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Cross-layer Design of Private MAC with TH-BPPM and TH-BPAM in UWB Ad-hoc Networks

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ABSTRACT

Ultra-wideband(UWB) is a killer technology for short-range wireless communications. In the past, most of the UWB research focused on physical layer but the unique characteristics of UWB make it different to design the upper layer protocols than conventional narrow band systems. Cross-layer protocols have received high attention for UWB networks. In this paper, we investigate the performance of two physical layer schemes: Time Hopping Binary Pulse Position Modulation(TH-BPPM) and Time Hopping Binary Pulse Amplitude Modulation (TH-BPAM) with proposed private MAC protocol for UWB ad-hoc networks. From pulse level to packet level simulation is done in network simulator ns-2 with realistic network environments for varying traffic load, mobility and network density. Our simulation result shows TH-BPAM outperforms TH-BPPM in high traffic load, mobility and dense network cases but in a low traffic load case identical performance is achieved.

key Words : UWB, TH-BPPM, TH-BPAM, Cross-layer protocol, Private MAC, Ad-hoc network.

Ⅰ. Introduction

The basic idea of Ultra-wideband(UWB) for wireless communication starts in the late 1960s. In early 1990, it has gained a lot of attention as a radio transmission scheme for short-range wireless communications and has been approved by the Federal Communications Commissions(FCC) in 2002. Today, UWB technology has been considered as one of the most attractive candidates of wireless personal area networks(WPAN) with unique potential advantages such as high-rate, low-transmission power, immunity to multipath propagation, low capability of detection, capability in precise ranging and positioning. FCC defined UWB system as one having fractional bandwidth of 0.20 - 0.25 and assigned the unlicensed bandwidth from 3.1 GHz to 10.6 GHz[1]. UWB transmissions are allowed at very lower power levels(≤ - 41.3 dBm/MHz) so that it can co-exist with the existing narrowband systems. It is the most suitable technology for small-range wireless ad-hoc networks[2]. UWB systems can be single-band or multi-band. Our interest is on single band approach where each radio transmission will occupy the whole chunk of the permitted bandwidth and it is also called impulse radio(IR).

The Time Hopping(TH) spread spectrum scheme

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for IR-UWB is proposed in[3]. It was originally introduced to eliminate catastrophic collisions for multi-user environments. More attention is paid to TH-BPPM and TH-BPAM UWB systems. There are several studies on these systems [4-6] done by other researchers. Even though significant research has been done in the physical layer, upper layer communication paradigm for UWB networks is not clear till now. Thanks to the unique physical properties of UWB, we should assess these potential properties from the upper layer to improve communication performance. In our knowledge, there is no literature regarding the direct impact of the physical layer schemes: TH-BPPM and TH-BPAM with upper layer protocols in UWB ad-hoc networks.

Physical aware or cross-layer MAC protocols have received high attention for UWB networks where physical layer scheme act as a mirror image of the MAC layer. An analysis for UWB network is introduced in[7]. Authors search for a jointly optimal routing, scheduling and power control scheme for UWB networks. In[8] DCC-MAC is proposed that adapts the channel code to the level of interference and send incremental redundancy as required using puncturing bits. In a different work[9], a CSMA/CA based MAC protocol called medium access control with concurrent transmission (CT-MAC) is introduced. For a given bit error rate and a transmission rate, UWB can effectively support concurrent transmissions within the receiving range of a receiver node as long as they are outside an exclusion region. But the optimization problem and extra information exchange overhead make it less advantageous and also more and more difficult in the view of protocol implementation.

Our goal is to avoid exclusion region by using unique TH code spreading in the protocol level for parallel transmissions. In this work, we carry out a systematic performance evaluation of TH-BPPM and TH-BPAM with upper layer protocol. We want to extract the relative nature of these physical layer schemes in the network viewpoint. The motivation is that a better understanding of the relative merits will serve as a cornerstone for the development of more effective cross-layer protocols for UWB ad-hoc networks.

