Finding the Optimal MAC Protocol for Low-Power High Data Rate Ultra-Wideband (UWB) Networks

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Abstract - **In this paper, we explore the possibility of designing an optimal medium access control (MAC) layer for high data rate ultra-wideband (UWB) transmission systems that transmit very little power especially in mobile devices. MAC in UWB wireless networks is necessary to coordinate channel access among competing devices. The unique UWB characteristics offer great challenges and opportunities in effective UWB MAC design. We first study the background of UWB and available MAC protocols that have been used in UWB. Secondly, we analyse the power consumption for UWB in mobile devices based on competing short-range wireless technologies such as Bluetooth and Wi-Fi as references. Finally we present the key issue that will be considered in the design of an optimal MAC layer that will fully exploit UWB potential as a low-power, high data rate, short range wireless transmission system.**

Index Terms – **Ultra-wideband (UWB), medium access control (MAC), low-power consumption**

I. INTRODUCTION

Ultra-wideband (UWB) has emerged as a technology that offers great promise to satisfy the growing demand for low-cost, high data rate, short range wireless transmission system such as digital wireless indoor and home networks. The growing numbers of media-intensive devices such as mobile phones, PCs, digital cameras, high-definition TVs and gaming systems have increased the need for a high-bandwidth wireless solution for easy connection and media exchange. UWB presents a unique opportunity to become a widely adopted radio solution for wireless personal networking technology because of the enormous bandwidth available, the potential for high data rates, and the prospective of small size and low power requirements along with low implementation cost.

II. OVERVIEW OF UWB

UWB is defined as any transmission that occupies a bandwidth of more than 20% of its centre frequency, or more than 500 MHZ [1]. In 2002, the Federal Communications Commission (FCC) has mandated that UWB radio transmission can legally operate in the range 3.1 to 10.6 GHz at a transmitter power of -41.3 dBM/MHz. The use of UWB technology under the FCC guidelines can provide huge capacity over short ranges. Currently, UWB is able to support various data rates, ranging from 110 to 480 Mbps, over distances up to 10 meters [1].

The basic idea of UWB can be traced back to the first wireless communication system in the late 1890s [2]. However the main concept of UWB was only developed in early 1960s through research in time-domain electromagnetic, where impulse measurement techniques were used to characterize the transient behaviour of a certain class of microwave networks [1]. Similar to spread spectrum or code division multiple-access (CDMA), UWB technology was firstly used in a military environment and just recently introduced in the commercial market. Today, UWB has been considered as one of the most promising candidates for wireless communications within a short range and has been creating a lot of interests from research community worldwide.

UWB system implementation at the physical layer can be achieved either by using a pulse-based approach [3], [4], [5] or a multiband-orthogonal frequency-division multiplexing (MB-OFDM)-based approach [6], [7]. Pulses of an extremely short duration in the order of nanosecond are used for data transmission in a pulse-based UWB system while OFDM and hybrid frequency hopping are applied in the MB-OFDM UWB system. Each of these two UWB technologies has its advantages and disadvantages for communications in multipath propagation environment.

Pulse-based UWB benefits from a simple transmitter and rich resolvable multipath components where the receiver can take advantage of multipath diversity effectively. However, it needs a long channel acquisition time and also requires high speed analog-to-digital converters (ADCs) for signal processing. MB-OFDM offers robustness to narrowband

ISBN: 978-1-902560-19-9 © 2008 PGNet

interference, spectral flexibility and efficiency but in turn requires a slightly complex transmitter.

UWB technology is attractive for high-rate (over 100Mb/s) short-range (less than 10 m) or low-rate (less than a few Mb/s) moderate-range (100 to 300 m) because of the large bandwidth and low transmission power density [2], [8]. Among potential UWB applications are multimedia services such as voice and video conversations, video streaming and high-rate data transfer. In addition to these conventional applications, UWB can also be utilized in industrial automation and control, medical monitoring and vehicular radar systems [9].

III. OVERVIEW OF UWB MAC PROTOCOL

In UWB wireless networks, the medium is shared among multiple mobile nodes. Interference or collision can occur if access to the medium is not controlled. The function of medium access control (MAC) is to coordinate the access among the competing nodes in a systematic and efficient approach. UWB MAC research are generally divided into two major directions, IEEE 802.15.3 [10] and an alternative MAC specification defined by multiband OFDM alliance (MBOA) [11]. However, by taking into account the unique UWB characteristics, such as large bandwidth, low power requirements, pulse transmission, precise positioning capability and long acquisition time, there are still a lot of open issues to improve and enhance UWB MAC especially in four major areas; multiple access, overhead reduction, resource allocation and quality of service (QoS) provisioning [9].

