Performance of Slotted-Aloha over TH-UWB

Hwee-Xian Tan*, Ranjeet K. Patro†, Mun-Choon Chan*, Peng-Yong Kong‡, Chen-Khong Tham†
*School of Computing, National University of Singapore (NUS)
†Dept of Electrical and Computer Engineering, NUS
‡Institute for Infocomm Research (I^{2}R), Singapore
hweexian@comp.nus.edu.sg, {eleprk, dcscmc, eletck}@nus.edu.sg, kongpy@i2r.a-star.edu.sg

***Abstract*—Aloha has been proposed as the *de facto* MAC protocol in the IEEE 802.15.4a UWB-PHY standard for Low Rate WPANs (LR-WPANs). Unlike conventional wireless narrowband systems, the UWB-PHY provides Time-Hopping (TH) to enable multiple users to transmit simultaneously, thereby potentially increasing the overall system throughput. The intrinsic properties of the impulse-based UWB renders most existing narrowband MAC protocols which make use of carrier sensing unsuitable for use in UWB systems. In this paper, we study the throughput performance of *slotted*-Aloha, an enhanced version of the Aloha MAC protocol, over the TH-UWB physical layer, using both theoretical analysis and simulations. Our results show that slotted-Aloha over TH-UWB is able to provide good throughput performance when there exists an algorithm to optimally assign TH codes to the multiple users in the network.**

I. Introduction

Ultra Wide Band (UWB) is an emerging wireless short-range technology which has the potential to satisfy the requirements of low data rate and low power applications. It is currently being adopted as an alternative PHY (physical) layer in the IEEE 802.15.4a Task Group (TG4a). The narrow UWB pulse supports precise ranging and provides accurate location information within centimeter resolution even in the presence of strong multipath interference. This unique feature of UWB makes it best fit for positioning and location tracking applications such as home health care systems and personalized customer service systems in malls. The noise-like behavior of the UWB signal greatly reduces the probability of detection and provides a reasonably secure communication system. This characteristic is essential for security alarm systems and wireless body area networks which are envisaged for medical supervision. For the success of UWB technology, it is necessary to have an efficient and low power MAC protocol which exploits the specific natures of UWB. There exists some pioneer work on UWB-based MAC protocols, such as U.C.A.N. [1] and the now-defunct IEEE 802.15.3a standard [2] for High Rate WPANs; however, these are mainly suited for high data rate applications. Consequently, alternative MAC schemes for low rate IEEE 802.15.4a UWB-based systems, such as DCC-MAC and $(\text{UWB})^2$ have been proposed in the literature.

DCC-MAC [3] dynamically adapts the data rate to interference from concurrent transmissions instead of enforcing exclusion. It proposes a interference mitigation scheme to cancel the interfering energy and tries to fully utilize the specific properties of UWB to achieve low protocol complexity. Di Benedetto et al. propose $(\text{UWB})^2$ [4], another MAC protocol for low data rate UWB networks. $(\text{UWB})^2$ is based on a hybrid scheme combining dedicated data channels associated with transmitter TH codes and a common control channel, which is provided by a common TH code. The usage of the control channel greatly simplifies the receiver structure. $(\text{UWB})^2$ does not assume the presence of synchronization and adopts a pure Aloha approach. However, results of $(\text{UWB})^2$ are obtained over simplified channel conditions, i.e. an AWGN channel.

In the IEEE 802.15.4a standard [5], the Aloha MAC protocol is proposed for use over the Time-Hopping (TH) UWB PHY layer. In this paper, we study the performance of the *slotted*-Aloha protocol over the TH-UWB PHY layer. Slotted Aloha over TH-UWB is much simpler than proposed UWB MAC protocols (DCC-MAC and $(\text{UWB})^2$) which make use of complex encoding mechanisms and control packet signaling; it does not incur any additional signaling overheads and is well-suited for UWB systems. Using theoretical and simulation studies, we show that despite the poor performance of slotted-Aloha in single-channel narrowband systems, it is able to yield reasonable performance results when used over a TH-UWB physical channel.