The remaining of this paper is organized as follows. In section II, system models for TH-BPPM and TH-BPAM are provided. In this section we also outline the Private MAC protocol that is used as an upper layer protocol. In section III, we present a critique of the two physical layer schemes that will cause performance variation in cross-layer protocol implementation. Section IV describes our simulation model and obtained results in detail. Finally, conclusion is presented in section V.

Ⅱ. System Description

2.1 TH-BPPM System Model

We model our asynchronous TH-BPPM UWB system with N_u active users. Assume that each user has a unique TH code for transmission. A typical transmitted signal of the *k*-th user can be expressed as

$$s_{BPPM}^{(k)}(t)=\sqrt{\frac{E_b}{N_s}}\sum_{j=-\infty}^{+\infty} w(t-jT_f-c_j^{(k)}T_c-d_{\lfloor j/N_s\rfloor}^{(k)}\delta)\ , \qquad (1)$$

where t is time, $w(t)$ is a pulse waveform shown in Fig.1 such that $\int_{-\infty}^{+\infty} w^2(t)dt=1$, E_b is the information bit energy, N_s is the number of pulses used to transmit a single information bit in TH-UWB systems, called code repetition length, δ is the delay for BPPM modulation, T_c is the chip time, T_f is the frame time and $c_j^{(k)}$ is the TH code for the *k*-th source; it is a pseudorandom integer value in the range $0\le c_j^{(k)}<N_h$, where N_h is the number of hops such that T_f = N_hT_c, $d_j^{(k)}\in\{0,+1\}$ is the *j*-th binary data bit transmitted by *k*-th source and the bit duration is T_b = N_sT_f .

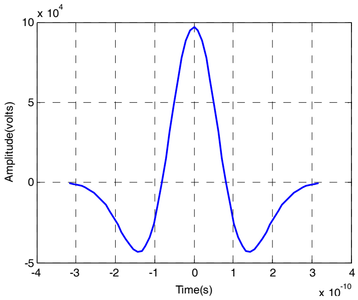

Fig. 1. Pulse waveform(gaussian monocycle) with shape factor 0.2877 ns

We consider all N_u users are transmitting asynchronously on an AWGN channel, and then the received signal is

$$r_{BPPM}(t) = \sum_{k=1}^{N_u} A_k s^{(k)}(t-\tau_k) + n(t) \quad , \qquad (2)$$

where $s^{(k)}(t)$ is the TH-BPPM signal, $n(t)$ is additive white gaussian noise with two sided power spectral density $N_0/2$, $\{A_k\}_{k=1}^{N_u}$ represents the channel gains for all transmitted signals and $\{\tau_k\}_{k=1}^{N_u}$ represents time shift due to user asynchronisms. A major restriction to UWB networks is multi-user interference (MUI). Under the assumptions and analysis in [6] we model total MUI for (N_u - 1) interfering signals as

$$I_{BPPM} = \sqrt{\frac{E_b}{N_s}} \sum_{k=2}^{N_u} A_k \sum_{m=0}^{N_s-1} \sum_{j=-\infty}^{+\infty} \tilde{R}(c_j^{(k)} T_c + \delta d^{(k)}_{\lfloor j/N_s \rfloor} + \tau_k - (m-j)T_f) \quad . \qquad (3)$$

Then, the bit error probability for the desired user is

$$P_{eBPPM} = \frac{1}{2} - \frac{1}{\pi} \int_0^\infty \frac{\sin(A_1 \sqrt{E_b N_s} \tilde{R}(\delta)\omega)}{\omega} \Phi_I(\omega) \exp\left(\frac{-\sigma_n^2 \omega^2}{2}\right) d\omega \quad , \qquad (4)$$

where $\Phi_I(\omega)$ is the characteristic function (CF) of the total MUI and σ_n^2 is the variance of the noise component for TH-BPPM. With standard gaussian approximation and assuming $\tau^{(k)}$ is uniformly distributed over [0, T_b], the received signal to interference and noise ratio (SINR) for N_u active link is