Multiple access techniques for UWB fall into two main categories: centralized and distributed MAC protocols. Centralized MAC protocols rely on the aid of a central controller such as a base station or access point. The central controller collects information about the state of the network and determines the resource sharing manner of all mobile nodes by polling, reservation or demand assignment, it then informs the nodes of the scheduling decisions. In distributed MAC protocols, nodes are responsible for managing access to the medium on their own.

Centralize MAC protocols offer high throughput and quality of service (QoS) guarantees for smaller networks since information is collected about the state of the network. Collisions can be avoided because the central controller guarantees exclusive access to the channel. These protocols are often adopted for WPANs for multimedia devices and low-latency computer peripherals where such networks are usually limited to less than ten devices to reduce overhead and maintain serviceability [12]. The IEEE 802.15.3a standard for WPANs with UWB radios is a centralized protocol that utilizes both time and code division multiple access [13]. Figure 1 shows an 802.15.3a network which consists of several piconets. Each piconet consists of one or more logically associated devices sharing the same channel. The MAC protocol is time-division multiple access within a piconet while collocated piconets operate on different code channels to avoid interfering with one another. Centralised coordination is provided by the piconet coordinator (PNC) which will assigns code channels, enforces QoS requirements, control power saving modes and manages access to the piconet. The role of PNC will be taken by a device within the piconet where any transfer of data is not required to pass through PNC. Interpiconet communications however occur through a gateway node which is a normal node in the parent piconet but a PNC in the child piconet. The child piconet operates on the same channel as the parent and is synchronized to avoid interference with the parent piconet. All communications within the child piconet occur during time slot assigned by the parent piconet.

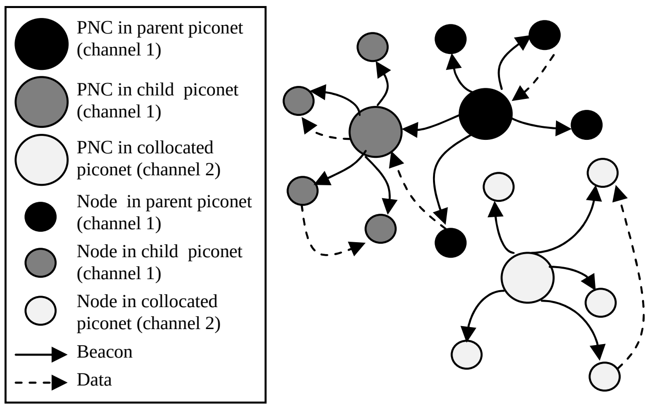

Fig. 1. Piconets defined in IEEE 802.15.3a

In a distributed MAC protocols, each node makes an independent decision to transmit without any central guidance, thus eliminating central point of failure and central synchronisation. Security is improved since the network cannot be attacked at specific point. Distributed protocols also can be easily scaled to arbitrarily large networks especially huge robust networks since these protocols cannot provide strict QoS guarantees. Random access protocols such as ALOHA and its slotted version [14] constitute the main part of distributed MAC protocols. Carrier-sense multiple access (CSMA) based protocols [15] improve on the problem of collision in ALOHA through the mechanism for a node to sense the channel before the transmission to make sure the channel is available and defers it if the channel is busy. To contend with the hidden terminal and exposed terminal problems, handshaking based on request-to-send / clear-to-send (RTS/CTS) is also adopted. Collision resolution can be achieved by using back-off and/or persistence mechanisms [15], [16].

The MAC protocols provide the upper layer with a bit pipe in the traditional layered architecture of data networks and are independent of the lower physical layer. The existing solutions typically designed for wireless networks can be directly incorporated into design of a UWB MAC if the same approach is applied to MAC in UWB [17]. Recent research however has suggested that UWB characteristics should be considered and taken into account in MAC to achieve superior and efficient system implementations. UWB systems exhibit distinctive physical layer characteristics such as the low-power requirement and precise positioning capability which are different from conventional narrowband or wideband networks [9], thus needing a novel MAC protocol to fully exploit these unique characteristics.

