

WiMedia UWB Systems Measurements and Distributed Multiband MAC Layer Design
for High Rate Residential UWB Wireless Networks

by

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B.Eng., McMaster University, 2007

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of the Requirements for the Degree of

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ABSTRACT

Ultra wideband (UWB) systems have the potential for high data rate applications such as high-definition video streaming, high speed data transfer, etc. Recently, WiMedia based UWB evaluation systems and commercial products are available from industry. In order to understand the true performance of the WiMedia UWB system, it is important to study its characteristics from mathematical models and practical measurement tests. One of the key objectives of this thesis is to determine the important parameters in the path loss model based on the measurement results from the intended environments. Our focus is on residential environments including office buildings and houses, where intensive measurements are performed from various layers of a network (e.g. physical layer, packet level and application level). The results show that the WiMedia UWB system is fully capable of handling different high rate applications in residential networks. Another goal of this thesis is to propose a medium access control (MAC) protocol design tailored to high rate residential UWB wireless networks. The proposed multiband distributed MAC design utilizes the unique capabilities of UWB technology and the environment characteristics. We elaborate the design details and build a discrete event simulation program for performance evaluation purpose. By evaluating from both theoretical

analysis and simulation, we show that the proposed MAC design has substantial advantage over single channel MAC in a high rate residential UWB wireless network.

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DEDICATION

This thesis would be incomplete without a mention of the support given to me by my parents, to whom this thesis is dedicated. And it is also dedicated to my grandma, who passed away one year ago. Thank you for your legacy of love and hard work for our family, grandma. Rest in Peace.

Chapter 1 Introduction

The Federal Communication Commission (FCC) of United States allocated the 3.1 – 10.6 GHz frequency band to ultra-wideband (UWB) in 2002. Other regulatory regimes, including Japan and the European Union, made similar spectrum allocation to UWB. According to FCC and Industry Canada, any wireless communication technology which produces signals with a bandwidth wider than 500 MHz or a fractional bandwidth (which is the bandwidth of a device divided by its center frequency) greater than 0.2 is considered as UWB. With all its unique characteristics, such as high channel capacity, low power consumption, low transmission power and small size in chipset implementation, UWB becomes a promising wireless broadband communication to meet the needs of the rapidly growing arena of personal communication technology.

In this chapter, a brief overview of the UWB technology will be presented, introducing different UWB standard campaigns, followed by a detailed discussion on the campaign namely WiMedia in a more technical manner. Moreover, as with any other new technologies, what people really care about UWB is its applications and how well it will perform as an actual product. Therefore, a general survey and discussion about UWB's applications and products will be presented in Section 1.3. Both advantages and challenges are described, and the importance of the problems to be addressed is highlighted. Finally, the organization of this thesis is shown at the end of the chapter.

1.1 Brief Overview of Ultra Wideband Communication

The most distinctive feature of ultra wideband communication, as its name states, is the enormous bandwidth, in both relative (typically, larger than 20% fractional bandwidth)

and absolute (larger than 500 MHz) senses. Also, the FCC regulation limits the radiation power of indoor communication UWB systems to be as low as -41.3 dBm/MHz in the 3.1-10.6 GHz frequency range [2], while the newly published Canadian UWB regulation set the limits to be -70 dBm/MHz in the frequency range of 1.61-4.75 GHz and -41.3 dBm/MHz from 4.75 GHz to 10.6 GHz [3]. Such strict restrictions avoid interference to existing communication systems, which makes it possible for UWB communication systems to co-exist with narrowband systems without negligible interference. Large bandwidth and low power spectrum make UWB signals very similar to noise, and very difficult to intercept [4]. These features lead to plenty of new possibilities in both communications and applications. For this reason, UWB has been the topic of studies for many years, and it is now divided into two major campaigns based on the different physical layer implementations: pulse-based and Orthogonal Frequency Division Multiplexing (OFDM) based.

The research in pulse-based UWB communication system is a field that is old and young at the same time. One way of interpreting how pulse-based UWB works is to consider the propagation of a short pulse through a medium, and its interaction with objects such as planes, half-planes, and wedges. This distinctive feature makes UWB system highly resistant to fading. Let us consider a narrowband system with 1 Mbps throughput data rate (e.g. 802.11b wireless LAN), its signal length is approximately 1 ms. In order to differentiate the multipath, the minimum distance difference between two paths is $10 \text{ ms} * 3 * 10^8 = 300 \text{ m}$. On the other hand, the typical pulse width of a pulse-based UWB system is about 1 ns, which only requires $1 \text{ ns} * 3 * 10^8 = 0.3 \text{ m}$ to tell the difference between two paths. In conventional narrowband systems, the received signal strength undergoes fluctuations, caused by multipath components (MPC), i.e., echoes from different scatters and reflectors and signals caused by diffractions, which interfere with each other constructively or destructively, depending on the exact locations of

transmitter, receiver and scatters [1]. For a pulse-based UWB system, the transceiver can resolve most MPCs, which eliminates deep fades. Moreover, thanks to UWB's large range of frequencies, its low-frequency components can easily penetrate all kinds of obstacles like walls, doors and etc, while most other high frequency communication systems will have their energy reflected due to their monotonous short wavelengths.

These theoretical investigations have been performed since the days of Sommerfeld at the beginning of the last century [5]; a summary of the history of this work can be found in [14]. However, this theoretical work was not applied to simulations of typical wireless scenarios until the beginning of the current century, when Qiu analyzed the impact on UWB system design [15]. In the late 1990s and early 2000s, UWB communication research has gathered more interest, especially after the standardization activities of IEEE 802.15.3a [16] and 802.15.4a [17], which provided industry with an important stimulus. At the same time, more and more academic researchers have now focused on UWB related topics.

Another well-known UWB campaign is led by WiMedia Alliance. WiMedia Alliance was merged from WiMedia Alliance and MultiBand OFDM Alliance Special Interest Group (MBOA-SIG) in 2005, and it is now transferring all current and future specifications to the Bluetooth Special Interest Group (SIG), Wireless USB Promoter Group and the USB Implementers Forum. WiMedia UWB is the basis for the industry's first UWB standards. The WiMedia Ultra-Wideband (UWB) Common Radio Platform incorporates media access control (MAC) layer and physical (PHY) layer specifications based on Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) [8]. The solution enables short range multimedia file transfers at data rates up to 480 Mbps with low power consumption, and operates in the 3.1 to 10.6 GHz UWB spectrum, which makes it a perfect candidate for the next generation wireless multimedia residential network.

Although UWB systems have substantial advantages compared to traditional narrowband systems, the risen technical difficulties and challenges cannot be ignored. For example, in pulse-based UWB system, the high accuracy requirement of the local oscillators and timing circuits makes hardware implementation very difficult. On the other hand, synchronization and channel estimation remain an important area of study in both academic and industrial research and development. More importantly, how to utilize the “media” (7.5 GHz bandwidth) efficiently in multi-users networks will have direct influence on the future of UWB systems.

1.2 Overview of WiMedia

In March 2007, the ECMA International standard for ultra-wideband (UWB) technology, elaborated from the WiMedia UWB Common Radio Platform, has been approved for release as an ISO/IEC International Standard. The ECMA-368 standard, titled ‘High Rate Ultra-Wideband PHY and MAC Standard’, was approved as ISO/IEC 26907 [6], which specifies a distributed medium access control (MAC) sub layer and a physical layer (PHY) for wireless networks. The PHY and MAC specified in this ECMA standard are compatible to high data rate communications between a diverse set of mobile and fixed electronic devices. In conjunction with this standard, the ECMA-369 standard, titled ‘MAC-PHY Interface for ECMA-368’, was approved as ISO/IEC 26908 [7] and specified the MAC-PHY interface for a high rate, ultra-wideband wireless transceiver [8]. Although this MAC-PHY Interface (MPI) is not mandatory for the manufacturers to follow, it does offer interoperability between PHY and MAC IC developers. That is, it allows PHY ICs and MAC ICs to be independently developed by different companies without running the risk of interoperability problems between them when they are integrated into a single system. Owing to the fact that the trend for WiMedia UWB is in single IC solutions (to reduce cost), the MPI specification may not

play a major role in the future. However, it has so far been well received and adopted by most UWB PHY developers [9].

The following sections will present WiMedia UWB PHY and MAC specifications separately from a high-level overview angle, introducing some of the basic concepts and terminologies which are highly related to the content of this thesis, and some important subjects will be further discussed and redefined as we proceed. Concepts such as interleaving, error correction authentication and data encryption are also in the standard but beyond the scope of this work. Readers are highly recommended to consult the ECMA-368 [11].

In the rest of this thesis, the terms “WiMedia UWB”, “ECMA-368” and “WiMedia PHY and MAC” will be used interchangeably.

1.2.1 Physical Layer

From an OSI reference model [10] point of view, the Physical Layer (PHY) is the lowest layer that converts data into a suitable form for transmission across the physical medium. For WiMedia UWB, the transmission form is a frequency-hopped OFDM radio signal, and the medium is simply the air space between the devices along with the frequency spectrum allocated by the regulatory bodies.

The PHY uses OFDM for transmission, which has 128 subcarriers: 12 of them are pilots, 100 of them will carry data and 10 of them are reserved as guards. Finally, the remaining subcarriers are zeros, which are used as zero-padded suffix or zero-postfix to mitigate the effect of multipath. Fig. 1.1 [9] shows an example of WiMedia UWB OFDM signal. These subcarriers use Quadrature Phase Shift Keying (QPSK) modulation or a new technique called Dual-Carrier Modulation (DCM), a variation of 16 Quadrature Amplitude Modulation (QAM). Higher order modulations such as 64 QAM are not used because of the low power regulation.

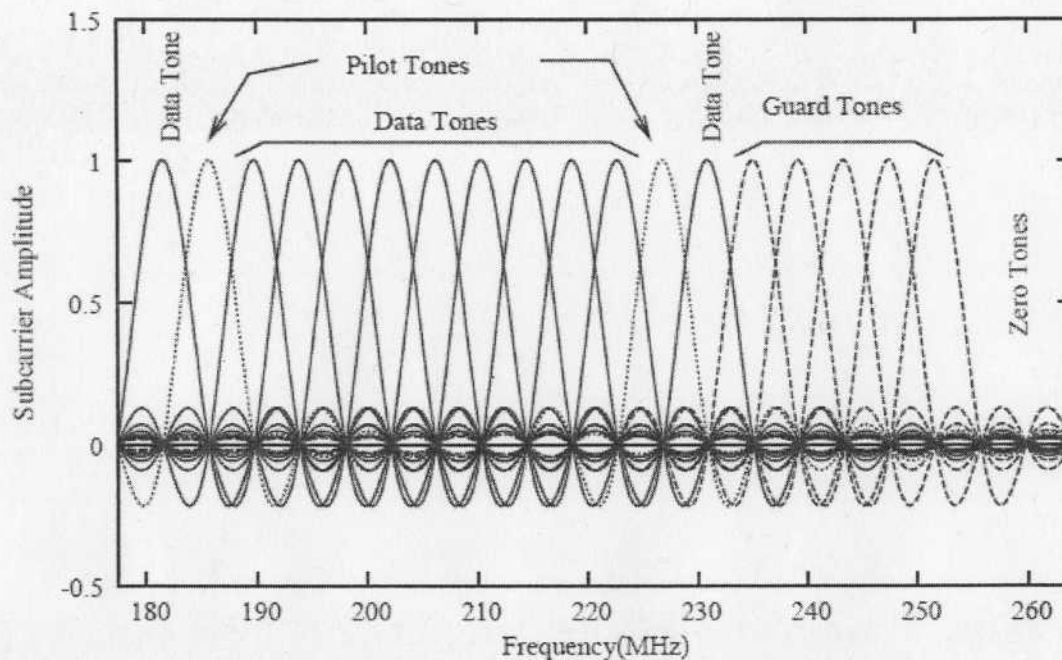


Fig. 1.1 An example of WiMedia UWB OFDM signal with subcarriers

The entire 7.5 GHz UWB spectrum is divided into 14 bands, which are 528 MHz wide and centered on odd multiples of 264 MHz. On top of these 14 bands, they are grouped into six band groups, each consisting of two or three bands. Fig. 1.2 [2] and Table 1.1 [11] show the WiMedia bands and band groups.

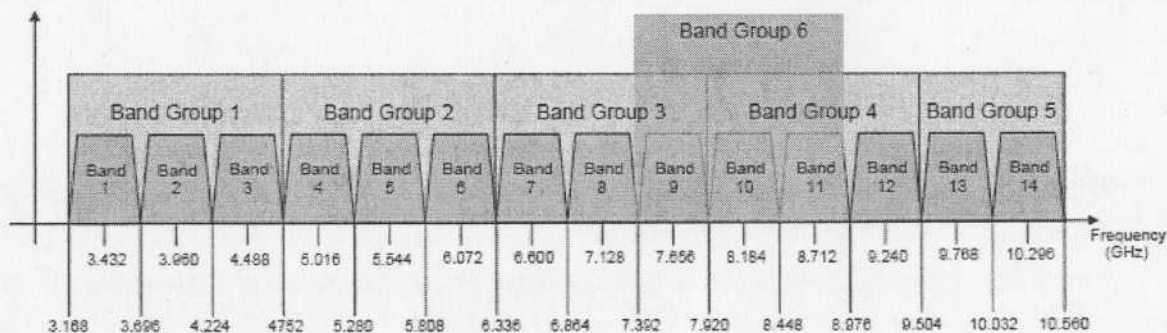


Fig. 1.2 WiMedia bands and band groups

Table 1.1 WiMedia bands and band groups

Band group	Band	Center Frequency (MHz)
1	1	3432
	2	3960
	3	4488
2	4	5016
	5	5544
	6	6072
3	7	6600
	8	7128
	9	7656
4	10	8184
	11	8712
	12	9240
5	13	9768
	14	10296
6	9	7656
	10	8104
	11	8712

The PHY requires the ability to frequency hop over multiple bands of frequency. The center frequency is selected from a set of three available center frequencies or bands, which are in turn selected from a set of band groups. The six band groups span the entire 7.5 GHz of the UWB spectrum. The WiMedia PHY uses a technique called frequency spreading in which data is placed on multiple OFDM subcarriers to gain diversity and thereby improve performance in fading channels. The hopping only occurs within the bands in a single band group. Thus, for most of the band groups, the instantaneous PHY RF bandwidth is 528 MHz and the total active RF bandwidth is three times that, or 1584 MHz. For Band Group 5, there are only two bands, so the total active RF bandwidth is 1056 MHz. Frequency hopping of the OFDM signal adds considerable complexity to the RF frontend, but does mean that the data converters need not be designed to sample the entire 1584 MHz available bandwidth. Worldwide regulations insist that UWB signals have limited power spectral density, but this is measured over relatively long time-frames (1 ms) to the UWB symbol time. Thus, frequency hopping over three bands allows the fundamental PHY sampling rate to remain 528 MHz, but also permits three times the instantaneous transmit power. [9]

WiMedia uses Time Frequency Codes (TFCs) as hopping patterns, shown in Table 1.2 [11]. Notice that TFCs 1-4 and 8-10 are Time-Frequency Interleaved (TFI) modes, which allow for full or two-thirds of full power transmission as described above. On the other hand, TFCs 5-7 are fixed-frequency transmissions, also known as FFI, and only allow one-third of full power transmission.

Table 1.2 Time Frequency Codes

TFC	Hopping pattern					
1	1	2	3	1	2	3
2	1	3	2	1	3	2
3	1	1	2	2	3	3
4	1	1	3	3	2	2
5	1	1	1	1	1	1
6	2	2	2	2	2	2
7	3	3	3	3	3	3
8	1	2	1	2	1	2
9	1	3	1	3	1	3
10	2	3	2	3	2	3

During the frequency hopping, the band switch time is required to be no more than five samples (about 9.47 ns) by the standard. As we can see from Table 1.2, the hopping pattern has a hop frame of six symbols length, which means all PHY transmissions are multiples of six symbols.

In order to deliver high data rates, the WiMedia UWB uses a straightforward but powerful convolutional code, which has a base rate $1/3$ code. This base rate code is further punctured to achieve several code rates: $1/2$, $5/8$ and $3/4$. Table 1.3 shows the relationship between different modulations, code rates and data rates. In the Table, S_T and S_F are the spreading factors of time and frequency spreading. Parameters N_c and R_c are the number of bits per hop frame and code rate, respectively, and $N_c * R_c$ gives the information bits per hop frame, N_b . The WiMedia offers the data rate $R_d = N_b / 6T_s$, where T_s is the symbol duration of 312.5 ns.

Table 1.3 WiMedia data-rate table

Mode	Modulation	Spreading	\bar{N}_c	R_c	\bar{N}_b	$R_d(\text{Mbits/s})$	Rate ID
Mode 1	QPSK	Sr=2 and SF=2	300	1/3, 1/2	100	53.3	0
					500	80	1
Mode 2	QPSK	ST=2 and SF=1	600	1/3, 1/2, 5/8	200	106.7	2
					300	160	3
					375	200	4
Mode 3	DCM	ST=1 and SF=1	1200	1/2, 5/8, 3/4	600	320	5
					750	400	6
					900	480	7

Moreover, the WiMedia UWB supports both Standard mode and Burst mode transmission. In the Standard mode, successive packets are separated by one Short Inter Frame Spacing (SIFS) duration, which gives enough time for any device to turn around between transmitting and receiving. On the other hand, the Burst mode allows a sequence of packets to be sent from a single transmitter, which means transmit to receive turnaround time is no longer required. Therefore, a shorter inter-frame spacing called Minimum Inter-Frame Spacing (MIFS) is used to reduce overhead and increase throughput. A detail measurement test for this unique burst mode will be presented in later section.

1.2.2 Medium Access Control Sublayer

As part of the Data Link Layer, the Medium Access Control (MAC) Sublayer provides effective resource control to make sure users do not interfere with each other, and the medium can be utilized in an efficient and fair way. In WiMedia UWB specifications, the MAC sublayer acts as the brain of the PHY layer, telling whether the PHY should transmit/receive, use a certain hopping pattern and etc. In order to provide such capabilities in a robust fashion, the MAC protocol is quite sophisticated and complex. However, it is certainly worth the throughput, Quality of Service (QoS) and network reliability that it affords.

The WiMedia has two types of MAC schemes: Distributed Reservation Protocol (DRP) and Prioritized Contention Access (PCA). For those who are familiar with communication network, the easiest way to visualize these two MAC schemes is to think of them as TDMA [12] and CSMA/CA in 802.11 [13] in analogy.

The DRP is fundamentally similar to existing TDMA-base reservation protocols, providing guaranteed access and performance to users. As mentioned earlier, WiMedia UWB use band groups and TFCs hopping for transmission. For a given hopping pattern in a band group, the medium is shared through a TDMA base using superframe structure, as shown in Fig. 1.3 [11].

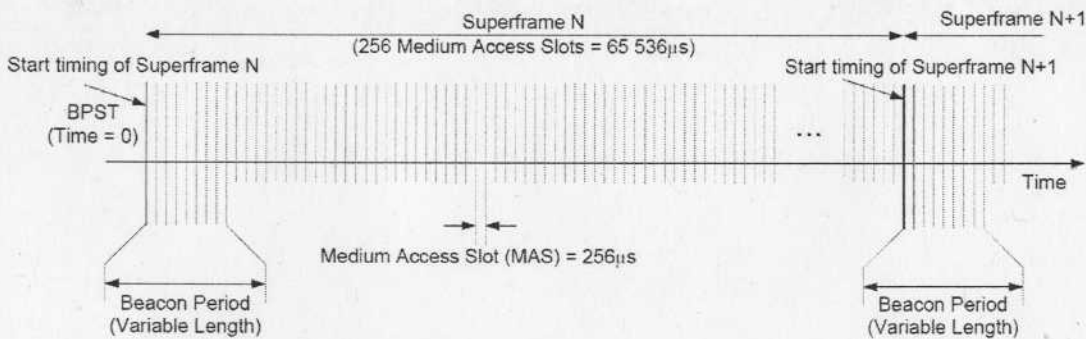


Fig. 1.3 MAC superframe structure

Starting with a Beacon Period Start Time (BPST), a superframe contains 256 Medium Access Slots (MASs) for data transmission. The duration of one MAS is 256 µs, which makes a superframe 65536 µs long. Within a superframe, the Beacon Period (BP) overlays the first N MASs with fixed length (85 µs) Beacon Slots for transmitting coordination beacon packets purpose. No data, command or control frame may be transmitted during the BP.

DRP allows users (or devices) to reserve a set of MASs for communications by sending DRP Information Elements (IEs) in their beacon or command frames. A successful reservation allows the reservation owner and target devices to have exclusive right to exchange data packets without contention. However, DRP reservations later

evolved to be capable of reserving MASs for PCA-type transactions, which will be discussed later in this section. There are five reservation types:

- Hard DRP
- Soft DRP
- Private DRP
- PCA
- Alien Beacon

The first two reservation types are of interest to this thesis: in Hard DRP, the reservation owner and target have exclusive use of reserved MASs, while in Soft DRP, reserved MASs might be used by the neighbours of the reservation owner if the owner cannot maintain SIFS timing between its frames. Also, in order to make sure that the medium is shared fairly by all devices, the WiMedia MAC specifications impose certain limitations on the use of DRP reservations in Annex B of ECMA-368 [11].

The DRP provides a fair and guaranteed medium access procedure that is maintained by peer devices in a neighbourhood, making the channel access more efficient, without the need for time/power consuming coordination efforts. At the same time, this “no central control” MAC scheme can robustly adapt to the dynamically changing wireless channel condition without losing connection. In addition, the reservation-based channel access scheme ensures the QoS to the applications and users.

Nevertheless, pure DRP has its short-comings: if the reservation owner has nothing to transmit in its reserved MASs, the time period is likely to be wasted, which will degrade the overall performance. Thanks to the Prioritized Contention Access (PCA) offered by WiMedia MAC, the degradation is compensated. Even though PCA implementation is optional from the MAC standard perspective, it is as important as DRP in both academic research and industrial product development.

In PCA, each device contends with its neighbours to achieve a Transmission Opportunity (TXOP) for medium access. A typical PCA procedure is given as follows: the intending device will have to determine a particular part in the superframe for PCA

communication. It will test the channel periodically and wait till the end of the current transaction if there is any activity. After the current transaction finished, the device will have to wait for a time period called Arbitration Inter-Frame Space (AIFS) plus a certain backoff time before it gains the TXOP. The AIFS time varies based on different access categories (ACs) of traffics, so higher priority traffic has a higher chance of getting TXOP. Eq. (1) shows the relationship between AIFS and AC,

$$AIFS(AC) = SIFS + AIFS_n(AC) * (\text{Duration of Backoff Slot}) \quad (1)$$

Four AC values are defined in the WiMedia MAC standard. Fig. 1.4 [11] shows an example of PCA operation, where AC_BE, AC_VI and AC_VO represent Best Effort, Video and Voice traffics, respectively.