The rest of this paper is organized as follows: Section II describes the UWB physical layer model. We present the slotted-Aloha over a time-hopping based UWB channel and its theoretical analysis in Section III. Simulation results and analysis are discussed in Section IV. We conclude with directions for future work in Section V.

II. Background

A. IEEE 802.15.4a-UWB PHY Signal

The signal transmitted by a node in IEEE 802.15.4a network with UWB PHY can be expressed as:

$$S(t) = \sum_k S^{(k)}(t) \tag{1}$$

where $S^{(k)}(t)$ is the transmitted waveform during k^{th} symbol interval. The combined Burst Position Modulation (BPM) and Binary Phase Shift Keying (BPSK) is used to modulate the symbols, with each symbol composed of active burst of UWB pulses.

$$S^{(k)}(t) = [1 - 2b_1^{(k)}](\sum_{n=0}^{N_{cpb}-1} [1 - 2C_{n+kN_{cpb}}] \\ p(t - b_0^{(k)}T_{BPM} - N_{TH}^{(k)}T_{burst} - nT_c)) \tag{2}$$

where $b_0^{(k)}$ and $b_1^{(k)} \in \{0,1\}$ are two information bits transmitted during k^{th} symbol interval. $b_0^{(k)}$ is encoded into the burst position and $b_1^{(k)}$ is encoded into the burst polarity. $N_{TH}^{(k)}$ is the burst hopping position for the k^{th} symbol, where N_{cpb} number of UWB pulses are transmitted; *p(t)* is the transmitted pulse shape; and $C_{n+kN_{cpb}} \in 0,1,\ n = 0,1,\ldots,N_{cpb}$ is the scrambling sequence used in the k^{th} symbol interval for spectral smoothing of the transmitted waveform.

The transmitted signal *S(t)* experiences large scale fading and small scale fading as described in [6]. The large scale fading in UWB channel is dependent on frequency and can be characterized by equation 3:

$$PL(d) = PL(d_0) + 10nlog\frac{d}{d_0} + 20log\frac{f}{f_c} + S \tag{3}$$

where *S* is the lognormal random variable with zero mean and standard deviation σ_S; *f* is the bandwidth of interest; f_c is the center frequency of the channel; and *n* is the pathloss exponent. In our work, the values of *n* and σ_S are taken to be 1.79 and 2.22 respectively, which simulates a residential LOS environment. The small-scale fading in UWB channels can be characterized by the Nakagami distribution with pdf:

$$f(r) = \frac{2}{\Gamma(m)}(\frac{m}{\Omega})^m(r)^{2m-1}exp(\frac{-m}{\Omega})r^2 \tag{4}$$

where $m \geq 0.5$ is the Nakagami *m*-factor; $\Gamma(m)$ is the gamma function; and Ω is the mean-square value of the amplitude.

B. Multiple Access Interference

When K users are active in the UWB multiple access system, the combined received signal at the receiver can be expressed as:

$$R(t) = \sum_{i=1}^{K}[A_m S_m(t - \delta_m)] + n(t) \tag{5}$$

where A_m represents the attenuation of the signal from transmitter *m*; δ_m represents the propagation delay of the signal from transmitter *m*; and $n(t)$ is white Gaussian receiver noise.

We obtain throughput results for slotted-Aloha over TH-UWB in both capture and non-capture modes. In the non-capture mode, a collision occurs whenever there is overlap in the transmission periods of any two packets. In the capture mode, a transmission is considered to be successful as long as the SINR value of the signal is greater than the receiver threshold T, even when packet transmission periods overlap:

$$\frac{S_0}{N_0 + I} > T \tag{6}$$

where S_0 is the received power from the intended transmitter; N_0 is the noise power; and I is the interference power.

The value of of I can be calculated as follows:

$$I = \sum_{i=1}^{N_I} S_i \tag{7}$$

where N_I is the number of interferers and S_i is the received power from the i^{th} interfering node.

