EVALUATING THE IEEE 802.15.4A UWB PHYSICAL LAYER FOR WSN APPLICATIONS

EDDY IRWAN SHAH BIN SAADON

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Universiti Tun Hussein Onn Malaysia

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ABSTRACT

Wireless communications are becoming an integral part of our daily lives such as wireless local area networks (WLANs) and wireless sensor networks (WSNs). Since more and more devices are going wireless today, it is essential that future wireless technologies can coexist with each other. Ultra wideband (UWB) is a promising solution to this problem due to can coexist with other wireless devices, make it a good candidate for short to medium range wireless system such as WSNs. This research presents the analysis of the IEEE 802.15.4a UWB physical layer (PHY), a novel short range wireless communication technology, for wireless sensor network applications. We analysed and compared the performance of the UWB PHY using the MIXIM framework for a discrete event based simulator called OMNeT++. Among the objectives of our study is to compare the performances by evaluate the bit error rate (BER), throughput and impact of Reed Solomon (RS) coding. In this context, we simulated various types of channels – free space path loss, Ghassemzadeh statistical indoor channels and IEEE 802.15.4a channel models with a variety of configurations such as data rate, bandwidth and forward error correction. An analysis on BER over distances and throughput will be discussed to evaluate the channels performance. The simulation results can be explored for planning and deploying IEEE 802.15.4a based sensor networks with specific performance demands. Besides, specific protocol limitations in real time environment can be identified and solutions can be suggested.

ABSTRAK

Kini komunikasi wayarles merupakan sebahagian daripada keperluan dalam kehidupan kita seharian seperti rangkaian kawasan tempatan wayarles (WLANs) dan rangkaian pengesan wayarles (WSNs). Memandangkan terdapat banyak peranti wayarles pada masa ini, penting sekiranya teknologi wayarles pada masa hadapan boleh wujud bersama-sama dengan yang lain. Jalur lebar lampau (UWB) menjanjikan penyelesaian kepada masalah ini memandangkan ia boleh wujud bersama-sama dengan peranti-peranti tanpa wayar yang lain, membuatkan ia menjadi pilihan yang baik untuk sistem wayarles yang berjarak pendek hingga sederhana seperti WSNs. Penyelidikan ini membentangkan analisa lapisan fizikal (PHY) UWB IEEE 802.15.4a, teknologi komunikasi wayarles berjarak pendek untuk aplikasi WSN. Analisa dan perbandingan tentang pelaksanaan UWB PHY dijalankan menggunakan rangka kerja MiXiM berasaskan simulator diskret yang dipanggil OMNeT++. Antara objektif kajian ini ialah membuat perbandingan pelaksanaan dengan menilai dari segi kadar kesalahan bit (BER), jumlah paket yang diterima dan juga impak pengkodan Reed-Solomon (RS). Dalam konteks ini, beberapa jenis simulasi telah dijalankan ke atas beberapa jenis saluran - kehilangan laluan ruang bebas, saluran statistikal kediaman Ghassemzadeh dan model saluran IEEE 802.15.4a dengan konfigurasi yang berbeza seperti kadar data, jalur lebar serta pembetulan ralat ke hadapan. Bagi menilai prestasi saluran , analisa tentang BER terhadap jarak dan jumlah paket yang diterima akan dibincangkan. Hasil simulasi boleh diterokai bagi merancang dan menggerakkan IEEE 802.15.4a berasaskan rangkaian pengesan dengan permintaan pelaksanaan yang spesifik. Di samping itu, had protokol tertentu dalam persekitaran sebenar boleh dikenalpasti dan seterusnya penyelesaian boleh dicadangkan.

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LIST OF SYMBOLS AND ABBREVIATIONS

BW	-	Bandwidth
B_{frac}	-	Fractional bandwidth
c	-	Speed of light
C	-	Channel capacity
d	-	Distance
d_0	-	Distance at 1 meter
f_c	-	Centre frequency
f_H	-	Upper frequency
f_L	-	Lower frequency
G_t	-	Transmit gain
$G(x)$	-	Gaussian function
L	-	Mean number of cluster
n ,γ	-	Path loss exponent
N_{burst}	-	Number of time burst positions
N_{cpb}	-	Chips per burst
N_{hop}	-	Number of time hopping burst positions
N_{sym}	-	Number of preamble symbol repetitions
P_L	-	Path loss
P_r	-	Received power
P_t	-	Transmit power
PL_0	-	Path loss at the reference distance
S	-	Shadow fading
T_B	-	Burst duration
T_{BPM}	-	Burst position modulation duration
T_{burst}	-	Burst duration
T_c	-	Chip duration
T_G	-	Guard time interval

T_S	-	Symbol duration
T_{sym}	-	Symbol duration
Γ	-	Inter-cluster decay constant
Λ	-	Inter-cluster arrival time
η_r	-	Receive antenna efficiency
η_t	-	Transmit antenna efficiency
μ_γ	-	Mean path loss exponent
μ_o	-	Mean standard deviation of the shadowing
σ	-	Standard deviation
σ_s	-	Shadowing standard deviation
$\sigma_{cluster}$	-	Cluster shadowing variance
σ_γ	-	Standard deviation of path loss exponent
σ_σ	-	Standard deviation of the shadowing
BER	-	Bit error rate
BPSK	-	Binary phase shift keying
CSS	-	Chirp spread spectrum
dB	-	Decibel
dBm	-	Decibel miliwatt
DSL	-	Domain specific language
DSSS	-	Direct sequence spread spectrum
EIRP	-	Effective isotropic radiated power
FCC	-	Federal Communication Commission's
FH	-	Frequency hopping
FFD	-	Full function device
GHz	-	Gigahertz
IDE	-	Integrated development environment
IEEE	-	Electrical and Electronics Engineers
IP	-	Internet protocol
IR	-	Impulse radio
ISI	-	Intersymbol interference
LR-WPAN	-	Low rate wireless personal area network
m	-	metre
MAC	-	Medium access layer

