On the MAC Layer Performance of Time-Hopped UWB Ad Hoc Networks

Ioannis Broustis, Angelos Vlavianos and Srikanth V. Krishnamurthy
Department of Computer Science and Engineering, University of California, Riverside, CA 92521
{*broustis, aggelos, krish*}*@cs.ucr.edu*

***Abstract*— Ultra Wide Band (UWB) is a promising technology for short-range wireless networks. In this paper we present our efforts on investigating the impact of the multipath delay spread on the MAC layer performance of time-hopped impulse-based UWB ad hoc networks. We discuss a simplified channel model for the multipath delay spread and we simulate a single-band MAC protocol which employs binary pulse position modulation. Our simulation results demonstrate that the performance is determined by the properties of the time hopping sequences of the nodes. We observe that the right parameter values depend on the number of nodes deployed, and the delay spread experienced. If the topology changes dynamically, adaptive strategies for varying system parameters are required for achieving the best performance.**

***Index-terms:* Ultra Wide Band (UWB), Short-Range Communications, Ad Hoc Networks, Multipath Delay Spread, Modulation.**

I. Introduction

Ultra Wide Band (UWB) is a novel wireless short-range technology, which presents significant opportunities for networking research and development. The unique nature of UWB necessitates the design of novel higher layer protocols that are synergetic with the physical layer and are capable of exploiting its characteristics [16]. We examine how the uniqueness of the UWB physical layer affect higher layer protocol design. We present our efforts on investigating the effects of the multipath delay spread on the performance at the MAC layer in impulse-based UWB ad hoc networks. Our motivation stems from the fact due to delay spread, multiple time-shifted copies of each transmitted UWB pulse appear at the receiver. This causes *inter-symbol interference* (ISI), wherein the delayed copies of one pulse interfere with subsequent pulse transmissions [3]. This degrades the performance at the MAC layer, since packets are dropped more frequently. Understanding the implications of the delay spread on the MAC layer behavior can help design more efficient MAC protocols for use with UWB wireless networks.

We present our observations assuming that the multiplicity of pulse copies (produced by the delay spread) occupy a window of fixed size, which is equal to the delay spread duration (order of nanoseconds [19]). In particular, we examine the performance of a simplified MAC protocol very similar to what has been proposed in [9]. Note that the scope of this work is not to propose a MAC protocol for UWB ad hoc networks, but to examine the impacts of the multipath delay spread, on the MAC layer performance. To date, there have been very few MAC protocols proposed for UWB ad hoc networks; all of them use time hopping in some form [9][32]. This work differs from previous studies on the capacity of UWB networks, in that we are focusing on the effects of the delay spread on the MAC layer performance and behavior, rather than on estimating the achievable physical layer or Shannon capacity[1].

The remainder of this paper is organized as follows. In section II, we provide the relevant background on UWB communications and we discuss the MAC - PHY layer dependencies. In section III, we provide a brief description of the candidate MAC protocol. In section IV, we present our simulation results and interpret our observations. In section V we discuss relevant previous work. Finally, section VI concludes the paper.

II. The UWB Physical Layer

In this section, we discuss the UWB physical layer and the impact of the multipath delay spread. Details of some of the aspects of UWB can be found in [1], [14], [31] and [15].

a) **The Basics of UWB Communications:** In a nutshell, two key properties distinguish UWB from other wireless technologies: large spectrum and short transmission range. The Federal Communications Commission (FCC) has defined a set of specifications known as the Part 15.209 rules [1] that govern the operation of unlicensed UWB systems within the 3.1 to 10.6 GHz spectral band. These rules state that each transmitter must use signals that span at least 500 MHz of absolute bandwidth or occupy a fractional bandwidth $W/f_c \geq 20\%$, where W is the transmission bandwidth and f_c is the frequency at the center of the band. The rules also place an upper bound on the power spectral density (PSD) measured in a 1-MHz bandwidth when an omni-directional antenna is used. These imposed limits are referred to as FCC's *spectral mask*. UWB systems have traditionally achieved high bandwidths by using pulses that are of very small or narrow time duration. A typical UWB pulse belongs to the family of *Gaussian* shaped doublets [14], [15]; these shapes are generally used since they can be easily generated by hardware. The modulation scheme that we employ in this paper is a commonly deployed scheme called Binary Pulse Position Modulation (BPPM) [15]. With BPPM, each pulse represents a bit. The pulse represents either a "0" or "1" depending on its *position* within a *chip time* T_c. If the pulse

This work is supported in part by the NSF CAREER Grant No.0237920 and the NSF NRT grant No. 0335302.

[1]In other words, we consider a more practical setting as opposed to the theoretical framework considered in [7] [8].

occupies the first part of the chip-time, it represents a bit value of "0"; otherwise, a bit value of "1" is implied. We assume that a Viterbi decoder is deployed at the receiver [2] and this enables the soft-decision decoding of the received information.

b) **Time Hopping:** Time hopping has been used with UWB for sharing a single frequency band among multiple users [9] [10]. It provides an effective way of providing media access control in impulse-based UWB systems. In ad hoc networks, imposing fixed TDMA like schedules is difficult due to the fact that nodes could be mobile. A completely random access scheme requires nodes to acquire synchronization at arbitrary unpredictable time instants. Time-hopping is a form of spread spectrum communications and has been specifically designed for impulse based systems. Nodes transmit as per pseudo-random time-schedules. The pseudo-random nature of time-hopping provides a reasonable level of robustness to collisions. To the best of our knowledge, all MAC protocols designed thus far, for impulse based UWB ad hoc networks, use time hopping as the basic means of providing multiple-access.