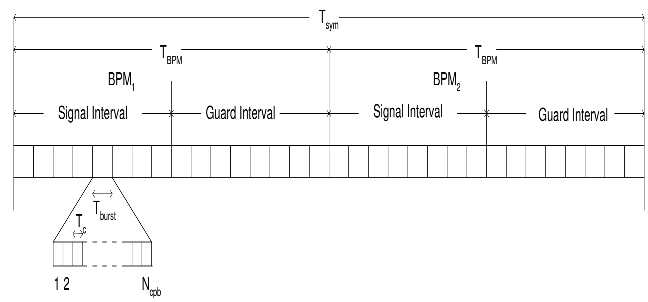

Fig. 1. IEEE 802.15.4a-UWB PHY symbol structure

C. IEEE 802.15.4a-UWB Symbol Structure

The symbol structure of IEEE 802.15.4a with UWB PHY is illustrated in Figure 1. The symbol consists of an integer number of bursts N_{burst}, each burst of duration T_{burst}; hence $T_{sym} = T_{burst} \cdot N_{burst}$. Within each T_{burst} duration, N_{cpb} number of UWB pulses can be transmitted; therefore $T_{burst} = N_{cpb} \cdot T_c$, where T_c is the chip or pulse duration. The symbol interval is divided into two BPM intervals, BPM_1 and BPM_2, each of duration $T_{BPM} = \frac{T_{sym}}{2}$. The burst duration is much shorter than the BPM duration, i.e. $T_{burst} \ll T_{BPM}$. Each BPM interval comprises of the signal interval and the guard interval. The signal interval has $\frac{N_{burst}}{4}$ number of burst positions.

UWB pulses are transmitted in one of the burst positions within the signal interval. The two information bits $b_0^{(k)}$ and $b_1^{(k)}$ as described in Equation 2 and a time hopping code together determine the position of the burst in the symbol interval. $b_0^{(k)}$ determines the location of burst in either BPM_1 or BPM_2, and the time hopping code determines the position of burst in the signal interval of the corresponding BPM interval. $b_1^{(k)}$ is used to modulate the phase of the burst. Each burst position can be varied on a symbol to symbol basis according to a time hopping code.

The time hopping code reduces multiple access interference and improves channel throughput. Before symbol mapping, data is encoded using the Reed Solomon encoder and Systematic Convolutional encoder with an overall FEC rate of 0.44. Assuming that N_{burst} remains constant, the symbol duration and hence data rate are both dependent on the value of N_{cpb}. A data rate of 0.85 Mbps can be achieved with a peak PRF of 499.2 MHz, N_{burst} = 32 and N_{cpb} = 16.

III. Slotted Aloha over TH-UWB

A. The Slotted-Aloha MAC Protocol

The IEEE 802.15.4a standard proposes the Aloha MAC protocol over the UWB PHY. In Aloha, a node that wishes to transmit will transmit immediately without checking if the channel is free. Packet collisions that occur are typically handled via acknowledgments and retransmissions. In slotted-Aloha, discrete time-slots are used to limit the time when a node can commence its data transmission. A node may transmit its data only during the beginning of a time slot;if a packet is generated at any other times, then the node has to defer its transmission until the start of the *next* time slot. Collisions in the slotted-Aloha system can also be handled through mechanisms involving retransmissions.

It is well-known that the theoretical maximum throughputs of Aloha and slotted-Aloha MAC protocols in single channel narrowband systems with Poisson packet arrivals are approximately 18% and 36% respectively [7]. Therefore, it is evident that slotted-Aloha over TH-UWB will have better performance than pure Aloha over TH-UWB. In addition, time hopping (TH) allows concurrent transmissions from different users using varying TH codes, within the same slot. As a result, the throughput of slotted-Aloha with time hopping is expected to be greater than that for slotted-Aloha. In this paper, we study the effect of varying the time hopping code on a packet by packet basis and obtain the normalized throughput of the slotted-Aloha MAC protocol over UWB PHY.