MAI	-	Multiple access interference
MB-OFDM	-	Multi band Orthogonal frequency division multiplexing
Mbps	-	Megabits per second
MHz	-	Megahertz
MPCs	-	Multipath components
NED	-	Network description
ns	-	nanoseconds
OFDM	-	Orthogonal frequency division multiplexing
OS	-	Operating system
PAN	-	Personal area network
PHR	-	Physical layer header
PHY	-	Physical layer
PPM	-	Pulse position modulation
PRF	-	Pulse repetition frequency
PSD	-	Power spectral density
PSDU	-	physical service data unit
RF	-	Radio frequency
RFD	-	Reduced function device
RS	-	Reed-Solomon
SFD	-	Frame delimiter
SHR	-	Synchronisation header
SNR	-	Signal to noise ratio
SYNC	-	Synchronisation
TCP	-	Transmission control protocol
TG4a	-	Task group 4a
TH	-	Time hopping
TOA	-	Time of arrival
UI	-	User interface
UWB	-	Ultra wideband
WiFi	-	Wireless fidelity
WLAN	-	Wireless local area network
WSN	-	Wireless sensor networks
XML	-	Extensible mark up language

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CHAPTER 1

INTRODUCTION

1.1 Background

WSNs have attracted a wide range of disciplines where close interactions with the physical world are essential. The distributed sensing capabilities and the ease of deployment provided by a wireless communication paradigm make WSN an important component of our daily lives. By providing distributed, real-time information from the physical world, WSN extend the reach of current cyber infrastructures to the physical world.

WSN differ fundamentally from general data networks such as the internet, and as such they require the adoption of a different design paradigm. Often sensor networks are application specific; they are designed and deployed for special purposes. Thus the network design must take into account the specific intended applications. More fundamentally, in the context of WSN, the broadcast nature of the medium must be taken into account. For battery-operated sensors, energy conservation is one of the most important design parameters, since replacing batteries may be difficult or impossible in many applications. Thus sensor network designs must be optimized to extend the network lifetime. The energy and bandwidth constraints and the potential large-scale deployment pose challenges to efficient resource allocation and sensor management. A general class of approaches such as cross layer designs has emerged to address these challenges. In addition, a rethinking of the protocol stack itself is necessary so as to overcome some of the complexities and unwanted consequences associated with cross-layer designs.

UWB technology has recently received significant attention in both academia and industry for applications in wireless communications. UWB activity has picked up drastically since Federal Communication Commission's (FCC) 2002 allowed the transmission of UWB and the subsequent standardization efforts with Institute of Electrical and Electronics Engineers (IEEE). The FCC [1] formally defined, UWB signals is the fractional bandwidth greater than 20% or with UWB bandwidth equal to or greater than 500 MHz. This is much wider than any existing communication system. Although research and development efforts in recent years have demonstrated that UWB radio is a promising solution for low rate short range and medium range wireless communication and ranging, further extensive investigation, experimentation and development are necessary to produce effective and efficient UWB communication systems. In particular, UWB has found a new application for lower rate short and medium range wireless communications, illustrated by IEEE 802.15.4a with joint communication and ranging capabilities unique to UWB.

The low rate UWB PHY was standardized in 2007 under the IEEE 802.15.4a study group to define a new physical layer concept for low data rate applications utilizing UWB technology at the air interface. The main purpose of task group 4a (TG4a) was to provide communications and high precision ranging with low-power and low cost devices. The study group addresses new applications that require only moderate data throughput, but long battery life such as low-rate wireless personal area networks, sensors and small networks. IEEE 802.15.4a decided on a signal bandwidth of 500 MHz. A UWB device can transmit in one or more of the following bands according to the IEEE 802.15.4a standard.

1.2 Motivation and Problem Statement

WSNs, which normally consist of hundreds or thousands of sensor nodes each capable of sensing, data processing and communicating are deployed to monitor certain physical phenomena or to detect and track certain objects in an area of interests. Since the sensor nodes are equipped with battery only with limited energy, energy efficient information processing is of critical importance to operate the deployed networks as long as possible. Thus, UWB with IEEE 802.15.4a had proven to offer significant advantages with respect to robustness communications with variable data rate over short distances, energy consumption and location accuracy.

The selection of frequency band also an important criteria that need to be consider in designing a wireless communication system such power restriction allows UWB systems to reside below the noise floor of a typical narrowband receiver and enables UWB signals to coexist with current radio services with minimal or no interference. However, this all depends on the type of modulation used for data transfer in a UWB system.

Hardware testing for UWB is very expensive. Simulation is one of the methods that can save the testing cost. Simulations take the testing phase out of the loop by using the model already created in the design phase. Most of the time, the simulation testing is cheaper and faster than performing the multiple tests of the design each time. In that case, network simulator tool (OMNET++) is used to perform the capabilities of UWB technologies over WSNs. So, the process of building good simulation models is extremely important in such environments.

ZigBee is an open global standard for wireless technology designed to use low-power digital radio signals for personal area networks. ZigBee operates on the IEEE 802.15.4 specification and is used to create networks that require a low data transfer rate, energy efficiency and secure networking. Many researches have been done in recent years on IEEE 802.15.4 standard and ZigBee. Since IEEE 802.15.4a is amendment and complies with UWB PHY which is clearly better than ZigBee in low rate wireless personal area network (LR-WPAN), this research is providing an evaluation and analysis on low rate ultra wideband as the communication medium for WSNs.

1.3 Research Objectives

The objectives of this research are:

(a) To compare the distance, throughput and bit error rate (BER) for the various channels and timing parameters using several channel models.

(b) To analyse the effect of data rate and bandwidth to the BER and throughput.

(c) To analyze the impact of the forward error correction on the distance and BER.

