Performance of Slotted-Aloha over TH-UWB

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***Abstract*—In the IEEE 802.15.4a UWB-PHY standard for Low Rate WPANs (LR-WPANs), the UWB-PHY provides Time-Hopping (TH) to enable multiple users to transmit simultaneously, thereby potentially increasing the overall system throughput. However, the intrinsic properties of the impulse-based UWB renders existing narrowband MAC protocols which make use of carrier sensing unsuitable for use in UWB systems. In the standard, Aloha has been proposed as the MAC protocol. 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 *random* time-hopping can be detrimental to the throughput performance of the network. An optimal method of assigning TH codes to the different symbols in each packet is necessary in order to exploit the benefits of time-hopping, which can potentially allow concurrent transmissions in multi-user systems.**

***Index Terms*—MAC, normalized throughput, slotted-Aloha, Time-Hopping, UWB**

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 the 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 pioneering 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 and are typically centralized protocols which may not be able to scale well in large networks. 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.

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

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 $C_{n+kN_{cpb}} \in 0, 1,\ n = 0, 1, \ldots, N_{cpb} - 1$ 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:

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

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. The small-scale fading in UWB channels can be characterized by the Nakagami distribution with pdf:

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

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:

$$R(t) = \sum_{p=1}^{K}[A_p S_p(t - \delta_p)] + n(t) \qquad (5)$$

where A_p represents the attenuation of the signal from transmitter p; δ_p represents the propagation delay of the signal from transmitter p; and $n(t)$ is white Gaussian receiver noise.

We obtain throughput results for slotted-Aloha over TH-UWB using packet-by-packet theoretical analysis (Section III-B) and symbol-by-symbol simulations (Section IV). In the packet-by-packet analysis, each packet is transmitted using a single TH code, and 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:

$$\frac{S_0}{N_0 + I} > T \qquad (6)$$

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

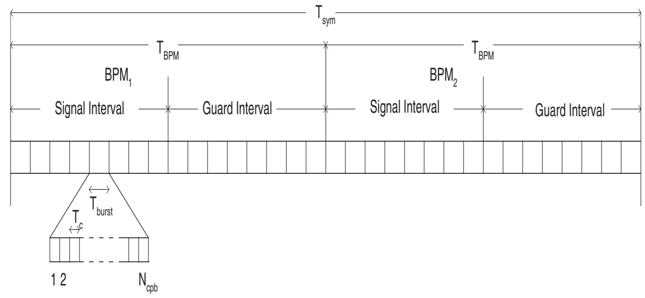

Fig. 1. IEEE 802.15.4a-UWB PHY symbol structure

The value of of I can be calculated as follows:

$$I = \sum_{i=1}^{N_I} S_i \qquad (7)$$

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

In the symbol-by-symbol simulations, an entire packet is discarded as long as the SINR value of any *one* symbol does not satisfy Equation 6.

C. IEEE 802.15.4a-UWB Symbol Structure

The symbol structure of IEEE 802.15.4a with a 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 the 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}. In addition, 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 [5].

III. Slotted Aloha over TH-UWB

A. *The Slotted-Aloha MAC Protool*

The IEEE 802.15.4a standard proposes the Aloha MAC protocol over the UWB PHY. In Aloha, a node that wishes to transmit will do so 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 normalized throughputs of Aloha and slotted-Aloha MAC protocols in single channel narrowband systems with Poisson packet arrivals are approximately $\frac{1}{2e}$ (18.4%) and $\frac{1}{e}$ (36.8%) 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 when there is an optimal assignment of TH codes to the nodes that enables them to transmit simultaneously without collisions. In this paper, we study the effect of varying the TH codes on a packet-by-packet basis (Section III-B) as well as on a symbol-by-symbol basis (Section IV) and obtain the normalized throughputs of the slotted-Aloha MAC protocol over a UWB PHY.

B. *Analysis*

In this section, we provide an analytical model for the performance of slotted-Aloha with TH codes 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 slot sizes of one packet transmission duration each. We also assume that the number of time-hopping positions 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 a mean of 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 (in packets/sec) 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 (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 conventional slotted-Aloha case where the result is either one or nothing. Another important difference in the case of slotted-Aloha with TH is that the per node throughput available is $\frac{1}{N_{TH}}$ of that available in slotted-Aloha (without TH).