With time hopping, a fixed number of chip-times are aggregated to form a *sequence frame*. The duration of each sequence frame is T_f, and thus, the number of chip-times per sequence frame is T_f/T_c. Each transmitter sends a pulse in only one of the chip-times in each sequence frame. The specific chip-time is determined by the node's time hopping sequence (THS), which is typically generated via a pseudo-random number (PN) code. In our work, we assume that nodes periodically announce the state of their PN code generators. Time hopping sequences may be either sender-based or receiver-based. In receiver-based time hopping, potential transmitters use the THS of the receiver when they attempt a transmission. In the sender-based case, the transmitter sends pulses based on its own THS[2].

Note that it is extremely difficult to guarantee that time hopping sequences of nodes are orthogonal to each other. If one had to provide this requirement, each node will have to have a dedicated chip-time per sequence frame. This would result in extremely long sequence frames and results in poor spectral utilization and longer delays, especially at low loads. The average spacing between successive transmissions as per the THS will affect the achieved performance. With shorter spacing between the time-hops, the pulses could be sent at a faster rate[3]; however, there is a higher possibility of collisions. With longer spacing, the possibility of collisions is reduced; however, large delays could be incurred. We observe this tradeoff, taking into account the multipath delay spread effects.

c) **Multipath delay spread:** UWB transmissions will experience *multi-path delay spread*. As a consequence of reflections from various objects, a UWB receiver will receive multiple copies of the same transmitted signal, each of which may have a different amplitude, phase and delay. Beyond a certain delay threshold (an inherent characteristic of the channel being considered), called the *delay spread*, the signal amplitudes may be considered negligible.

For indoor environments, measurements have shown that the delay spread is of the order of tens of nanoseconds [19]. If the time-spacing between the UWB pulses is smaller than the delay spread of the channel, copies of the a transmitted encoded bit interfere with the subsequent encoded bits. This is called *inter-symbol interference* or ISI for short. Equalizers are typically used to combat ISI [2]. The higher the level of the ISI, the higher the complexity and sophistication of the required equalizer. Equalizers also require the transmission of a training sequence prior to information communication. This can be expensive in terms of the overhead consumed. With UWB transmissions, a preamble is needed to allow for the sender and receiver to synchronize prior to communications. By acquisition, we mean that the receiver learns how to recognize a pulse train in the presence of thermal or other noise factors. The aforementioned acquisition preamble is considered expensive in terms of overhead [18]. The deployment of a sophisticated equalizer will further increase the overhead costs incurred with UWB. Another strategy for combating ISI would be to use direct sequence CDMA in conjunction with a Rake receiver. However, the long codes with CDMA could still incur capacity penalties. Furthermore, with CDMA, the sender and receiver require code synchronization in addition to the acquisition and this would incur a further cost in terms of overhead. One alternative that we explored in [32] is to separate the pulses by at least the delay spread of the channel. By doing so, the pulse width could be increased to some extent since this is unlikely to interfere with future encoded bits. Increasing the pulse width allows for the use of lower pseudo-carrier frequencies and thus, facilitates the use of multiple frequency bands. In this paper, however, we reiterate that our objective is to understand the effects of the ISI in the single–band case.

d) **FCC Regulations About Transmission Power:** The FCC regulations limit the effective isotropic radiated power (EIRP) to -41.25 dBm/MHz (Part 15 of the regulation) [1] [14]. Thus, the power used on average, per bit cannot exceed this imposed limit. Let us denote the transmit power by P_T dBm/MHz, the received SNR at a distance d by SNR_d dBm/MHz and the central frequency in the band used by f_c. Let the power spectral density of the thermal noise be N_o dBm/MHz. Then, the signal to noise ratio is given below [14]:

$$SNR_R = P_T - N_o - 20\log\left(\frac{4\pi f_c}{c}\right) - 20\log d. \qquad (1)$$

If P_T is -41.25 dBm/MHz and if the received power i.e., P_R is to be 3 dB higher[4] than the noise margin, wherein N_o = 114 dBm/MHz [14], one can compute the maximum range of transmission for the given value of f_c. Note here that, the higher the value of f_c, the lower the maximum range. For the 7.5 GHz bandwidth we have f_c = 6.85 GHz; this is translated to

[2]The sender-based strategy is robust; in this case, one of the two transmissions is perceived by the receiver as a useful signal, while the other contributes to multi-user interference. Note however that in this case the receiver must tune its hardware to the right code [33]. The receiver-based approach is much simpler to implement; however one could encounter collisions between the pulses from different transmitters, directed toward the same receiver.

[3]The FCC regulations impose a limit on the pulse repetition frequency as will be discussed later.

[4]SNR = 3 dB.

a maximum coverage of around 10 m. We have used the above values for our simulation experiments. As a result, the UWB scheme that we examine conforms with the FCC regulations.

e) **Time Synchronization:** The protocol that we test requires the division of time into frames; thus, nodes must be synchronized in time. Several methods have been proposed to achieve time-synchronization [23], [24]. We assume that synchronization is achieved with one of these methods.

III. The MAC Protocol for UWB Ad Hoc Networks

In this section, we briefly present the single-band MAC protocol that we test. This protocol has many similarities with [9]. However, here we consider a simplified version. The design of protocols that can use the insights gained by this study will be taken up in future efforts.

