or when only the relay receives the packet successfully but

later drops the packet after reaching the maximum retry limit.

7.3 Distribution of the Channel Gain

Statistics of the channel quality is obtained through time domain measurements using the Agilent infiniiium DSO80804B real-time oscilloscope as described in Section 3.1. E8257D PSG Analog Signal Generator provided the carrier signal at 2.4 GHz. The same omni-directional antenna as described in Section 3.5 was used in narrowband measurements. According to the antenna specifications [69], the antenna gain decreases at frequencies lower than 3.1 GHz, however, other features of the antenna remain in the acceptable range.

The antennas were fixed against body using a dielectric band with dielectric constant close to the air dielectric constant to prevent unwanted reflections. A dielectric material matching the air dielectric constant and thickness of 2 mm was used to distant the antenna from the skin surface.

Consider the scenario described in Chapter 6 where the source node (S) is attached to the left wrist and the hub (H) is positioned on the right side of the waist. Measurements show that R_1 and R_2 as shown in Figure 7.3 can be used to position the relays as R_1 and R_2 have constant connection with both S and H .

The experiments were performed while the subject mimicked walking for about 17 seconds where 250 samples of the channel responses were captured during this time. Figure 7.4.a shows the channel gain variation for R_2 - H path.

Figure 7.3: Measured on-body links.

The channel gains are obtained as the ratio of the received power to the transmitted power of the signal generator. Akaike Information Criterion (AIC) was used to score the candidate distributions for the variations of the channel gain. Log-normal, Rayleigh and Rician were ranked using AIC. Based on the AIC score, log-normal distribution is the best model for the statistics of the channel gain variations among the other candidates which is in accordance with the measurement results reported in [9]. Figures A.1-A.7 in Appendix A show the channel gain and distribution fitting to the channel gain variations at the links shown in Figure 7.3. Parameters of the log-normal distribution for the measured links are given in Table 7.1.

Channel coherence time is a measure of how fast the channel is changing. Channel coherence time is calculated through the following equation [87],

(a) Channel gain variations.

(b) Distribution of the channel gain variations.

Figure 7.4: Channel gain variations and its distribution

Table 7.1: Parameters of the log-normal distribution of channel gain variation at $2.4GHz$.

Channel	μ	σ
$S-H$	-8.364	1.043
$S-R_1$	-7.396	0.463
$S-R_2$	-7.515	0.716
R_1-H	-8.124	0.472
R_2-H	-7.489	0.558

$$T_c = \sqrt{\frac{9}{16\pi}} \frac{1}{f_d}, \quad (7.24)$$

where, f_d is the maximum doppler frequency and is defined as,

$$f_d = f_0 \frac{\nu}{c} \cos(\theta), \quad (7.25)$$

where, $\nu \cos(\theta)$ is the component of the relative velocity of the transmitter in the direction of the receiver. This is important because, depending on the rate of the channel variations, different frames in a session may experience different channel qualities. The fastest moving node in our experimental setting is the wrist node during walking measurements with a maximum velocity of about 0.7 m/s towards

the hub. The estimated channel coherence time for the link between S and H is about $76ms$ while the longest session is a successful transmission to a relay in adaptive scheme. The time it takes for this session to complete is about $2.1ms$ which is much shorter than the estimated channel coherence time. Hence, it is safe to assume that the channel quality remains constant during one communication session.

7.4 Comparison and Results

In this section, the mathematical energy model derived in Section 7.1 is evaluated through simulation and compared for adaptive, single hop and two hop schemes. The network topology is shown in Figure 7.5.

Figure 7.5: Topology of the network.

The suggested modulation in the standard [15] for 2.4 GHz carrier is $\pi/4$ -DQPSK at 600 ksymbol/s. Parameters of the system are given in Table 7.2.

In the evaluation of the mathematical model and simulations discussed below, values

Table 7.2: System Parameters.