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 $i \leq min\{j, N_{TH}\}$. The average number of packets that can be successfully transmitted for a given j is:

$$E_j = \sum_{1 \leq i \leq min\{j, N_{TH}\}} i * P(i, j, N_{TH}) \tag{10}$$

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

$$\frac{1}{N_{TH}} \sum_{1 \leq j \leq K} P_j E_j \tag{11}$$

We normalize by $\frac{1}{N_{TH}}$ since a maximum of N_{TH} packets can be transmitted in a slot. Note that the values of $P(i, j, N_{TH})$ depend on the choice of the time-hopping codes. In the worst case, all nodes shared a single time-hopping position 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. This is achieved when each node is statically assigned a distinct time-hopping position and N_{TH} packets are successfully transmitted in one slot.

In the next section, we will determine through simulations, the normalized throughput for the case when TH codes are randomly chosen, on a symbol-by-symbol basis.

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 a UWB-PHY and slotted-Aloha MAC protocol for TH-UWB. In our implementation of slotted-Aloha, we consider neither acknowledgements nor retransmissions, and we do not consider the effects of synchronization overheads. 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. The values of n and σ_S in Equation 3 are taken to be 1.79 and 2.22 respectively, which according to [6] represents a residential LOS environment. The Nakagami fading model is used, and approximated as the superimposition of the Rayleigh and Ricean distributions with an average Nakagami-m factor of 5.0. Generally, BER curves are obtained through Matlab simulations or experiments. We make use of the BER vs $\frac{E_b}{N_0}$ data which is obtained via Matlab experiments by the Institute for Infocomm Research (I^2R), 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, for each received symbol. The BER is then converted to the corresponding error probability to evaluate the condition of each symbol at the receiver; the presence of any corrupted symbol causes the entire packet to be discarded. 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 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 of L bits to a specific destination according to a Poisson traffic model with a mean packet arrival rate τ. We vary the traffic load in two different ways: (i) increasing the number of source-destination pairs in the network (Section IV-B); and (ii) increasing the packet arrival rate of a small set of nodes (Section IV-C).

3) TH Codes: Each node transmits a total of $\frac{L}{2}$ symbols for a packet of length L. The slot length in the slotted-Aloha MAC protocol is of one packet duration. There are a total of N_{TH} TH codes (or possible hopping positions); each symbol in each packet is transmitted using an assigned TH code. The assignment of the TH codes is done in two ways: (i) random; and (ii) pre-computed optimal. In the former, the TH code used by each symbol is randomly selected from a uniform distribution (between 1 to N_{TH}). In the latter, all transmitting nodes are assumed to pick different and non-conflicting TH codes for each symbol during each packet transmission; however, this is subject to the requirement that the total number of transmitting nodes is less than N_{TH}. As the length of the slot is proportional to N_{TH}, 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 parameters used in our simulations are summarized in Table I.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
Terrain Size	8m × 8m
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, 6, 8 }
Burst Duration T_{burst}	32.05 ns
Packet Arrival Rate (per source) τ	1000 to 10000
Packet Length L (after FEC encoding)	56 bytes

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 1000 packets/second. According to the standard, a data rate of 0.85 Mbps can be achieved with N_{TH} = 8. For the purpose of comparison, we also simulate using different TH values ranging from 1 to 8, denoted as TH-1, TH-2, TH-4 and TH-8 to represent N_{TH} = 1, 2, 4 and 8 respectively.

Figure 2 shows the throughput performance of the network in a system with a large population of nodes. Generally, the normalized throughput increases with the increase in the number of sources (traffic load) until the saturation point at a normalized load of 1.0 (which is equivalent to 32 users). After which, 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 over single channels at the physical layer [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}. Recall from Equation 10 that the average number of successful transmissions depends on the number of transmitting users and the likelihood of these users choosing different TH codes. Larger N_{TH} values reduce the probability of TH collisions for the same number of users, and vice versa for smaller N_{TH} values. However, a larger N_{TH} value also increases the packet transmission time, leading to more nodes transmitting simultaneously with the same load. Our result shows that the increase in collisions caused by longer packet transmission times (more contenting users) has a larger impact than the benefit of having more TH codes. The overall result is that larger N_{TH} leads to more collisions and lower throughput.