B. Analysis

In this section, we provide a analytical model for the performance of slotted-Aloha with TH code in a UWB system, where the TH codes vary on a packet by packet basis. We assume that there are K transmitting nodes and the channel time is divided into slots of size of one packet duration. We also assume the number of hopping position is N_{TH} and each node selects its hopping position randomly. Assuming that the packets for all nodes arrive for transmission according to a Poisson arrival rate with mean τ packets per slot, the probability that m nodes attempt to transmit at the same time slot, P_m, is simply:

$$P_m = \frac{\tau^m e^{-\tau}}{m!} \tag{8}$$

In slotted-Aloha, a packet collision occurs when two or more nodes transmit packets in the same slot. The throughput is often approximated as:

$$\tau * P_0 = \tau e^{-\tau} \tag{9}$$

With slotted-Aloha and TH, two packets will collide in a slot only if they are transmitted using the same TH code (or transmitted in the same time hopping position). As a result, in a single slot, some nodes can successfully transmit a packet while others cannot. This is in contrast to the slotted-Aloha case where the result is either one or nothing. Another important difference in the TH case is that the per node throughput available is $\frac{1}{N_{TH}}$ of that available in slotted-Aloha (without TH).

We assume that there are $j \leq K$ packets to be transmitted in a slot. Let $P(i, j, N_{TH})$ be the probability that there are i successful packet transmissions, given j packets to be sent over N_{TH} possible time hopping positions. Note that $i \leq min\{K, N_{TH}\}$. The average number of packets that can be successfully transmitted for a given j is:

$$E_j = \sum_i i * P(i, j, N_{TH}) \tag{10}$$

The throughput of slotted-Aloha with TH can be computed as:

$$\frac{1}{N_{TH}} \sum_j P_j E_j \tag{11}$$

Note that the values of $P(i, j, N_{TH})$ depend on the choice of the time hopping codes. In the worst case, the same code is always chosen and the normalized throughput achieved is only $\frac{1}{N_{TH}} e^{-1}$. For $K = N_{TH}$, the normalized throughput achieved can be 1.0 if each node is statically assigned a distinct time hopping position. For TH codes that are randomly chosen, we obtained the normalized throughput achieved through simulation in the next section.

IV. Simulation Results and Analysis

The Qualnet simulator [8] is used to study the performance of slotted-Aloha over a time-hopping UWB physical layer. We follow the layered approach of the Qualnet simulator and develop the UWB propagation medium, time hopping in UWB physical layer and slotted-Aloha MAC protocol for TH-UWB. The three components of the UWB propagation medium include: (i) pathloss model; (ii) fading model; and (iii) shadowing model, which are developed with the parameters as mentioned in II-A. We simulate the residential LOS channel with n = 1.79 and σ_S = 2.22. The Nakagami fading model is used, and approximated as the superimposition of the Rayleigh and Ricean distributions. The value of the Nakagami parameter m is varied between 1.5 to 10 for LOS channel conditions. Generally, BER curves are obtained through Matlab simulations or experiments. We have been provided with BER vs $\frac{E_b}{N_0}$ data which is obtained via Matlab experiments, by the Institute for Infocomm Research (I^{2}R), Singapore. In our simulations, the SINR value is calculated and the corresponding BER is obtained via the BER vs $\frac{E_b}{N_0}$ look-up table, whenever a packet is received. The BER is converted to the corresponding *PER* value to evaluate the packet condition at the receiver. Details of the TH implementation and network simulation environment are provided below.

A. Simulation Environment

1) Network Topology: We consider the network topology whereby the sinks are always placed in the center of the terrain. A variable number of source nodes are uniformly distributed throughout the network terrain, and within a single transmission hop to the sinks.

2) Traffic: We consider one-to-one communications, whereby each source node generates data packets to a specific destination according to a Poisson traffic model with a mean packet arrival rate τ. The size of each packet is fixed at *L* bits, and variable numbers of source-destination pairs are used to vary the traffic load in the network.