Parameter	Value [15, 88]
Carrier Freq.	2.4GHz
Modulation	$\frac{\pi}{4}$ -DQPSK
Symbol Rate	600ksym/sec
<i>SIFS</i>	75 μ sec
<i>CIFS</i>	100 μ sec
<i>TO</i>	30 μ sec
β	145 μ sec
N_n	10
N_r	2
w_0	8
w_m	32
m	5
r_m	5
e_b	10^{-6}
P_{rx}	52 μ W
α_0	1.28×10^{-4}
L	1024 bits

of the parameters are set as given in the Table 7.2 unless the parameter is a variable. Simulations are implemented in MATLAB using the transmission rules described in Chapter 5. In the following figures, solid line depicts the mathematical model prediction while markers indicate simulation points. As seen in the figure, the mathematical model can predict the simulation results with high accuracy.

Figure 7.6 shows the total energy consumption per bit for different values of α_0 . Clearly, only the energy consumption of the adaptive protocol is a function of α_0 . As the figure shows, there is an optimum value for $\alpha_0 = 1.28 \times 10^{-4}$ where the energy consumption per bit is minimum, $\bar{E}_{adaptive} = 3.60 \text{ nJ/bit}$, which is about 54.14% less than the next minimum $\bar{E}_{Singlehop} = 6.65 \text{ nJ/bit}$. At this threshold, the source node optimally switches between direct and relayed transmission strategies.

In addition, the best relay path is chosen to minimize the transmission energy. The figure also confirms that the best strategy of routing data is dependent on the channel conditions. As the figure shows, the average energy consumption per bit for two hop scheme using relay 2 is lower than single hop as the channel quality of this relay is higher on the average. On the other hand, the energy consumption for two hop scheme using relay 1 is highest due to the less favorable channel conditions from R_1 to H as given in Table 7.1 and increased overhead of relayed routing. This would further confirm the necessity of adaptively changing routing strategy to preserve the energy of the nodes. As α_0 approaches zero, the energy consumption of the adaptive scheme reaches single hop energy as the relay is almost never used. On the other hand, for large values of α_0 , relay paths are used more frequently. The average energy cost for adaptive at higher values of α_0 is lower than two hop scheme for both relays because, adaptive routing chooses the best path to route its data and hence consume less energy on the average.

Figure 7.7 shows the energy consumption per bit vs. increasing payload size (L). At small payload sizes, single hop transmission is better due to the less protocol overhead. By increasing the size of the payload, the protocol overhead has less contribution than the payload in total energy consumption per bit. In addition, the energy consumption per bit decreases by increasing the payload size which is mainly due to the reduced cost of protocol overhead relative to the payload. Another advantage of larger payload size is that for the same number of retries due to the collision of *RTS* packets, larger number of bits are transferred. Adverse effect of

Figure 7.6: Energy cost per bit vs. α_0 .

larger payload size is the increased packet error probability.

Figure 7.7: Energy cost per bit vs. payload size (L).

Figure 7.8 shows that the energy cost of transmitting an information bit rises by increasing the number of nodes in the network. The main contributors to this rise in energy cost are the higher number of collisions and longer waiting time before a successful contention session is obtained. Energy cost for two hop increases at a higher rate due to the contribution of energy consumption of the relay to the total energy cost. Unlike a generic sensor network, the number of nodes in a body area network is normally limited to a few nodes e.g. less than 10 nodes. However, investigating the effect of larger node numbers is interesting since in the future, such networks will share the medium with users of other BANs and the total number of

the nodes can be large.

Figure 7.8: Energy cost per bit vs. number of nodes in the network (N_n).

Figure 7.9, shows the probability of outage for adaptive scheme as a function of α_0 . As seen in the figure, the two hop scheme has the highest probability of outage as it requires that both packet transfers from source to relay and relay to hub be successful. As expected, lower values of α_0 in adaptive routing result in outage probabilities similar to the single hop scheme and as α_0 gets larger the outage reaches two hop scheme outage probability since the relays are used more often. Nevertheless, at the optimum channel quality threshold where the energy cost is minimized ($\alpha_0 = 1.28 \times 10^{-4}$), the outage probability of the adaptive scheme ($p_o^{adaptive} = 0.06$) is only slightly higher than the single hop outage probability ($p_o^{singlehop} = 0.05$).