$$SINR_{BPPM}(N_u) = \frac{E_w N_s (1-\tilde{R}(\delta))^2}{N_0(1-\tilde{R}(\delta)) + \frac{M_{BPPM}}{T_f} \sum_{k=2}^{N_u} E_w^{(k)}} \quad , \qquad (5)$$

where E_w is the received energy for one pulse, $\tilde{R}(\delta)$ is autocorrelation value for the pulse waveforms and M_{BPPM} is the modulation parameter for BPPM.

2.2 TH-BPAM System Model

A typical transmitted signal of the k-th user can be expressed as

$$s^{(k)}_{BPAM}(t) = \sqrt{\frac{E_b}{N_s}} \sum_{j=-\infty}^{+\infty} d^{(k)}_{\lfloor j/N_s \rfloor} w(t - jT_f - c_j^{(k)} T_c) \quad , \qquad (6)$$

where $d_j^{(k)} \in \{+1, -1\}$ is the j-th binary data bit transmitted by k-th source and all other notations and terminologies are same as (1).

When N_u active users are transmitting asynchronously on an AWGN channel, the received signal is

$$r_{BPAM}(t) = \sum_{k=1}^{N_u} A_k s^{(k)}(t-\tau_k) + n(t) \quad , \qquad (7)$$

where $s^{(k)}(t)$ is the TH-BPAM signal and others are same as (2). Under the assumptions and analysis in [6] we model total MUI for (N_u - 1) interfering signals as

$$I_{BPAM} = \sqrt{\frac{E_b}{N_s}} \sum_{k=2}^{N_u} A_k \sum_{m=0}^{N_s-1} \sum_{j=-\infty}^{+\infty} d^{(k)}_{\lfloor j/N_s \rfloor} R(c_j^{(k)} T_c + \tau_k - (m-j)T_f) \quad . \qquad (8)$$

Then, the bit error probability for the desired user is

$$P_{eBPAM} = \frac{1}{2} - \frac{1}{\pi} \int_0^\infty \frac{\sin(A_1 \sqrt{E_b N_s} \omega)}{\omega} \Phi_I(\omega) \exp\left(\frac{-\sigma_n^2 \omega^2}{2}\right) d\omega \quad , \qquad (9)$$

where $\Phi_I(\omega)$ is the CF of the total MUI for TH-BPAM. With standard gaussian approximation and assuming $\tau^{(k)}$ is uniformly distributed over [0, T_b], the received SINR for N_u active link is

$$SINR_{BPAM}(N_u)=\frac{E_w N_s}{\frac{N_0}{2}+\frac{M_{BPAM}}{T_f}\sum_{k=2}^{N_u}E_w^{(k)}}, \qquad (10)$$

where E_w is the received energy for one pulse and M_{BPAM} is the modulation parameter for BPAM.

2.3 Private MAC Protocol

The proposed private MAC protocol was introduced with dynamic channel coding and incremental redundancy as in[8]. We model the proposed Private MAC protocol with a small modification. The dynamic channel coding and incremental redundancy are removed and the upper layer is simplified, because we want to extract the actual physical layer performance in cross-layer protocol implementation. We moved the interference handling from MAC layer to the physical layer and the physical layer will keep reception(R_x), transmission(T_x), collision and idle state that is simply mirrored by the MAC layer. Each receiving node in the network will maintain a list of all ongoing packet transmissions for average interference and at the end of packet reception calculates the SINR to determine the bit error from a lookup table. Thus the received SINR in a node directly impact on the MAC layer packet error and hence packet retransmissions.