The single-band MAC protocol is based on a priori known THSs of nodes i.e., each node is aware of the THSs of its neighbors. Moreover, after some appropriate handshaking (to be discussed), each pair of transmitters and receivers agree to switch to a unique THS for exchanging data packets. This new THS is uniquely different for each pair of neighbors and is known only to that pair. This mechanism is motivated by the fact that by switching to another (unique) THS, the data packet transmission is protected from prolonged collisions[5].

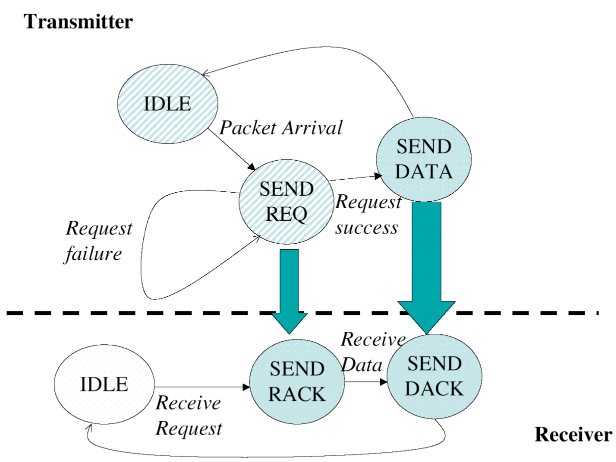


Fig. 1. Finite State Machine Representation of MAC protocol

We now briefly describe the algorithmic steps of the single-band MAC protocol. The steps are depicted in Figure 1. Let us assume that **(1)** node A wishes to send a packet to node B, **(2)** node B is idle, i.e., it does not have a packet to send and it is not engaged by an ongoing transmission and, **(3)** nodes A and B are neighbors.

Request transmission (REQ): Node A transmits a request message to B, using B's THS. After transmitting the request, node A switches to the common predetermined THS that is unique for communication between nodes A and B.

Acknowledgment of the request (RACK): If node B is idle, it listens on its THS. If it receives the REQ message correctly. it will immediately switch to the common THS between A and B. Node A will have already switched to this THS. Node B will further transmit a RACK to A as per this new THS, indicating that it correctly received the REQ from A.

Data transmission (DATA): Upon the successful receipt of the RACK, node A will transmit its data packet to B, using the common unique THS.

Acknowledgment of data (DACK): If node B receives the data packet successfully, it will transmit a short acknowledge message (DACK) to A.

Beacon transmission (BEACON): After the transmission of the DACK, both A and B switch to their respective THSs, where they transmit a short beacon (not shown in the figure), indicating that they are now idle.

We will now proceed with explaining some possible situations that may arise. There are two cases wherein node B will not receive the REQ message.

– Collision between requests: Two nodes (say nodes A and C) may transmit a request to the same receiver (say B) at the same time; in this case, the two messages will collide (since the same THS *(of node B)* is used). Then, nodes A and C will switch to different THSs waiting for the RACK from B. Due to the collision, B will not send a RACK to either A or C. After waiting for a preset duration, nodes A and C will switch to the THS of B. Node B will transmit its BEACON as per its THS, since it detected the collision. After detecting this BEACON, nodes A and C will further initiate backoff timers. Upon the expiry of their timers, they reattempt request transmissions to node B[6].

– Node B is busy on another transmission: Node A may attempt to transmit to B while B is busy. Thus its request never reaches B. Node A switches to B's THS and awaits a BEACON message from B. Upon the receipt of this BEACON, node A sets its backoff timer; it transmits its request again after the expiry of this timer.

The THSs of the different nodes are *not* orthogonal and could overlap, as explained earlier. If many simultaneous transmissions occur in the same neighborhood, this THS overlap may cause pulse collisions. With large overlaps, many pulses will collide. To increase reliability, each bit is represented by a set of pulses. If this set is small, the bit error rate will increase, thus making node B incapable of correctly receiving the data packet. In that case, node B will not send a data acknowledgement back to A. Thus, node A will retransmit the request to B. However, we do not consider this case in our simulations. Even though we consider pulse collisions in terms the bit error rate, we do not retransmit partially or totally collided packets.

IV. Simulations

In this section we present our simulation results. We have developed a C++ simulator by largely extending a previous

[5]Note that if two transmitters try to communicate with a receiver on its THS, prolonged collisions are possible [9]

[6]An exponential backoff policy is followed as in [9].

simulation effort [12]. Our focus is on the performance at the MAC layer; we assume that data is injected at the MAC layer and the transmissions of a node are intended for a neighbor. We use assumptions that are widely used in prior UWB studies and incorporate as many realistic details at the physical layer, as possible.

Simulation details: In our implementation, the physical layer consists of a number of virtual links. Each link has a separate buffer and connects a node with its neighbors; a node has m attached links, one for each neighbor. The MAC layer of the transmitter delivers the packet to the appropriate link. The physical layer converts the bits to pulses, which will be transmitted on the appropriate link. The channel characteristics, discussed in Section II are applied and distort the transmission. The receiver picks each pulse, decodes a set of pulses that form a bit (if possible), and stores the bit in a buffer. A bit may be discarded either due to collision or due to its corruption by thermal noise. When a set of bits that form a packet have been received correctly, the packet is re-constructed and delivered to the receiver's MAC layer. The arrival of two or more pulses, simultaneously from different links, denotes a collision.