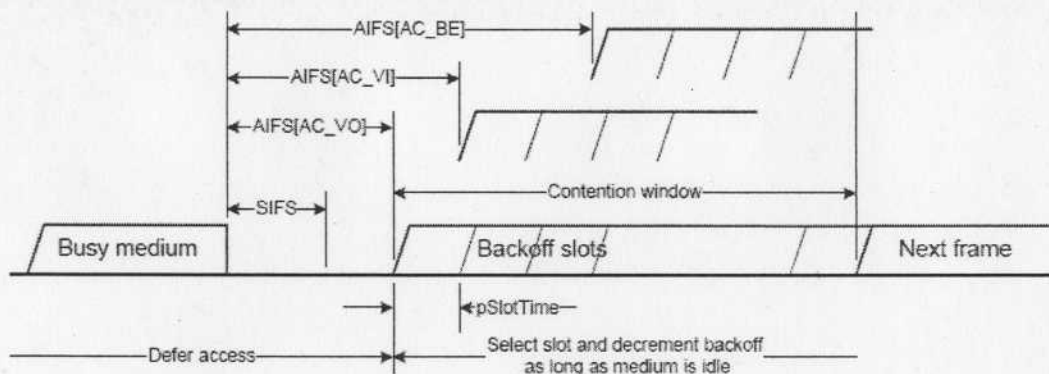


Fig. 1.4 Example of Prioritized Contention Access

With both DRP and PCA access schemes, WiMedia UWB specification becomes a well-rounded MAC standard for delivering high throughput performance. Several research literatures have focused on the analysis of WiMedia UWB, such as Wong et.al.'s work on analyzing the UWB MAC with respect to beacon period, DRP and PCA [19] [20]. A discrete time Markov chain model was built to show the theoretical throughput for PCA with saturated traffic. Ling et.al. analyzed PCA and verified their model with in-house simulation in [21]. And all these research results show that WiMedia standard is the solution to a reliable, high-speed wireless network.

1.3 UWB Applications and Products

Thanks to its unique characteristics, UWB can be utilized in various applications, from low-speed data collection and accurate localization/ranging to very high data-rate wireless high quality video streaming. Due to its high bandwidth signals, the time-domain resolution of UWB is extremely high, which makes UWB signal a perfect choice for high-precision ranging on the order of centimeters, while the traditional narrow band systems can only offer precision on the order of meters, such as GPS. On the other hand, when it comes to high speed connectivity networking, UWB reveals its potential to be the best combination of avoiding messy cables and providing a reliable, high-speed wireless network connection.

Even though the 802.11 WiFi technology has been a huge success, its throughput limit is still a bottle-neck for high-speed multimedia applications. Instead, the high rate connectivity has usually been in the form of cables: for example, USB cable is very popular for high data-rate applications in the PC market, and the High-Definition Multimedia Interface (HDMI) cable is playing a key role in today's home entertainment arena. However, cables have their down sides such as lack of flexibilities (fixed length, and "point-to-point" connection), costly installations, and not to mention their unsightly look when you have a large clutter of them. Another shortcoming of WiFi devices is that they are very power-consuming which makes them unsuitable for portable applications.

With its unique characteristics, high-speed UWB technologies have the true potential to fill the need for high-capacity, low power and low cost applications and products. Among the different high-speed UWB technologies, ECMA-368 [11] (from WiMedia Alliance, which we will also refer to as WiMedia UWB throughout this thesis) is clearly the winner, not just because of its technological merits, but more due to the political alliances formed in the industry around it. With industry giants such as Intel, Nokia, NEC,

Samsung, NXP/Philips, STMicroelectronics, etc., behind this technology, it has become the de facto standard of high-speed UWB [9].

Wireless USB (W-USB) is one of the first use cases of WiMedia UWB technology. With the support from Intel, W-USB has been considered to be the replacement of USB cable by adopting WiMedia PHY and MAC standard. Theoretically, the W-USB solution can support up to 127 connections at the same time, as opposed to one for each wired USB port. The related products are in forms of adaptors and hubs that can be found in the consumer electronics market nowadays. The usage of W-USB applications is well illustrated in Fig. 1.5 [9].

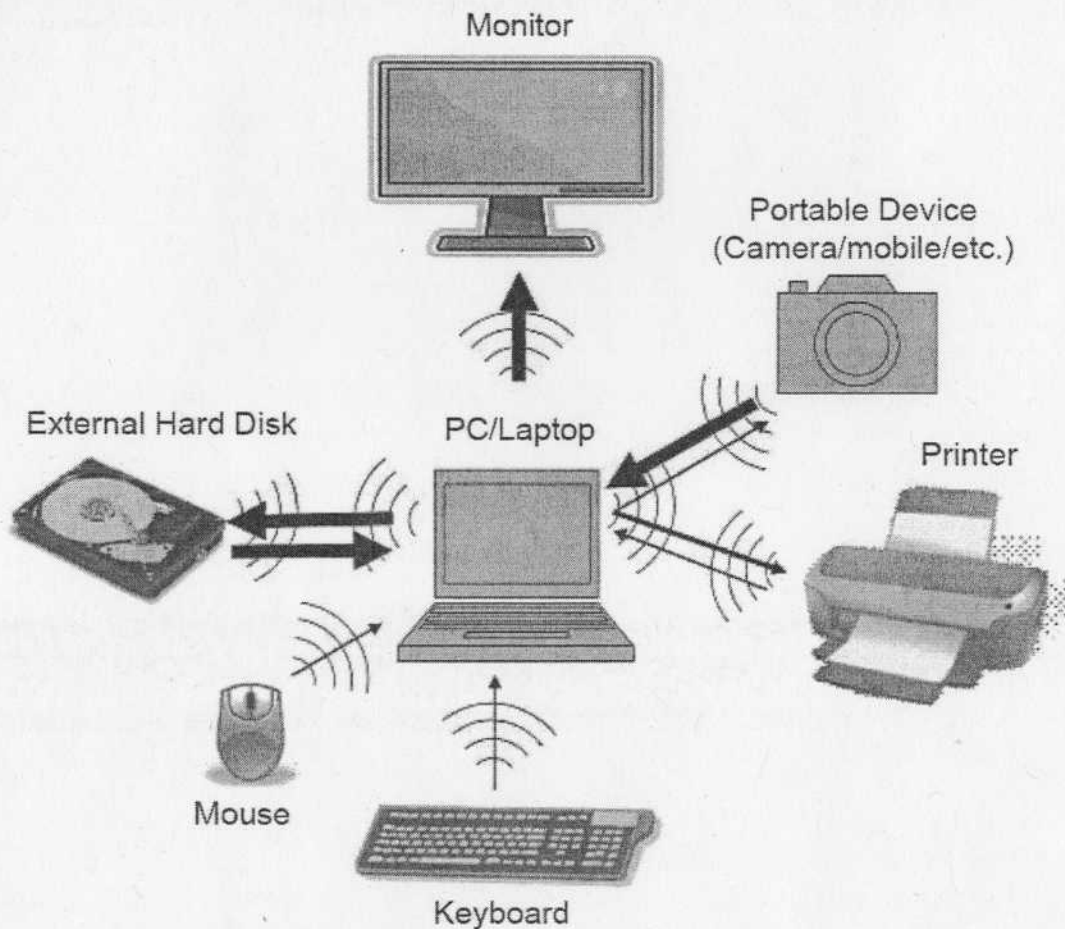


Fig. 1.5 Examples of W-USB Applications

Furthermore, one of the most data-intensive applications is high definition video streaming, which requires very high data rate and high level of QoS. The video source could be a high definition DVD player, a game console or a HD camcorder, etc. These video applications can be used in home/office, or even in the area of “in-vehicle” network, where UWB can easily meet the bandwidth and range requirements in these types of environment. In fact, the short range of UWB can be a beneficial factor in such situation where high bandwidth applications are localized. This is because that the short range characteristic will allow UWB systems in different rooms to operate in their full bandwidth capacity without sharing the resource. If a WLAN system is used in this situation, all applications will have to share the bandwidth in WLAN’s wide range. And this could lead to a scenario that if someone in the house is using high definition video streaming in the living room, the internet access in others rooms will suffer severely from insufficient bandwidth, and we’ve seen this situation quite a lot for WLAN users.

There are lots of other WiMedia UWB application areas, such as UWB-over-IP, which can be used in surveillance and monitoring; UWB-over-FTTH (Fiber to the Home) for the next generation of high speed residential communication network, and so on. Some of them are not yet standardized but a successful feature for these applications are certainly in sight. The assiduous efforts from the industry developers have led to recent product release of WiMedia UWB devices on the market. However, the performance of WiMedia UWB products has not been reported in the literature. A big question is, after many years of talk and scientific research, can UWB deliver on its promise?

1.4 Agenda

The goal of this thesis is two-fold: providing a comprehensive link budget analysis and throughput measurement for WiMedia systems, and proposing a novel MAC protocol for indoor UWB system to fully unfold its potential. Based on the theoretical analysis and

practical measurement, the relative path loss model, multipath fade margin, shadow fade margin and different obstacle effects are investigated in details. In addition, a detail description of the proposed MAC protocol together with its performance simulation is presented as well. The rest of the thesis is organized as follows.

Chapter 2 examines different WiMedia UWB products by performing comprehensive throughput measurements, as well as path loss and link budget analysis based on the measured data in office and residential environments. The tested UWB products conform to WiMedia's multi-band orthogonal frequency division multiplexing specification. The link budget analysis results together with detailed throughput versus range measurements demonstrate the impressive performance of the WiMedia UWB module for high speed data transfer under very low power constraint, e.g., 0 dB fade margin and capable of supporting up to 324 Mb/s in IPERF. Also, some commercial, off-the-shelf (COTS) UWB products are also evaluated in terms of user-level experiences.

Chapter 3 proposes a novel distributed multiband MAC protocol for residential high rate UWB systems. Detailed procedure descriptions and computer simulation results are presented for better understanding of the protocol. Due to the unique characteristics of UWB systems, traditional media access schemes are no longer suitable, and the current existing ones still have their shortcomings. Therefore, the protocol needs to be specifically tailored to the requirements and characteristics of indoor residential high rate UWB systems. In this chapter, all of these specifications are taken into consideration, and analyzed.

Chapter 4 summarizes the overall contributions of this thesis and discusses the future improvements and research topics.

Chapter 2 Link Budget Analysis and Evaluation of Multi-antennas WiMedia UWB Systems and Products

The WiMedia UWB products have been developed and improved over the years since the publication of ECMA-368 standard. Nowadays, early products are either available to academic research labs or on the commercial market, including high performance Evaluation Kit (EVK) systems, high definition video streaming systems, high speed wireless USB, and etc. These systems provide tools for researchers to evaluate the achievable performance of realistic UWB products, to understand UWB propagation and build basic propagation model of UWB channels. They also shed light on the gap between implementation performance and standard target performance. In an indoor environment, typical residential areas such as in house and office buildings, there are many different factors affecting the rate and reliability of wireless communications. For example, structural walls, furniture and people activities can all lead to significant degradation for traditional narrowband systems like Bluetooth, WiFi devices. In this chapter, various WiMedia systems will be evaluated and tested in residential environment, and the results will be presented in terms of objective throughput data rates as well as subjective user visualizations. Furthermore, the path loss model obtained from WiMedia system measurements will be presented including the path loss exponents, shadow fade margin, obstacle effects and so on. We also carried out a block-ACK throughput test to reveal the true potential of WiMedia systems. The last but not the least, a commercially available UWB product is tested from a high level point of view to complete our full evaluations on WiMedia UWB systems.

2.1 Related Work

There are a few efforts reported in testing real UWB devices. In 2007, Mlinarsky and Ziegler published an article for comprehensive UWB product testing in EETimes, focusing on two main UWB solutions in the market – WiMedia and CWave [28]. In [22], the authors presented wireless video streaming trials by streaming high quality HDTV video over a UWB testbed called PULSERS [23]. It showed that UWB platform has better performance than 802.11g and 802.11n in high-resolution video streaming. Cui and his colleagues presented a wireless display system to transport raw, uncompressed analog video signals from a Smartphone to a data projector by UWB-based communication in [24]. Another video streaming test over UWB evaluation kit was carried out by Ruby et al. in [25]. All these research works showed that UWB is becoming one of the most promising wireless candidates in high quality video streaming. Recently, Hori evaluated the throughput performance of a WiMedia prototype system in [26] and showed that high throughput rate about 200 Mbps can be reached at around 2 meters. However, the testified range in [26] of supporting such high data rate is too short to prove WiMedia UWB is the ideal choice for residential communication network. In our experimental work [27], we investigated in a commercially available WiMedia evaluation kit system and showed a much longer distance in which high data rate can be maintained.

2.2 Path Loss (PL) and Link Budget Analysis

In this section, we present the path loss model for indoor WiMedia UWB system. Based on the measurements from an industrial WiMedia UWB product, we are able to prove some key parameters such as path loss exponent, multipath and shadow fade margins, etc. for office and residential environments. Furthermore, a link budget analysis for the WiMedia UWB system is carried out for both CM1 and CM3 models, which are

developed by the IEEE 802.15.3a UWB working group. Link budget is a calculation that is used to predict the range or performance of a wireless link versus distance. Typically, a wireless link can sustain a certain level of performance if the transmit power minus the path loss (that is, the received power) exceeds a required threshold for a given data rate. That threshold usually is not a fixed number but, rather, depends upon the fading conditions of the wireless channel. Path loss models of various complexities have been developed for many types of wireless environments ranging from free-space path loss to cellular propagation in an urban environment (e.g., Cost Hata Model [29]). Examples of the sources of wireless attenuation that path loss models can account for include loss versus distance, multipath fading (Rayleigh, Rician, etc), lognormal shadowing, diffraction and absorption.

2.2.1 Test System Setup

The WiMedia UWB system we tested is one of the main products from TZero Technologies Inc.: ZeroWire reference design module in a Mini-PCI type 3A form factor. The ZeroWire Module is a FCC (US) and ETSI (European Union) certified mini-PCI card with integrated TZero UWB chipset and two RF connectors for attaching the antennas. This card can be plugged in any standard mini-PCI slot for evaluation or design purposes. Moreover, the built-in ubiquitous IP network protocol for connectivity enables multiple peer-to-peer connections over industry-standard protocols. The ZeroWire reference design module operates in the 3.1 GHz to 4.8 GHz portion of the UWB spectrum.

In the test system setup, we install two ZeroWire Mini-PCI cards on two Linux (CentOS 4.7) based computers. One Omron S1 antenna is used at the server and two identical antennas are used at the client as shown in Fig. 2.1. The technical data for S1 antenna are shown in Table 2.1.

Table 2.1 Technical data for Omron S1 high gain antenna

	3.168 GHz	3.432 GHz	3.696 GHz	3.960 GHz	4.224 GHz	4.488 GHz	4.752 GHz
Average [dBi]	1.6	1.4	1.6	1.3	0.8	1.4	0.8
Peak [dBi]	7.1	6.7	6.8	6.6	7.3	5.6	5.4
+3dB range [meters]	100	100	110	110	90	120	120
+5dB range [meters]	80	70	80	70	60	40	20



Fig. 2.1 The server station (right) and client station (left)

Sets of received signal strength indicator (RSSI) measurements were taken in the hallway of an office building at the University of Victoria, Victoria, BC, Canada, as shown in Fig. 2.2 and Fig. 2.3. The hallway is 2.35 meter wide with sections of concrete walls and drywalls. There are metal and wood doors, displaying windows and metal shutters along the sides of the hallway. During the test, location of the server (transmitter) was fixed and the client (receiver) was moved along the hallway. This propagation environment is line of sight (LOS), and the scenario where there is one person blocking the direct LOS path is denoted as soft NLOS (sNLOS). The soft NLOS case gives us very important information about how the WiMedia's products do in the reality environment.

On the other hand, hard NLOS (hNLOS) refers to the scenario where the server and client are separated by walls, floors, or other structures. The other test environment is a residential home with floor plans of a 2-floor house shown in Figs. 2.4 and 2.5.



Fig. 2.2 Hallway floor plan.

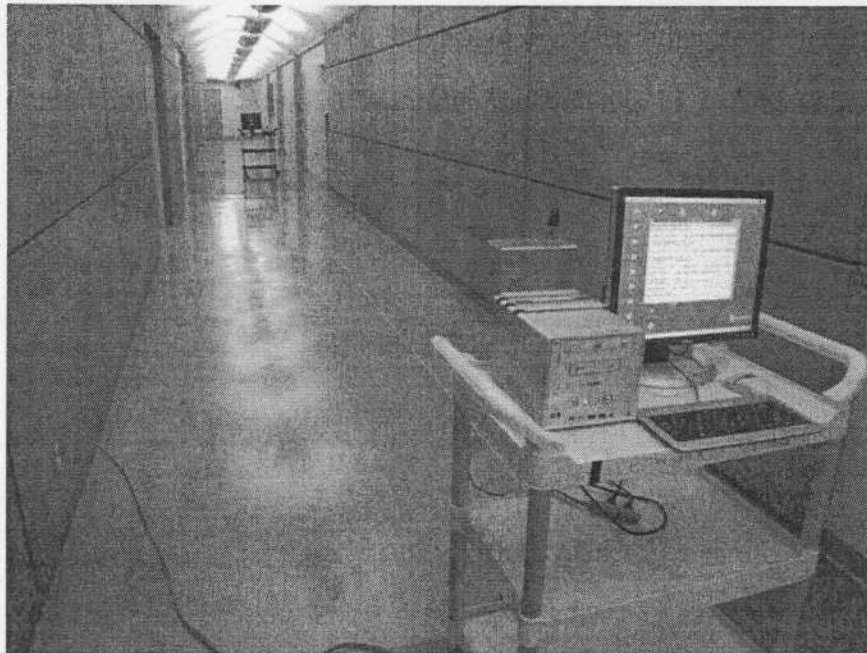
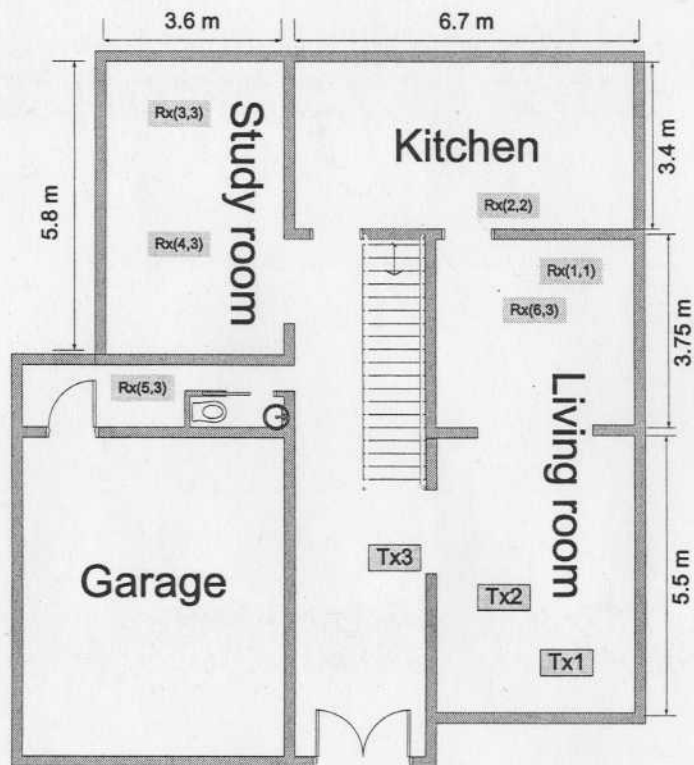
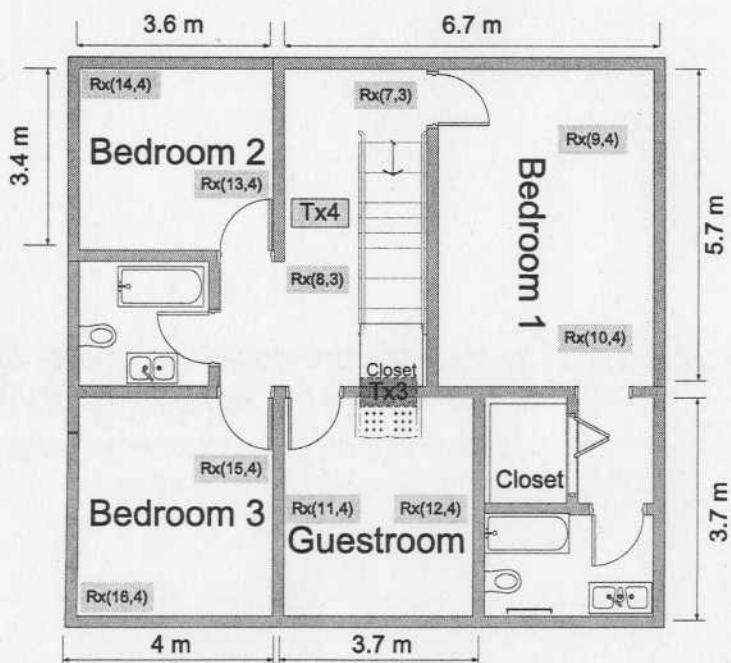


Fig. 2.3 Test system setup in the hallway of an office building

Fig. 2.4 Floor plan of 1st floorFig. 2.5 Floor plan of 2nd floor

2.2.2 Path Loss

As indoor propagation of cellular and Wi-Fi signals at various frequency ranges have been studied extensively in [31], we model the indoor propagation of the WiMedia ultra-wideband signal generated by TZero's ZeroWire system in this work, and show that the path loss exponent as well as fade margins are less for this WiMedia system than for narrowband radio technologies. Like narrowband studies, the waveguide effect [32] is observed for the UWB signal inside the hallway.

The simplest path loss model is of the form:

$$L(d) = 10n \log_{10} \left(\frac{4\pi F}{c} \right) + 10n \log_{10}(d) \quad (2)$$

where $L(d)$ is the path loss in dB at distance d , n is the so called path loss exponent, F is the signal's center frequency and c is the speed of light. When $n = 2$ this formula represents the free-space path loss in which the first term represents the antenna aperture effect and the second term represents the fact that, in free-space, radio signals attenuate in proportion to $1/d^2$ (i.e., proportionally to the surface area of a sphere). For indoor propagation, it is common to add terms which represent multipath fading, shadowing and attenuation through floors/ceilings and walls. We therefore introduce Eq. (3) as our indoor propagation model:

$$L_{F,n}(d, N, M) = 20n \log_{10} \left(\frac{4\pi F}{c} \right) + 10n \log_{10}(d) + NL_{\text{floors}} + ML_{\text{walls}} + \phi + \psi \quad (3)$$

where the first term is the 1-meter reference of path loss (assumed to be free-space), which gives 43 - 45 dB for systems operating in the 3 - 5 GHz spectrum allocated for UWB, NL_{floors} and ML_{walls} represent the loss through N floors and M walls respectively, ϕ is the multipath fade margin and ψ is the shadow fade margin. Although Multipath fading is a statistical phenomenon, for the purpose of a link budget calculation, we will just assign a single number to provide enough margins to overcome the expected range of

multipath fading we might encounter. Shadowing is a statistical variable that is typically treated as having a log-normal distribution. For our purposes, the shadow margin is used to represent signal blocked by people standing between the transmitter and the receiver. The path loss exponent n is propagation environment dependent and will be determined by the best fit for the data.

The acceptable amount of path loss is the difference between the transmit power and the receiver sensitivity, where the transmit power is limited by worldwide regulatory authorities (FCC, ETSI, TELEC and soon other countries) to an average power spectral density of -41.3 dBm/MHz for the maximum Equivalent Isotropic Radiated Power (EIRP). This transmit power is measured with a RMS detector using a 1 ms averaging time constant. WiMedia UWB signals operate in hopping and non-hopping modes according to the channel assignments in Table 2.2 [33]. Because the hopping rate for WiMedia UWB is 3.2 MHz, the apparent duty-cycle of the signal as measured by the RMS detector is one over the number of hopping bands. Thus, for TFC codes using band hopping, the transmit power can be increased by the number of hopping bands as shown in Table 2.2. The 4th column for 1 m path loss is the value used in our calculations for the first term of Eq. (3).