1.4 Research Scopes

The scopes of this project are:

(a) To analyse the good use of UWB unlicensed spectrum.

(b) To simulate the IEEE 802.15.4a UWB PHY as closely and accurately as possible.

(c) To apply the UWB PHY simulation model to a WSN.

(d) To produce a UWB simulation using OMNeT++ software.

1.5 Research Limitation

The following assumptions been taken into account during simulation:

(a) The simulations experiments are repeatable.

(b) Interferences from other technologies are negligible.

(c) Uniform random number is used .with specific radian and mean.

1.6 Thesis Outlines

This thesis can be structured into seven chapters.

Chapter 1 discusses the background of the research. In addition, project objectives, problem statements, scopes of work, expected results and thesis structure outlines are presented.

Chapter 2 consist of literature review of the previous research related to IEEE 802.15.4a and UWB technology.

Chapter 3 gives an overview of key requirements for wireless sensor network that are offered by UWB technology.

Chapter 4 presents the basic theory behind the use of UWB technology. It describes the definition and regulation, type of signals, advantages and application. Channel models are also described.

Chapter 5 presents a comprehensive discussion on IEEE 802.15.4a standard including channel allocation, transmitter structure and signal model, system parameters and packet format.

Chapter 6 provides an overview on OMNeT++ simulation environment including introduction and general concepts of OMNeT++ and MiXiM.

Chapter 7 discusses how the IEEE 802.15.4a UWB PHY is simulated in OMNeT++ environment under MiXiM framework. It describes the general research methodologies, designing stages, important parameters and assumptions that are considered.

Chapter 8 presents and analyses the various simulation result including channel model effects, data rata effects, bandwidth effects and forward error correction effects.

Chapter 9 gives a conclusion of the research efforts of this thesis. Future work is recommended and discussed.

CHAPTER 2

LITERATURE REVIEW

This chapter describes previous research related to UWB technology and IEEE 802.15.4a UWB PHY.

D. Porcino and W. Hirt [2], C. Chong, F. Watanabe and H. Inamura [3], W. Hirt [4], T.K.K. Tsang and M.N. El-Gamal [5] discussed on the key characteristics and capabilities of UWB radio technologies for next generation wireless communications. Overall the papers had outlined the UWB regulation and standard, advantages of UWB such as extremely low power spectral density (PSD), spectrum reuse, robust performance under multipath conditions, low loss penetration, security and scalability. Technical challenges especially on antenna design, propagation channel, timing acquisition and synchronisation, coding and modulation and UWB networking also had been highlighted in these papers. Furthermore the application of UWB has been discussed such as object and personal location, smart home and offices, ad-hoc networking and smart highway. The authors agreed that UWB is promising technologies for next wireless communication.

A. F. Molisch et al. [6] discussed the IEEE document of IEEE 802.15.4a channel modelling subgroup. Different channel models are specified based on the Saleh-Valenzuela. The interesting contributions from the paper include the following:

(a) Models for a large number of environments.
(b) Frequency dependence path loss and thus implicitly the distortions of each separate multipath components (MPCs).

(c) Modelling the number of clusters of MPCs according to the Saleh-Valenzuela model as a random variable.

(d) A power delay profile that models a “soft” onset, so that the first arriving paths can be considerably weaker than later MPCs; this is critical for accurate assessment of ranging capabilities of UWB.

(e) A new model for body-area network that includes correlated lognormal shadowing.

E. Karapistoli et al. [7] highlighted the IEEE 802.15.4a standard that specifies a wireless physical layer to enable precision ranging. The waveform of UWB PHY is based on impulse radio signalling scheme using band-limited data pulse which supports three independent bands of operation: the sub-gigahertz band, low band and high band. In managing the UWB PHY few parameters are consider such as centre frequency, occupied bandwidth, possible mean pulse repetition frequencies (PRFs), chip rates, data rates, preamble codes, preamble symbol lengths, forward error correction, waveform and optional ranging.

J. Zhang et al. [8] and A. F. Molisch et al. [9] discussed the compatibility of UWB systems for low rate wireless sensor networks and IEEE 802.15.4a standard. Its also compared the key requirements for transceiver in sensor note that complies with ZigBee and UWB. They prove that UWB had provide more requirements that needed by sensor networks in term of robustness, variable data rate and heterogeneous networking. Furthermore, the paper also compared the performances between ZigBee, WiFi and UWB. Compared to narrowband direct sequence spread spectrum (DSSS) and WiFi , UWB offers significant advantages.

J. Zhang et al. [8] defined for low rate sensor networks, neither orthogonal frequency division multiplexing (OFDM) nor DSSS is suitable since they require sampling, analog to digital conversion and processing with high rate, entailing high complexity and large energy consumption while frequency hoppinh (FH) and time hopping-impulse radio (TH-IR) offer much better performance / complexity tradeoff. Since FH can create worse interference to legacy system and is prohibited in several regulatory domains, TH-IR is the method of choice for UWB sensor network application.

H.W. Pflug [10] discussed a calculation method to analyse ultra wideband pulse shape used for wireless communication using the IEEE 802.15.4a standard. The presented equations provide a simple way for designing a standard compliant pulse shape generated with low power consumption. The pulse shapes in this paper are trapezoidal, exponential and piece-wise constant.

M. Aboelaze and F. Aloul [11] and I.F. Akyildiz et al [13] recommended UWB or impulse radio (IR) for future wireless sensor networks technology due to resistance of multipath characteristic and low transmission power.

K.D. Wong [12] studied on three main classes of physical layer technologies for use in WSNs, based on bandwidth. (narrowband, spread spectrum and UWB). UWB appears to be a promising alternative physical layer technology.

X. Xian, W. Shi and H. Huang [14] compared the performances between three well known WSN simulators - OMNET++, NS2 and OPNet. Overall OMNET++ is better than the other simulator in terms of available protocols and models, network topology and hierarchical models, programming model and simulation library and debugging and tracking.