The interference caused by the multipath delay spread is modelled as a window of pulse copies. During the simulation, a window of the k previous slots is maintained for each node (this window is constantly updated during the simulation). The value of k corresponds to the time duration of the delay spread, in pulse slots[7]. Whenever a pulse p arrives at the receiver, we search the receiver's window for other pulse transmissions during the last k slots. If such a transmission is logged in the window, our model decides on whether it will interfere with pulse p and if this will be further counted as a pulse collision. Note that a receiver does not log a collision unless its own packet was involved in the collision.

At this point we should note that the model's decision about whether a pulse collision occurs or not, is determined by the following two considerations:

– First, we take into account the *receiver's power thresholds*. In particular, we assume that the receiver maintains an upper and a lower power threshold. If the received power falls below the lower threshold, the receiver does not take into account the received energy. If the received power (within a T_c) exceeds the upper threshold, the receiver will assume that a collision has occurred. Finally, if the received power falls between the lower and the upper threshold, the receiver will assume a correct reception. It is important to correctly set the appropriate upper power threshold. If this threshold is set to a very low value, a transmission from a distant transmitter could interfere with ongoing transmissions from a closer transmitter.

– Second, in our physical layer implementation we take into consideration the *average signal attenuation*. This is given by the following equation (Frii's law [14]) and has an impact to the received signal power.

$$\alpha = \left(\frac{c}{4 \cdot \pi \cdot d_{ij} \cdot f_c}\right)^2 \tag{2}$$

where c is the speed of light, f_c is the central frequency of the band and d_{ij} is the distance between the transmitter and the receiver. Note that the above equation depicts the observed effects *on average*, and does not imply that *each* transmitted signal experiences the *same* level of attenuation. As explained earlier, the nodes' time hopping sequences are not orthogonal and this can cause pulse collisions. Let us assume that two pulses arrive at a given receiver, at the same pulse slot. If these pulses are attenuated to some extent, then their simultaneous reception *may not* trigger a collision at the receiver. This is because their additive received power may not exceed the receiver's upper power threshold. In that case, the receiver will assume that it correctly received a pulse. Note here that the receiver correlates the received signal with a reference signal, and does not check upon the shape of the received pulse; the correlation reflects the received energy. This is because the transmitted signal is expected to be distorted (by the channel and filters) anyway.

Simulation scenarios: The nodes form an ad hoc network. We vary the number of nodes from 6 to 26. We restrict the nodes to a $30m \cdot 30m$ square region. As mentioned in section II, the maximum range of a transmitter is considered to be 10 meters. A transmitter always selects a receiver randomly from its neighbors. The nodes are deployed in a way such that the network is not partitioned, and the nodes *do not* form a fully connected graph, i.e., they do not form a clique topology. We use CBR (Constant Bit Rate) traffic in our simulations. Table 1 lists the simulation parameters that are held fixed in all of our experiments; we discuss experiment specific parameters later, as relevant.

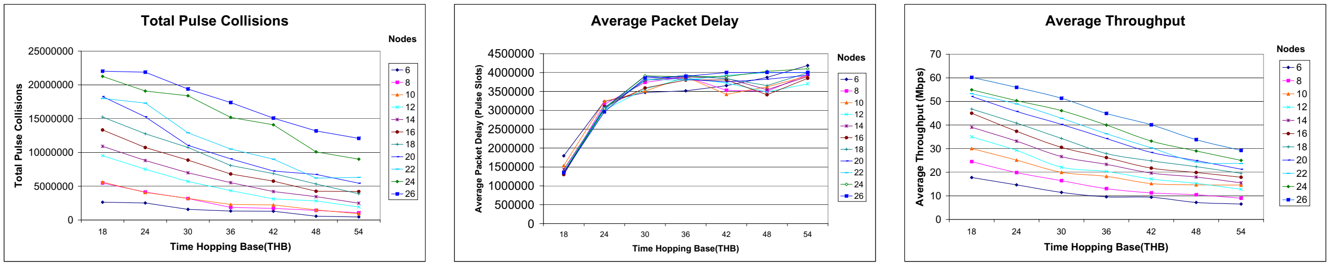
A pulse collision is defined as an instance wherein two or more pulses arrive during the same T_c period. A bit is received in error when *all* of the pulses that make up the bit collide or if it is corrupted due to thermal noise.

In our experiments we vary the ratio T_f/T_c, i.e., the number of chip-times contained within a sequence frame. We call this number *Time Hopping Base*, or THB. We expect that by increasing this ratio, collisions will be less frequent. Furthermore, for a specific value of this ratio we increase the packet arrival rate to a large value, and observe the capacity of the network in terms of throughput. For a specific value of the THB, we also observe the performance when we vary the number of pulses per bit.

Simulation results: We evaluate the performance of our scheme by measuring the number of pulse collisions, the BER, the MAC layer average throughput of the network and the average packet delay.

Initially, we observe the behavior of the MAC layer as we vary the value of THB. In Figure 2(a), we plot the total number of pulse collisions as a function of the number of chip-times in a sequence frame. Each plot in Figure 2(a) corresponds to

[7]We assume that this duration is 30 nsec [19].



(a) Number of pulse collisions, as a function of the time hopping base (THB)

(b) Average packet delay in the network. The packet delay increases as the time hopping base increases.