Figure 7.9: Outage probability vs. α_0 .

Increasing the maximum number of retries will decrease the dropped packets number and thus the outage probability as depicted in Figure 7.10. This, however, results in higher energy consumption as shown in Figure 7.11. Hence, there is a trade off between energy cost and outage probability.

Figure 7.10: Outage probability vs. maximum retry limit (r_m).

To evaluate the performance of the adaptive routing in UWB channel and compare with the narrowband channel, the adaptive routing was analyzed with UWB PHY layer as specified in the standard. The parameters of the system are given in Table 6.2. The system was analyzed using the UWB channel in Chapter 4. The energy cost per bit for the adaptive scheme is given in Figure 7.12 vs. different values of α_0 and is compared with single hop and two hop schemes. As seen in the figure, the

Figure 7.11: Energy cost per bit vs. maximum retry limit (r_m).

same trend is observed as with the narrowband PHY.

7.5 Conclusion

In this chapter, an adaptive scheme is proposed to improve the energy efficiency of the nodes in the network. The key idea is to adaptively change the routing strategy based on the quality of the channel. The adaptive protocol is mathematically analyzed based on the medium access procedures of the IEEE 802.15.6 standard. The analytical model is then validated through simulations. The adaptive scheme is compared with the existing methods and it is shown that it reduces the transmission energy cost per bit by 54%.

Figure 7.12: Energy cost per bit vs. α_0 for UWB PHY layer.

Chapter 8

Conclusions and Recommendations

8.1 Conclusions

In this research, a novel and comprehensive channel model for dynamic radio links of wireless body area networks is developed. The model is based on thorough and precise measurements performed on different parts of the body and for several subjects. In addition, a new adaptive routing protocol is developed for wireless body area networks. In this protocol, the source node decides on the routing scheme based on the channel information. The adaptive routing protocol is then evaluated using the dynamic channel model for WBAN. It is shown that the adaptive protocol can significantly reduce the energy consumption of the nodes and hence increase

the lifetime of the network. In addition, results show that the adaptive routing can significantly improve the packet delivery success rate of the source node while reducing the outage probability. The main contributions of this work are as follows:

Real-time Dynamic Channel Measurements on Human Body in Indoor Environment

A comprehensive measurements campaign was performed for on body radio channel in different postures. Static measurements were performed for standing, sitting and lying postures while walking as the most common daily activity was used for dynamic measurements. Measurements were performed using a real-time oscilloscope and in both narrow band and ultra-wideband.

Channel Model for Dynamic Surface to Surface Radio Links on Human Body

A novel channel model based on the real-time measurement of the dynamic radio channels in a body area network is provided. Statistical analysis is performed on different parameters of the channel and typical values of the parameters and their distributions are presented. In addition, an algorithm for reconstructing the samples of the channel response for different radio links over the body is provided. Finally, the performance of the model in predicting the channel and system parameters such as RMS delay spread and BER is evaluated and compared with the estimated parameters from the real-time measured data. The results show that the proposed

model can closely predict the BER performance of a system designed to work in an on-body environment.

Opportunistic Routing in Wireless Body Area Networks

This research introduces Coded Bit Modulation (CBM), a new modulation for UWB impulse radio which is based on time-hopping binary phase-shift keying (TH-BPSK). In CBM, bit information is modulated in the spreading code associated with each symbol rather than the amplitude of the pulses. It is shown that this scheme enables the intermediate nodes to combine and transmit packets from other nodes together with their own packets without extra energy usage. This advantage can be utilized in wireless sensor networks to increase the redundancy where a node can combine its data with a neighbor node's data in a single stream and transmit. Receiver design for CBM is presented and the BER performance is derived mathematically.