M. Kim, H. Kim and J. Kim [15] focussed on developing MATLAB models for IEEE802.15.4a standard. The performance evaluation of the BER calculated through comparison of input and output bits.

J. Rousselot and J. Decotignie [16] present a novel symbol-level simulator for UWB-IR which can accurately model path loss, large-scale fading, small-scale fading and collisions. This physical layer is used to implement a model of an IEEE 802.15.4A UWB-IR radio transceiver based on energy detection.

A. Köpke et al. [17] introduced MiXiM to the OMNet++ community – a powerful simulation framework and concise modelling chain for mobile and wireless networks.

CHAPTER 3

WSNs KEY REQUIREMENTS

This chapter provides an overview of key requirements needed by a UWB-based WSN

3.1 Overview

In WSNs, many spatially distributed radio transceivers with attached sensors are used to monitor environmental conditions, such as temperature, sound, vibration, pressure, motion, etc., at different locations. Usually these transceivers should be small and inexpensive so that they can be produced and deployed in large numbers. The main goal of the network is to communicate sensor data with given reliability and delay constraints. To achieve this, different nodes typically communicate with each other in an ad hoc fashion without a fixed infrastructure. The transmission of data from the source to the destination may occur in several hops, where some nodes in the network operate as relays for the transmission of the information. Such relaying makes it easier to transmit information across a large network, and transmission over various paths also increases the robustness with respect to an individual node failure. The key requirements for transceivers in sensor networks based on ZigBee are as follows [8]:

(a) Low cost: Since a large number of nodes are to be used, the cost of each node must be kept small. For example, the cost of a node should be less than 1% of the cost of the product it is attached to.

(b) Small form factor: Transceivers' form factors (including power supply and antenna) must be small, so that they can be easily placed in locations where the sensing actually takes place.

(c) Low energy consumption: A sensor usually has to operate for several years with no battery maintenance, requiring the energy consumption to be extremely low.

Some additional requirements are needed to make the WSN effective offered by UWB [8]:

(a) Robustness: Reliability of data communication in spite of interferences, small-scale fadings, and shadowing is required so that high quality of service (e.g., with respect to delay and outage) can be guaranteed.

(b) Variable data rate: Although the required data rate for sensor networks is not as high as multimedia transmissions, low data rates may be adequate for simple applications while some other applications require moderate data rates.

(c) Heterogeneous networking: Most sensor networks are heterogeneous, i.e., there are nodes with different capabilities and requirements. Typically, the network has some full function device (FFD) that collects data from different sensors, processes them, and forwards them to a central monitoring station. An FFD has fewer restrictions with respect to processing complexity (as there are few FFDs, cost is not such an important factor) and energy consumption (since an FFD is usually connected to a permanent power supply). The sensor nodes themselves, on the other hand, are usually reduced function devices (RFDs) with extremely stringent limits on complexity and power consumption.

Apart from data communication, geolocation is another key aspect for many wireless sensor network applications. Normally, a number of nodes communicate their sensing (measurement) results to each other and/or a control centre. In many cases, the control centre or the receiving nodes need to know the exact location of the transmitter.

CHAPTER 4

OVERVIEW OF UWB TECHNOLOGY

In this chapter, we present the basic theory behind the use of UWB technology. It describes the definition and regulation, type of signals, advantages and application. Channel models are also described.

4.1 UWB Definition and Regulations

UWB has defined to be a signal with a fractional bandwidth greater than 20% or with UWB bandwidth equal to or greater than 500 MHz. The main feature of UWB signals is that occupy a much wider frequency band than conventional signals. Thus, they need to share the existing spectrum with current radio technologies. The fractional bandwidth is calculated as the difference between the upper frequency f_H of the -10 dB emission point and the lower frequency f_L of the -10 dB emission point. Figure 4.1 represents the FCC UWB definition and the mathematical expression of fractional bandwidth B_{frac} is defined as :

$$B_{frac} = \frac{2(f_H - f_L)}{f_H + f_L} \tag{4.1}$$

Moreover, the transmission centre frequency f_c is defined as the average of these cut-off points,

$$f_c = \frac{(f_H + f_L)}{2} \tag{4.2}$$

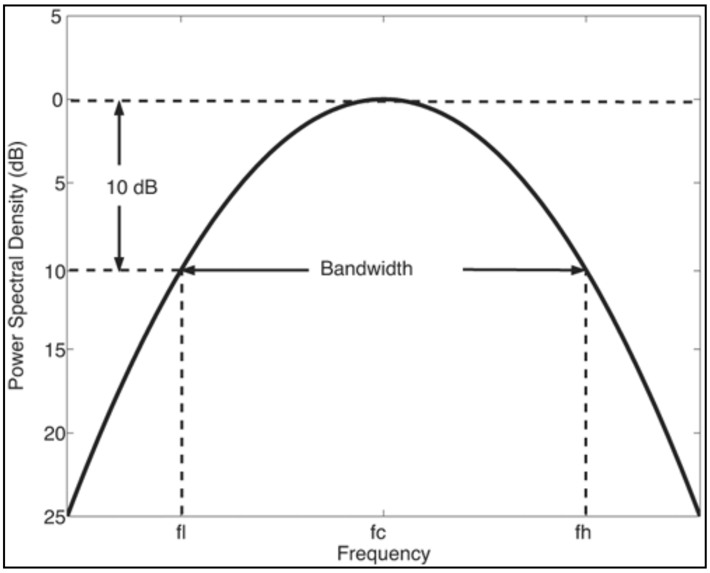

Figure 4.1: FCC definition for the UWB systems

The FCC also allows emission between 3.1 GHz to 10.6 GHz unlicensed frequency band with total of 7500 MHz spectrum band, while specifying a set of rules to control harmful interference from UWB devices. Emission limits are given in terms of effective isotropic radiated power (EIRP). According to the FCC regulations, the maximum EIRP in any direction should not exceed -41.3 dBm. Figure 4.2 shows the spectrum mask for indoor operation permitted under Part 15 of the FCC rules.