Table 2.2 WiMedia channels assignments (Time-Frequency Codes)

TFC	Bands	Allowable Tx Power boost	1 m path loss	Tx Power
1, 2, 3, 4	1, 2, 3	+4.8 dB	44.2 dB	-15.5 dB
5	1	0 dB	43.1 dB	-20.3 dB
6	2	0 dB	44.4 dB	-20.3 dB
7	3	0 dB	45.5 dB	-20.3 dB
8	1, 2	+3 dB	43.7 dB	-17.3 dB
9	1, 3	+3 dB	44.2 dB	-17.3 dB
10	2, 3	+3 dB	44.9 dB	-17.3 dB

Each UWB band has an occupied bandwidth of 500 MHz (this is the minimum bandwidth allowed by FCC regulations). Thus, the average transmission power per band corresponding to -41.3 dBm/MHz is -14.3 dBm. However, in reality, the maximum

transmit power is substantially less than this. The actual transmit power is backed off by about 6 dB to account for (a) the peak antenna gain of roughly 3 dBi, (b) transmit spectral flatness (roughly 1 dB) and (c) the spectral peak-to-average ratio of the UWB OFDM signal itself (roughly 2 dB). Thus, for the link budget, the transmit power is given in the last column of Table 2.2, and these calculated transmit powers include the effect of inter-packet and inter-symbol spacing.

In this work, we provide the measured received signal strength indicator (RSSI) with TFC1 at various distances in several office and residential environments, and derive the pass loss exponents, multipath fade margin φ , shadow fade margin ψ , NL_{floors} , ML_{walls} and the multiple antenna gain G_d from these data by curve fitting. Fig.2.6 shows the measured RSSI and the corresponding linear curve fit to each set of the measured data. On the legend, the fit line is indicated by (-slope/10, intersection with y-axis), which respectively correspond to the path loss exponent n and $P_T + G_t + G_r - L_{F,n}(I,N,M)$ where P_T is the transmit power, G_t and G_r are the transmit antenna and receive antenna gains in dBi. The path loss exponent $n = 1.52$ in the LOS hallway is better than the free space path loss due to the waveguide effect. The path loss exponent is not much changed by two antenna reception. The multi-antenna processing is reflected as a diversity gain $G_d = -50.99 + 52.93 = 1.94$ dB. For the employed omni-directional antennas with gain 3 dBi, $P_T + G_t + G_r = -15.5 + 3 + 3 = -9.5$ dB and we hence have $L_{F,n}(I,N,M) = -9.5 - (-52.93) = 43.43$ dB. In Eq. (3), the 1 m free space path loss for TFC1 is about 44 dB and $NL_{floors} = ML_{walls} = \psi = 0$ dB in the LOS hallway environment, we conclude the multipath fade margin $\varphi \approx 0$ dB. For the people blocking sNLOS case, the shadow fading margin $\psi \approx -52.93 - (-59.82) = 6.89$ dB and the diversity gain $G_d = -56.51 - (-59.82) = 3.31$ dB. The path loss exponent $n = 1$ for the sNLOS measurements. One explanation for this very small n is as follows. In our measurement, the person blocking the LOS path always stands in the middle of the transmitter and receiver. The blocking

effect is more severe when the distance d is small, as the person is close to both antennas. This leads to more power drop in RSSI at smaller d while less attenuation at larger d , causing a small n .

Fig. 2.7 shows the path loss measurement for a home environment, indicating the effects of wall and floor. The floor plan of the 1st floor is shown in Fig. 2.4 and the measurements were done between the kitchen and the living room, as well as cross floors. Fig. 2.7 indicates that the path loss exponent increases from LOS to hNLOS (1 wall) and from diversity ON to OFF in the range of $n = 2.02$ to 2.36 , slightly worse than the free space path loss. The one wall effect is $L_{walls} = 0.26$ dB and one floor effect is $L_{floors} = 28.7$ dB. The loss caused by wall is larger as the distance grows, reflected in the path loss exponent. The diversity gain in the LOS channel is 2.15 dB and in the hNLOS channel is 0.85 dB. Fig. 2.8 plots another set of data measured in the living room. The path loss exponent increases from LOS to sLOS (also slightly worse than the free space propagation), the diversity gain is 2.27 dB and 1.93 dB in LOS and sNLOS environments, and the shadow fading due to people blocking is about 5.3 dB. Note that the position of the people blocking is fixed at about 1 meter away from the transmitter in this measurement.

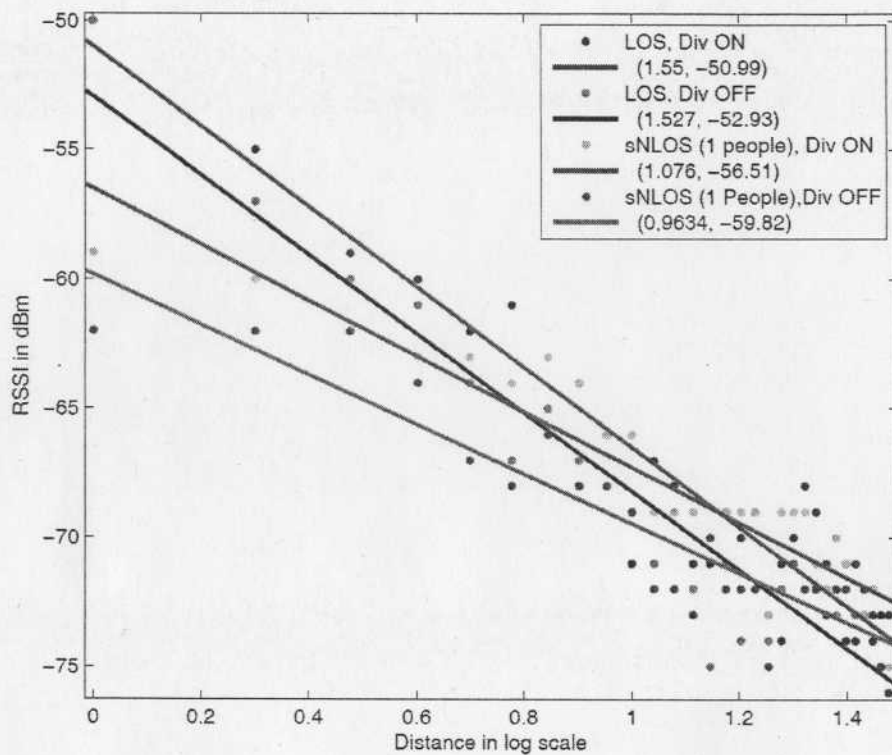


Fig. 2.6 Measured RSSI in hallway, TFC1

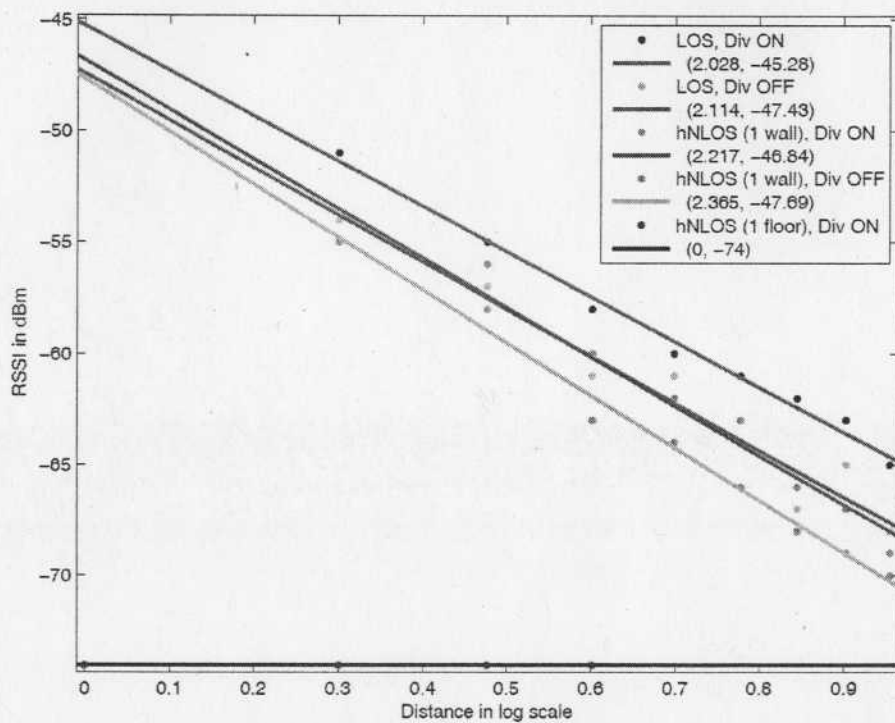


Fig. 2.7 Measured RSSI in home, effects of walls and floors, TFC1

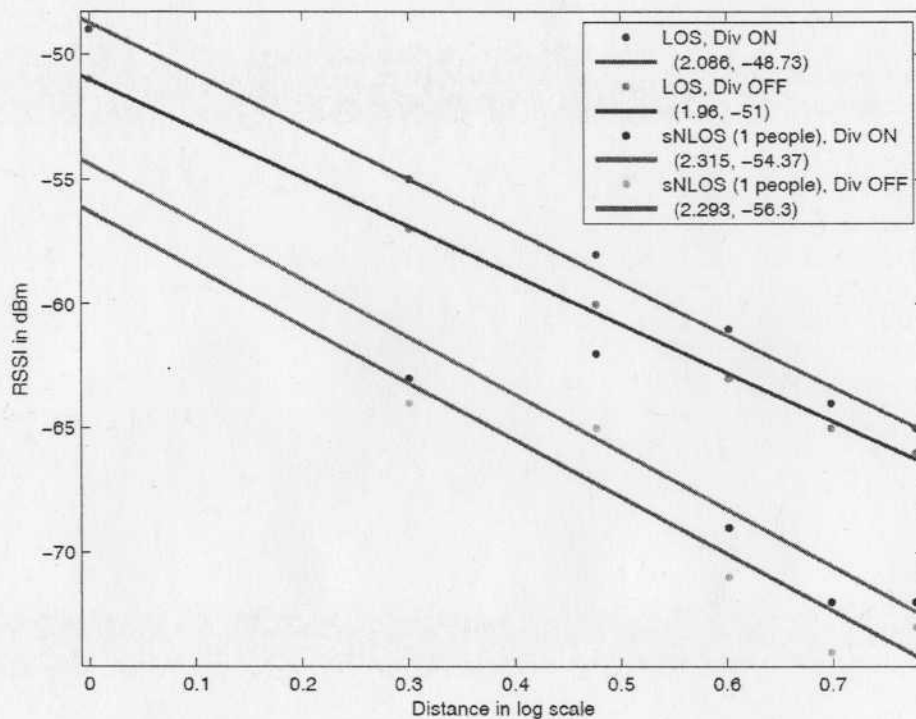


Fig. 2.8 Measured RSSI in home, effect of people shadowing, TFC1

2.2.3 Link Budget Analysis

In telecommunications, there are two very important terms for evaluating system performance: receiver sensitivity and link budget. The sensitivity of a detector device, such as receiver, is the minimum magnitude of input signal required to produce a specified output signal having a specified signal-to-noise ratio, or other specified criteria [30]. And a link budget is the accounting of all of the gains and losses from the transmitter, through the medium (free space, cable, waveguide, fiber, etc.) to the receiver in a telecommunication system [30].

In this context, the receiver sensitivity is a function of the PHY data rate and the wireless channel condition, which is a power level, typically stated in dBm. The WiMedia PHY specification provides the minimum receiver sensitivity conditions for an AWGN channel, which is shown in Table 2.3. According to TZero, their Mini-PCI wireless modules exceed the WiMedia receiver sensitivity requirements by about 5 dB.

For wireless channels, Table 2.3 gives the sensitivity numbers provided by TZero. Note that CM1 and CM3 models are the LOS and NLOS wireless channels proposed by the IEEE 802.15.3a UWB working group, with RMS delay spread of about 5 ns and 14 ns respectively. These sensitivity numbers do not include the benefit of TZero's multi-antenna receive processing, which is reflected in the path loss exponent and diversity gain. Finally, the link budget can be determined from the difference between the last columns of Table 2.2 and Table 2.3, as presented in Table 2.4.

Table 2.3 Receiver Sensitivity

PHY Rate	WiMedia Requirements	Tzero CM1 (Single antenna)	Tzero CM3 (Single antenna)
53.3 Mb/s	-80.8 dBm	-85.0 dBm	-84.5 dBm
80 Mb/s	-78.9 dBm	-82.9 dBm	-82.3 dBm
106 Mb/s	-77.8 dBm	-81.4 dBm	-80.6 dBm
160 Mb/s	-75.9 dBm	-79.3 dBm	-78.4 dBm
200 Mb/s	-74.5 dBm	-78.0 dBm	-77.0 dBm
320 Mb/s	-72.8 dBm	-75.6 dBm	-74.2 dBm
400 Mb/s	-71.5 dBm	-74.2 dBm	-72.5 dBm
480 Mb/s	-70.4 dBm	-73.0 dBm	-71.0 dBm

Table 2.4 UWB Link Budget (dB) for CM1 and CM3

PHY Rate	Non hopping (CM1/CM3)	2-band hopping (CM1/CM3)	3-band hopping (CM1/CM3)
53.3 Mb/s	64.7/64.2	67.7/67.2	69.5/69.0
80 Mb/s	62.6/62.0	65.6/65.0	67.4/66.8
106 Mb/s	61.1/60.3	64.1/63.3	65.9/65.1
160 Mb/s	59.0/58.1	62.0/61.1	63.8/62.9
200 Mb/s	57.7/56.7	60.7/59.7	62.5/61.5
320 Mb/s	55.3/53.9	58.3/56.9	60.1/58.7
400 Mb/s	53.9/52.2	56.9/55.2	58.7/57.0
480 Mb/s	52.7/50.7	55.7/53.7	57.5/55.5

2.3 Throughput Measurements in Residential Area

One of the most important metrics of measuring how good a wireless product performs is whether it can deliver a solid performance to the end users. In most cases, end users do

not know about the numbers in either path loss models or wireless link budget analysis. What they do care about is how fast this wireless device can deliver in terms of Megabit per second (Mbit/s or Mb/s or Mbps). In other words, high level data rates determine the market potential of a wireless product.

In this section, we present a comprehensive throughput measurement test of the ZeroWire reference design module from a packet-level point of view. With the same system setup as described in the previous section, the FCC certified ZeroWire Module delivers a solid performance in two typical indoor environments: office building and residential house. Since the Media Access Control (MAC) protocol that comes with ZeroWire Module's firmware is not yet perfectly implemented, the throughput performance from our test results still has potential for growth. To realize this, we introduce a block-ACK throughput test by modifying the existing MAC policy to maximize the packet-level throughput in an office environment. Last but not least, we evaluate the capability of this WiMedia device by emulating it as a gateway for the in-home network.

2.3.1 Measurement Test Setup and Scenarios

The test device used in the throughput measurement test is the ZeroWire reference design module from Tzero Technology Inc., and its detail specifications are well illustrated in Section 2.2. In order to measure the packet-level throughput, a commonly used network testing tool, namely IPERF, is used on top of the traditional IPv4 network. IPERF allows the user to set various parameters that can be used for testing or evaluating a network, with either UDP or TCP data streams. When used for testing UDP capacity, it allows the user to specify the datagram size and provides results for the datagram throughput and the packet loss [33]. The TCP traffic capacity of ZeroWire is beyond the scope of this thesis.

The throughput measurement test took place in the same office hallway and residential house as described in the previous section.

2.3.2 Measurement Results and Analysis

2.3.2.1 Hallway Throughput Test

The UDP throughput from the server to the client was measured and gathered using IPERF at different distances in the hallway. The average throughput (over 100 seconds) from each distance check point indicates the supportable range for different PHY data rate settings. People blocking in the middle between the server and the client are measured to show how the WiMedia products perform in a variety of realistic environments.

The results presented in this section are obtained with auto rate setting, multiple antenna processing and ACK ON (acknowledged for each successfully received UDP packet). The auto rate setting adapts the PHY rate based on the channel condition to obtain close to zero packet error rate (PER) with Automatic Repeat Request (ARQ). For the LOS environment, the data rate throughput held at around 200 Mbps up to 7 meters and dropped slightly to about 150 Mbps from 8 meters to 15 meters as shown in Fig. 2.9. After 15 meters, the throughput reached about 100 Mbps and this was maintained up to 20 meters. To our surprise, the throughput bounced back to about 150 Mbps around 25 meters, and back to about 100 Mbps around 30 meters, at which point we ran out of the test space. The increased rate at a larger distance could be caused by the changes in building materials and fixtures along the two sides of the hallway. When there are people blocking in between the server and client, the throughput decreased in most distance points. However, we still can see some soft NLOS results were better than the LOS results at the same distance, and this situation occurred more frequently at further

distances. This is due to the fact that at further distances there are more multipath components. The multiple-antennas implementation in the TZero receiver allows gathering spatially diverse multipath components and its signal processing techniques enable gathering the multipath energy constructively. Fig. 2.10 shows similar throughput results using TFC8.

An interesting observation of these curves is that, even in the LOS case, the throughput changes gradually rather in steps as the PHY rate changes. This is due to the automatic rate adaptation algorithm which selects the PHY rate, layer-2 PER and number of re-tries to maximize the application layer throughput. Note that a real-time compressed high definition (HD) video stream requires as much as 80 Mbps for visually lossless playback, and TZero WiMedia UWB system shows its capability to deliver such throughput. The multiple antenna technology coupled with the adaptive optimization of the receiver to the channel conditions appears to enable the extended range performance.

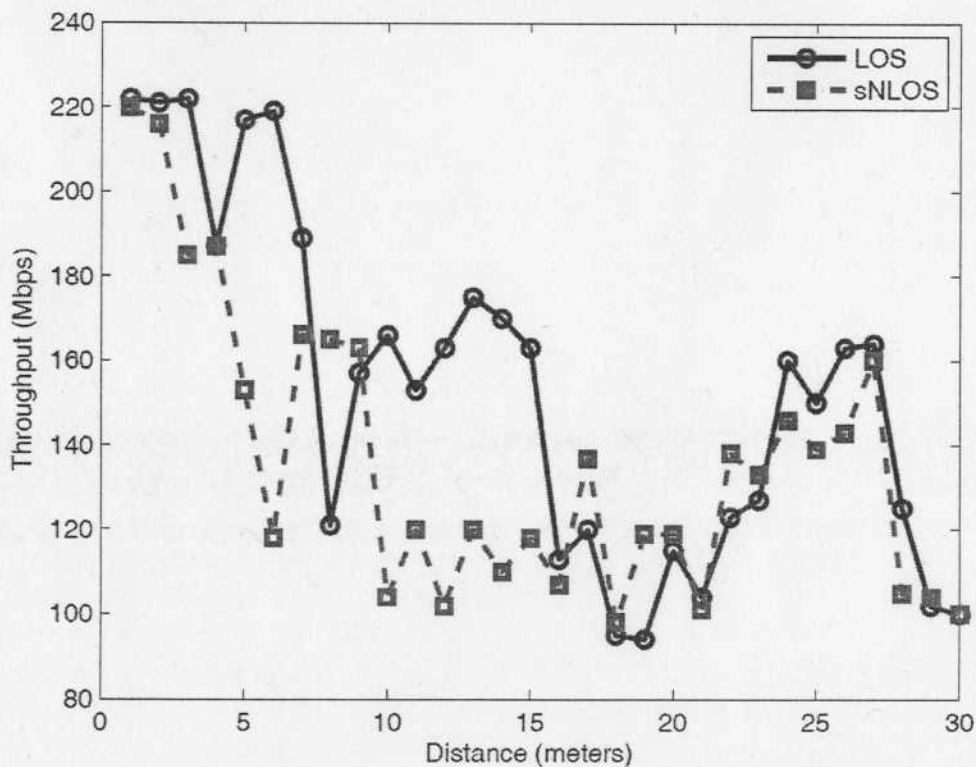


Fig. 2.9 Hallway throughput measurement test with TFC1

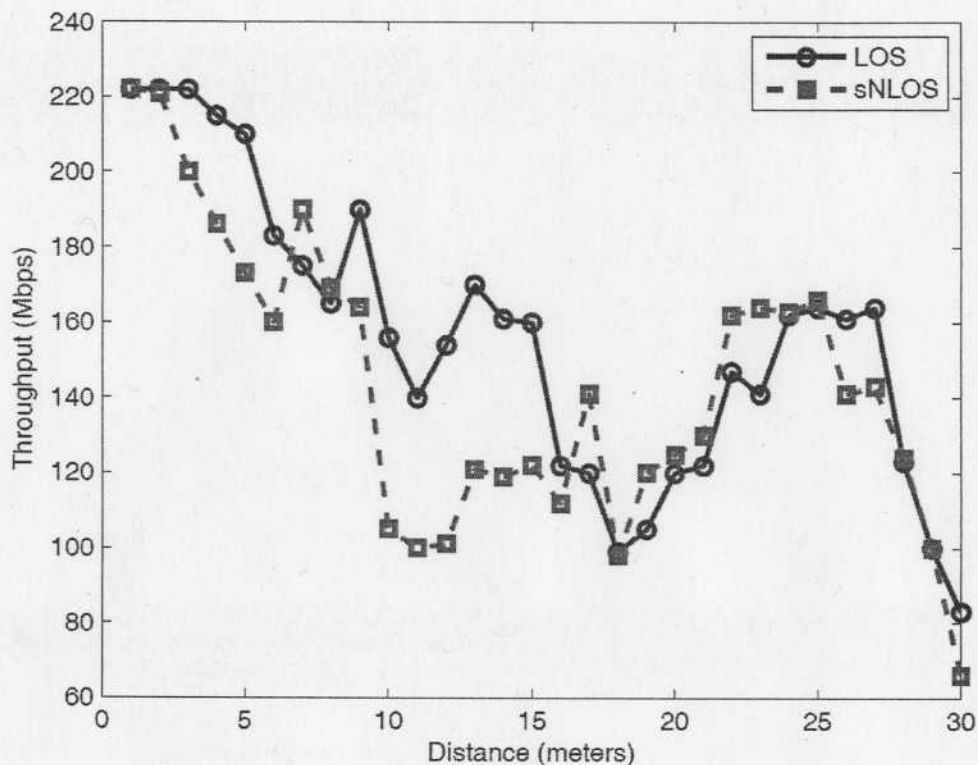


Fig. 2.10 Hallway throughput measurement test with TFC 8

2.3.2.2 Hallway Throughput Boundary Test

In order to test the maximum throughput that can be delivered, we adapt the block-ACK mechanism and setup the test in the office hallway. The block-ACK mechanism allows acknowledgement of a group of frames (packets) instead of every single frame (packet), significantly improving the MAC efficiency. Although the system module did not come with this feature, we were informed by TZero that block-ACK has been implemented in hardware but with no software support yet. Therefore, we can simulate the block-ACK mode to see the possibility of very high throughput once block-ACK is fully implemented. The test was performed in the same office building hallway. In order to make one acknowledgement frame correspond to more than one data frame, we manually change the frame length and inter-frame spacing in a way that acknowledgement frames are sent slower than data frames. PHY rate is set at 480 Mbps,

multiple antenna processing is on and regular ACK is turned off, which means there is no ACK in the test. The simulated block-ACK throughput reached 324 Mbps at the distances up to 5.65 meters with TFC1 and 5.55 meters with TFC8, while maintaining the PER less than 1%. These data indicate that as soon as the real block-ACK mode is supported in software, with all the packet error recovery mechanisms enabled, the overall performance will be even better than reported here.