3) TH Codes: Each slot length in the slotted-Aloha MAC protocol can accommodate a total of $4 \times N_{TH}$ sub-intervals (including guard intervals, as described in Section II-C), where N_{TH} is the total number of possible hopping positions. Hence, a node which has data to transmit will send its packet within

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Network Size (number of nodes)	16 to 160
Transmission Power P	-14.32 dBm
Channel Frequency f	4 GHz
Center Frequency f_c	4492.8 MHz
Channel Bandwidth B	499.2 MHz
Overall FEC rate	0.44
Number of Hopping Positions N_{TH}	{ 1, 2, 4, 8 }
Packet Arrival Rate (per source) τ	500 to 3000
Packet Length L	56 bytes

one out of the first N_{TH} sub-intervals, according to its pre-assigned TH code. The assignment of the TH code is done in two ways: (i) non-optimal random; and (ii) pre-computed optimal. In the former, nodes randomly select a hopping position to transmit *each* packet. In the latter, all transmitting nodes are assumed to pick different and non-conflicting hopping positions during each packet transmission; however, this is subject to the requirement that the total number of transmitting nodes is less than N_{TH}. Correspondingly, the slotted-Aloha MAC protocol with smaller N_{TH} values will have shorter slot lengths than that with larger N_{TH} values, and nodes can transmit more frequently within the same time interval.

4) Performance Metric: We study the aggregated throughput performance of the network, which gives a measure of the efficiency of the slotted-Aloha MAC protocol over a UWB PHY channel. The traffic load and throughput values are both normalized with respect to the theoretical maximum capacity of the network, which is obtained when all the N_{TH} hopping positions within a single slot length are used simultaneously by different nodes to transmit data.

The various simulation parameters are summarized in Table I.

B. Large Population

We study the throughput performance of the network when the system has a large population of up to 160 nodes (thereby providing 80 unique source-destination pairs). Traffic load is increased by increasing the number of nodes in the system, while keeping the packet arrival rate τ of each source node constant at 500 packets/second. We use a total of 4 different values of N_{TH} - 1, 2, 4 and 8 (which are denoted as TH-1, TH-2, TH-4 and TH-8 respectively); each node randomly selects a TH code during each packet transmission.

Figure 2 shows the throughput performance of the network in a system with a large population of nodes, without considering any capture effects. Generally, the normalized throughput increases with the increase in traffic load until the saturation point at a normalized load of 1.0; afterwhich, the normalized throughput decreases rapidly due to excessive collisions resulting from the increased load. The throughput performance for TH-1 is consistent with that of slotted-Aloha

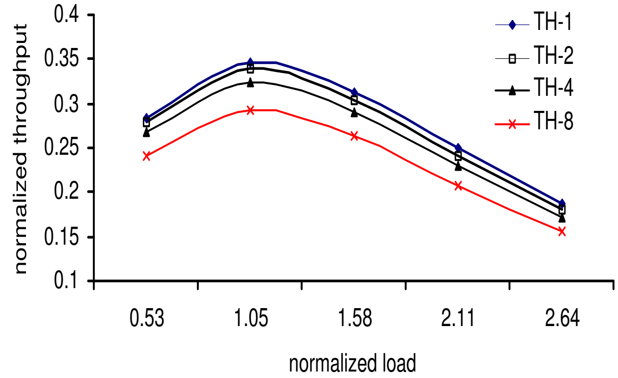

Fig. 2. System with large population with no capture effect

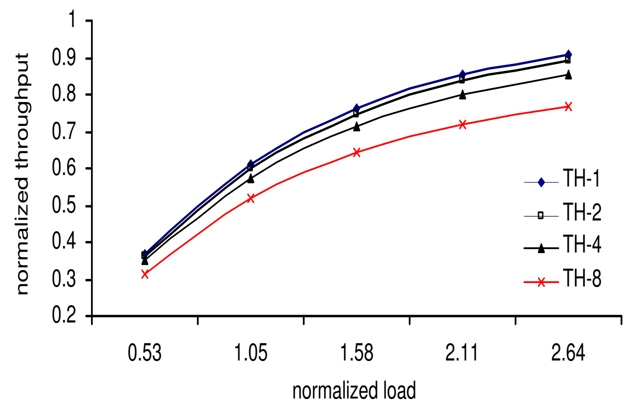

Fig. 3. System with large population with capture effect

over single channels at the physical layer without capture [9] - it peaks at a value of approximately 0.36 when the load is 1.0. It can also be noted that the throughput performance for smaller values of N_{TH} tend to perform better than larger values of N_{TH}. This is mainly due to presence of large numbers of transmitting pairs in the system, which exceed the maximum simultaneous transmissions that is possible within a single time slot.