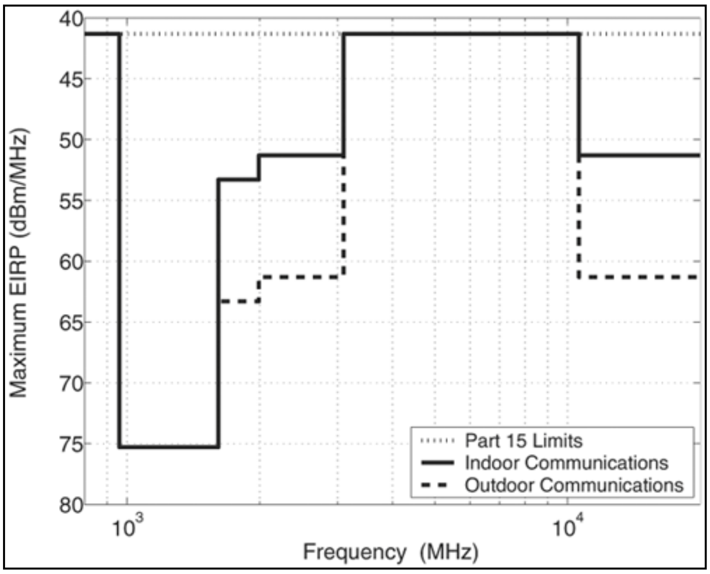

Figure 4.2: FCC emission spectral mask for indoor UWB communication system [2]

4.2 UWB Signalling Techniques

Many different pulse generation techniques may be used to satisfy the requirements of an UWB signal. Impulse radio (IR) and multi band orthogonal frequency division multiplexing (MB-OFDM) are two common UWB signalling techniques [19].

4.2.1 Impulse Radio (IR) UWB

IR refers to the generation of a series of very short duration pulses, of the order of hundreds of picoseconds. Each pulse has a very wide spectrum, which must adhere to the spectral mask requirements. Any given pulse will have very low energy because of the very low power levels permitted for typical UWB transmission. Therefore, many pulses will typically be combined to carry the information for one bit. This small pulse width gives rise to a large bandwidth and a better resolution of multipath in UWB channels.

The monocycle waveform can be any function which satisfies the spectral mask regulatory requirements. Common pulse shapes include Gaussian, Laplacian, Rayleigh or Hermitian pulses. UWB pulse shape known as Gaussian doublet as shown in Figure 4.3 is widely used in impulse radios. A Gaussian function *G(x)* is one which fits the well known equation,

$$G(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-x^2/\sqrt{2\sigma^2}} \tag{4.3}$$

where σ is standard deviation. This is the origin of the name Gaussian pulse, monocycle or doublet. Unlike in classic communications, the IR-UWB does not need a carrier modulation. Information is encoded with a time-hopping baseband signals.

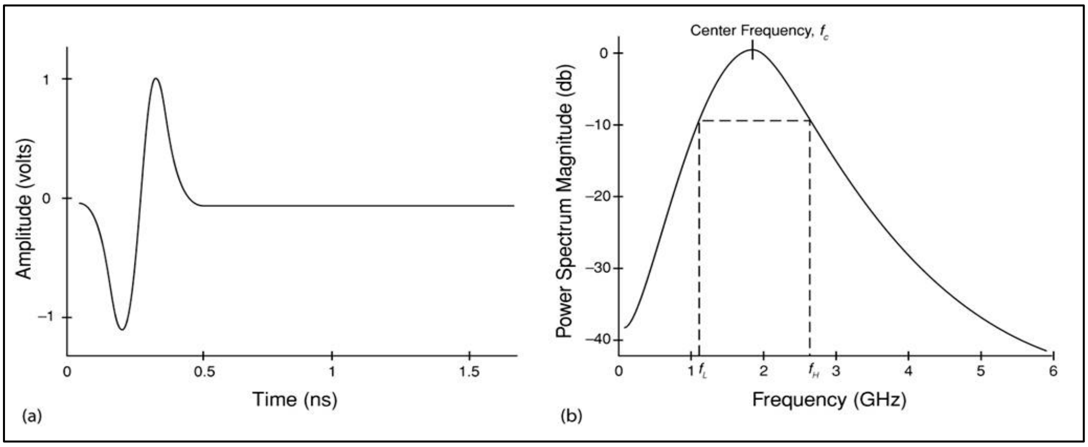

Figure 4.3: Gaussian monocycle in (a) the time domain and (b) the frequency domain

IR has the significant advantage of being essentially a baseband technique. Pulse position modulation (PPM) and binary phase shift keying (BPSK) modulation are some of the commonly used modulation techniques. The PPM encodes the data pulse stream by advancing or delaying individual pulses in time, relative to a reference pulse. BPSK modulation encodes the information by switching [5]. Both modulation schemes are shown in Figure 4.4. The most common impulse radio based UWB concepts are based on pulse position modulation with time hopping pulse position modulation (TH-PPM).

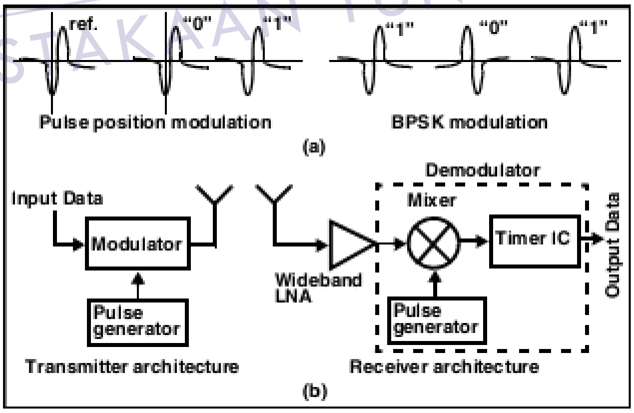

Figure 4.4: (a) UWB modulation schemes. (b) Transceiver architecture of an impulse radio system [5]

4.2.2 Multi Band OFDM

This approach combines the OFDM modulation scheme with the multiband technique [5], and divides the spectrum into several sub-bands that at least 500 MHz as shown in Figure 4.5. Multiple UWB signals are transmitted at the same time but do not interfere each other due to different operating frequencies.