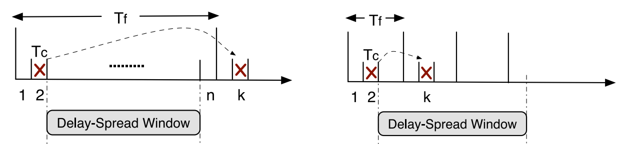
(c) Average Throughput observed during simulations

Fig. 2. MAC Layer behavior while varying the THB

Tc	1 nsec
Deployment region	30·30 m^2
THB	18
Pulse Repetition Rate	6
Used bandwidth	7,5 GHz
Receiver threshold	-110 dBm
Center frequency	6.85 GHz
Delay spread	30 Tc chips
Data packet size	256 Bytes
Control packet size	120 Bits
General CBR traffic	3.413 Mbps per node
Capacity CBR traffic (Figure 4)	40,96 Mbps per node
CBR traffic (Figure 6)	5.12 Mbps per node
Simulation duration	15,000,000 chip times

TABLE I

SIMULATION PARAMETERS, *when not variable*



(a) The delay spread duration is smaller than $2 \cdot T_f$

(b) The delay spread duration is larger than $2 \cdot T_f$

Fig. 3. Effect of delay spread duration to two successive pulses

different numbers of nodes in the network. We observe that as THB increases, the total number of pulse collisions decrease. This is somewhat expected, since when the THB is smaller than the total number of nodes, the probability of collision increases with the number of nodes. However, as the THB becomes larger than the number of nodes, the collision probability decreases.

The decrement in the collision probability with the increment of the THB, comes with a tradeoff: in Figure 2(b) we report the average packet delay in the network. The packet delay is the duration between the instance that a packet arrives to the MAC layer queue of a node, and the instance when it is reconstructed at its destination. This delay accounts for retransmissions that may occur due to the failure of the packet reception. From Figure 2(b) one can observe that as the THB increases, the average packet delay also increases. This is because as THB is increased, the sequence frame (T_f) becomes larger. As a consequence, the time between the transmissions of two consecutive pulses (from the same transmitter) is now large. This has an impact to the total transmission time of a symbol.

In Figure 2(c), we plot the average throughput of the network as a function of the THB. We observe that as the THB increases, the average throughput of the network decreases. This is caused by the increased time that a node has to wait before it can transmit the next pulse. In other words, the dominant factor causing the decreased average throughput is not the collisions, but the length of the sequence frame T_f. Another interesting observation is that for the various cases with different network sizes, and for a specific value of the THB, the average throughput is different and increases with the number of nodes in the network. This is because the maximum capacity of the network is not reached; the throughput will keep increasing until it reaches the upper bound on the achievable capacity at the MAC layer. Note that in Figure 2(c) we depict the average throughput in terms of correctly received bits and not correctly received packets. With proper access techniques, the bit throughput can be translated to the corresponding average packet throughput.

In our experiments we select relatively small values for THB. This is because we are interested in observing the severity of the impact of ISI on the transmission of successive pulses. We begin our experiments with THB=18, in order to ensure that successive pulses do not constantly suffer collisions with *prior transmissions from the same transmitter*. As stated earlier, the delay spread duration is approximately 30 nsec, i.e., 30 chip times in our simulations. With THB=18, the duration of two successive T_f sequence frames is 36 chip times, which is larger than the delay spread. The effects of the choice of T_f are depicted in Figures 3(a) and 3(b). In Figure 3(a) the delay spread duration is always smaller than $2 \cdot T_f$; hence there two successive pulses from the same transmitter are separated. However, in Figure 3(b) the delay spread is always larger than $2 \cdot T_f$; here, if we consider two successive pulses from the same transmitter, the second pulse always suffers some level of interference due to the copies of the first pulse. In the example depicted in Figure 3(b), the pulse in slot k will always experience interference from the copies of the pulse transmitted in slot 2 of the previous T_f. Setting THB to values lower than 18 will lead to a case where a pulse almost always interferes with the next pulse transmission from the same transmitter[8]. Taking this observation further, with such small THB values one would expect that almost all of the pulse transmissions would collide. However, as we observe from figure 2(c), this is not the case. We observe that even with small THB values, we manage to have many correct bit receptions. This is attributable to four factors. *First*, as explained earlier, transmitted pulses are attenuated. As a result, the reception of two or more pulses in the same pulse slot will not result in a collision unless the overall received power, within a T_c, exceeds the receiver's upper threshold. *Second*, the traffic arrival moments are different for each node; it is not likely that packets arrive at nodes' queues exactly at the same time. In other words, packet transmissions are also distributed over time. As a result, we do not have frequent concurrent packet transmissions. *Third*, nodes are deployed in such a way that they do not form a clique topology. Hence, even if parallel transmissions occur, a transmission may not affect other concurrent transmissions. *Fourth*, the receivers are chosen randomly, as per the MAC functionality. If we have a few nodes in the network, then finding an available receiver within coverage is quite difficult. It is possible that the intended receiver is busy in another session for a significant time. To illustrate this, let us consider the case with a 256-byte data packet, four 120-bit control packets (*REQ, RACK, DACK, BEACON*), a pulse repetition of 6 and a THB of 18. This set of packets will be transmitted during a session between two nodes (Recall section III). The transmission of the above set of packets takes approximately 273024 chip times in total; this will be longer if we increase the THB value. We note that the random receiver selection is a MAC design choice that we make in the absence of real data or traffic statistics. Note however that if the traffic is uniformly directed, these observations hold. The traffic model assumed here is in line with efforts on MAC layer design for UWB ad hoc networks [9].