CBM modulation for UWB impulse radio is incorporated in an opportunistic routing protocol to improve the energy efficiency of the routing in WBANs. The cooperation between the nodes is extended to the case when some nodes are located on moving parts of the body such as hand. Then, using an opportunistic approach, the hand movements were exploited to preserve the energy of the relay node and hence increase the overall lifetime of the network.

Adaptive Routing in Wireless Body Area Networks

This part has three major contributions, First, an analytical model for the transmission energy cost per bit of information is developed based on the Markov chain of the process and the model is validated through simulations. Second, power efficient adaptive routing protocol is proposed and the performance of the protocol in terms of energy efficiency and outage is evaluated and compared with the standard in system level through mathematical analysis and simulations. Third, a statistical model for the received power in a dynamic body area network is provided through time domain real-time measurements. Analysis based on the Markov model of the protocol shows that the adaptive routing can reduce the energy cost of information bit significantly.

8.2 Recommendations for Further Research

This work focuses on the communication in an intra-body network. However, by expanding the use of WBANs, there is a need for protocols for interactions between WBANs. Cooperation between nearby WBANs can improve the efficiency of the routing data to other networks and can provide opportunity for interesting applications. However, there are challenges which need to be addressed before these type of networks are realized.

One of these challenges is the dynamic channel modeling in intra-body communications. Existing indoor channel models mostly address the stationary scenario in

which both receiver and transmitter are stationary in an indoor environment. On the other hand, human body is a dynamic environment and hence the dynamic nature of the human body has to be incorporated in the channel model. In addition, interference between WBANs is another issue that needs to be addressed. When WBANs are pervasive, inter-communication between nodes in a BAN can affect the performance of a nearby BAN which can be catastrophic in the case of medical applications.

Another aspect of WBANs which need to be addressed is the security concerns in the privacy of the data transmissions and also integrity of the commands received from the base station. For example, consider a medical application in which some parameters of the body are being monitored by sensors and the data is transmitted to the medical center. Such application would need a high level of privacy and integrity in transmission of the private medical data of the patient. In addition, assume that based on the received information on the condition of the patients, some command are issued for the the active node to perform some action such a releasing a medicine into the body. Tampering these commands can raise major concerns in the use of WBANs unless these concerns are addressed.

Publications

International Journal

A. Maskooki, C. B. Soh, E. Gunawan, and K. S. Low, "Ultra-Wideband Real-Time Dynamic Channel Characterization and System Level Modeling for Radio Links in Body Area Networks," IEEE Transactions on Microwave Theory and Techniques, Vol. 61, Issue 8, 2013.

A. Maskooki, C. B. Soh, E. Gunawan, and K. S. Low, "Adaptive routing for dynamic radio links in Body Area Networks," submitted to IEEE Journal of Biomedical and Health Informatics (J-BHI), 2013.

International Conference

A. Maskooki, C. B. Soh, E. Gunawan, and K. S. Low, "Coded Bit Modulation for UWB Impulse Radio," Vehicular Technology Conference (VTC2013), Dresden, Germany, June 2013.

A. Maskooki, C. B. Soh, E. Gunawan, and K. S. Low, "Opportunistic Routing for Body Area Networks," 1st IEEE International Workshop on Consumer eHealth Platforms, Services and Applications, Consumer Communications and Networking Conference (CCNC), Las Vegas, Nevada, USA, January 2011.

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Appendix A

Distribution of the Channel Gain Variations

A.1 Narrowband at 2.4GHz

Figure A.1: Channel gain and its distribution at L_{01} (Top), L_{02} (Bottom).

Figure A.2: Channel gain and its distribution at L_{03} (Top), L_{04} (Bottom).

Figure A.3: Channel gain and its distribution at L_{05} (Top), L_{06} (Bottom).

Figure A.4: Channel gain and its distribution at L_{07} (Top), L_{10} (Bottom).

Figure A.5: Channel gain and its distribution at L_{12} (Top), L_{13} (Bottom).

Figure A.6: Channel gain and its distribution at L_{14} (Top), L_{15} (Bottom).

Figure A.7: Channel gain and its distribution at L_{16} (Top), L_{17} (Bottom).