Figure 3 shows the throughput performance when capture is being considered. The normalized throughputs for all the various values of N_{TH} increases with increasing traffic load, and saturates at a normalized load of approximately 2.64. Unlike the scenario without capture effect, the throughputs do not decrease after the saturation point.

C. Small Finite Population

Figures 4 and 5 show the throughput performance of slotted-Aloha over TH-UWB when the number of users in the system is relatively small. There are a total of 16 nodes in the network, which form 8 unique source-destination pairs. The value of N_{TH} is varied from 1 to 8 and denoted by TH-1 to TH-8 as

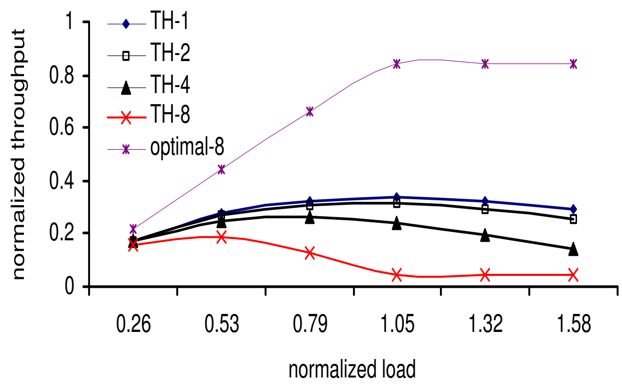

Fig. 4. 8 source-dest pairs with no capture effect

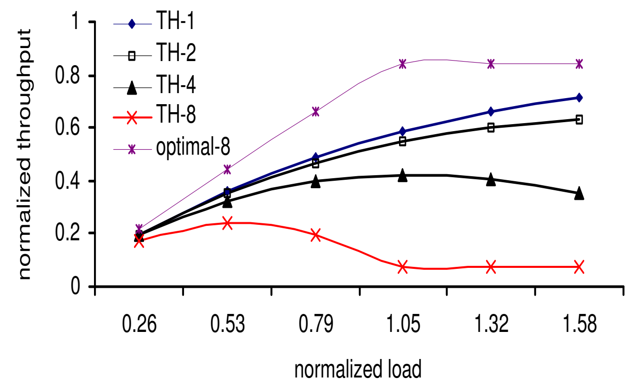

Fig. 5. 8 source-dest pairs with capture effect

like in Section IV-B. In addition, we study the performance of the network when $N_{TH} = 8$ and there exists an optimal TH assignment such that all the source-destination pairs are able to transmit concurrently without incurring any collisions - this is denoted by *optimal-8* in the graphs.

When capture is not considered, the throughput performance of the random TH-assignment schemes (TH-1 to TH-8) deteriorates very quickly when traffic load increases. This is due to the collisions caused by simultaneous transmissions of packets that are using the same TH code when random assignment is used. As schemes with smaller N_{TH} values (such as TH-1) have shorter slot lengths, the nodes are given more opportunities to transmit within the same time interval; hence they have better performance than schemes with larger N_{TH} values (such as TH-8). However, when there exists an optimal TH-assignment scheme such that all the transmitting nodes are assigned non-conflicting TH codes, the performance of the network increases significantly and saturates at a load of 1.0 (see *optimal-8* in Figure 4) as the nodes can transmit concurrently within the same slot length, using different TH codes.