2.3.2.3 Home Throughput Test

All home tests were carried out with auto rate setting, TFC1, multiple antenna processing and ACK ON. As demonstrated by Figs. 2.4 - 2.5 and Tables 2.5-2.6, the system performed well in a home environment which has all kinds of furniture, electronic devices, and appliances and so on. Most scenarios tested in the house are hNLOS where the server and client are separated by walls and structures. In the hNLOS case, we still tested the scenario where a person stood in front of the server or client, and the throughput data are shown in the tables. The locations of receiver are denoted by $Rx(m, n)$ as shown in Fig. 2.4, where m and n are receiver and transmitter indices, respectively. The throughput consistently reaches 200 Mbps range and even in long hNLOS cases minimum 40 Mbps can be achieved in a regular sized two-level house.

Table 2.5 Throughput measurement on the 1st floor, TFC 1

Locations	Distance from Tx	Throughput without people blocking	Throughput with people blocking
Rx(1,1)	6.00 m	192 Mb/s	168 Mb/s
Rx(2,2)	6.00 m	103 Mb/s	100 Mb/s
Rx(3,3)	8.06 m	39 Mb/s	39 Mb/s
Rx(4,3)	7.21 m	53 Mb/s	39 Mb/s
Rx(5,3)	4.92 m	70 Mb/s	45 Mb/s
Rx(6,3)	5.00 m	78 Mb/s	69 Mb/s

Table 2.6 Throughput measurement on the 2nd floor, TFC 1

Locations	Distance from Tx	Throughput without people blocking	Throughput with people blocking
Rx(7,3)	5.80 m	221 Mb/s	168 Mb/s
Rx(8,3)	3.60 m	73 Mb/s	n/a
Rx(9,4)	4.61 m	202 Mb/s	101 Mb/s
Rx(10,4)	4.92 m	216 Mb/s	122 Mb/s
Rx(11,4)	5.00 m	222 Mb/s	206 Mb/s
Rx(12,4)	5.39 m	72 Mb/s	50 Mb/s
Rx(13,4)	1.41 m	222 Mb/s	206 Mb/s
Rx(14,4)	3.91 m	195 Mb/s	120 Mb/s
Rx(15,4)	4.12 m	185 Mb/s	115 Mb/s
Rx(16,4)	7.13 m	63 Mb/s	45 Mb/s

2.3.2.4 In-home Gateway Emulation Test

Potentially, the high speed wireless connectivity of the WiMedia devices can provide wireless HD video, gaming and normal data networking simultaneously from a single WiMedia UWB gateway. To explore this possibility we tried to locate such spot for a gateway (transmitter) that could cover the whole floor as much as possible while maintaining a satisfactory data rate and QoS.

We performed the emulation test on the 1st floor of the house, and several potential locations shown in Fig. 2.11 are tested for data throughput by IPERF. The location that provides the overall best throughput for the entire 1st floor is selected as the “gateway spot”.

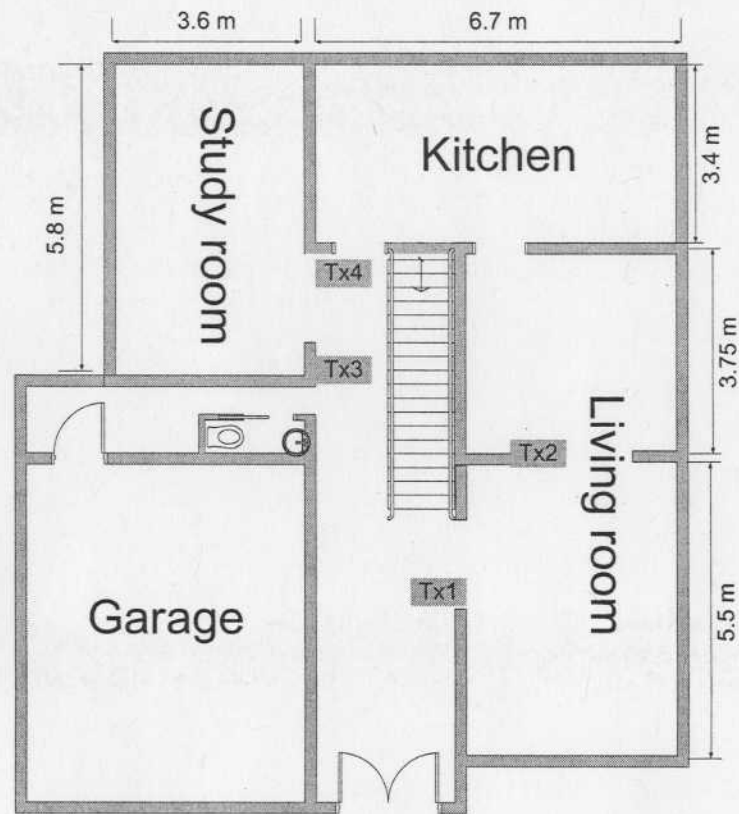


Fig. 2.11 Potential gateway locations

After testing all 4 potential gateway locations labelled in Fig. 2.11, we find that location Tx3 outperforms others in terms of overall coverage. For example, location Tx2 provides a very high data rate in the living room area, but it cannot cover the study room well. Location Tx4 offers high data throughput in the study room and the kitchen; however, it fails to support the farther away living room area. On the other hand, location Tx3 is identified as the spot which provides good coverage to living room, study room and the kitchen. Fig. 2.12 and Table 2.7 show the corresponding data rates at different receiving locations with a gateway transmitting at Tx3.

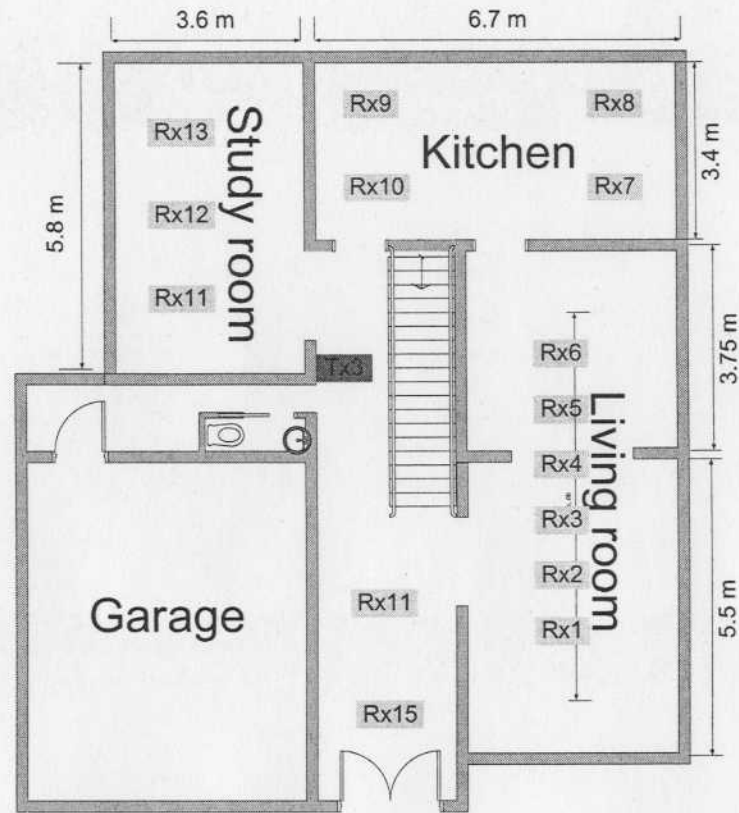


Fig. 2.12 The selected gateway location (Tx3) and receiver locations

We can see that the data throughput ranges from 60 Mbps to 222 Mbps in the area of the 1st floor tested and the average value is 153 Mbps. The relatively low data rates in locations Rx1, Rx2, Rx3, Rx7 and Rx8 were due to the closet under the stairway in between the transceiver set.

This gateway emulation test, together with results in Table 2.6 and Fig. 2.5, demonstrated that the WiMedia device can successfully cover the majority of the floor area on the same level in the house tested while maintaining its promising high data rate and QoS.

Table 2.7 Throughput for test locations in Fig. 2.12

Locations	Throughput without people blocking	Corresponding Area
Rx1	60 Mb/s	Living room
Rx2	72 Mb/s	Living room
Rx3	98 Mb/s	Living room
Rx4	120 Mb/s	Living room
Rx5	200 Mb/s	Living room
Rx6	77 Mb/s	Living room
Rx7	43 Mb/s	Kitchen
Rx8	44 Mb/s	Kitchen
Rx9	215 Mb/s	Kitchen
Rx10	221 Mb/s	Kitchen
Rx11	222 Mb/s	Study room
Rx12	222 Mb/s	Study room
Rx13	189 Mb/s	Study room
Rx14	222 Mb/s	Hallway
Rx15	201 Mb/s	Hallway

2.4 Commercial Products Testing: ZeroWire HDMI video set

Recently, several WiMedia-based commercial products have been released to end-users, featuring high definition video streaming and high speed wireless data transfer. Even though we proved that these features should work flawlessly by mathematical model and packet-level throughput test, it is still crucial to test their performance directly. In order to reveal its true capability of high definition video streaming, a commercially available WiMedia-based product was tested.

2.4.1 Test Setup and Scenarios

The ZeroWire HDMI video set from Tzero Technology Inc. was chosen for the video streaming test. Comparing to the ZeroWire reference module, the ZeroWire HDMI video set has the same chipset and antenna implementation, and provides standard and high-

definition video connection ports. The test was setup by connecting a SONY Blu-ray DVD player to the transmitter side (server), and a 40 inch 1080p Toshiba HDTV to the receiver side (client), as shown in Fig. 2.13. Both the server and the client were placed 90 cm above the ground. The HQV benchmark Blu-Ray DVD [34] was used as the media source for more convincing results. The content of the benchmark DVD used for testing is a continuous playback of a ship slowly sailing across the sea (from the left to the right of the screen). There are clearly visible continuous movements of the ship and water while at the same time the overall video content does not change dramatically so that any small video quality degradation can be easily perceived. In addition, a 122 minutes long high definition movie was used for a two-hour long test.

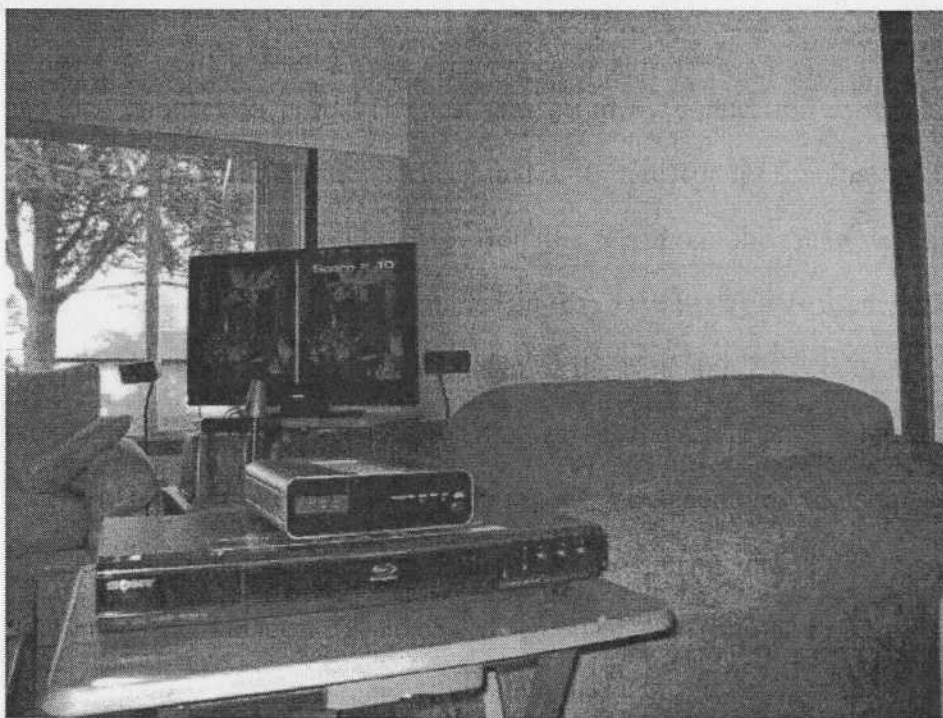


Fig. 2.13 Test Setup for the ZeroWire HDMI video set.

We performed the test in the living room area of the same house environment in the previous section. Fig. 2.14 shows the test layout and floor plan. The whole living room can be divided into two sections, and the 40 inch HDTV was placed in the first section with the client (receiver), while the Blu-Ray DVD player was connected to the server

(transmitter) and placed at several locations in the other section of the living room. The video set was evaluated by comparing the video (1080P) quality on the HDTV received wirelessly with the video quality connected directly via HDMI cable.

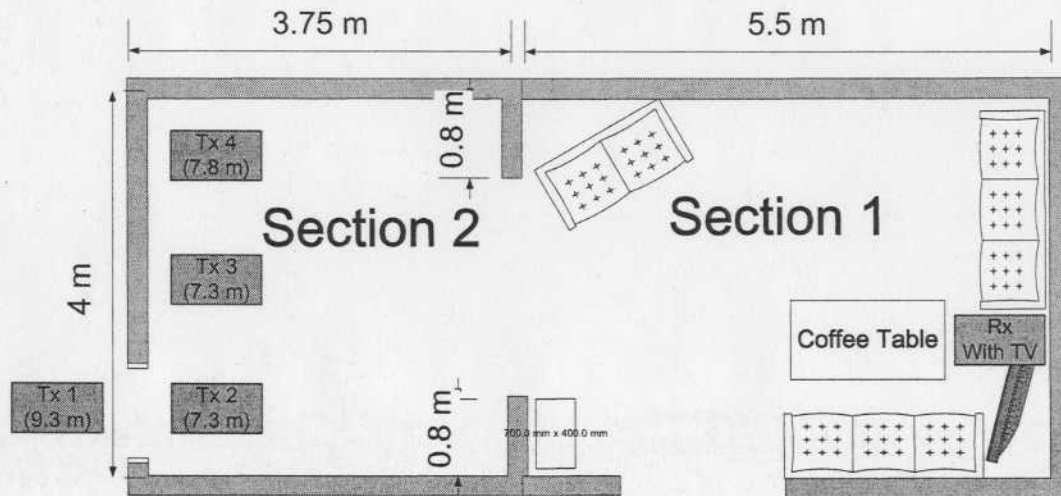


Fig. 2.14 Video test layout and floor plan

2.4.2 Test Results and Analysis

By using the HQV HD Benchmark Blu-Ray DVD, we found that the quality of the HD video received through ZeroWire HDMI was as good as using HDMI cable connection when the server (transmitter) was placed anywhere in Section 1. Even three people actively walking around in Section 1 did not affect the video quality.

When the transmitter was placed at the far end of Section 2 (Tx2-Tx4), the video quality was still fine and fulfilled the HD video requirements. If a person got in the way on the LOS path and stayed stationary, the video showed a transient interference effect and then returned to the fine quality as if there were no blocking. However, when there were dynamic people activities blocking the LOS path, noticeable video quality degradation appeared.

Playing the Blu-ray DVD movie showed better effect than playing HQV Benchmark DVD. The video quality matched that of cabled HDMI even at the far end of Section 2,

with slight interruption only when constant intentional body movement blocked the LOS path within 1 meter in front of the server (Tx). In a realistic user viewing environment, such an artificial setting will be unlikely to happen.

According to TZero, the ZeroWire HDMI set we tested does not have the optimal rate adaption and multiple antenna processing algorithms which are currently being implemented in the new off-the-shelf ZeroWire HDMI product. Nonetheless, we were still impressed with the performance of TZero's product.

The overall performance is much better than that reported in literature [35], which claimed that WiMedia products can only achieve a throughput limited to approximately 30 to 40 Mbps with a distance limit of 0.5 meter. The low expectations in [35] might due to the fact that the WiMedia products examined in that report were still at a very early stage when [35] was published. We believe that the test results obtained from the TZero products in this report are far more representative of the capability of MB-OFDM technology. In comparison with the published results in [35] for the alternative, proprietary UWB technology from Pulse_LINK called CWave, the throughput of ZeroWire Mini-PCI is higher for ranges beyond 3-4 meters and robust for a long distance (at least 30 meters) for both LOS and NLOS. The tests in [35] only contain LOS results. The current generation of TZero products award significant confidence to WiMedia UWB for HD video distribution in terms of both data throughput versus range and real wireless HD video experience.

2.5 Summary

This chapter examines WiMedia UWB products by performing comprehensive throughput measurements and path loss and link budget analysis based on the measured data in office and residential environments. The link budget analysis results together with detailed throughput versus range measurements demonstrate the impressive performance

of the WiMedia UWB module for high speed data transfer under very low power constraint. On one hand, the link budget analytical model gives a fairly accurate low layer performance expectation for the WiMedia UWB system, On the other hand, the packet-level throughput measurements show that the WiMedia UWB system can achieve high data rate while maintaining satisfactory QoS in office building (up to 30 meters) and home environments. Moreover, we showed that future block-ACK mechanism implementation can push the data rate to more than 300 Mbps with low PER. Also, the video streaming test and in-house gateway emulation test show that the WiMedia UWB product delivers what it is promised for and a solid performance in its intended applications.

The test results of various network layers (from PHY/MAC layers to application layer) clearly reveal the true capability and potential of WiMedia UWB for delivering high data rate and full HD video content in residential wireless networks.

Chapter 3 A Novel Distributed Multiband MAC Layer Design for High Rate Residential UWB Wireless Network

In the past decades, the technology of UWB wireless communication has become more and more developed, especially in the physical layer design and its hardware implementations. Meanwhile, as UWB being the most promising technology for home all-purpose networks, the multiple access mechanism for UWB networks is becoming one of the most important factors in maximizing the overall network performance. In order to optimize this state-of-art technology, various Media Access Control (MAC) designs have been proposed and published in the literature or standardized by various standards bodies.

In this chapter, we overview the existing research work for UWB MAC, and propose our multiband MAC layer design for high rate UWB communications. The idea of this novel yet simple MAC layer design comes from two important concepts: first of all, the application decides the design of MAC protocol. In this way, the protocol will be the best fit for the intended application, and it will be more realistic to be applied than some hypothetical ones that are not possible to be implemented in the near future. Secondly, the MAC protocol design should conform to the characteristics of the technology. Therefore, the combination of UWB wireless communication technology and its tailored MAC protocol can give full play to its strengths and excellence and avoid to its inadequacy based on its own features.

The new proposed MAC protocol "SL-MAC" is based on our previous work [49], which focuses on high data rate residential UWB wireless network, and takes advantage of the unique characteristics of UWB. It is very efficient for home and office type

networks, yet avoids the complicated implementations that most current UWB MAC designs have to face. The detailed design and behaviours of the proposed MAC protocol will be comprehensively elaborated, as well as some theoretical analysis. Finally, corresponding computer simulations will be presented together with discussions on simulation results.

3.1 Existing Research Work for UWB MAC

It is clear that UWB technology is becoming a promising candidate to realize high bit rate transceivers that can be used for a wide set of applications. Meanwhile, a large body of literature has been dedicated to the deployment of the multiply access techniques and their performances on UWB systems. Also, various UWB MAC designs and protocols that have been proposed in the recent years, for both high rate and low rate UWB applications. Generally speaking, high data rate applications are implemented by MB-OFDM based UWB, while low data rate UWB applications are implemented by pulse-based UWB, as described in Chapter 1. In this chapter, the MAC protocols of low rate UWB is out of the scope, and the focus is on high rate UWB applications.

Generally, most MAC designs can be categorized as “centralized MAC” or “distributed MAC”. The existence of a central coordinator or not distinguishes the two classes. In a centralized-type MAC, a predefined or elected master node is responsible for scheduling all other slave nodes. A popular application of this kind of MAC is Bluetooth. While in a distributed-type MAC, without a central coordinator, nodes access the medium by a selected contention scheme. For example, the most widely used 802.11 wireless-LAN runs CSMA/CA as its contention mechanism. Both MAC classes have their own advantages and disadvantages.

The most well-known MAC protocol for high rate UWB is the IEEE 802.15.3 MAC [16]. However, one of its main disadvantages is its centralized architecture, which can

cause problems when dealing with Peer-to-Peer (P2P) mobile applications. To address this issue, the WiMedia Alliance has come up with a new high rate UWB MAC with a distributed architecture, which was standardized in [11] and known as WiMedia MAC. The most important contribution of WiMedia MAC protocol is that it solves the problems of IEEE 802.15.3 MAC due to the centralized architecture and supports the mobile P2P or ad-hoc UWB network applications. As described earlier (in Chapter 1, Section 1.2), Distributed Reservation Protocol (DRP) and Prioritized Contention Access (PCA) are two main features of the WiMedia MAC for handling multiple access, which are evaluated in [19] and [20], respectively. Also, another evaluation of the PCA scheme in WiMedia was carried out by Ruby et al. in [47], and Maryam et.al. proposed a distributed reservation algorithm for video streaming over WiMedia UWB networks in [50]. Nasim and his colleagues proposed an analytical model of the PCA queue in [48].

Other than the standardized protocols as mentioned above, there are quite a few efforts reported in the literature on high rate UWB MAC designs. Francesca Cuomo and her colleagues presented a general framework for radio resource sharing for different classes of traffic requiring both elastic-dynamic and guaranteed-reserved bandwidth in UWB ad-hoc network in [36]. A distributed opportunistic access scheme for uplink OFDMA systems was proposed in [37], and showed better spectral efficiency than traditional centralized OFDMA systems by significantly reducing overheads. In [38], C. Viswannathan proposed an Ad-Hoc MAC model for UWB mobile computing applications, and analyzed it in terms of number of packets sent/received and efficiency. Kong and his colleague proposed a MAC protocol called medium access control with concurrent transmission (CT-MAC) in [39], which assumed no specific physical layer and adopts the UWB by stating the transmission bandwidth to be at least 500 MHz. The drawback of [39] was that CT-MAC inherits pure CSMA/CA method from IEEE 802.11 MAC protocol, which was proven to be incompatible with UWB technology in [40].

Recently, Zhang and Ying proposed a multi-channel MAC protocol of UWB Ad-Hoc wireless network based on location information in their work [41] and showed the channel assignment with the help of UWB's accurate positioning capability to be an efficient solution. Thanks to UWB's abundant bandwidth, one can increase the throughput immediately by making use of multiple channels as researchers showed in [42] – [44], which yields impressive enhancements in many aspects than single-channel MAC.

Inspired by these previous research works, we propose a novel media access control scheme for high rate residential UWB network. It is inspired by the special characteristics of UWB technology and our UWB measurement results in Chapter 2. The rest of this chapter will progressively elaborate our proposed work.