The capacity of the network, in terms of achieved throughput, is depicted in Figure 4. In this scenario all nodes have extremely high CBR arrival rates[9]. The reason for this choice of traffic is that we want to find the MAC layer throughput limit. From the graph it is clear that the upper bound on the capacity of the network is reached with 22 nodes and the maximum achievable average throughput is approximately 152 Mbps. We performed experiments with different values of THB, and we found that the behavioral pattern of graph remains approximately the same. The only difference is that the maximum throughput is achieved for different numbers of nodes in the different experiments; as we vary the T_f duration, the total number of nodes that can utilize the available slots and achieve

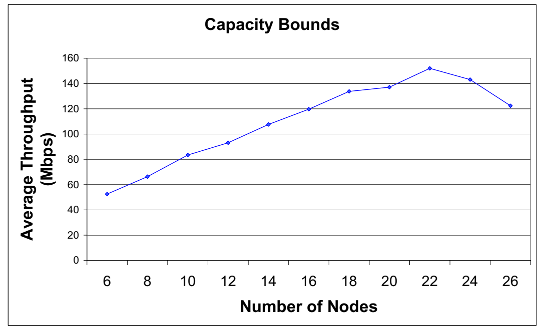


Fig. 4. Capacity Bound of the Network. THB=18

the maximum throughput is different. As one might expect, initially, the collisions are infrequent and as the number of nodes is increased, the throughput increases; however, beyond a certain density (number of nodes), higher levels of collisions begin to decrease the achieved throughput.

We also observe the behavior of the network for different values of the pulse repetition rate (the number of pulses comprising a bit). Depending on the level of interference, sometimes this parameter has to be adjusted, in order to achieve a desired level of reliability in the network[10]. In our simulations we vary the pulse repetition rate from 6 to 36, increasing by 6 each time, and we set the value of THB to 18. In Figure 5(a), we plot the average BER as a function of the pulse repetition rate. We observe that, as the pulse repetition rate increases, the BER decreases. This is justified by the fact that when the same bit is made up of *more* pulses, the probability that all of the pulses that make up the bit are corrupted is smaller. With an increase in load, increasing the number of pulses would increase the number of transmitted pulses and one may expect the collision rate to increase; however, this is not the case as we discuss below.

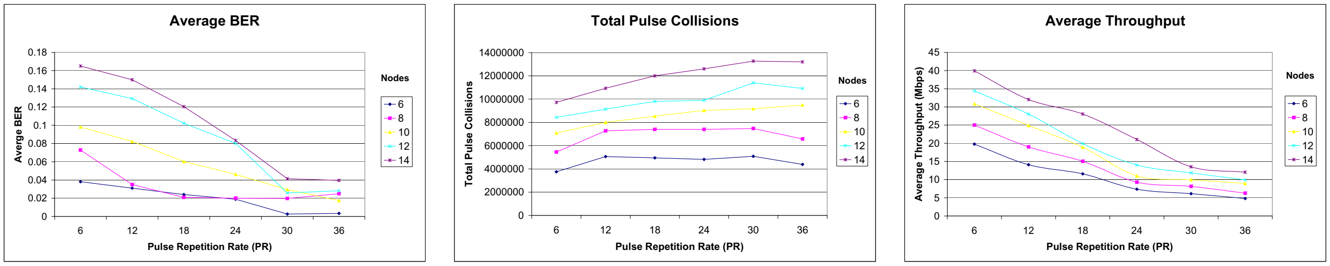
In Figure 5(b), we observe that the number of pulse collisions initially starts increasing with the repetition rate. Transmitting more pulses per bit implies that more pulses are likely to collide. However, if we increase the pulse repetition rate, it takes much more time for a bit to be received. As a consequence the time for the whole packet to be received is much longer. In other words, a session between a pair of users is prolonged. Hence other potential nodes have to wait for this pair to become idle. This is mostly observed for low density networks. These nodes that have to wait do not have the chance to transmit all of their packets. Thus, fewer parallel transmissions occur in the same neighborhood. This justifies the drop in the number of collisions for larger pulse repetition rates. However, the average throughput decreases with an increase in pulse repetition rate as shown Figure 5(c); the overhead due to the redundant pulses affects the average throughput negatively.

Finally, we examine the impact of variations in the delay spread on the network throughput. We depict the relative

[8]We observed this during our simulation experiments.

[9]A new packet arrives every 50usec

[10]In [9] the authors present a MAC protocol, based on dynamically adjusting the pulse repetition rate, according to the interference levels of the channel.



(a) The Bit Error Rate decreases as the Pulse Repetition rate increases

(b) Pulse Collisions

(c) Average Throughput observed during simulations

Fig. 5. Behavior of the network for different values of pulse repetition rate

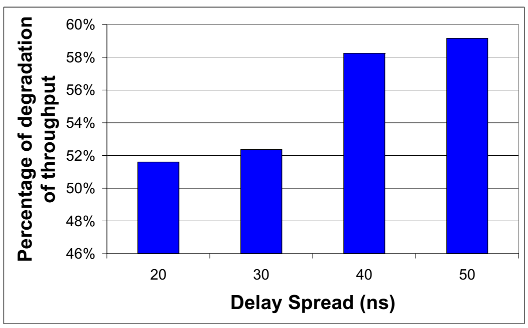


Fig. 6. Percentage of the average throughput degradation in the network, for different durations of the delay spread. The degradation is computed with regards to the ideal case wherein the delay spread does not cause any interference.

degradation in network throughput with respect to a baseline case where there is no delay spread. As one might expect, with an increase in delay spread, the interference effects increase and we observe higher degradations relative to the case where there is no delay spread.