The received power from an interferer within exclusion region is much larger than the power of a pulse received from the source outside an exclusion region. To manage interference from the close interferer within exclusion region we used interference mitigation scheme as in[10]. So for the bit level decision we used a threshold demodulator and declare an erasure when the received energy is larger than the defined threshold. The resulting rate reduction due to erasures is much smaller and we consider this by the cost of reduced complexity for low data rate applications. The optimal value of the threshold(D) depends on both the power of the interferer and the white noise. It is found that a suitable value of the threshold is $D = 3N + X$, where N is the average white noise power and X is the estimated received signal power [8].

We used typical hybrid ARQ process. When a potential sender wants to send a packet to a destination; it adds a CRC to the packet and encodes it with a fixed rate then sends with maximum available power; as power control is useless in UWB[11]. After receiving the packet, destination node decodes the data and checks the CRC. If the decoding is successful, a positive acknowledgement(ACK) is sent back to the sender. Otherwise, a negative acknowledgement (NACK) is sent for retransmission. If the receiver cannot even detect reception of data, it cannot send a NACK. In this case the sender will timeout and takes attempts for next transmission.

Many senders may communicate simultaneously within the same collision domain and a sender cannot know if the intended receiver is idle or busy other than by actively listening to packets to or from it. The proposed private MAC protocol solves this problem by a combination of receiver-based and invitation-based time hopping code spreading in the protocol level. Contention for a destination uses the public time hopping sequence(THS) of the destination but an established communication uses the private THS to a source-destination pair. The public THS of a user with MAC address A is the THS produced by a pseudo-random number generator (PRNG) with seed A. The private THS of users A and B is the THS produced by the PRNG with a seed equal to the binary representation of the concatenation of A and B.

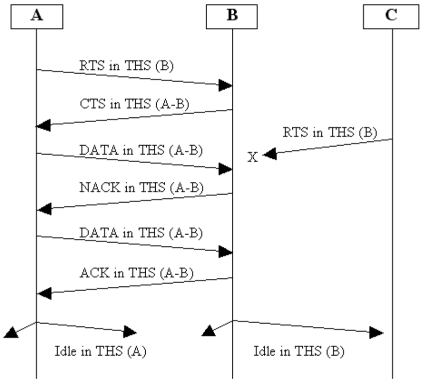

Fig. 2. Private MAC

In the idle state all nodes in the network will be in the listen mode at its own public THS. As shown in Fig.2, when a potential node A has a data packet to send to a destination node B, it sends a RTS in B's public THS. Node B responds with a CTS using private THS of the pair A-B. Then A starts transmitting the data packet on the THS private to A and B. After the transmission, node A listens for an ACK sent by node B on the private THS. If a NACK is received the sender will retransmit the packet. If no ACK or NACK is received, node A retries transmission after a random backoff, up to a certain retry limit. After a transmission, both sender and receiver issue a short idle signal each on their own public THS to inform other nodes that they are idle.

Other node C may wish to communicate with node B that is receiving a packet from node A. Node C sends out a RTS to node B; this will create some interference but will usually not disrupt the private communication between A and B, since it is on a different THS. Node C then switches to B's public THS and listens for the idle signal. When it hears the idle signal, it waits for a random small backoff time. If the timer expires without the node overhearing a RTS from another node, a RTS is sent. Otherwise, the node defers transmission and pauses the backoff timer until it hears the idle signal again.

Ⅲ. TH-BPPM versus TH-BPAM

We are interested in designing a cross-layer protocol, so physical layer scheme selection is very important to achieve the desired performance. Our goal is to increase network throughput by concurrent transmissions without considering exclusion region. In a real network, many senders may communicate simultaneously in the same collision domain. So multi-user interference is a crucial issue to design a novel cross-layer protocol. To manage these interferences we used interference mitigation with the conjunction of TH-BPPM and TH-BPAM.