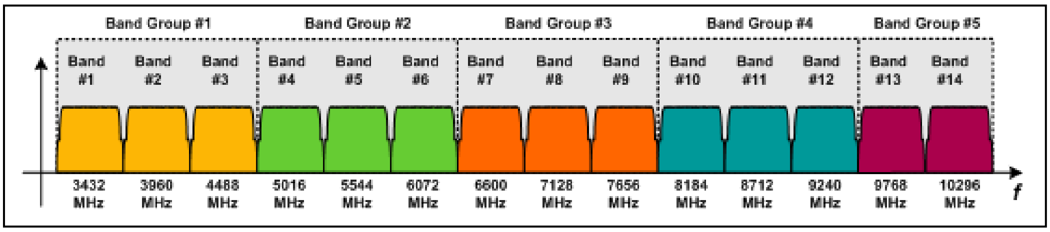

Figure 4.5: MB-OFDM channel allocation

The frequency hopping OFDM technique is used in each band, which increases the symbol period duration. This significantly reduces the effects of inter-symbol interference (ISI) and makes it less sensitive to timing jitters in the receiver, when compared to the impulse radio approach. Furthermore, spectrum shaping for interference control is easier and more effective, but at the price of increasing the baseband circuit complexity and power consumption. One of the challenges in frequency-hopping systems is the increased complexity of the frequency synthesizer. Very fast hopping rates become extremely difficult to achieve with reasonable phase noise specifications. The hopping rate is limited by the finite settling time of the frequency synthesizer, which is dictated by the loop bandwidth and the ringing effects of the resonant structures [5].

4.3 UWB Propagation Channel Models

For wireless technology, the signals travel through space encounter various distortions from multiple paths due to reflections, electromagnetic interference from other wireless signals. Existing propagation channel models can be classified mainly into two categories: deterministic and statistical approaches [20]. The first group contains the algorithms based on field and wave theory, as well as ray-tracing algorithms. Whereas the statistical methods use simpler models that are based on statistics from large scale propagation measurement and have to be chosen accordingly to the scenario they will be applied to, like indoor or outdoor or according to the terrain occupation (urban, suburban, rural). This topic will discuss on empirical channels for UWB.

4.3.1 Free Space Propagation Model

Free space propagation can be simplified as the transmitted signal reaches the receiver only through a direct path. For this free space propagation scenario, the received power at frequency *f* and distance *d* can be expressed as,

$$P_r(d,f) = P_t G_t(f)\eta_t(f)\eta_r(f)(\frac{c}{4\pi f d})^2 \tag{4.4}$$

where P_t is the transmit power , G_t and G_r are the antenna gains for the transmit and receive antenna respectively, *c* is the speed of light, η_t and η_r are the efficiencies for transmit and receive antenna respectively. From equation (4.4), it is observed that if the gain of the antennas vary considerably with frequency, the receive power level can change significantly too. In other words, unlike narrowband system, for which the gains can be considered as frequency independent, the gains can vary over the frequency range of a UWB system.

Another source of frequency dependency comes into play through the antenna efficiency. One factor that affects the antenna efficiency is the impedance bandwidth of an antenna, which specifies a frequency band over which the signal loss is not very significant. For UWB antenna, it is quite challenging to limit this signal loss to low and fixed levels over a wide frequency band. Therefore, antenna efficiency is also commonly a frequency dependent term.

4.3.2 Ghassemzadeh Channel Model

Ghassemzadeh et al. [22] have developed a statistical path loss model for UWB propagation in residential environments, for both line of sight and non line of sight environments. It is based on 300 000 frequency-response measurements of 1.25 GHz-wide pulses with a central frequency of 5 GHz, taken in 23 homes. The path loss in dB at a distance *d* as follows:

$$PL(d) = \left[PL_0 + 10_\gamma \log_{10}\frac{d}{d_0}\right] + S(d), d \geq d_0 \qquad (4.5)$$

where the reference distance d_0 is equal to 1 meter, PL_0 is the path loss at the reference distance, γ is the path loss exponent and S is the shadow fading. The shadow fading is shown to be log-normal (with a standard deviation σ) in their measurements. Their path loss model considers γ and σ as random variables. The path loss at the reference distance PL_0, is a parameter whose values are given for both line of sight (LOS) and non line of sight (NLOS) environments in Table 4.1.

Table 4.1: Parameters of the Ghassemzadeh statistical channel models for LOS and NLOS residential environments

Parameter	Description	LOS	NLOS
PL_0	Path loss at d_0	47 dB	51 dB
μ_γ	Mean path loss exponent	1.7	3.5
σ_γ	Standard deviation of the path loss exponent	0.3	0.97
μ_o	Mean standard deviation of the shadowing	1.6	2.7
σ_σ	Standard deviation of the shadowing	0.5	0.98

4.3.3 The IEEE802.15.4a Channel Model

The channel model was proposed during the development of IEEE802.15.4a standard [6]. The following environments are important for sensor network applications and are those ones for which the model is parameterised:

(a) Indoor residential: These environments are critical for "home networking," linking different appliances, as well as safety (fire, smoke) sensors over a relatively small area. The building structures of residential environments are characterized by small units, with indoor walls of a reasonable thickness.

(b) Indoor office: Some of the rooms are comparable in size to residential, but other rooms (especially cubicle areas, laboratories, etc.) are considerably larger. Areas with many small offices are typically linked by long corridors. Each of the offices typically contains furniture, bookshelves on the walls, etc., which adds to the attenuation given by the (often thin) office partitions.