When capture is taken into account in the simulations, the throughput of slotted-Aloha with smaller N_{TH} values generally increases with traffic load. However, the performance of the network decreases sharply for large N_{TH} values (e.g. $N_{TH} = 8$) when the traffic load is increased. As like for the previous scenario, the overall throughput performance of the network is the best when all the source-destination pairs are able to transmit data simultaneously, which is made possible via the optimal assignment of TH codes (as shown in *optimal-8* in Figure 5).

D. Overall Summary and Discussion

From the simulation results obtained in Section IV-B and Section IV-C, we can see that the performance of slotted-Aloha over a Time Hopping UWB physical layer with only 1 TH code available, is similar to the performance of slotted-Aloha over conventional wireless narrowband networks. It appears that the performance of the network is generally poorer for large N_{TH} values, if the TH codes are randomly assigned. However, if there is an optimal way to assign the TH codes to the transmitting node pairs, the overall network performance is increased significantly as the nodes can exploit the availability of multiple TH codes to transmit concurrently within the same time slot, without any collisions. Nevertheless, this is only possible with small finite populations where $N_{TH} \geq$ number of sources.

V. Conclusion

Ultra-Wideband (UWB) has been included as an alternative PHY layer in the IEEE 802.15.4 standard, for the provision of low data rate communications at short ranges and ultra-low powers. The standard also proposes the use of the Aloha MAC protocol over a Time-Hopping PHY layer to provide multiple access. In this paper, we evaluate the theoretical throughput of the slotted-Aloha MAC protocol, which is an enhanced version Aloha, over a TH-UWB physical layer. We also make use of extensive simulations to study the performance of slotted-Aloha over TH-UWB, with varying traffic loads and TH codes. Our simulation results reveal that TH is more well-suited for low traffic loads and small number of users. In addition, a proper and optimal assignment of TH codes to multiple users is crucial to exploit the advantages of concurrent transmissions among multiple nodes, which is possible with the use of TH codes.

Acknowledgment

The authors would like to thank the Digital Wireless Dept at Institute for Infocomm Research (I^2R), Singapore, for providing the BER vs E_b/N_0 data for UWB PHY based on the IEEE 802.15.4a draft specification. This work is done under the USCAM-CQ project which is part of the UWB-Sentient Computing Research Programme funded by SERC, A*STAR Singapore.

REFERENCES

[1] F. Legrand *et al.*, "U.c.a.n.'s ultra wide band system: Mac and routing protocols," in *2003 International Workshop on Ultra Wideband Systems (IWUWBS 2003)*.

[2] G. Goth, "This little standard went to market; this little standard blew up," *IEEE Distributed Systems Online*, vol. 17, no. 12, 2006.

[3] J.-Y. L. Boudec, R. Merz, B. Radunovic, and J. Widmer, "Dcc-mac: A decentralized mac protocol for 802.15.4a-like uwb mobile ad-hoc networks based on dynamic channel coding," in *BROADNETS*, vol. 00. Los Alamitos, CA, USA: IEEE Computer Society, 2004, pp. 396–405.

[4] M.-G. D. Benedetto, L. D. Nardis, M. Junk, and G. Giancola, "(uwb)2: uncoordinated, wireless, baseborn medium access for uwb communication networks," *Mob. Netw. Appl.*, vol. 10, no. 5, pp. 663–674, 2005.

[5] *Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specification for Low-Rate Wireless Personal Area Networks (LR-WPANs)*, IEEE Std. 802.15.4a, 2006.

[6] A. F. Molisch *et al.* (2004, Nov.) Ieee 802.15.4a channel model - final report. IEEE 802.15 WPAN Low Rate Alternative PHY Task Group 4a report. [Online]. Available: ftp://ftp.802wirelessworld.com/15/04/15-04-0662-00-004a-channel-model-final-report-r1.pdf

[7] D. Bertsekas and R. Gallager, *Data Networks*. Prentice Hall, 1992.

[8] Qualnet network simulator, scalable network technologies, inc. [Online]. Available: www.qualnet.com

[9] L. G. Roberts, "Aloha packet system with and without slots and capture," *SIGCOMM Computer Communications Review*, vol. 5, no. 2, pp. 28–42, 1975.