Our studies lead us to argue that the network can generate useful throughput only for values of THB equal or greater than a specific value. We explain this claim with a simple network consisting of two nodes. If the sender transmits a pulse, then it won't be able to transmit successfully another pulse in the immediately following slots due to the multiple copies of its own signal. In other words, the sender is interfering with itself, due to multipath delay spread. An estimation of the number of slots that the sender won't be able to transmit is determined by the delay spread which is a function of the PHY layer.

Given these properties, a MAC layer designer has to choose the right THB and pulse repetition rate depending on the number of nodes deployed, and the delay spread experienced. If the topology changes dynamically, adaptive strategies for varying these parameters may be needed to get the best performance from the network.

V. Related Work on UWB networks

There are no previous studies that investigate the effects of the multipath delay spread from the MAC layer (or higher layers) point of view.

Delay Spread Models and Measurements: In [20], Ghassemzadeh et al., present models for the UWB channel delay profile, based on processing of two large data sets. Their simulations show that their model accurately predicts key properties of the measured channel, such as the distribution of the RMS delay spread. Opshaung and Enge in [21] also quantify the multipath channel in terms of delay spread. They find several cases wherein multipath components are stronger (in magnitude) than the direct signal. Moreover, in [22] Foerster takes a commonly known delay spread model and applies it to the study of a UWB system. Finally, in [28] Greenstein et al., compare three UWB indoor delay spread models [29], [30], [20].

UWB MAC Schemes: Le Boudec et al. [9], [11] propose a scheme that uses dynamic channel coding. The transmitter dynamically varies the code rate upon receiving feedback from the receiver with regard to channel conditions. In [13] the authors describe theoretical and practical approaches toward the development of a THS based MAC protocol for radio resource sharing in UWB ad hoc networks. The effects of multipath and in particular delay spread are not addressed in these papers. In [25], all nodes share a THS and the receiver broadcasts an invitation, as per this sequence. Potential transmitters compete during a contention period, to lock on to the receiver. In [27] the authors propose a full-duplex access scheme for impulse-based UWB networks. The scheme takes advantage of the low duty cycle to maintain physical links among two nodes for the lifetime of their logical link, thereby removing the requirement that the sender and receiver resynchronize for every packet to be exchanged. In [32] a new multiband MAC protocol is presented. The authors propose to prolong the chip-time duration to be equal the delay spread, so as to completely eliminate the delay spread interference. Most other studies consider master-slave configurations [4], [26], [12]. The IEEE 805.15.3a task group proposal [4] for media access control is based on the notion of piconets. Each piconet includes a master-coordinator, which assigns resources to slaves. The task group has evaluated numerous proposals for the UWB physical layer. One of them is an OFDM solution, proposed by the WiMedia Alliance [5] [6]. This PHY/MAC specification aims to provide high speed wireless connectivity, while providing quality of service and security for real-time transfer of wireless multimedia, with payload data rates of up to 480 Mbps. This architecture involves PHY and MAC design, coexistence and fairness (including support for multiple applications, e.g. Wireless USB, Wireless Firewire, IP), a protocol adaptation layer for the Internet Protocol and IP-based application profiles. However MAC layer studies for Ad Hoc networks with Multiband OFDM are yet to emerge.

VI. Conclusions

With UWB standards and commercial products still under development, research efforts could have a significant impact in shaping the direction of the technology. In this paper we investigate the impact of the multipath delay spread on the MAC layer performance of impulse-based UWB networks. This work is motivated by the fact that the multipath delay spread can create considerable interference in the real world deployment of UWB networks. This is especially the case in the absence of a sophisticated equalizer. This artifact is not taken into consideration in most previous studies on MAC design for such networks. Some of these studies either assume that nodes are equipped with such an equalizer, or do not discuss this issue at all. We consider a time-hopped impulse-based MAC protocol and perform a set of simulations; we interpret our observations on the behavior of the system in different scenarios. We measure the network performance with delay spread considered as a limiting factor. We observe how the time hopping base (T_f/T_c ratio) and the pulse repetition rate affect the performance of the network and we point out the *performance vs reliability* trade off that comes with the choice of these parameters. These findings are very important and will help in future research on this problem. Currently we are in the process of importing a more realistic multipath delay spread model into the PHY layer of our simulation platform.

References

[1] Federal Communications Commission: “Revision of Part 15 of the Commission’s Rules Regarding Ultra-Wideband Transmission Systems”, First Report and Order, ET Docket 98-153, 04-2002.

[2] J. G. Proakis: “ Digital Communications”, McGraw-Hill, N.Y. 2001, 4th edition.

[3] R. Gitlin, J. F. Hayes and S. Weinstein: ”Data Communication Principles”, Plenum Press, 1992.

[4] IEEE 802.15.3 MAC standard.

[5] Multiband OFDM Physical Layer Proposal for IEEE 802.15.3a, September 2004, http://www.multibandofdm.org

[6] WiMedia, http://wimedia.org

[7] A. Rajeswaran and R. Negi: “Capacity of power constrained ad-hoc networks”, Infocom 2004.