(c) Outdoor: While a large number of different outdoor scenarios exist, the current model covers only a suburban-like microcell scenario, with a rather small range.

(d) Industrial environments: Characterized by larger enclosures (factory halls), filled with a large number of metallic reflectors. This is anticipated to lead to severe multipath.

(e) Agricultural areas/farms: For those areas, few propagation obstacles (silos, animal pens), with large distances in between, are present. The delay spread can thus be anticipated to be smaller than in other environments.

The distance dependence of the path loss in dB is expressed as follows:

$$PL(d) = PL_0 + 10n\log_{10}\left(\frac{d}{d_0}\right) \tag{4.6}$$

where the reference distance d_0 is set to 1 metre, PL_0 is the path loss exponent. The path loss also depends on the environment, whether or not a LOS connection exists between transmitter and receiver. Table 4.2 and Table 4.3 show the key parameters of IEEE802.15.4a statistical models.

Table 4.2: Key parameters of IEEE802.15.4a residential and indoor office models

Parameter	Description	Residential		Indoor Office	
		LOS CM1	NLOS CM2	LOS CM3	NLOS CM4
PL_0	Path loss (dB)	-43.9	-48.7	-36.6	-51.4
n	Path loss exponent	1.79	4.58	1.63	3.07
σ_S	Shadowing standard deviation	2.22	3.51	1.9	3.9
L	Mean number of clusters	3	3.5	5.4	1
Λ (1/ns)	Inter-cluster arrival time	0.05	0.12	0.016	-
Γ (ns)	Inter-cluster decay constant	22.6	26.3	14.6	-
$\sigma_{cluster}$	Cluster shadowing variance	2.7	2.9		-
Validity	Range (meter)	7-20	7-20	3-28	3-28

Table 4.3: Key parameters of IEEE802.15.4a outdoor and industrial environment models

Parameter	Description	Outdoor		Industrial Environments	
		LOS CM5	NLOS CM6	LOS CM8	NLOS CM9
PL_0	Path loss (dB)	-43.29	-43.29	-56.7	-56.7
n	Path loss exponent	1.76	2.5	1.2	2.15
σ_S	Shadowing standard deviation	0.83	2	6	6
L	Mean number of clusters	13.6	10.5	4.75	1
Λ (1/ns)	Inter-cluster arrival time	0.0048	0.0243	0.0709	NA
Γ (ns)	Inter-cluster decay constant	31.7	104.7	13.47	NA
$\sigma_{cluster}$	Cluster shadowing variance	-	-	4.32	NA
Validity	Range (meter)	5-17	5-17	2-8	2-8

4.4 Advantages of UWB Technology

UWB has several features that differentiate it from conventional narrowband system:

(a) Large instantaneous bandwidth enables fine time resolution for network time distribution, precision location capability or use as a radar.

(b) Short duration pulses are able to provide robust performance in dense multipath environments by exploiting more resolvable paths.

(c) Low power spectral density allows coexistence with existing users and a low probability of intercept.

UWB communications system offer many advantages over narrowband technology. Improved channel capacity is one major advantage of UWB. The channel is the RF spectrum within which information is transferred. Shannon's capacity limit equation shows capacity increasing as a function of BW (bandwidth) faster than as a function of SNR (signal to noise ratio).

$$C = BW \log_2(1 + SNR) \tag{4.7}$$

where C is channel capacity (bits/sec), BW is channel bandwidth (Hz) and SNR is signal to noise ratio. The advantages of UWB has been summarised in Table 4.4.

Table 4.4: Advantages and benefits of UWB communication [3][4][5]

Advantages	Benefits
Coexistence with current narrowband and wideband radio services	Avoids expensive licensing fees.
Large channel capacity	High bandwidth can support real-time high-definition video streaming.
Low transmit power	Provides high degree of security with low probability of detection and intercept.
Resistance to jamming	Reliable in hostile environments.
Robust performance in multipath channels	Delivers higher signal strengths in adverse conditions.
Simple transceiver architecture	Enables ultra-low power, smaller form factor, and better mean time between failures, all at a reduced cost.

4.5 Applications of UWB

Referring to the advantages that offered by UWB, it has a huge potential in wireless platforms that support a variety applications such as [3][4] :

(a) Industrial inventory control – these applications specialise in locating without much communication and are less time critical than others. Accurate of the state of all the items is important. Changes of state (leaving, entering the warehouse) are important. Example includes healthcare inventory tracking.

(b) Home sensing, control and media delivery – these applications are consumer oriented and involve at least unidirectional and often bidirectional communication for support sensing and control functions. Examples include sensing or tracking children, pets or assets.

(c) Logistics – these applications generally help improve the efficiency of the operations in which they are used. Finding and tracking are essential elements for those applications. Examples include warehouse and supply chain management, package tracking and sport tracking.

(d) Industrial process control and maintenance – these applications are similar to those in industrial inventory control. In these applications, sensors and actuator are generally part of the item being located and the information from the sensors and information to the actuators needs to be communicated. Examples include wireless sensor networks, aircraft and ground vehicle anti collision.

(e) Safety and health monitoring – these applications have human life at stake. Tracking is often an important element of these applications. Examples include emergency monitoring (earthquakes, fire), military tactical unit situational awareness and finding avalanche victims.

(f) Personnel security – these applications generally involve real time location and may involve tracking and some uplink communication. Examples include security and surveillance functions in public areas, automobile auto unlocks when owner in range, workstation lock and unlock authentication.

(g) Communications – these applications are those for which communication is primary and location is secondary. An example is body area networks.

4.6 Summary

An overview on UWB technology had been presented in this chapter. Generally, UWB technology is better than existing narrowband technology and a promising technology for future communication. Next, we present a comprehensive discussion on IEEE 802.15.4a UWB PHY that proposed for UWB technology.