3.2 Proposed MAC Protocol Design

In order to design an effective MAC scheme for high rate UWB residential wireless networks, it is important to understand the specific characteristics of the applied environment and scenarios. For a residential network, typically “in home” or “in office” type network, there are 4 key characteristics: enclosure space, relative short transmission range, relative small amount of nodes and lots of human activities. Some of these components could be performance constraints, but they can also be beneficial to the MAC design if being utilized properly.

In our proposed work, we take full advantage of both environment's characteristics and UWB's special features. Thanks to its ultra high rate and short communication range (comparing to the most commonly used residential wireless network technologies such as Wi-Fi), UWB makes itself a natural fit for the high rate residential wireless network. Compared to the Wi-Fi technology, UWB has the following advantages: i) high data rate (as shown in Chapter 2); ii) less interference to neighbours; iii) less interference among devices; iv) low power spectrum density and thus less electromagnetic (EM) radiation

leading to green environments. Moreover, most applications in residential network only require short range transmission, such as in-home video streaming and transferring data files. Therefore, the network is required to maintain a desired QoS level for short range transmission.

For a residential wireless network, especially an “in home” network, the number of communication nodes (or stations) is usually less than 15, which makes the MAC design different from dealing with a network consisting hundreds of hypothetical nodes.

3.2.1 Motivation

With the 3.1 GHz to 10.6 GHz frequency band allocated to UWB, the question arises how to utilize this vast 7.5 GHz bandwidth. High rate UWB systems developed so far are based on OFDM signalling that occupies approximately 528 MHz. Although more bandwidth can be adopted for a UWB signal, generally the wider the signal bandwidth the higher the cost, complexity and power consumption of the transceiver. Therefore, a high rate UWB system is usually limited to 528 MHz bandwidth. Within the allocated UWB spectrum, there are 14 sub-bands each with 528 MHz bandwidth. The way the WiMedia/ECMA standard utilizes the spectrum is to group every 2 or 3 sub-bands into a band group. As described before, there are altogether 5 band groups. A transmitter may use one sub-band in a band group, or hop across the 2 or 3 sub-bands in the group for link transmission. One hopping/non-hopping pattern corresponds to a time frequency code (TFC). The idea behind the TFC is firstly to boost the transmission power and increase range when hopping is employed, secondly to achieve some frequency diversity, and thirdly to allow certain level of multiple access as initially envisioned. In theory, hopping over sub-bands in time can lower multiple access interference (MAI) and thus leading to more users accommodated. In reality however, because of the low number of frequency bands in a group, this type of frequency hopping cannot mitigate much MAI but create a

rather complicated interference scenario due to its use of multiple sub-bands. For nodes within a beacon group using the same TFC to communicate, their multiple access is coordinated by the single channel ECMA MAC protocol. When different beacon groups operate in the same region, because they may use TFCs that partially overlap with one another in frequencies and their operations are not coordinated in time, nodes in different beacon groups may cause interference to others but the ECMA MAC protocol has no specifications to deal with such interference.

This motivates us to reconsider how to efficiently use the rich frequency resources in UWB to increase its overall network performance. Instead of assigning more sub-bands in the physical layer for frequency hopping, we propose to apply the multiple sub-bands for multiple access, leading to a multi-channel MAC design. Each physical layer transmission occupies only single sub-band, and the transmitter and receiver of a communication link use different sub-bands/channels. By creating multiple orthogonal frequency channels, many parallel transmissions can happen at the same time in the same region without mutual interference. Channel assignment for each node is carried out in a dynamic and distributed manner that offers significant flexibility.

3.2.2 Self Listening MAC Protocol Design

A. Design Objectives

As a general principle, the role of the MAC layer is to allow multiple users to share a common resource. The definition of resource, and of the procedures by which access to the medium is granted, depends on the adopted transmission and multiple access techniques. Key MAC design objectives should be: i) to maximize throughput, ii) to guarantee an acceptable delay, and iii) to grant fair access. The above goals must be fulfilled in a dynamic environment, i.e. under variable channel conditions, traffic

characteristics, and local network topologies. Flexibility is thus an additional feature which an advanced MAC should incorporate [45].

In our proposed method, we adopt the distributed-type as the design basis. One reason is that a distributed network is more easily scalable in terms of adding a new terminal into an existing network than a centralized network. Secondly, a distributed network has a flat topology, and no central controller unit is needed. The MAC algorithm in one terminal will be similar to the other. While in a centralized network, the central coordinator is more complex and expensive to build, and could become the bottleneck of traffic. More importantly, the number of terminals in a home or office network will vary upon people's need, for example, a new laptop or a new HD television can join or leave the network. Therefore, a distributed network design is more suitable under this consideration.

Our objective is to have a distributed MAC design that can handle multiple access by taking advantages of UWB technology and residential environment, and it should be of low implementation complexity.

B. Assumptions

There are several key assumptions based on the characteristics of the UWB technology and the intended network environment.

1. The network is an enclosure space
2. The number of nodes (or stations) within the network is less than 15
3. The density of nodes (or stations) within the UWB transmission range is low
4. The sizes of the control packets (e.g. beacon packets, acknowledgment (ACK) and negative acknowledgment (NACK) packets) are very small compared to the data packets.
5. The physical layer support for the multiband MAC design is that transceiver of each node can configure its radio frequency module to send and receive on different sub-bands

C. Design Descriptions

As is well known, one of the most challenging problems in designing MAC protocol for wireless networks is how to alleviate the contention for resource among nodes. Our proposed MAC protocol provides a simple yet effective solution to this problem for residential UWB wireless network.

The idea is to utilize the entire 7.5 GHz UWB bandwidth by dividing it into sub-bands and assigning each sub-band to each individual node. By doing so, each node has its own exclusive frequency band and it will use this frequency band for receiving data packets. Any node who wants to send packets to another node must switch to the receiver's frequency band. The major advantage of this method is that, in all cases, there is only one receiver in one channel. Therefore, simultaneous transmission for multiple pairs is not a problem any more and the probability of packet collisions can be held at a very low level. And the multiple access problem that we need to worry about is degenerated into the single receiver with multiple transmitters' case. A simple solution for this case will be presented later.

A few remarks are in place before we introduce the detailed design:

1. UWB's abundant bandwidth resources allow us to divide the entire 7.5 GHz frequency band up to 15 sub-bands while each of them is still qualified for UWB transmission standard (≥ 500 MHz).
2. A residential network has limited number of nodes, so the amount of UWB sub-bands can satisfy the need of exclusive frequency band for each node.
3. In the occasion that the number of nodes is greater than the number of UWB sub-bands, some sub-bands can be reused between nodes that are outside the transmission range of each other. This is extremely useful thanks to the short range transmission and power control features of UWB communications. In this case, the extra nodes will still have their exclusive frequency bands without interfering others.

4. The short range transmission feature of high rate UWB communication also enhances the security level of the intended residential network. The network security of 802.11 Wi-Fi has long been criticized for allowing unauthorized terminals to access the network. For example, people often complain about their neighbours “stealing” their Wi-Fi networks. While in our design, the enclosure home space and the confined UWB transmission range can help relieve this security problem by bounding the network to the intended area.

The proposed MAC design is called “Self Listening MAC” (SL MAC), which well explains the main idea of the protocol by having each node receiving data on its own frequency band. One major difference between the proposed SL-MAC and the WiMedia standard is how they make use of the vast UWB bandwidth. In the WiMedia standard, frequency hopping codes are used in the physical layer to assign different communication channels to users, and multiple access issues within the same channel are handled by either DRP or PCA schemes in the MAC layer. While in the proposed SL-MAC, multiple accesses are handled by assigning exclusive ownerships of sub-bands to users in the MAC layer, to reduce potential collisions by a big margin. And then it will use an enhanced CSMA/CA method for access of multiple transmitters to the same receiver.

Detailed steps of the proposed MAC algorithm are presented in the following section.

D. General Algorithm Steps

Step 1. The entire 7.5 GHz frequency band is divided into n ($n < 15$) sub-bands depending on the overall network parameters (size of the network and data rate requirements).

Step 2. The first node (N_1) enters the network and senses all available sub-bands. By doing so, it will then take the ownership randomly from the available sub-bands (e.g., N_1 can be the owner of sub-band SB_1 , and N_2 can take SB_2 and etc.) and enter its

IDLE state. Notice that the “n+1” Node (N_{n+1}) will still be able to find an “available” sub-band when all sub-bands are occupied by its preceding nodes. This scenario will be explained in details later (*E. Frequency Reuse*).

Step 3. During the IDLE state, a sub-band owner will send out periodic “ownership” beacon on all sub-bands and listening on its own sub-band for any incoming beacon packets, transmission requests or data packets..

Step 4. Meanwhile, nodes will create reference mapping table (RM-Tables) for the mapping between the neighbours and their corresponding sub-bands based on any received beacon packets.

Step 5. If a node (e.g. N_x) has data for another node (e.g. N_y), it will look up its reference table for N_y 's sub-band, and switch its transmitter onto sub-band_y. After changing its state from IDLE to TRANSMISSION, it will send a transmission request (RTS) to N_y on sub-band_y, and start a timer.

Step 6. Upon receiving the request from N_x , N_y will send back an acknowledgement (ACK_{CTS}) or negative acknowledgment ($NACK_{CTS}$) packet to the requester depending on its current state. For example, if multiple sending requests are received, N_y will send ACK_{CTS} to one node, and $NACK_{CTS}$ to others.

Step 7. If an ACK_{CTS} packet is received at N_x , N_x will send off the data packets to N_y on sub-band_y, and fire off a timer. If N_x receives a $NACK_{CTS}$ packet from N_y or does not receive any response before the timer expires, it will back off by a random time, chosen uniformly over $[0, 2^{N_r} \cdot T_p]$ (N_r is the number of retransmission, and T_p is the channel propagation time) and repeat Step 5 until it reaches the maximum retransmission limit. The data packet will be dropped if the retransmission limit is reached.

Step 8. Upon successfully receiving a data packet, N_y will send a Data Acknowledgment (D-ACK) packet to N_x .

Step 9. If N_x received a D-ACK packet from N_y , it will schedule the next data packet and send it to N_y on sub-band $_y$. However, if N_x doesn't receive the corresponding D-ACK packet before the timer expires, it will repeat Step 7 until the maximum number data packet retransmission is reached.

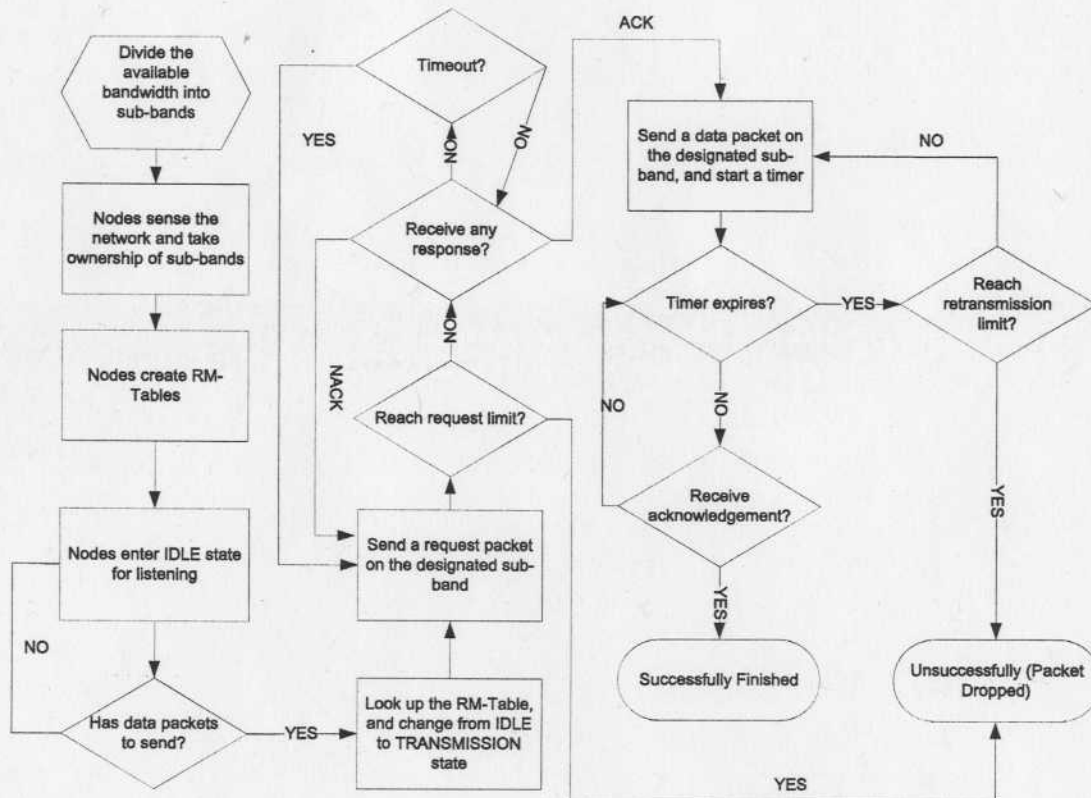


Fig. 3.1 Flowchart of SL-MAC basic behaviours

The above steps and Fig. 3.1 show the basic behaviours of the SL-MAC, and now we will discuss some important components of the design such as frequency reuse and handling the packet interference's problem as mentioned previously.

E. Frequency Reuse

Thanks to UWB's short transmission range, frequency channel reuse is possible even in a compact size home environment. Let's consider the following scenario shown in Fig. 3.2: node $_1$ uses sub-band "Freq $_1$ " as its exclusive frequency band for receiving data,

and node₂ is 3 hops away from node₁. Therefore, node₂ can reuse the sub-band “Freq₁” as its exclusive band without raising any confusion for their neighbours. For example, if node₃ has data to send to node₁, it will check its RM-Table and decides to use sub-band “Freq₁” for sending data packets. Even though node₂ is also using sub-band “Freq₁” as its exclusive frequency band, node₂ will not pick up the data packets sent by node₃ due to its limited communication range. As the same time, node₄ is listening on its own sub-band “Freq₄”, so it will not notice the ongoing packet transmission between node₁ and node₃.

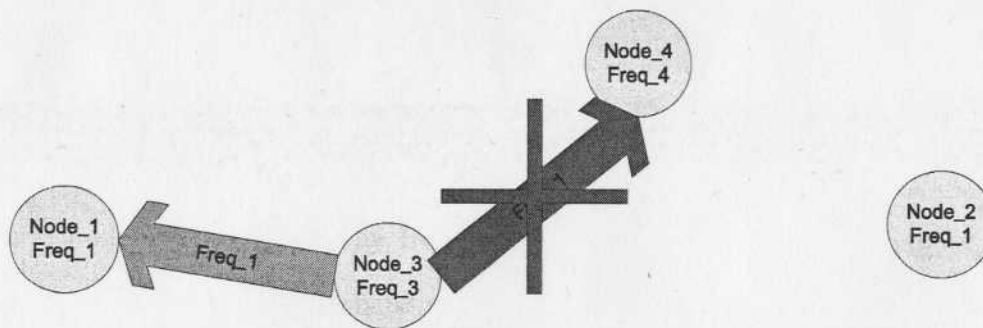


Fig. 3.2 Example of frequency reuse in SL-MAC

Therefore, the Frequency Reuse Safety Distance (FRSD) for nodes to reuse sub-bands without interfering with each other is 2 hops, as shown in Fig. 3.3. Ideally, any node that is within the FRSD of a given node, it must use a different sub-band to avoid frequency overlapping. Fortunately, with the amount of sub-bands provided by UWB technology and the low network density characteristics of residential networks, this frequency reuse scheme is feasible and effective. Furthermore, the communication range of UWB is adjustable through power control, which makes the FRSD more dynamic according to the intended environment.

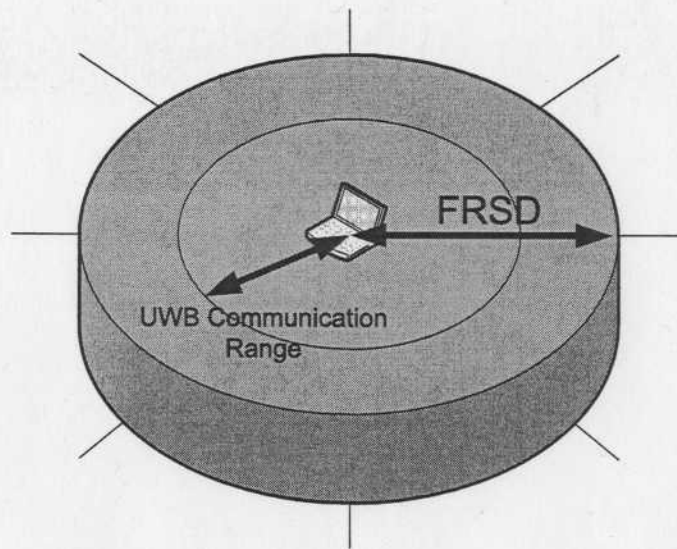


Fig. 3.3 Frequency Reuse Safety Distance (FRSD) in SL-MAC

One major challenge of this frequency reuse method is how to make one node be aware of another node's selected sub-band outside its communication range but within its FRSD. If this cannot be guaranteed, it may cause collisions of concurrent transmissions, which is shown in Fig. 3.4.

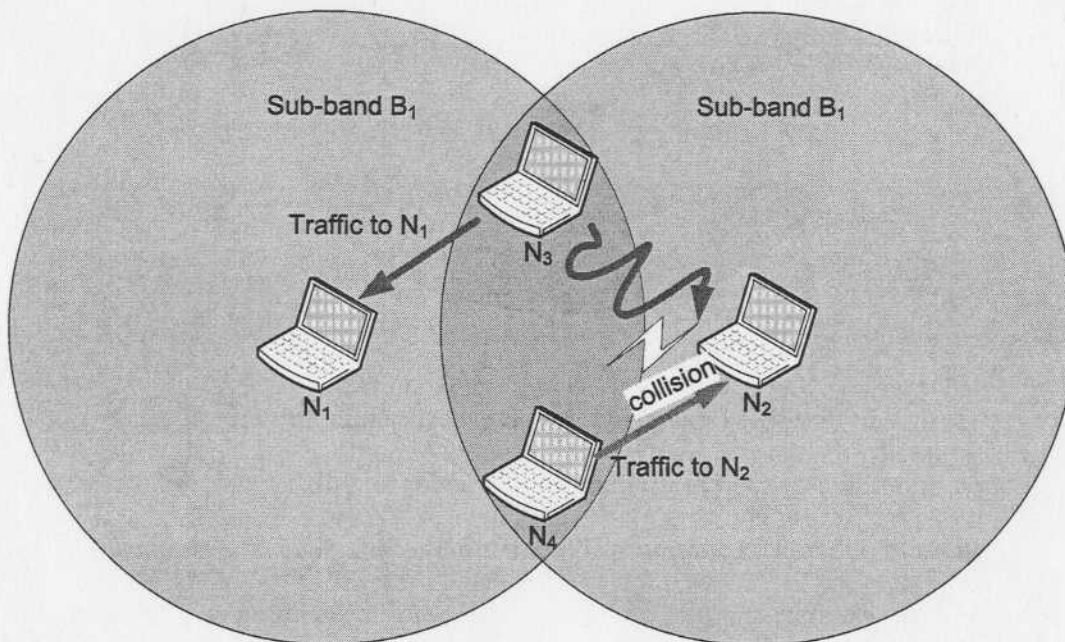


Fig. 3.4 Potential collisions of concurrent transmissions

As we can see, node N_1 has its sub-band B_1 , and node N_2 also chooses B_1 as its sub-band. This situation is possible because when N_2 enters the network and senses for available sub-bands, it is not aware of N_1 's "ownership" beacon on B_1 due to its limited communication range. Therefore, problem will arise when N_3 and N_4 start to transmit data to N_1 and N_2 respectively. Two concurrent transmissions will interfere with each other on sub-band B_1 . Fortunately, this issue can be solved by making use of the RTS packet sent by N_3 . Since N_3 is trying to send data to N_1 , it will first send out a RTS packet to N_1 on sub-band B_1 . As a neighbour of N_3 , N_2 will also receive this RTS packet on its current sub-band B_1 . However, when N_2 realizes this RTS packet is not intended for it, it immediately knows there is a potential frequency overlapping within its FRSD. Therefore, upon receiving the "incorrect" RTS packet, N_2 will re-sense all available sub-bands with the knowledge of B_1 being taken. After the sub-band reallocation process, N_2 will claim another sub-band and notify all of its neighbours by ownership beacons. Finally, N_1 and N_2 will use different sub-bands and the collision can be avoided.

This sub-band reallocation process has several advantages: first of all, it can update the network sub-band allocation towards the ideal scenario as mentioned earlier, where no sub-band is reused within the FRSD of a given node. Secondly, it will not force the sub-band reallocation until any potential collision is sensed. In other words, the reallocation process is dynamic based on the network traffics. More importantly, it makes the entire network sub-band allocations more dynamic since nodes will update their sub-band ownerships according to the network traffic condition.

In all media access control research works, as far as we know, the most closely related one is the "receiver code" design in [46] by E.S. Sousa and J.A. Silvester. They proposed a spreading code protocol which says that each node has a unique code for receiving, and the transmitter tunes to the code of the intended receiver for transmitting data packets. Comparing to [46], our proposed method states that each node has its own frequency

channel instead of spreading code, benefiting from the vast bandwidth provided by the UWB spectrum regulation. By avoiding use of spreading codes for receivers, we can utilize the spreading code method combining with other multi-access schemes such as Aloha to further mitigate the packet collisions due to multiple simultaneous transmissions to a same node.

More importantly, even though the SL-MAC is based on a distributed MAC design, it inherently comes with a “temporally centralized” characteristic. This is because only one receiver is communicating with all potential senders in any given frequency channel, which turns out to be similar to a single channel communication system with a parent node that can communicate with all its children nodes. Consequently, the receiver can act as a temporary coordinator for all its senders, and forms a “temporary centralized piconet”, which can be utilized for better control purposes. Keep in mind that any node can be a receiver, so the deployment of “temporary centralized piconet” is dynamic. In other words, nodes within a “temporary centralized piconet” will be different from time to time depending on the network traffic distribution. The concept of “temporary centralized piconet” will give SL-MAC more control abilities like those centralized MAC protocols while maintaining its flexibility as a distributed MAC. A detailed elaboration can be found in the next section.

F. Transmission Interference Handling

As mentioned earlier, SL-MAC solves the “concurrent transmissions of multiple pairs” issue (shown in Fig. 3.5) to a much simpler “single receiver” scenario (shown in Fig. 3.6). In the SL-MAC supported UWB residential network, the major cause of packet level interferences is simultaneous multiple transmissions to a single receiver.