BPPM and BPAM modulation schemes are adopted to modulate the information data symbols. However, there are several important differential parameters, which may give rise to significant performance variations in cross-layer protocol implementation. In case of BPPM, optimization of δ is important. When $R(\delta) = 0$, the modulator uses orthogonal signaling but if $R(\delta) > 0$, the receiver experiences a loss in performance, that is, an increased signal energy is required to achieve the same error probability as orthogonal signaling. Only if $R(\delta) < 0$, moderate performance is achieved. Whereas in BPAM, received signal to thermal noise power ratio is half the energy on the bit compared to orthogonal BPPM. This can lead BPAM a better performance than BPPM in cross-layer protocol implementation.

Now we characterize BPPM and BPAM considering robustness against MUI. Assuming all delays and codes are independent and pulse collision in one frame is independent from collisions occurring in all other frames. Then the modulation parameter M_{BPPM} and M_{BPAM} affects corresponding SINR, and consequently the bit error. A comparative analysis of these two parameters is simulated in Fig.3 with varying modulation delay. It is found that M_{BPPM} asymptotically tends to be a value that is twice the value of M_{BPAM}. Again it is found form the exact analysis as in[6] that average bit error rate (BER) decreases with increasing SINR in the same trend for BPPM and BPAM for 7 asynchronous interferers with code repetition length 4. But BPAM performs better than BPPM by 2 dB at BER 10^{-3} and the difference increases slightly at lower BER. This performance degradation in BPPM will significantly affect the cross-layer protocol implementation.

In the UWB ad-hoc network scenario, communicating nodes may spontaneously leave and join a group due to mobility and traffic generated from applications. In the absence of a coordinating unit, this implies the spontaneous transmissions of a node will have a significant impact on the transmission and reception of other nodes. So a mobile node will create more or less interference

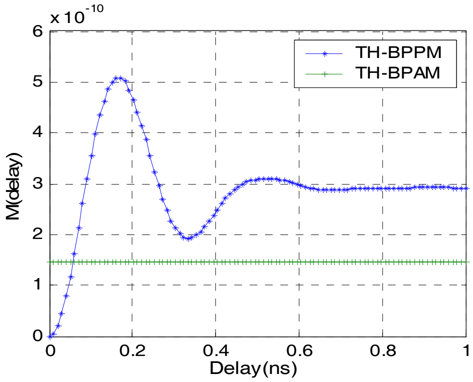

Fig. 3. M(delay) function for TH-BPPM and TH-BPAM with shape factor 0.2877 ns

to its collocated active nodes in a time varying nature. This time varying interference must be controlled in the physical layer in an efficient manner. Better robustness against MUI of TH-BPAM will also lead it to perform better than TH-BPPM in cross-layer protocol implementation for mobile nodes. Thus a novel cross-layer protocol interaction will allow several spontaneously co-existing nodes to share the same bandwidth with increased network efficiency and better quality of service(QoS) support.

In traditional exclusion based MAC protocols such as IEEE 802.11[13], there is no modulation scheme; hence no bit error. In the physical layer, it only implements some threshold level for the reference distance. For the communication process, sender and receiver exchange RTS and CTS frames having information regarding the identity of the destination node and the length of the data packet to be transmitted. Any other node, which hears either the RTS or CTS frames, must use the data packet length information to update its network allocation vector(NAV). NAV indicates the period for which the channel will remain busy and other nodes should avoid starting a transmission, so the entire region within the radio range of a transmitter node and its intended receiver node is exclusively reserved. As no other nodes within the exclusion region can transmit concurrently, there will be significant throughput degradation in comparison with exclusion free cross-layer protocol.

Table 1. Simulation Parameters.