A.2 UWB

Figure A.8: Channel gain and its distribution at L_{01} (Top), L_{02} (Bottom).

Figure A.9: Channel gain and its distribution at L_{03} (Top), L_{04} (Bottom).

Figure A.10: Channel gain and its distribution at L_{05} (Top), L_{06} (Bottom).

Figure A.11: Channel gain and its distribution at L_{07} (Top), L_{10} (Bottom).

Figure A.12: Channel gain and its distribution at L_{12} (Top), L_{13} (Bottom).

Figure A.13: Channel gain and its distribution at L_{14} (Top), L_{15} (Bottom).

Figure A.14: Channel gain and its distribution at L_{16} (Top), L_{17} (Bottom).

Appendix B

Samples of Power Delay Profile

Figure B.1: Power delay profile at channel 1.

Figure B.2: Power delay profile at channel 2.

Figure B.3: Power delay profile at channel 3.

Figure B.4: Power delay profile at channel 4.

Appendix C

BER Analysis of CBM Receiver

In this section, we analyze the bit error rate (BER) performance of the receiver described in Section 6.3 in AWGN. The received signal is passed through two correlator branches. One for each vector, $\bar{v}_1$ and $\bar{v}_2$. Then based on the amplitude and sign of the correlation results, the most likely bit sequence is sent to the output. The signal space has two basis $\{s_1(t), s_2(t)\}$ where,

$$s_1(t) = \sum_{i=1}^{N_f} a_i^1 g(t - iT_f - \tau_{c1i}) \quad (\text{C.1})$$

$$s_2(t) = \sum_{i=1}^{N_f} a_i^2 g(t - iT_f - \tau_{c2i}) \quad (\text{C.2})$$

where $g(t)$ is the pulse shape. Note that we assume synchronization between the receiver and transmitter and omit the delay between transmitter and receiver Δt .

Assuming s_1 is sent, the received signal r after passing through AWGN channel is,

$$r(t) = s_1(t) + n(t). \quad (\text{C.3})$$

where $n(t)$ is AWGN with power spectral density of $N_0/2$. The components of the received signal along s_1 and s_2 vectors, are obtained by correlating the signal with a template of s_1 and s_2 . At the output of each correlator branch in Figure 6.2 we have,

$$\begin{aligned} I_1 &= r.s_1 = s_1.s_1 + n.s_1 \\ &= \int_{T_s} s_1^2(t)dt + \int_{T_s} n(t)s_1(t)dt \\ &= E_s + n'_1. \end{aligned} \quad (\text{C.4})$$

$$\begin{aligned} I_2 &= r.s_2 = s_1.s_2 + n.s_2 \\ &= 0 + \int_{T_s} n(t)s_2(t)dt \\ &= n'_2. \end{aligned} \quad (\text{C.5})$$

where $s_i.s_j = \int_{T_s} s_i(t)s_j(t)dt$ is the projection of $s_i(t)$ on $s_j(t)$ and $E_s = N_f E_p$. The first term on the right side of the Equation C.4 is the sum of the energies of all N_f pulses of the symbol s_1 or the symbol energy E_s . The second term is the projection

of the noise on s_1 (n'_1). Similarly in Equation C.5, n'_2 is the noise component on s_2 .

We have,

$$E(n'_i) = E\left(\int_{T_s} n(t) s_i(t) dt\right) = \int_{T_s} E(n(t)) s_i(t) dt = 0. \quad (\text{C.6})$$

and,

$$\begin{aligned} E(n'_i n'_j) &= E\left(\int_{T_s} n_i(t) s_i(t) n_j(\tau) s_j(\tau) dt d\tau\right) \\ &= \int_{T_s} \int_{T_s} E(n_i(t) n_j(\tau)) s_i(t) s_j(\tau) dt d\tau \\ &= \frac{1}{2} N_0 B \int_{T_s} \int_{T_s} \delta(t - \tau) s_i(t) s_j(\tau) dt d\tau \\ &= \frac{1}{2} N_0 B \int_{T_s} s_i(t) s_j(t) dt \\ &= \frac{1}{2} N_0 B E_s \delta_{i,j}. \quad \forall i, j | i, j \in \{1, 2\} \end{aligned} \quad (\text{C.7})$$