IV. COMPARATIVE STUDY

The purpose of this research is to look into the possibilities of designing an optimal MAC layer for low-power high data rate UWB networks. Therefore initial comparisons need to be made between UWB and established wireless technologies such as Bluetooth and wireless fidelity (Wi-Fi) especially in terms of power consumption. These comparisons should assist us in understanding the requirements that needs to be met in order to design a novel MAC layer for UWB.

Bluetooth, defined in the IEEE 802.15.1 standard is based on a wireless radio system designed for short-range communications. It is intended to replace cables for computer peripherals and mobile devices where the applications are deployed over a wireless personal area network (WPAN). Wi-Fi, on the other hand, serves the needs to wirelessly connect computers and mobile devices to the network and the Internet where the range of these applications is deployed over a wireless local area network (WLAN). Wi-Fi is defined in the IEEE 802.11a/b/g standards. Table I summarizes the main differences among Bluetooth, Wi-Fi and UWB [18].

Bluetooth is intended for portable devices and portable products with limited battery power that needed short-range low data rate communications. Consequently, it offers very low power consumption and measurably will not affect battery life. Wi-Fi on the other hand is designed for a high data rate long range communications and supports devices with a substantial power supply. On the other hand, UWB will offer the highest data rate when compared to Bluetooth and Wi-Fi, but the connection range is in between the two technologies. In terms of protocol complexity, a comparison is made based on the numbers of primitives and host controller interface events for Bluetooth and MAC / PHY layers primitives for Wi-Fi and UWB in [18]. Table II summarised the number of primitives and events for each protocol. It can be deduced that Wi-Fi, based on IEEE 802.11a/b/g is the simplest one while Bluetooth based on IEEE 802.15.1 is the most complicated protocol.

TABLE I
COMPARISON OF BLUETOOTH, WI-FI AND UWB PROTOCOLS

Standard	**Bluetooth**	**Wi-Fi**	**UWB**
IEEE spec.	802.15.1	802.11a/b/g	802.15.3a
Frequency band	2.4 GHz	2.4 GHz, 5 GHz	3.1-10.6 GHz
Max. signal rate	1 Mb/s	54 Mb/s	110 Mb/s
Nominal range	10m	100m	10m
Nominal Tx power	0-10 dBm	15-20 dBm	-41.3 dBm/MHz
Number of RF channels	79	14 (2.4 GHz)	1-15
Channel bandwidth	1 MHz	22 MHz	500 MHz – 7.5 GHz
Modulation Type	GFSK	BPSK, QPSK, COFDM, CCK, M-QAM	BPSK, QPSK
Spreading	FHSS	DSS, CCK, OFDM	DS-UWB, MB-OFDM
Coexistence mechanism	Adaptive freq. hopping	Dynamic freq. Selection	Adaptive freq. hopping
Basic cell	Piconet	BSS	Piconet
Extension of basic cell	Scatternet	ESS	Peer-to-peer
Maximum number of cell nodes	8	2007	8

TABLE II
COMPARISON OF PROTOCOL COMPLEXITY

Standard	**Bluetooth**	**Wi-Fi**	**UWB**	**Standard**
IEEE Spec.	802.15.1	802.11a/b/g	802.15.3	IEEE Spec.
Primitives	151	32	77	MAC primitives
HCI events	37	43	29	PHY primitives

A practical comparison has also been made in [18] between Bluetooth, Wi-Fi and UWB in terms of power consumption by using chipsets that are publicly available. BlueCore2 [19] from Cambridge Silicon Radio (CSR), CX53111 [20] from Conexant and XS110 [21] from Freescale are used to represent Bluetooth, Wi-Fi and UWB respectively. Table III summarize the current consumptions of the transmit (TX) and receive (RX) conditions for each technology while Figure 2 shows the comparison of the normalised energy consumption.