[8] H. Zhang and J. Hou: “Capacity of Wireless Ad Hoc networks Under Ultra Wide Band with Power Constraints”, Infocom 2005.

[9] J. Y. Le Boudec, R. Merz, B. Radunovic and J. Widmer: “A MAC protocol for UWB Very Low Power Mobile Ad-hoc Networks based on Dynamic Channel Coding with Interference Mitigation”, EPFL Technical Report ID: IC/2004/02, 01-26-2004.

[10] J. Y. Le 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” *Proceedings of Broadnets*, 2004.

[11] R. Merz, J. Y. Le Boudec, J. Widmer, B. Radunovic: “A Rate-Adaptive MAC Protocol for Low-Power Ultra-Wide Band Ad hoc Networks”, *Proceedings of Ad-Hoc Now*, 2004.

[12] H. Yomo, P. Popovski, C. Wijting, I. Z. Kovacs, N. Deblauwe, A.F. Baena and R. Prasad: “Medium Access Techniques in Ultra-wideband Ad Hoc Networks”, 6th National Conference of Society for Electronic, Telecommunication, Automatics, and Informatics (ETAI), September 2003, Ohrid, Fyrom.

[13] F. Cuomo, C. Martello, A. Baiocchi and C. Fabrizio: “Radio resource sharing for ad hoc networking with UWB” IEEE Journal on Selected Areas in Communications, December 2002.

[14] S.Roy, J. R. Foerster,V. S. Somayazulu and D. G. Leeper: “Ultrawideband Radio Design: The Promise of High-Speed, Short-Range Wireless Connectivity”, *Proceedings of the IEEE*, February 2004.

[15] M. Ghavami, L. B. Michael and R. Kohno: “Ultra Wideband Signals and Systems in Communication Engineering”, John Wiley and sons, 2004.

[16] J. Foerster, E. Green, V. S. Somayazulu and D. Leeper: “Ultra-Wideband Technology for Short - or Medium - Range Wireless Communications”, Intel Technology Journal, Q2, 2001.

[17] M. Z. Win and R. A. Scholtz: “Impulse Radio: How It Works”, IEEE Communications Letters, Vol.2, No.1, 01-1998.

[18] J. Ding, L. Zhao, S. Medidi and K. M. Sivalingam: “MAC Protocols for Ultra-Wide-Band Wireless Networks: Impact of Channel Acquisition Time”, in SPIE-ITCOM Conference.

[19] K. Pahlavan and P. Krishnamurthy: Principles of Wireless Networks: A Unified Approach, Prentice Hall, 2002.

[20] S. Ghassemzadeh et al.:“UWB Delay Profile Models for Residential and Commercial Indoor environments”, IEEE VTC Fall 2003, Orlando, USA.

[21] G. R. Opshaung and P. Enge:“GPS and UWB for Indoor Navigation”, Institute of Navigation’s GPS Conference, September 2001, Salt Lake City, UT, USA.

[22] Jeffrey R. Foerster: “The Effects of Multipath Interference on the Performance of UWB Systems in an Indoor Wireless Channel”, Intel UWB Research, Hillsboro Labs, OR, USA.

[23] K.Romer: “Time Synchronization in Ad Hoc Networks”. In ACM MOBIHOC 2001.

[24] L. Meier, P.Blum and L.Thiele: “Internal Synchronization of Drift-Consistent Clocks in Ad-Hoc Sensor Networks”, In ACM Mobihoc 2004.

[25] A. Hicham, Y. Souilmi and C. Bonnet: “Self-balanced receiver-oriented MAC for ultra-wide band mobile ad hoc networks”, International Workshop on Ultra Wideband Systems, June 2003.

[26] F. Cuomo, A. Baiocchi, F. Capriotti, C. Martello: “Radio Resource Optimisation in an UWB Wireless Access”, Proceedings of IST Mobile Communications Summit 2002, Thessaloniki, Greece, June 17-19 2002, pp. 723–727.

[27] S. Kolenchery, J. Townsend and J. Freebersyser: “A Novel Impulse Radio Network for Tactical Military Wireless Communications”, in IEEE MilCom 1998.

[28] L. J. Greenstein, S. S. Ghassemzadeh, S. C. Hong, Member, V. Tarokh: “Comparison Study of UWB Indoor Channel Models”, IEEE Transactions on Wireless Communications (to appear)

[29] A.A.M. Saleh and R.A. Valenzuela: “A statistical model for indoor multipath propagation, IEEE J. Sel. Areas in Commun., vol. SAC-5, no. 2, pp. 128-137; Feb. 1987”

[30] D. Cassioli et al.: “The Ultra-Wide Bandwidth Indoor Channel: From Statistical Model to Simulations”, IEEE JSAC vol.20, August 2002.

[31] M.G. Di Benedetto and G Giancola: “Understanding Ultra Wide Band Radio Fundamentals”, Prentice Hall 2004

[32] I. Broustis, S. Krishnamurthy, M. Faloutsos, M. Molle and J. R. Foerster: “A Multiband MAC Protocol for Impulse-Based UWB Ad Hoc Networks”, IEEE SECON 2005.

[33] L. De Nardis and M.G. Di Benedetto: “Medium Access Control Design for UWB Communication Systems: Review and Trends”, Journal of Communications and Networks, December 2003.