where B is the bandwidth of the pulse. Hence, n'_1, n'_2 are Gaussian random variables with zero mean and variance of $\sigma^2 = 1/2 N_0 B E_s$. According to Table 6.1, one bit is detected in error if I_2 gives a larger absolute value than I_1 . On the other hand two bits error occurs if $I_1 < 0$. Hence the bit error probability is,

$$\begin{aligned} P(\mathbf{E} | s_1) &= \\ &= \frac{1}{2} \left[P(|I_1| < |I_2| | s_1) + 2P(I_1 < 0, |I_1| \geq |I_2| | s_1) \right]. \end{aligned} \quad (\text{C.8})$$

where I_1 and I_2 are normally distributed with variance $\sigma^2 = 1/2 N_0 B E_s$ with mean

of E_s and 0 respectively. $\mathbf{E}$ is the event that error occurs. The first term on the right in Equation C.8 can be written as,

$$\begin{aligned} P(|I_1| < |I_2| \mid s_1) &= P\left(\frac{|I_1|}{|I_2|} < 1 \mid s_1\right) \\ &= P\left(-1 < \frac{I_1}{I_2} < 1 \mid s_1\right). \end{aligned} \quad (\text{C.9})$$

Distribution of $Z = X/Y$ for the case when X and Y are normally distributed is given in [89]. By substituting $X \sim \mathcal{N}(Es, \frac{N_0 B E_s}{2})$ and $Y \sim \mathcal{N}(0, \frac{N_0 B E_s}{2})$ we have

$$\begin{aligned} P_Z(Z) &= \frac{\sqrt{SNR}}{\sqrt{2\pi}} \frac{Z e^{-\frac{1}{2} \frac{SNR}{Z^2+1}}}{(Z^2+1)^{\frac{3}{2}}} \left[1 - 2Q\left(\sqrt{SNR} \frac{Z}{\sqrt{Z^2+1}}\right) \right] + \\ &\quad \frac{1}{\pi(Z^2+1)} e^{-\frac{1}{2} SNR}. \end{aligned} \quad (\text{C.10})$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2} du, \quad (\text{C.11})$$

$$SNR = \frac{E_s}{N_0 B/2}. \quad (\text{C.12})$$

Hence,

$$P(|I_1| < |I_2| \mid s_1) = \int_{-1}^1 P_Z(Z) dZ. \quad (\text{C.13})$$

For the second term in Equation C.8 we have,

$$\begin{aligned}
 P(I_1 < 0, |I_1| \geq |I_2| \mid s_1) &= \\
 P(I_1 < 0 \mid |I_1| \geq |I_2|, s_1) P(|I_1| \geq |I_2| \mid s_1) &= \\
 = Q(SNR) \left[1 - P(|I_1| < |I_2| \mid s_1) \right] & \quad (C.14)
 \end{aligned}$$

where the second term is obtained using equations (C.8-C.13). Hence we can write,

$$\begin{aligned}
 P(\mathbf{E} \mid s_1) &= \\
 \frac{1}{2} \left[\int_{-1}^1 P_Z(Z) dZ + 2Q\left(\sqrt{\frac{2E_s}{N_0}}\right) \left(1 - \int_{-1}^1 P_Z(Z) dZ\right) \right] & \quad (C.15)
 \end{aligned}$$

where $P_Z(Z)$ is given in (C.10). This is the probability of error in case s_1 is sent. If p_i is the probability of sending s_i ($i \in \{1, \dots, 4\}$) then,

$$BER = \sum_i p_i P(\mathbf{E} \mid s_i). \quad (C.16)$$

If the occurrences of the symbols are equiprobable we have,

$$BER = \frac{1}{4} \sum_i P(\mathbf{E} \mid s_i). \quad (C.17)$$