TABLE III
POWER CONSUMPTION OF EACH CHIPSET FOR EACH PROTOCOL

Standard	Bluetooth	Wi-Fi	UWB
Chipset	BlueCore2	CX53111	XS110
VDD (volt)	1.8	3.3	3.3
TX (mW)	102.6	722.7	750.1
RX (mW)	84.6	709.5	750.1
Bit rate (Mb/s)	0.72	54	114

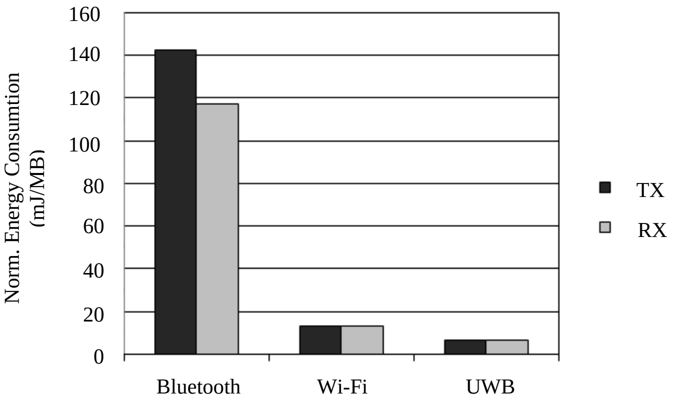

Fig. 2. Normalized energy consumption for each protocol.

Obviously, Bluetooth protocols consume less power compared with Wi-Fi and UWB. However, a comparison of normalised energy consumption based on bit rate shows that UWB offers the best efficiency in energy consumption although having a slightly complex protocol (based on 802.15.3b) compared to Wi-Fi. Based on the comparison of protocol complexity and power consumption, there is a possibility that an optimal MAC for UWB with reduced complexity can further decrease the power consumption of UWB devices while achieving higher data rate.

V. MAC DESIGN CHALLENGES AND OPPORTUNITIES

UWB MAC design presents a challenging task due to several reasons. UWB networks have a very strict transmission power constraint to allow coexistence with other narrowband networks. In non-cooperative UWB networks, very low transmission power is also very important because these networks usually operate simultaneously at a close range. The low-power requirement provides opportunities for supporting simultaneous transmission as long as the communication pairs are separated far enough in space, this also highlights the significance of power control.

UWB networks can be designed to support very high data rate transmission of more than 100 Mb/s in an indoor environment. Any overhead time introduced by the MAC in these high data rates may cost a substantial portion of system resources significantly degrading the system's throughput and efficiency. For this reason, when designing MAC for UWB, it is imperative to make sure that the overhead must be kept at a very low level.

Another main characteristic of UWB that needs to be considered is the long acquisition time between synchronising the receiver's clock with the transmitter's clock. This is carried out in order to achieve bit synchronisation. Long acquisition time is critical in UWB [22], [23] because the requirement of high precise synchronisation. In UWB system, the sender may send a preamble at the start of each transmission where the duration of the preamble varies from tens of microseconds to tens of milliseconds [24]. A large amount of time will be used obviously in every UWB transmission to perform acquisition. This will definitely degrade the efficiency and performance of UWB transmissions, particularly involving high data rate UWB system.

Ad-hoc networking is another main application of UWB where this type of networking is characterised by control functions that are not centralised and exist in non-fixed infrastructure. Each node in the system has to rely on local information because a fixed central controller does not exist in ad-hoc networks. Therefore, some control mechanism such as power allocation will become more complex and this characteristic should be considered in designing UWB MAC.

Apart from that, physical layer characteristics of UWB such as high bandwidth and low transmission power provide new challenges in designing an optimal MAC for UWB. Resource allocation will be more flexible because of UWB's unique pulse transmission and routing and power control can be simplified to exploit its extensive capability in positioning. By taking into account the advantages of all the unique characteristics of UWB and by considering its deficiencies, an optimal MAC can be designed to provide an efficient high-data rates for low-power UWB networks.

VI. CONCLUSION

In this paper, we have presented an overview of UWB and explored the possibility of designing an optimal medium access control (MAC) layer for high data rate UWB transmission systems that transmit very little power especially in mobile devices. MAC plays a very significant role in UWB networks to ensure efficient communications and it is essential to coordinate channel access among devices. The distinctive UWB characteristics present great challenges and opportunities in efficient UWB MAC design. Based on this preliminary study of UWB, we will try to answer the question whether it is possible to design an optimal MAC protocol for UWB that will provide very high data rates at very low power consumption. We will aim to design and develop a prototype MAC protocol and test the protocol in a simulated environment using the QualNet network simulator.

ACKNOWLEDGEMENT

The authors would like to thanks Government of Malaysia & Universiti Teknikal Malaysia Melaka (UTeM) for funding the research through PhD scholarship.

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