Item	Value
Transmitted power	-3 dBm
Received threshold	-96 dBm
Simulation time	30 sec
Propagation model	Tarokh [12]
Bandwidth	18 Mbps
Frequency	5 GHz
IFQ length	50 packets
Routing protocol	AODV
TH chip time	0.9 ns
Frame time	14.4 ns
Code repetition length	4
Pulse shape factor	0.2877 ns
Modulation parameters	δ = 0.15 ns $R(\delta)$ = -0.6183 M_{BPPM} = $5.001e^{-10}$ M_{BPAM} = $1.4508e^{-10}$

Ⅳ. Simulation and Results

We performed pulse-level to packet-level simulation in the network simulator ns-2 [14] with realistic physical layer model for UWB. Each receiving node in the network maintains a list of all ongoing packet transmissions and at the end of packet reception calculates the SINR to determine the bit errors from a lookup table. We used code repetition length N_s = 4 and frame time T_f = 14.4 ns, hence maximum data rate can be achieved R_b = $1/(N_sT_f)$ = 18 $Mbps$. In our simulation we used 16 nodes in a randomly generated network topology as shown in Fig.4. We randomly select half of the nodes as transmitter and remaining half as receiver. So we have 8 concurrent transmitters randomly selected from the network. Each data point represents an average of at least three runs with identical traffic models but different randomly generated network topology. The traffic sources are continuous bit rate(CBR). We assume that all nodes in the network have the identical physical module and transmit with the maximum available power when it has packet to transmit. Other simulation parameters are summarized in Table 1.

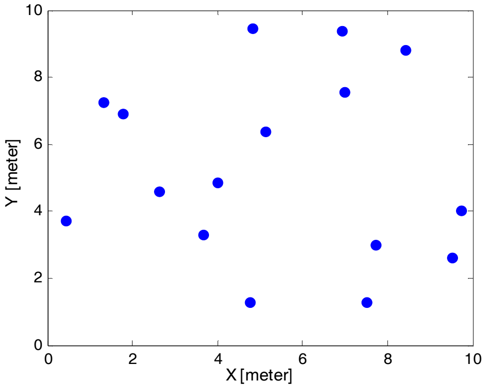

Fig. 4. Random topology generated with 16 nodes in a 10x10 square meter area

Fig.5 shows average network throughput per active user for TH-BPPM and TH-BPAM in a 10x10 square meter network size with CBR packet generation interval 0.001 seconds. We compared the performance for different packet size with simulation time. We found that TH-BPAM outperforms TH-BPPM by a factor 2.64 for packet size of 512 byte and by 1.87 for packet size of 256 byte. This result proves that TH-BPAM can combat MUI significantly compared to TH-BPPM in a real network. The reduced MUI in TH-BPAM leads smaller packet error than TH-BPPM; hence small retransmission in the protocol level. We also compared the throughput achieved with traditional exclusion based protocol IEEE 802.11 and find a significant throughput improvement for cross-layer or physical aware upper layer protocols.

Fig.6 shows average network throughput achieved by TH-BPAM and TH-BPPM in a 10x10 square meter network size with different CBR packet generation intervals. It is found that in heavy traffic or bursty load case TH-BPAM outperforms TH-BPPM. In case of CBR packet generation interval 0.001 seconds TH-BPAM outperforms TH-BPPM by a factor 2.64 for packet size 512 byte and by a factor 1.87 for packet size 256 byte, but as the traffic load decreases, their performance also decreases and approaches to an identical value. It is found from Fig.6 that when the offered traffic is reduced by a factor 10(at packet generation interval 0.01) TH-BPAM outperforms TH-BPPM by a factor 1.32 for packet size 512 byte and by a factor 1.05 for packet size 256 byte and finally their performance becomes identical at CBR packet generation interval 0.05 seconds. This occurs as in a reduced offered traffic loads, the packet delivery fraction for both TH-BPAM and TH-BPPM becomes identical. The packet error in TH-BPPM may be higher but it has enough time for retransmission before delivering the next packet.

Fig.7 shows the average network throughput performance in different network densities for TH-BPPM and TH-BPAM with CBR packet size 256 byte and packet generation interval 0.001 seconds. For all network sizes we used 16 random nodes and 8 concurrent transmitters are selected randomly. We define network density as the number of nodes in a square meter area and used network density 0.64, 0.16 and 0.07. It is found from Fig.7 that in lower network densities throughput performance decreases compared to higher network densities. When network density decreases by a factor 4; in TH-BPAM throughput decreases by 8% and in TH-BPPM it decreases by 3%. This is because distance between communicating entities increases. This result also proves that interference mitigation perform well in dense networks. And it is not practical to have effective receptions when a receiver node is collocated with an interfering node without using interference mitigation scheme.