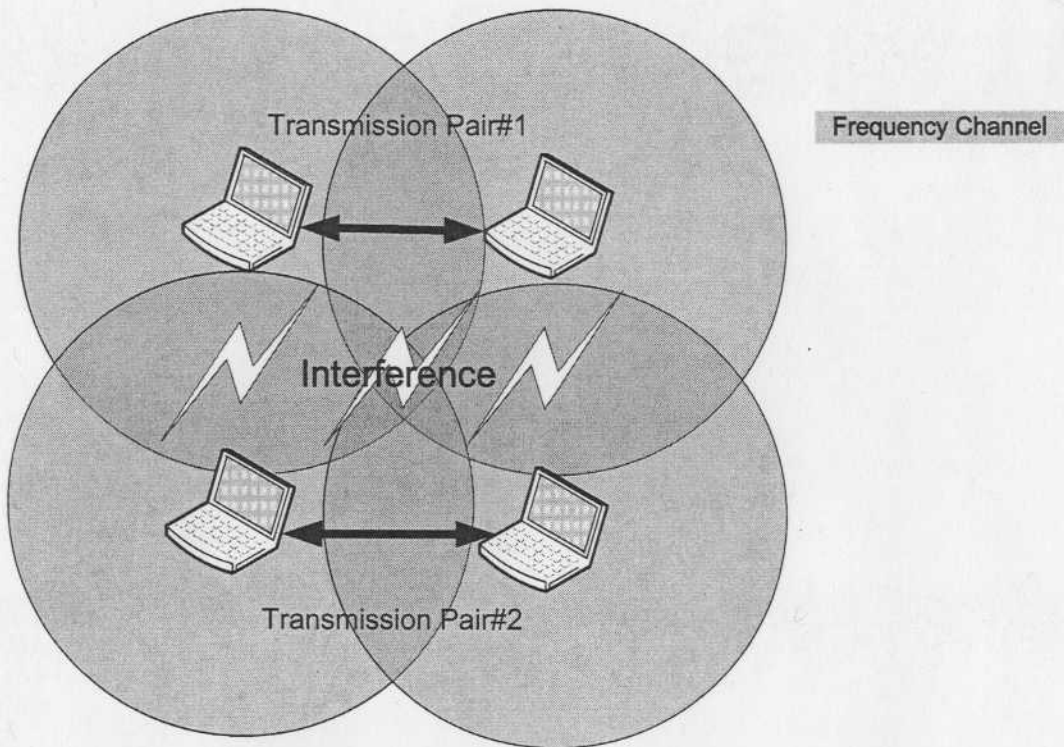


Fig. 3.5 Concurrent transmissions create interferences in the same channel

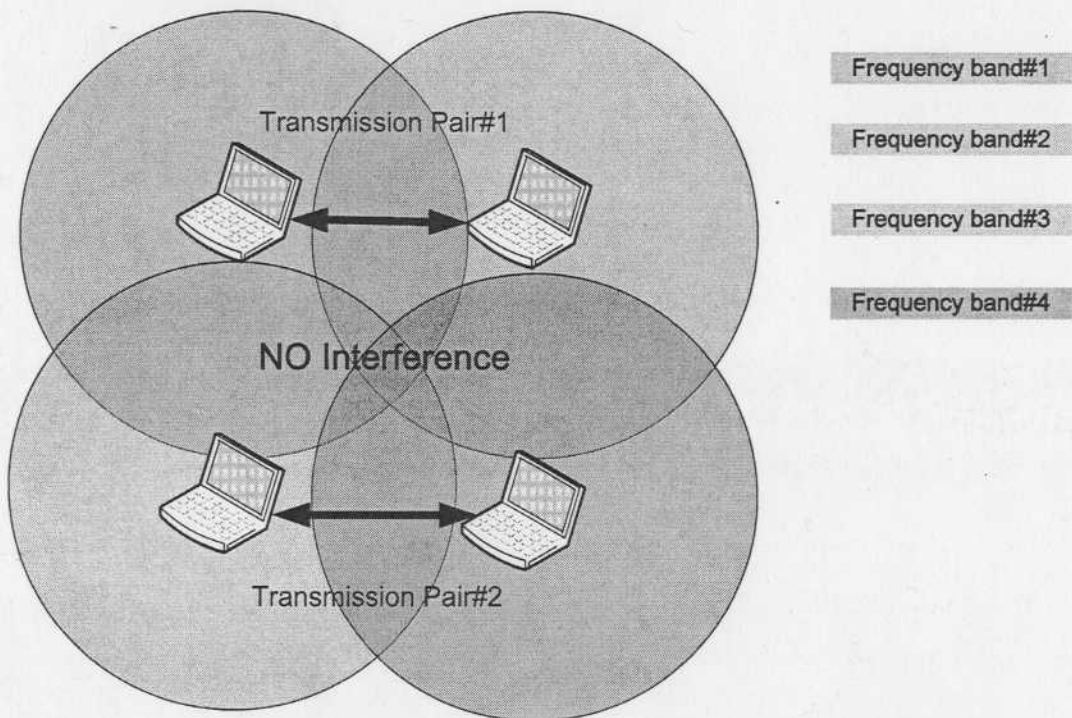


Fig. 3.6 SL-MAC allows only one receiver in a given frequency band

In order to solve this interference issue, we adopt and improve the legacy CSMA/CA scheme, specifically the RTS/CTS (Request to send/Clear to send) mechanism, which is modified to help alleviate the potential collisions. The main idea is that upon receiving a RTS packet, the receiver will reply a special CTS packet containing “token information”. In legacy CSMA/CA scheme, one CTS packet grants the permission of sending one data packet to the requester. While in SL-MAC, one CTS packet can grant the permission of sending multiple data packets to the requester, depending on its “token information”, and we call this method “Token Access Control” (TAC). Generally speaking, the priority service classes of different data types decide the “token information”: the higher priority the data has, the more packet permissions can be granted to the requester. In this work, we discuss 3 major priority service classes:

- 1st Priority Service Class, which requires high data rate, tightly constrained delay and delay variation, such as real-time video streaming applications.
- 2nd Priority Service Class, which requires a decent data rate but not very strict on time delay, such as file transfer and download applications.
- 3rd Priority Service Class, which has relatively low requirement on data rate and usually is delay tolerant, such as traditional computer communication applications.

With the above information in mind, let us consider the following scenario in Fig. 3.7: Node N_1 is listening on its own sub-band SB_1 , while Nodes N_2 , N_3 and N_4 all have data to send to N_1 . However, the data types are different: N_2 has video streaming data (1st Priority Service Class); N_3 has a group of files to transfer (2nd Priority Service Class); and N_4 has some data for traditional computer communication applications such as instant messaging and emails (3rd priority service class).

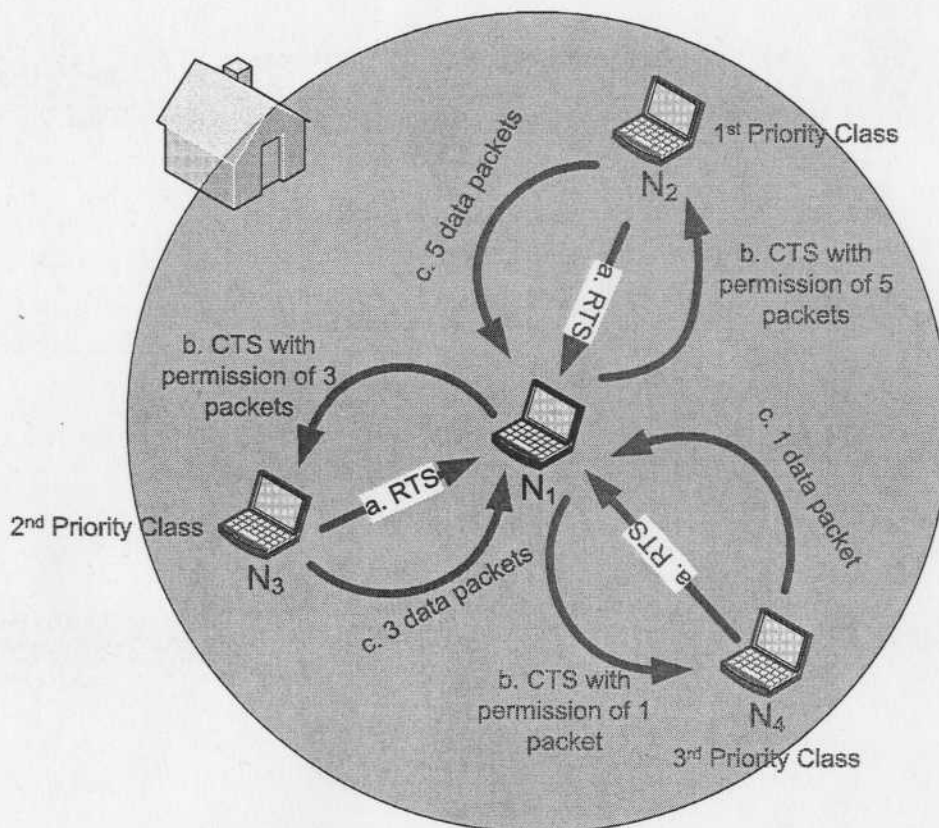


Fig. 3.7 Example of “Token Access Control” (TAC)

The senders send out their request (RTS) packets to N_1 in sub-band SB_1 , including the corresponding data priority information. Upon receiving one RTS packet, N_1 will send back a CTS packet with different “token information” depending on the data priority information. Table 3.1 shows the relationship between the Priority Service Class and Permission Token.

Table 3.1 Relationship between Priority Service Class and Permission Token

Priority Service Class	Permission Token
1 st Priority Service Class	5 data packets allowed
2 nd Priority Service Class	3 data packets allowed
3 rd Priority Service Class	1 data packets allowed

Note that N_1 acts as a network coordinator in this case by assigning different access permissions to N_2 , N_3 and N_4 in the “temporary centralized piconet”. After receiving the corresponding CTS packet, N_2 will start to send 5 data packets to N_1 without requesting for permission again at the end of each packet transmission. Similarly, N_3 and N_4 will

send out their allowable amount of packets to N_1 at the scheduled time based on their own CTS packets, respectively. When the permitted data packets are all sent out and acknowledged, senders will send out RTS packet again.

By using the TAC method, SL-MAC improves the overall network performance by utilizing prioritized traffic distribution, while maintaining satisfactory QoS levels for different network traffics. Moreover, the content of Table 3.1 can be updated easily according to any new QoS requirement for network traffic.

3.2.3 Performance Analysis of SL-MAC

In this section, we analyze the performance of the proposed SL-MAC by comparing to traditional single channel MAC designs. In order to make the focus of our analysis clear on the mechanism of SL-MAC, we adopt the following assumptions:

1. The packet processing time of each node is ignored
2. The sizes of all acknowledgment type packets including ACK_{CTS} , $NACK_{CTS}$ and D-ACK packets are considered to be very small.

Generally, multiband MAC designs have natural advantages over single channel MAC designs in reducing transmission collisions and unsuccessful transmissions (data packets dropped). Therefore, we only show the performance difference between the SL-MAC design and the single channel MAC design in terms of successful data packet transmissions. Let us consider the time needed to successfully deliver a data packets. The following equations show the channel transmission time for data packet, request packet and acknowledgment packets, respectively.

$$T_{data} = \frac{\text{Size of data packet in bits}}{\text{Channel Capacity in bits}} \quad (4)$$

$$T_{request} = \frac{\text{Size of request packet in bits}}{\text{Channel Capacity in bits}} \quad (5)$$

$$T_{ACK} = \frac{\text{Size of acknowledgement packet in bits}}{\text{Channel Capacity in bits}} \quad (6)$$

Notice that T_{ACK} can be applied to all three acknowledgment types discussed earlier. In order to calculate the total time of successfully delivery of one data packet, we first need to find out the upper bound of time for acquiring the sending permission, which is shown in Eq. (7), where T_{pd} represents the channel propagation delay time and N_r (N_r should be less than the maximum number of request retransmission $MAX_{request}$) is the number of retransmission for a given request packet. The term $T_{timeout_ack}$ is the timeout value of ACK packet waiting time.

$$T_{s-permission} = T_{request} + T_{pd} + N_r * Max(T_{NACKCTS}, T_{timeout_ack}) + N_r * T_{pd} + \sum_{i=0}^{N_r} 2^i * T_{pd} + T_{ACKCTS} \quad (7)$$

By taking into account that all acknowledgment type packets have the same size and assuming no timeout happened for all acknowledgement packets, we can replace all related terms by T_{ACK} , and Eq. (7) can be simplified to:

$$T_{s-permission} = T_{request} + \left(\sum_{i=0}^{N_r} 2^i * T_{pd} + N_r + 1 \right) * T_{pd} + (N_r + 1) * T_{ACK} \quad (8)$$

When the sending permission is granted, a data packet will be sent to its destination and the whole process takes $T_{sending}$ period, given in Eq. (9), where $T_{timeout}$ and N_{r-data} (N_{r-data} should be less than the maximum number of data packet retransmission MAX_{data}) represent the data packet timeout duration and the number of retransmission for a given data packet. Notice that N_{r-data} mainly depends on the probability of data packet collision during the transmission.

$$T_{sending} = \frac{T_{data} + T_{pd} + T_{timeout} * N_{r-data}}{(1-PER)} \quad (9)$$

Therefore, the time to successfully deliver a data packets can be represented in terms of all different time intervals discussed above, as described in Eq. (10), where DIFS and SIFS represent DCF Inter Frame Space and Short Inter Frame Space respectively.

$$\begin{aligned}
 T_{\text{successful}} &= T_{s\text{-permission}} + DIFS + T_{\text{sending}} + SIFS + T_{D\text{-ACK}} + T_{pd} \\
 &= T_{\text{request}} + \left(\sum_{i=0}^{N_r} 2^i * T_{pd} + N_r + 2 \right) * T_{pd} + (N_r + 2) * T_{ACK} \\
 &\quad + \frac{T_{\text{data}} + T_{pd} + T_{\text{timeout}} * N_{r\text{-data}}}{(1 - PER)} + DIFS + SIFS \quad (10) \\
 &\quad \text{(where } N_r < MAX_{\text{request}} \text{ and } N_{r\text{-data}} < MAX_{\text{data}})
 \end{aligned}$$

From Eq. (10), we know that $T_{\text{successful}}$ mainly depends on 3 major components: $T_{s\text{-permission}}$, T_{sending} and some constant values. When the channel capacity stays unchanged, N_r and $N_{r\text{-data}}$ have significant impacts on $T_{\text{successful}}$. As mentioned earlier, $N_{r\text{-data}}$ is influenced by the data packets collisions during packet transmissions, or the severity of transmission interference in the intended network. The SL-MAC eliminates the interferences between concurrent transmission pairs by using sub-bands and the unique self-listening mechanism, which can reduce the probability of data packets collisions in the network. Theoretically, the values of N_r and $N_{r\text{-data}}$ will decrease as the number of sub-bands increases. In other words, by reducing N_r and $N_{r\text{-data}}$, SL-MAC can cut down the duration of T_{sending} dramatically due to the multiplication effect of $N_{r\text{-data}}$ on the data packet timeout duration T_{timeout} , which is usually the biggest contributor to T_{sending} .

Another major improvement on the performance provided by SL-MAC is its ability to make the time spent on acquiring the sending permission more efficient. Let us consider the following scenario: There are n data packets in the network waiting to be delivered. For a traditional single band MAC, it takes $T_{\text{total}} = n * T_{\text{successful}}$ to finish the task, assuming that no data packet will be dropped. Alternatively, by utilizing the ‘‘Token Access Control’’ feature, SL-MAC can provide multiple sending permissions to a single request packet depending on the priority level of different data packets (referring to Table 3.1). In

this case, the total time to finish the task by SL-MAC is shown in Eq. (11), where n_1 , n_2 and n_3 represent the number of 1st priority service class packets, 2nd priority service class packets and 3rd priority service class packets, respectively.

$$T'_{total} = \left(\frac{n_1}{5} + \frac{n_2}{3} + \frac{n_3}{1} \right) * T_{s-permission} + n * (DIFS + T_{sending} + SIFS + T_{D-ACK} + T_{pd}) \quad (11)$$

(where $n_1 + n_2 + n_3 = n$)

By subtracting T'_{total} from T_{total} , we manage to save substantial amount of processing time by using TAC, as given by

$$T_{save} = T_{Total} - T'_{total} = \left(\frac{4}{5}n_1 + \frac{2}{3}n_2 \right) * T_{s-permission} \quad (12)$$

In summary, the proposed SL-MAC can not only reduce the overall packet processing time for the intended residential UWB wireless network, but also distribute the network load more intelligently by prioritizing different data traffics. The following section presents computer simulations of the basic SL-MAC behaviour, and the results will be discussed and compared with traditional single channel MAC.

3.3 Computer Simulation

In this section, the performance of SL-MAC over wireless UWB residential network is evaluated by computer simulations. We implemented the basic behaviours of SL-MAC with an event-driven program written in C. Each stage or any action of a given node is modeled into an individual event (e.g. generating data packets, transmitting, backing-off due to packets collision and so on), and processed in time sequence.

We discussed previously about different traffic types and their priority service classes, as well as the unique ‘‘Token Access Control’’ scheme in SL-MAC. However, we have only one traffic type in the simulation. In other words, all data packets are of the same priority service class, and the advantage of the ‘‘TAC’’ method is not shown in the

simulation results. The input parameter settings of the simulation program include channel capacity, data packet size and average packet error rate, etc.

3.3.1 Methodology

In the simulation program, we define the channel capacity in terms of data rate, based on the measurement results from our throughput measurement work. Notice that as the entire 7.5 GHz UWB frequency band being divided into sub-bands, they are distributed from 3.1 GHz low frequency end to 10.6 GHz high end. This may cause a problem since in reality high frequency bands usually have larger path loss than low frequency bands. Therefore, in order to simplify the software implementation while still maintaining the feasibility of the proposed model, we commit the following two changes:

1. Only the lower half of the entire UWB frequency band is taken into consideration in the simulation, which ranges from 3.1 GHz to 6.3 GHz. The reason is that even though UWB is permitted to operate on the entire 7.5 GHz frequency band, there still exist some limitations in the technology of transceiving UWB signals in the high end frequency band. Therefore, up to six 528 MHz sub-bands can be deployed in the simulation.
2. By only considering the “low end” section of the entire UWB bandwidth, we can assume that each sub-band has the same channel capacity and error performance as others in the simulation.

The data packets are generated randomly for the entire network based on Poisson distribution and then assigned to each node. The destination for each data packet is created randomly based on the total number of nodes and the system time at that moment. In this simulation work, we assume nodes always have data to send until the simulator comes to a predefined ending condition. In addition, a module which allows users to define specific node traffic patterns is implemented. Once all network parameters are set,

the simulator will start to emulate the basic behaviour of the SL-MAC by processing individual events based on their time stamps and trigger new events such as “packet collision” and “packet retransmission” based on the real time network status. The simulator will keep running until the ending condition is met, which can either be certain time duration or the total number of data packets delivered successfully. The following Fig. 3.8 shows a brief implementation flowchart of the SL-MAC simulator.

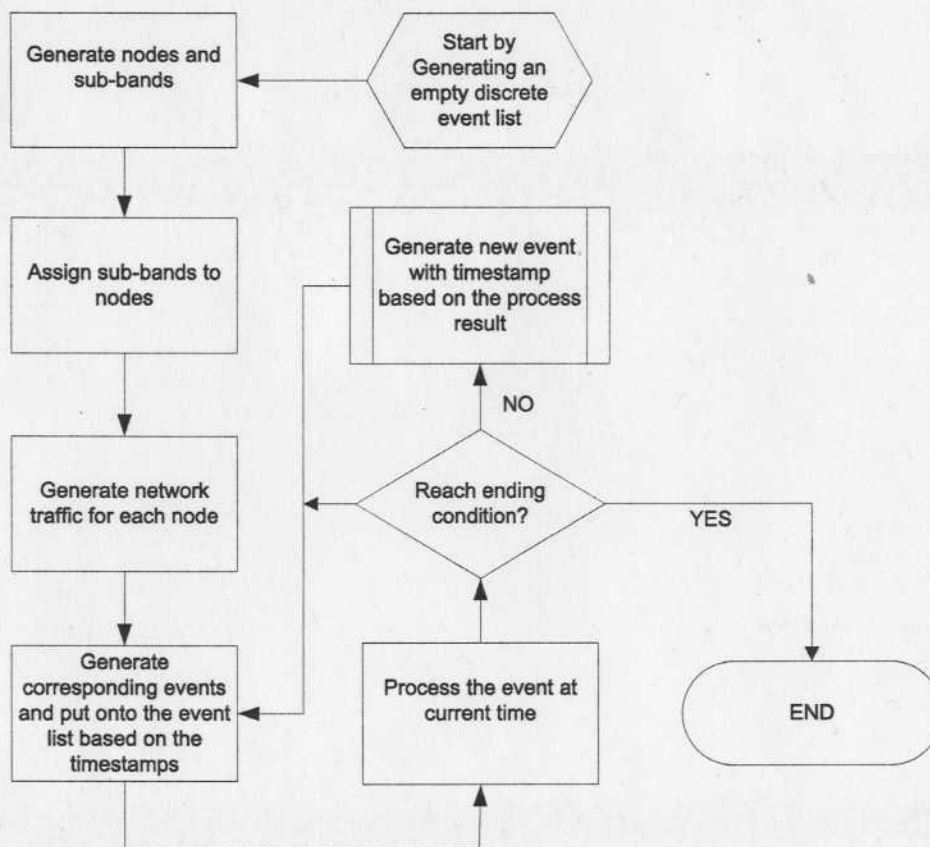


Fig. 3.8 The flowchart of SL-MAC simulator implementation

Once the network simulation finishes, the traced records for all processed events and performance counters will be saved and output to MATLAB for data post-processing and analysis.

The following Table 3.2 shows some key parameters used in the simulation, notice that the values of Packet Error Rate (PER), System Packet Arrival Rate λ_s and Channel Capacity are not given in the table. These 3 parameters are used as “drivers” for the SL-MAC simulator, and their values vary based on different simulation scenarios, which will be explained in details later.

Table 3.2 Parameters for the SL-MAC Simulator

Parameters	Values
Total number of Packets N_{total}	100,000
Total number of Nodes N_{node}	15
Data Packet Size DP_{size}	40,000 bits
Acknowledgment Packet size AP_{size}	16 bits
Packet Error Rate (PER)	<i>depending on simulation cases</i>
System Packet Arrival Rate λ_s	<i>depending on simulation cases</i>
Channel Capacity $C_{channel}$	<i>depending on simulation cases</i>

As mentioned earlier, the total number of packets will be used as the ending condition, which means the simulator will stop the simulation process after the total number of successfully delivered data packets reaching 100,000.

We evaluate the SL-MAC mainly in 4 aspects: average packet delay, average queue length, total finishing time and average system goodput, which are defined as follows:

- **Average packet delay:** the average time taken by a data packet from being generated to being successfully received.
- **Average queue length:** the average number of packets waiting in the queue of a given node during the simulation process.
- **Total finishing time:** the total amount of time for successfully delivering all data packets (e.g. 100,000).
- **Average system goodput:** the average number of successfully delivered information bits per unit of time by the network, excluding protocol overhead and retransmitted data packets.

According to the previous assumptions, we operate SL-MAC in two different modes: dual-band mode and six-band mode. In the first mode, two sub-bands of 528 MHz each are used for link transmission. The dual band mode is essentially two channel scenario, which would correspond to two band groups in the WiMedia specification, e.g., band groups 1 and band group 2 that occupies the frequency range from 3.1 GHz to 6.3 GHz. In the six-band mode, there are 6 sub-bands of 528 MHz spanning 3.1 GHz to 6.3 GHz. By manipulating the simulator “drivers”, we show the performance of the SL-MAC in comparison with those of the traditional single channel MAC and the dual channel MAC in different test cases. Note that the simulation parameters influence the absolute values of the simulation results, but the relative comparison among different MAC designs uses the same simulation parameters.