CHAPTER 5

OVERVIEW OF IEEE 802.15.4A UWB PHY

This chapter presents a comprehensive discussion on IEEE 802.15.4a standard. The IEEE established the 802.15.4a study group to define a new physical layer concept for low data rate applications utilizing UWB technology at the air interface. The study group addresses new applications that require only moderate data throughput, but long battery life such as low-rate wireless personal area networks, sensors and small networks.

5.1 IEEE 802.15.4a Network Topology

There are two main forms of network topology that can be used within IEEE 802.15.4a. These network topologies may be used for different applications and offer different advantages.

The two IEEE 802.15.4a network topologies are:

(a) Star topology: As the name implies the start format for an IEEE 802.15.4a network topology has one central node called the personal area network (PAN) coordinator with which all other nodes communicate.

(b) Peer to Peer network topology: In this form of network topology, there is still what is termed a PAN coordinator, but communications may also take place between different nodes and not necessarily via the coordinator.

It is worth defining the different types of devices that can exist in a network. There are three types:

(a) Full Function Device (FFD): A node that has full levels of functionality. It can be used for sending and receiving data, but it can also route data from to the nodes.

(b) Reduced Function Device (RFD): A device that has a reduced level of functionality. Typically it is an end node which may be typically a sensor or switch. RFDs can only talk to FFDs as they contain no routing functionality. These devices can be very low power devices because they do not need to route other traffic and they can be put into a sleep mode when they are not in use. These RFDs are often known as child devices as they need other parent devices with which to communicate.

(c) Coordinator: This is the node that controls the IEEE 802.15.4a network. This is a special form of FFD. In addition to the normal FFD functions it also sets the IEEE 802.15.4a network up and acts as the coordinator or manager of the network.

5.1.1 Star Topology

In the star topology, all the different nodes are required to talk only to the central PAN coordinator. Even if the nodes are FFDs and are within range of each other, in a star network topology, they are only allowed to communicate with the coordinator node. Having a star network topology does limit the overall distances that can be covered. It is limited to one hop. Example of star topology is shown in Figure 5.1.

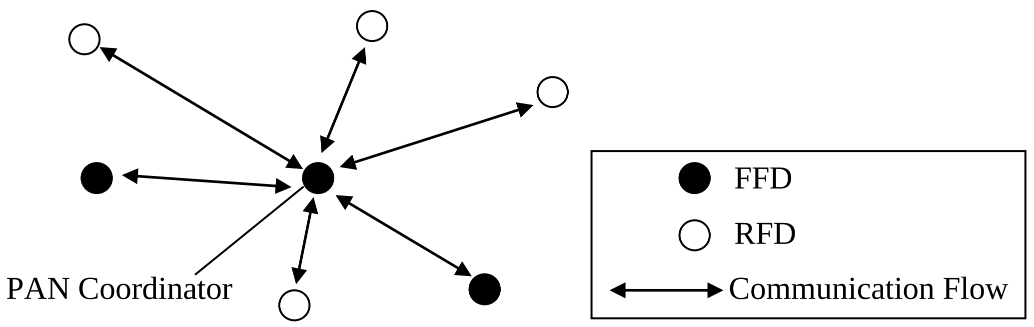

Figure 5.1: Star topology

5.1.2 Peer to Peer Topology

A peer to peer network topology provides a number of advantages over a star network topology. In addition to communication with the network coordinator, devices are also able to communicate with each other. FFDs are able to route data, while the RFDs are only able to provide simple communication. The fact that data can be routed via FFD nodes means that the network coverage can be increased. Not only can overall distances be increased, but nodes masked from the main network coordinator can route their data via another FFD node that it may be able to communicate with. Figure 5.2 shows an example of peer to peer network topology.

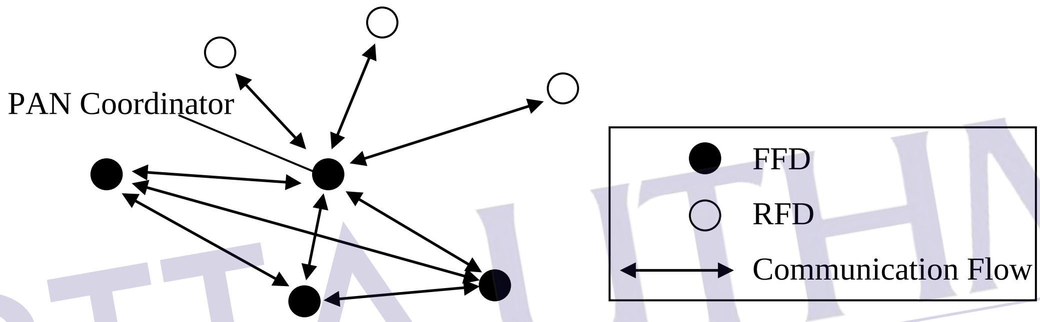

Figure 5.2: Peer to peer topology

5.2 IEEE 802.15.4a PHY

In March 2004, the IEEE 802.15 low rate alternative PHY task group (TG4a) was formed to design an alternate PHY specification for already existing IEEE 802.15.4 standard for wireless personal area networks (WPANs) [18]. The main purpose of the TG4a was to provide communications and high precision ranging with low power and low cost device. The TG4a's efforts resulted in the IEEE 802.15.4a standard in 2007. With additional features provided by the 15.4a amendment, the IEEE 802.15.4 standard now facilitates new applications and market opportunities.

The IEEE 802.15.4a specifies two optional signalling formats based on IR-UWB and chirp spread spectrum (CSS). The IR-UWB option can use 250 - 750 MHz, 3.244 - 4.742 GHz or 5.944 - 10.234 GHz bands, where the CSS uses the 2.4 - 2.4835 GHz band. For the IR-UWB there is an optional ranging capability, whereas the CSS signals can only be used for communications purpose.

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