Fig.8 shows average network throughput achieved for TH-BPPM and TH-BPAM in a 10x10 square meter area with 16 mobile nodes and 8 randomly selected concurrent transmitters. We used CBR packet size of 256 byte with packet generation interval 0.001 seconds. We consider moving speeds: 0.5 *m/s*(1.8 *km/hr*), 1.0 *m/s*(3.6 *km/hr*) and zero for the static case. We fixed the pause time to zero for the mobility scenarios and a mobile node starts its journey with a random speed from zero to its maximum limit. Fig.8 shows that TH-BPAM outperforms TH-BPPM by a factor 1.8 and with increasing mobility throughput performance degrades, since the link stability becomes worsen.

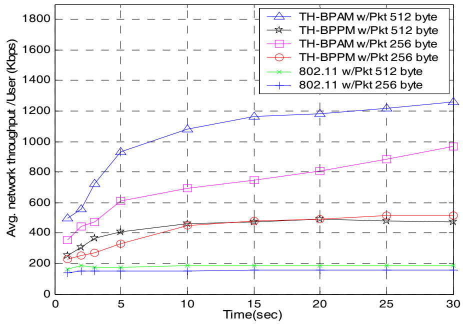

Fig. 5. Average network throughput per user in a 10x10 network size

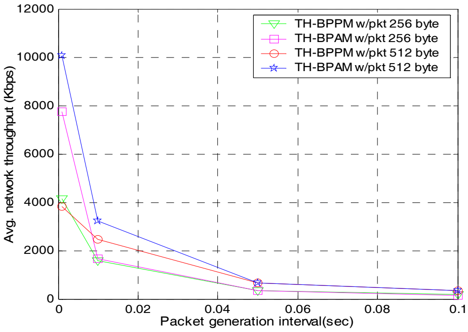

Fig. 6. Average network throughput for varying packet generation interval in a 10x10 network size

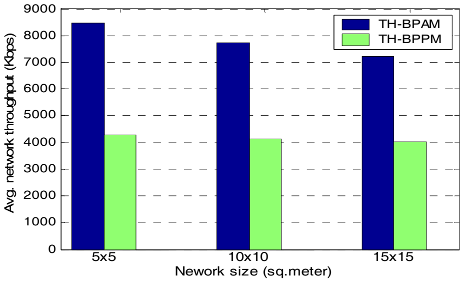

Fig. 7. Average network throughput for varying network density

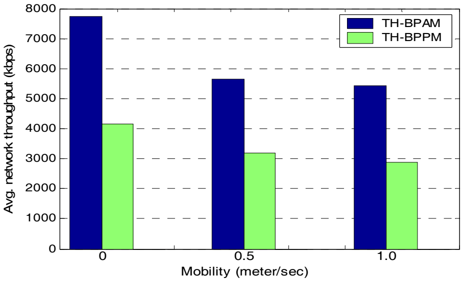

Fig. 8. Average network throughput for different mobility in a 10x10 network size

V. Conclusion

In this paper, we evaluate the performance of TH-BPPM and TH-BPAM with Private MAC protocol in a realistic network simulation environment. Our investigation will lead to design an optimal cross-layer protocol for UWB ad-hoc networks. To implement pulse level to packet level simulation detail modeling in system level and protocol level is analyzed. We also compare the performance with traditional exclusion based MAC protocol. Throughout our investigation, we find that TH-BPAM outperforms TH-BPPM in high traffic load, mobility and dense network cases but in a low traffic load case identical performance is achieved. We don't consider channel coding and energy consumption in our works. Further analysis is needed with considering these factors. Future works will deepen our research on optimal cross-layer protocol design for UWB ad-hoc networks.

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