3.3.2 Effect of Changing Arrival Rate

In this test case, we define the Packet Error Rate (PER) between 0% to 1%, and the channel capacity to be 53 Mbps, which is in consistence with our measurement work. By changing the System Packet Arrival Rate λ_s from 10 to as high as 10000, we obtained the simulation results in Fig. 3.9 – Fig. 3.11. The legends on the upper-right corner of each plot show the corresponding MAC protocols: “single” represents the traditional single channel MAC, while “dual” and “six” represent the dual-band and the six-band mode SL-MAC, respectively.

In Fig. 3.9, the average packet delay increases dramatically with System Packet Arrival Rate λ_s in the lower range of the x-axis, and decreases quickly after λ_s reached about 600. The average packet delay keeps decreasing and became stable after λ_s past 4000. This is due to the fact that the packet delay in the low system arrival rate range was mainly caused by insufficient incoming data packets from nodes, and most system time are wasted on waiting for incoming network traffic. However, as the network traffic

increasing towards saturation, we can see the performance differences among the three MAC schemes. Compared to the single channel MAC, the dual-band MAC reduces the average packet delay by almost 50%. Meanwhile, the six-band mode SL-MAC is able to reduce the average packet delay to about 20% of that in the single channel MAC.

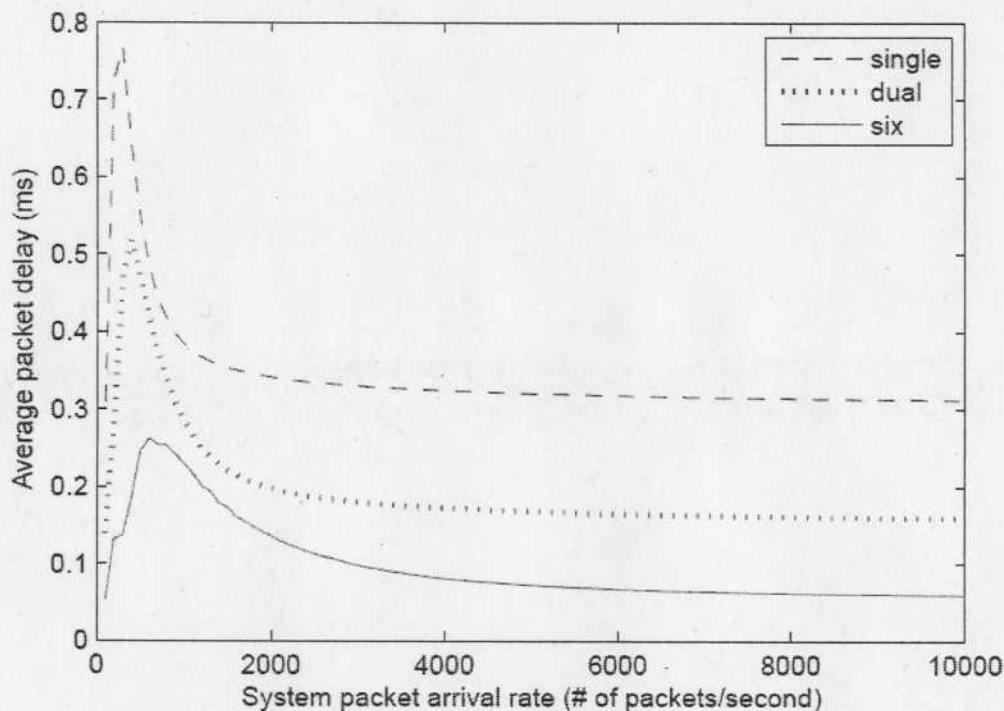


Fig. 3.9 Average Packet Delay vs. System Packet Arrival Rate λ_s

The average queue length increased almost linearly with the System Packet Arrival Rate λ_s in all three MAC schemes, as shown in Fig. 3.10. However, the growth rate is fairly low in the six-band mode SL-MAC, and the average queue length is maintained on a reasonable level. Notice that the average queue length is high flying in the single channel MAC when the System Packet Arrival Rate λ_s is high, while the dual-band MAC is able to cut that in half. The total finishing time of 100,000 successful data packet deliveries is presented in Fig. 3.11. We can see that the six-band mode SL-MAC handled all intended data packets transmission by taking only a quarter of the total finishing time in the single channel MAC, while the dual-band MAC has to use 47% more time than the SL-MAC scheme.

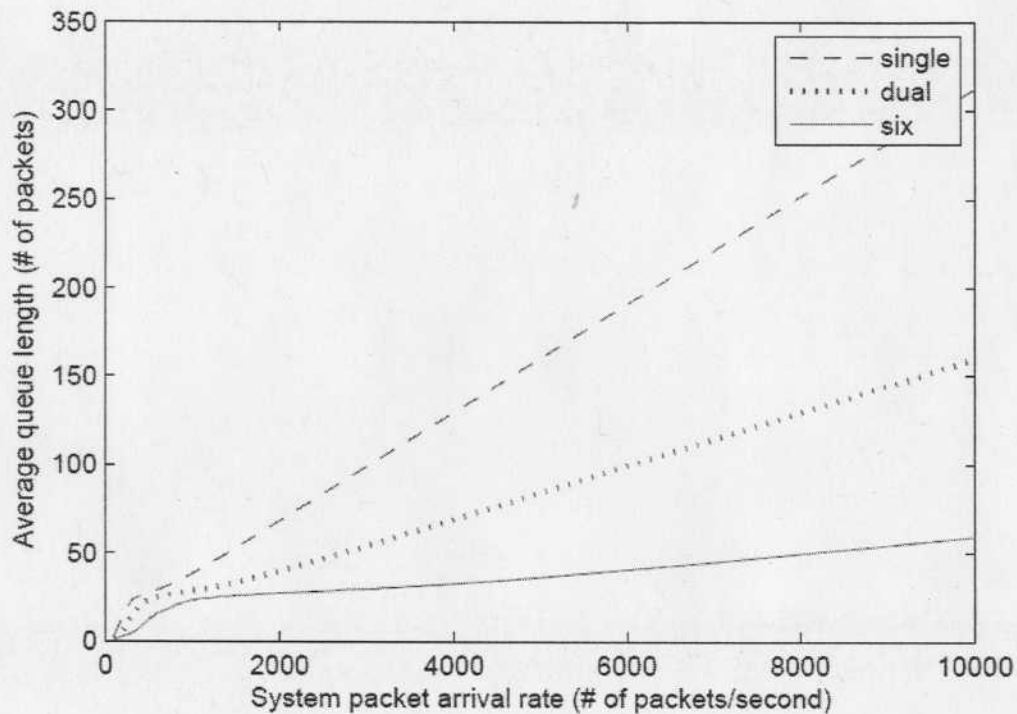


Fig. 3.10 Average Queue Length vs. System Packet Arrival Rate λ_s

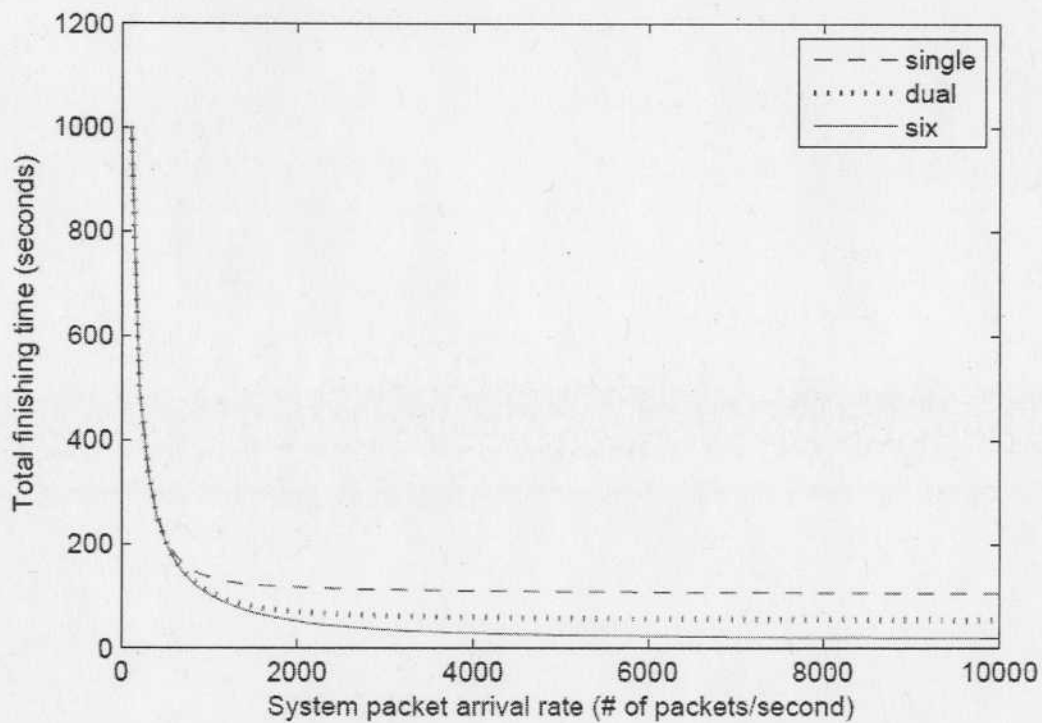


Fig. 3.11 Total Finishing Time vs. System Packet Arrival Rate λ_s

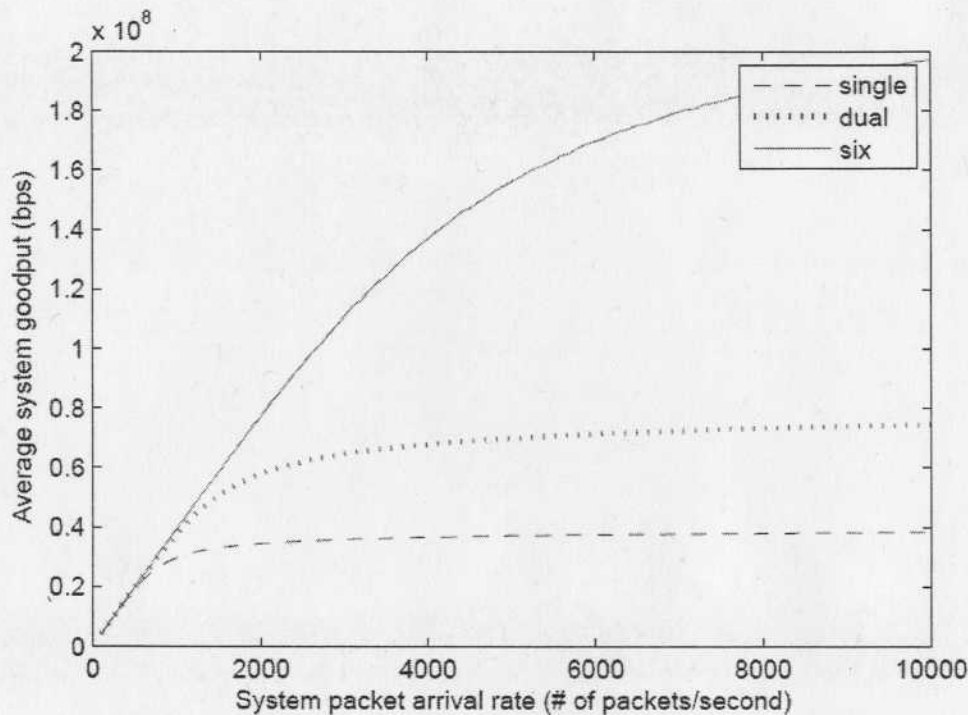


Fig. 3.12 Average System Goodput vs. System Packet Arrival Rate λ_s

Fig. 3.12 shows the SL-MAC has substantial advantages over the other two MAC designs in terms of average system goodput. We can see that the goodput of SL-MAC still has considerable growth potential while others become constant.

3.3.3 Effect of Changing Packet Error Rate

In this test case, the channel capacity and the System Packet Arrival Rate λ_s are set to be 53 Mbps and 4000, respectively. By gradually adjusting the Packet Error Rate (PER) from 0% to 80%, we can see the performance of SL-MAC under extreme network conditions. Average packet delay, average queue length and the total finishing time all increase as PER increases, as shown in Figs. 3.13 – 3.15. We can see that both the six-band mode SL-MAC and the dual-band MAC slow down the growth rates impressively in comparison to that of the single channel MAC. More importantly, in all three scenarios of average packet delay, average queue length and total finishing time, the six-band mode

SL-MAC delivers the best results out of all competitors, and it even has better performance in high PER level than that of the single channel MAC in low PER level.

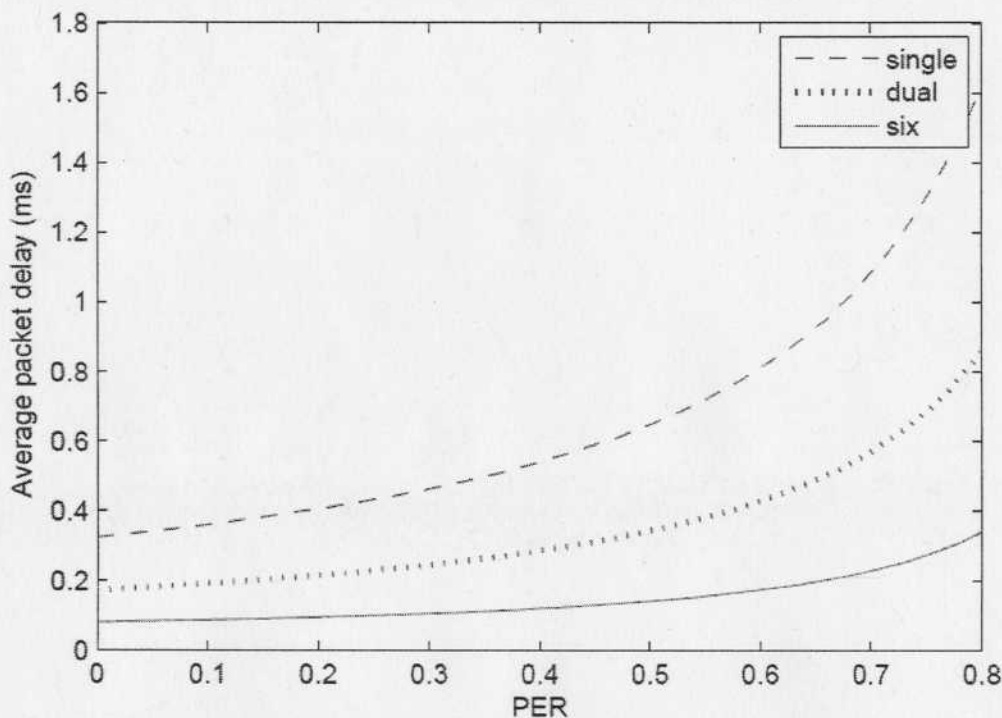


Fig. 3.13 Average Packet Delay vs. PER

As expected, the average system goodput decreases dramatically with the increase of PER in all three MAC designs. Thanks to the multiband design, the SL-MAC is still able to provide a decent goodput rate despite of the destructive effect to the network by high PER. This observation is very encouraging for the SL-MAC as the residential environments are usually full of uncertainties (e.g. intensive people movements, interference from other devices and etc.), and sometimes could lead to severe channel condition. Note that in Fig. 3.16, the average system goodput of the six-band mode SL-MAC decreases most sharply as the PER increases. This observation can be explained as follows: first of all, the six-band mode SL-MAC has the best goodput performance when the PER is low. Secondly, if the PER increases to 100%, the goodputs from all there MAC design will be approaching 0. Therefore, as the PER increases from zero to a very high level, the goodput of six-band mode SL-MAC has to decrease faster than others to

obtain similar results in the 100% PER case. It is a hypothetical example since PER will be as high as 80% for most networks. The figure explains that SL-MAC can compensate the adverse effect of poor PER with the increase of the number of multiband, resulting in goodputs at decent levels even when the PER is fairly high.

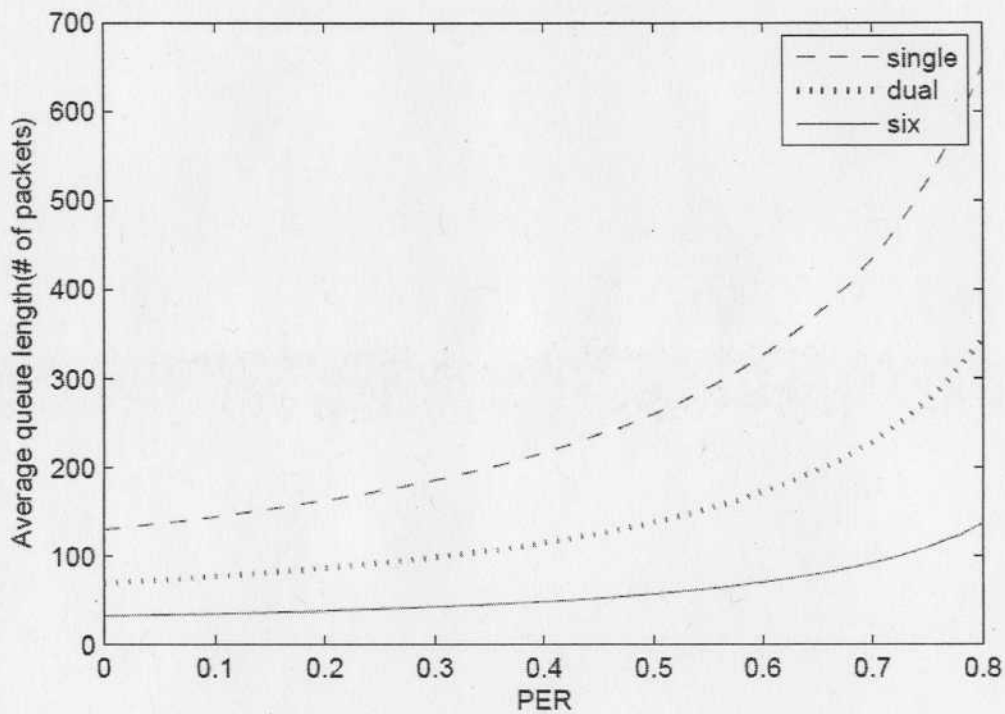


Fig. 3.14 Average Queue Length vs. PER

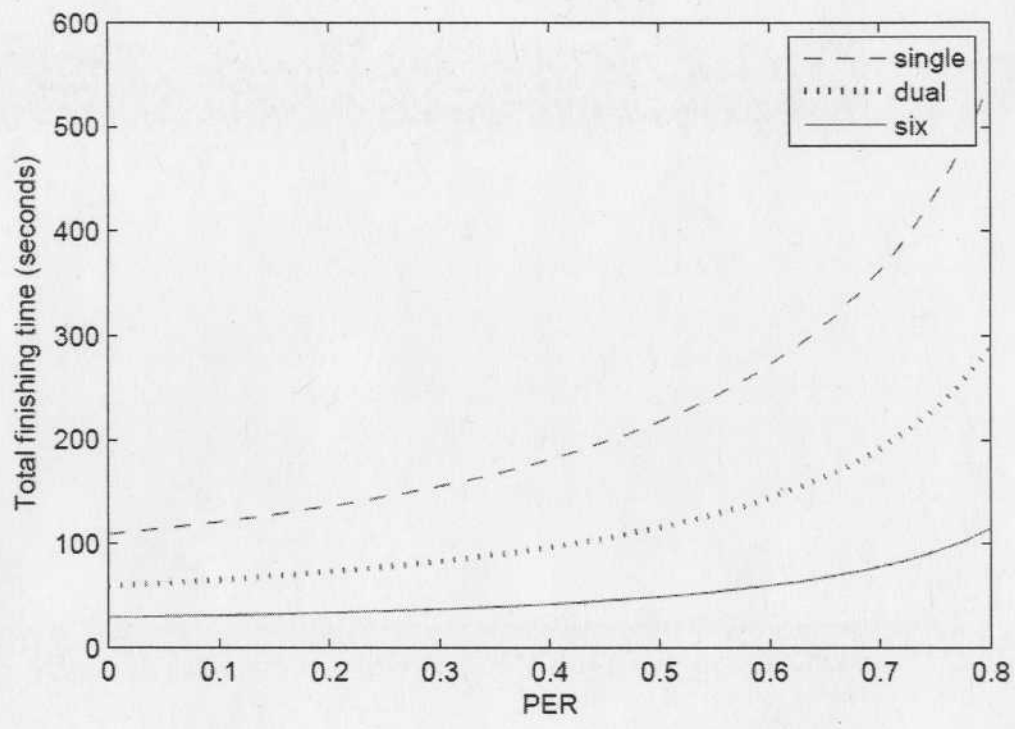


Fig. 3.15 Total Finishing Time vs. PER

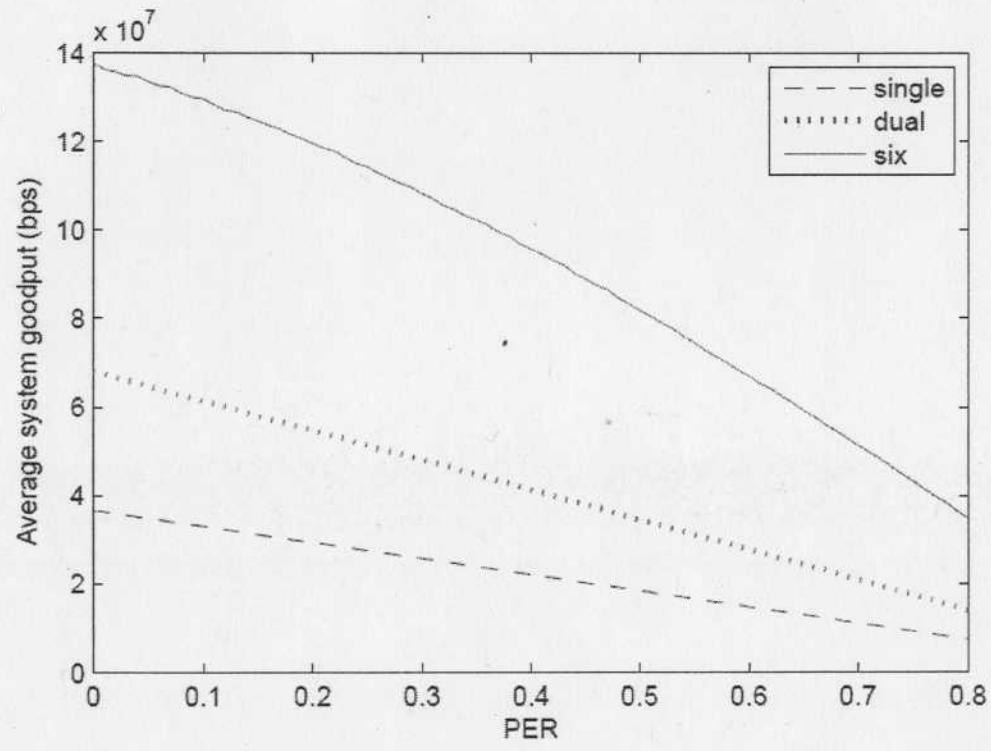


Fig. 3.16 Average System Goodput vs. PER

3.3.4 Effect of Changing Channel Capacity

This test case shows the effect of changing the channel capacity from 10 Mbps to 480 Mbps. In order to obtain meaningful results, we fix the System Packet Arrival Rate λ_s to 4000 and bounded the PER to be less than 1%. We can see from Figs. 3.16 - 3.19 that the SL-MAC has substantial advantages when the channel resource is relatively scarce. For example, when the channel capacity is about 53 Mbps, the six-band mode SL-MAC performs almost 2 times better than the single channel MAC in terms of average packet delay and average queue length. Similar observations are found in the Fig. 3.17 as well. However, when the channel capacity increases to very high level (e.g. 480 Mbps), all three MAC schemes perform closely, especially in terms of total finishing time. The same observation is made in Fig. 3.20, where the average system goodputs from all three cases become smooth and close to each other. The reason is that the extra channel capacity compensates the disadvantages of the single channel MAC. Nonetheless, such high level of channel capacity is only available at short distances, as shown in the previous chapter.

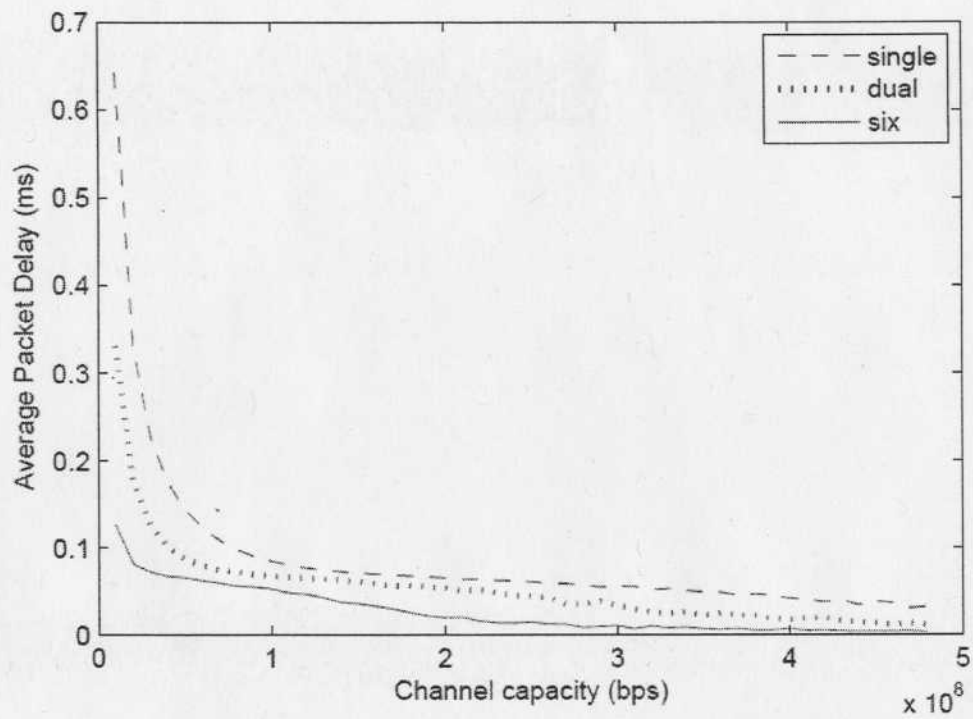


Fig. 3.17 Average Packet Delay vs. Channel Capacity

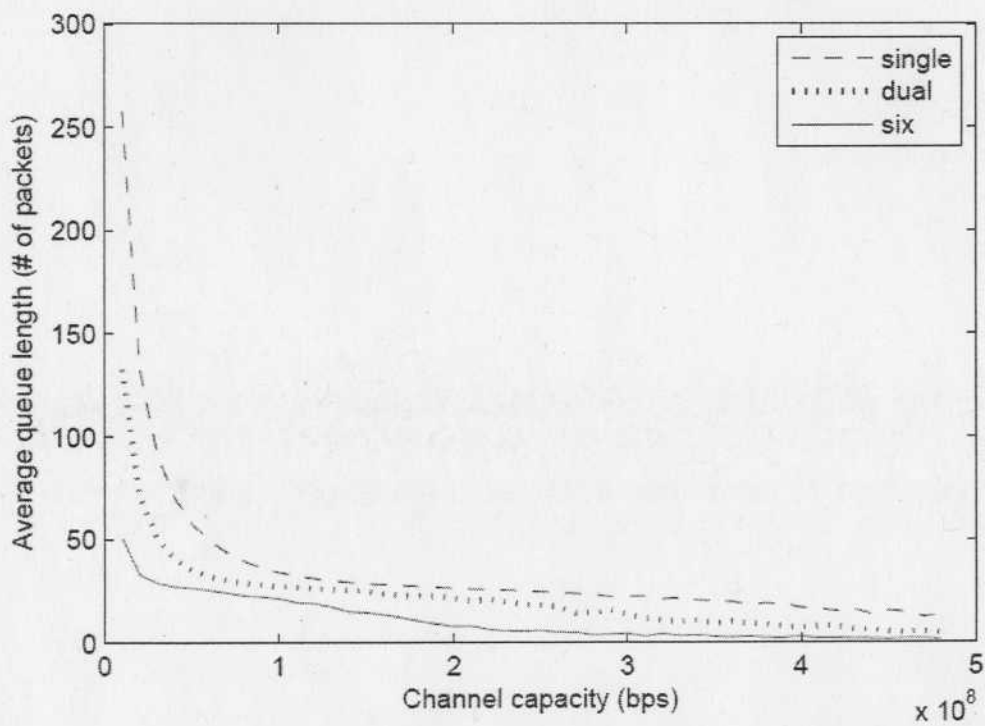


Fig. 3.18 Average Queue Length vs. Channel Capacity

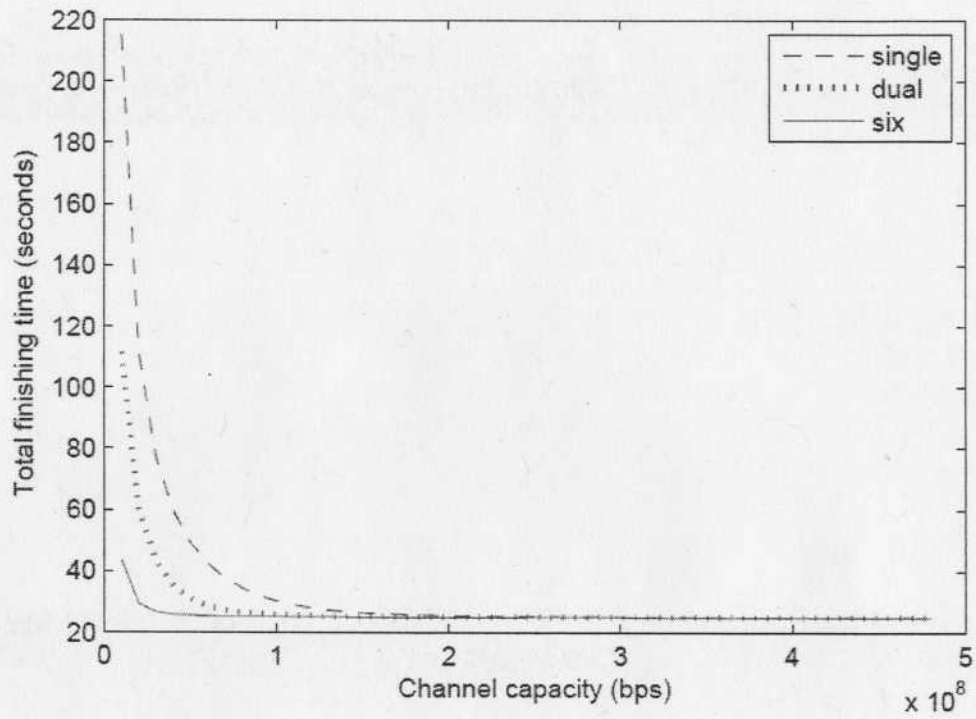


Fig. 3.19 Total Finishing Time vs. Channel Capacity

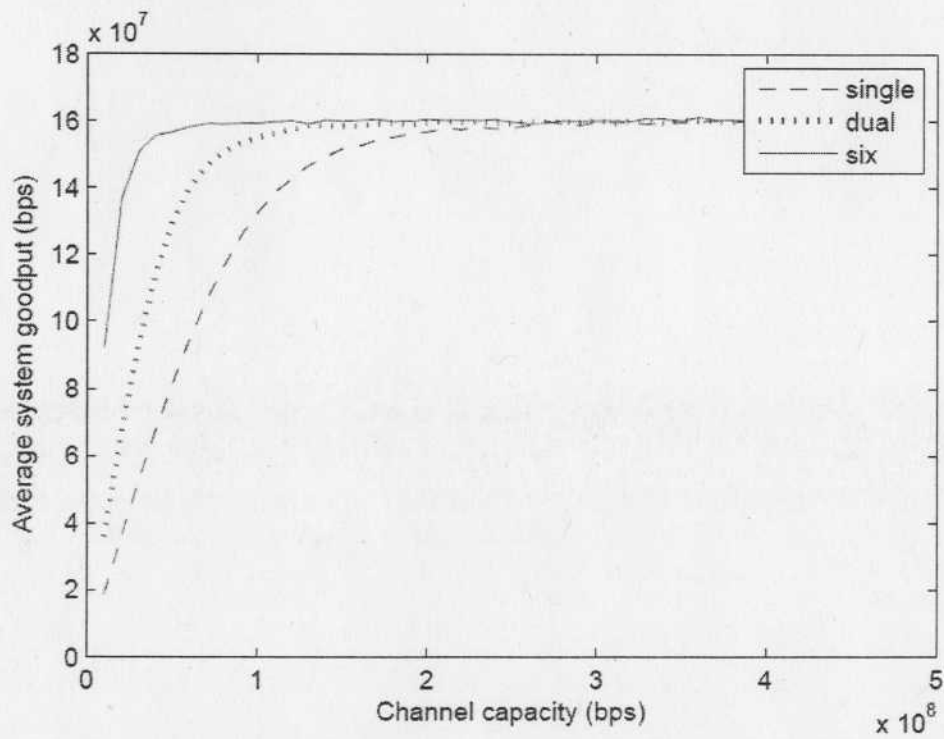


Fig. 3.20 Average System Goodput vs. Channel capacity

3.3.5 Simulation Results Discussion

The simulation results above have proven that the SL-MAC outperforms the dual-band MAC and the traditional single channel MAC in terms of average packet delay, average queue length, total finishing time and average system goodput in delivering a large number of data packets. Keep in mind that the SL-MAC simulator presented in this work only utilizes less than half of the FCC regulated UWB bandwidth, and some unique features such as the "Token Access Control" mechanism are not implemented in the current version of the simulation program. Nevertheless, the SL-MAC has already shown significant advantages over the legacy MAC schemes in handling residential UWB wireless network, especially when the network conditions are critical, such as high network traffic volume (large System Packet Arrival Rate), poor communication channel (high packet error rate), or limited channel capacity.

Figs. 3.21-3.23 show the capacity usage ratio $C\%$ of the three different MAC settings, which is defined as the percentage of achieved goodput (in bps) in total available channel capacity (in bps). This quantity is an indicator of the potential of single, dual and six band MAC settings because full channel capacity is not completely utilized.

Considering that the computer simulation presented in this chapter is a simplified scenario of SL-MAC, we are confident that if the full UWB bandwidth and all features of SL-MAC are enabled and implemented, the performance of the SL-MAC can be improved furthermore in all aspects. Also, different types of network traffics will be handled and distributed more efficiently with the TAC mechanism, which is extremely important for residential high speed wireless networks.

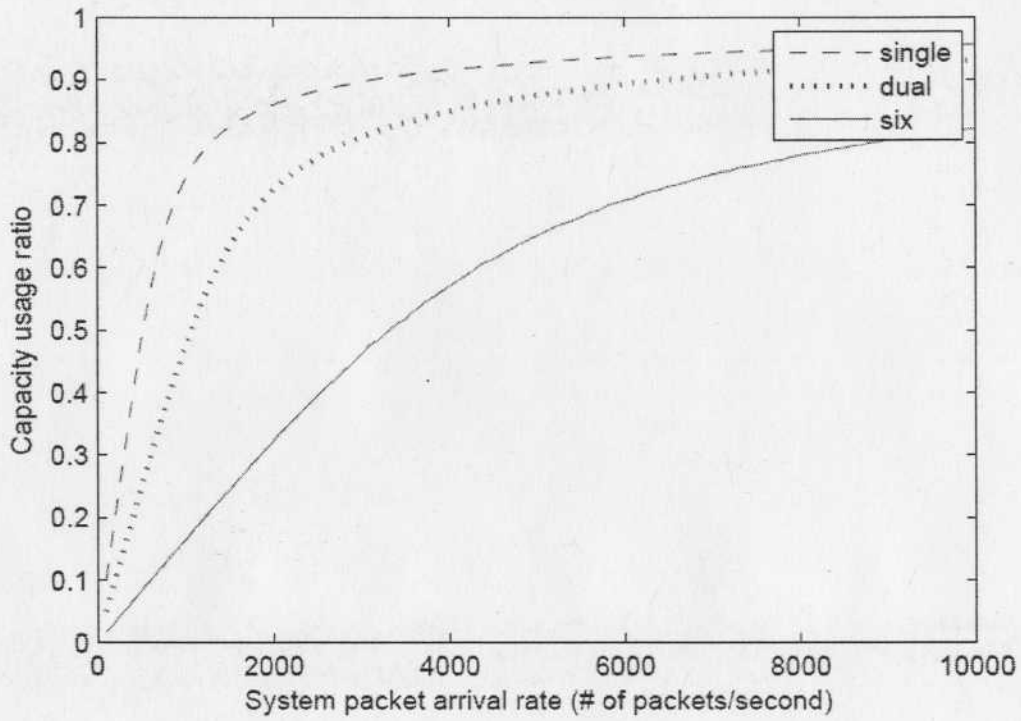


Fig. 3.21 Capacity Usage Ratio v.s. System Packet Arrival Rate λ_s

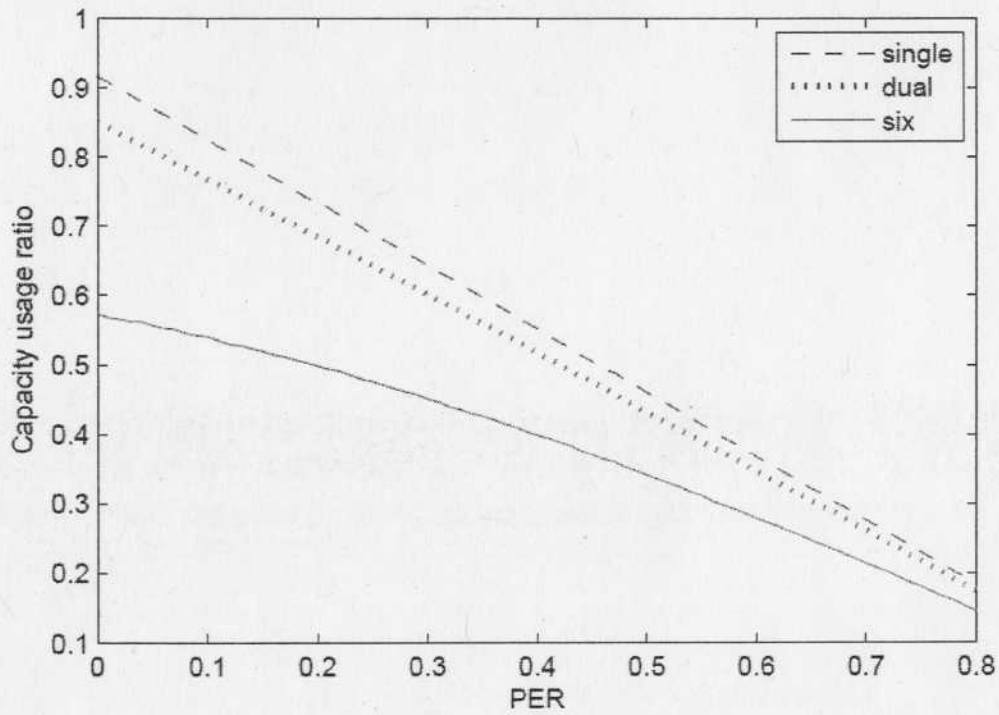


Fig. 3.22 Capacity Usage Ratio v.s. PER

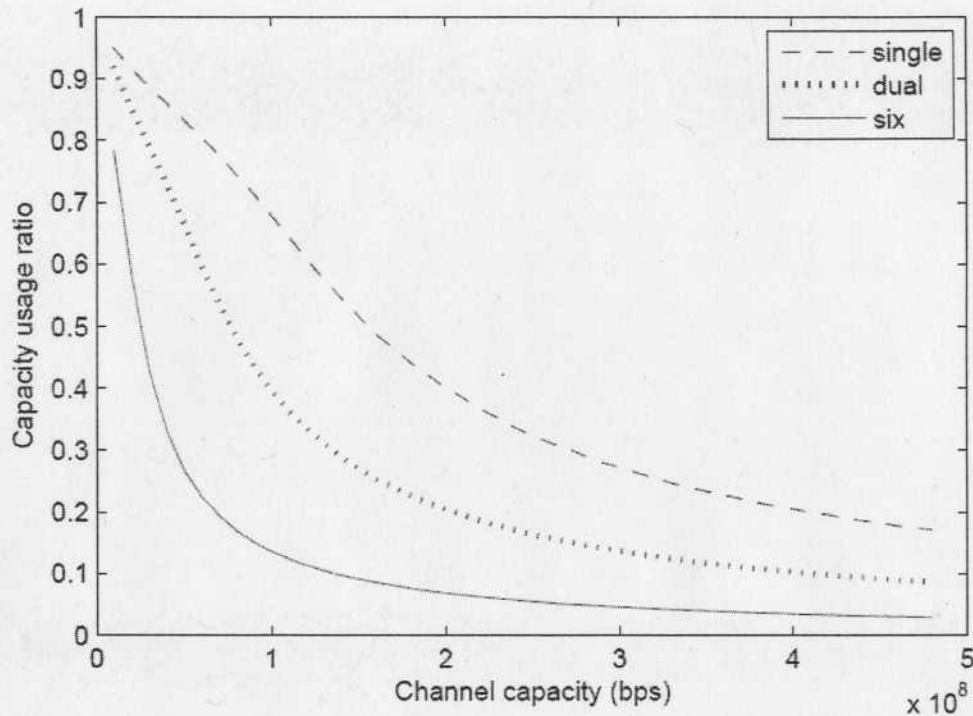


Fig. 3.23 Capacity Usage Ratio v.s. Channel Capacity

3.4 Summary

In this chapter, we have overviewed published research work on MAC designs for high rate UWB applications and networks. Based on these literatures and studying the characteristics of the UWB technology, we have proposed a novel MAC protocol model called “Self-Listening MAC” for high rate residential UWB wireless network, which utilizes the unique features of both UWB technology and the intended network environment. We first explain the motivation of designing the SL-MAC and then describe the design features in details. Also, a brief theoretical analysis on the performance of the proposed protocol model was presented, with the comparison to traditional single channel MAC designs. From the analysis, the SL-MAC showed its advantages over the traditional methods in the intended network environment. In addition,

a discrete-event computer simulation program has been built to emulate the basic functionalities of the proposed SL-MAC model. By comparing the simulation results with those of the emulated dual-band MAC and the single channel MAC model, we have showed that the SL-MAC outperformed the traditional model in all designated aspects, especially under severe network conditions. Finally, the follow-up discussion indicates that the simulation results of the SL-MAC would be even better if the full capacities and features are implemented.

By combining the proposed model with the encouraging UWB measurement results from Chapter 2, we are confident about the SL-MAC and its design concept. Nonetheless, more design details and improvements should be integrated into the proposed model to make the SL-MAC a comprehensive MAC protocol for residential UWB wireless network in our future work.

Chapter 4 Conclusions and Future Work

4.1 Conclusions

The UWB wireless communication technology has great potentials in short range high data rate applications, all thanks to its unique characteristics such as the abundant bandwidth resource, low power consumption and etc. Extensive research and product developments have proved UWB's physical layer performance. However, solid evidences on its performance from a high level design aspect are still lacking.

With the increasing demands from industry and the public, evaluations and testing on high rate UWB systems are becoming urgent tasks. In this thesis, two major UWB technologies are reviewed, and the main focus is on the MB-OFDM high rate campaign known as WiMedia. The study of the WiMedia standard provides useful information for evaluating the corresponding UWB products from both physical layer point of view and packet throughput level point of view. Besides the path loss model analysis and the comprehensive throughput measurement test on the WiMedia UWB system, a brief evaluation on actual commercial end user product is also presented to provide more convincing evidences for this promising technology. Moreover, a multi-channel protocol design is proposed for high rate UWB residential wireless networks. From the theoretical analysis and computer simulation results, the proposed model outperforms the traditional single channel MAC significantly and its design philosophy makes it practical to be implemented.

In Chapter 2, comprehensive throughput measurements on WiMedia UWB systems and path loss and link budget analysis based on the measured data are performed in office and residential environments. The results show the impressive performance of the WiMedia UWB systems in high rate residential wireless networks. The ability of achieving high

data rate while still maintaining satisfactory QoS level in decent transmission range (up to 30 meters) has proven its position as one of the best candidates for the ultra high speed wireless network application. Moreover, we showed that future block-ACK mechanism implementation can push the deliverable data rate to more than 300 Mbps with very low PER. Finally, the HD video streaming test and in-house gateway emulation test give us some impressive results, which prove that the WiMedia UWB product does deliver what it is promised and can be very successful in its intended applications.

Chapter 3 explains the need of an effective MAC protocol design for the particular scenario of high rate UWB residential network communications. By analyzing the characteristics of UWB technology and the intended network scenario, we propose a novel MAC design called "SL-MAC". Detailed descriptions and algorithm of the SL-MAC are presented together with some theoretical analysis. Moreover, a discrete event computer simulation program is created for further investigations on its performance. Although the simulator has not implemented the full features of SL-MAC, its test results show that the SL-MAC dominates the traditional single channel MAC in terms of average packet delay, average queue length, the time spent on the same amount of traffic loads and overall average goodput. In some extreme cases, the SL-MAC can outperform the traditional one by almost 4 times when the network is facing very high traffic loads or high packet error rate. From what has been discussed in this chapter, we have reasons to believe that a fully implemented SL-MAC will be suitable for high rate UWB residential wireless applications.

4.2 Future Work

Our current research work has led us to some issues that need to be further explored, which are listed as follows.

1. Despite the throughput measurement work on WiMedia systems provides

encouraging results, more measurement results from different residential scenarios can definitely improve the accuracy of our path loss model and the link budget analysis. Moreover, useful data can be collected from the measurement test as input parameters of the computer simulation program for our proposed MAC design and make the results more convincing.

2. The measurement test can be extended to other indoor environments, such as apartment buildings, commercial buildings and so on. Also, measurement tests with the presence of intensive people activities will help understand the performance of UWB devices under realistic network environment.
3. For the SL-MAC, more design details still needs be properly defined and added according to the standard requirements for a MAC protocol, such as frame structure, broadcast methods and etc. Also, more investigations and analysis on the current design are worthy for performance improvement.
4. For the SL-MAC simulation program, first of all, all current features of the SL-MAC should be implemented in the simulator for comprehensive evaluations of the proposed protocol design. Secondly, the computer simulation is built based on some key assumptions. On one hand, these assumptions greatly simplify the program implementations. However, on the other hand, their existences affect the accuracy of the simulation results to some extent. Therefore, detailed specifications on the simulator's parameters are needed for more realistic outcomes. Last but not the least, more simulation scenarios and test criteria can offer a more precisely evaluation on the proposed SL-MAC design.
5. The SL-MAC design can be extended to other indoor environments such as office buildings, industrial warehouse, etc.

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