C. Small Finite Population

The throughput performance of slotted-Aloha over TH-UWB when the number of users in the system is relatively small is illustrated in Figure 3. There are a total of 16 nodes in the network, which form 8 unique source-destination pairs. The normalized load is increased by increasing the packet arrival rate τ of each transmitting pair from 1000 to 10000, which subsequently reduces the inter-packet arrival time. The value of N_{TH} is varied from 1 to 8 and denoted by TH-1 to TH-8 as 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

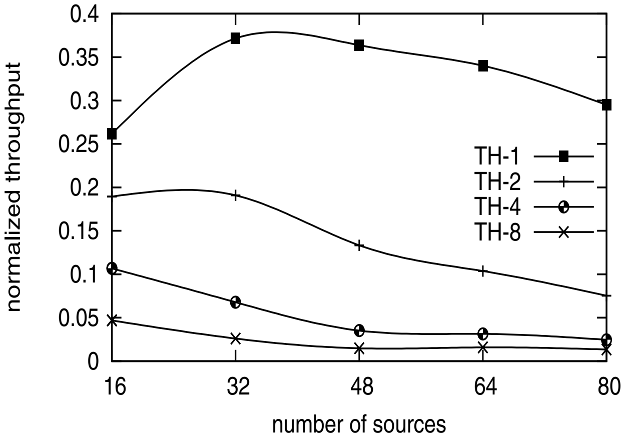

Fig. 2. System with large population

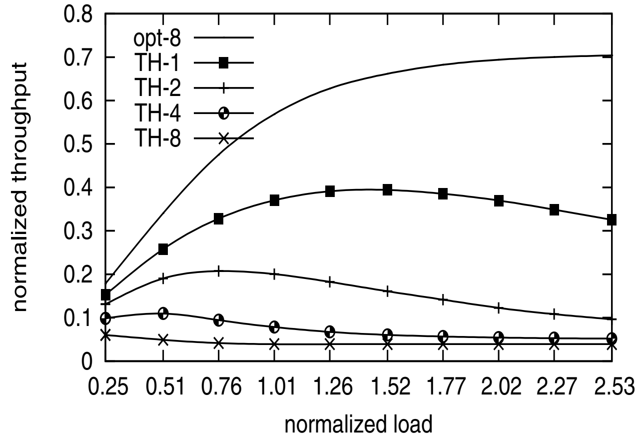

Fig. 3. System with 8 source-dest pairs

pairs are able to transmit concurrently without incurring any collisions - this is denoted by *opt-8* in the graphs.

The throughput of slotted-Aloha in a small finite population generally increases with the traffic load until a saturation point. After which, the performance of the network deteriorates due to excessive collisions of symbols that are transmitted using the same TH code when random assignment is used. This result is consistent with that published by Roberts in [9] for slotted-Aloha in the presence of capture, whereby the success of a transmission is dependent on the overall SINR value of the signal in the presence of interfering signals. Due to the larger slot lengths that are used with larger N_{TH} values, there are more nodes waiting for transmissions at the beginning of each time slot; this results in more overlapping transmissions from different source nodes per slot length. Hence, the performance of the network saturates more quickly and at lower throughput values for large N_{TH} values (e.g. $N_{TH} = 8$). The throughputs for smaller N_{TH} values at high loads are better since the smaller slot lengths reduce the number of concurrent transmissions among all the source nodes, and effectively alleviates collision effects.

With the presence of an optimal TH-assignment scheme, the throughput of the network at various traffic loads is significantly higher (see *opt-8*) than that for: (i) smaller N_{TH} values; and (ii) packets in which symbols are transmitted using randomly selected TH codes. This is possible as collisions are completely avoided when the symbols in each packet are transmitted using non-conflicting TH codes.

We also study the performance of the network when the number of sources in the system is less than N_{TH}, the number of available TH codes. Figure 4 shows the throughput attained by a network with $N_{TH} = 8$ and varying numbers of transmitting source-destination pairs. The packet arrival rate τ of each source node is fixed at 5000. As like in Figure 3, the throughput achieved with smaller N_{TH} values is generally better than that using larger N_{TH} values. However, it is interesting to note that when the network size is extremely small (with ≤ 4 transmitting pairs), using an optimal code allocation

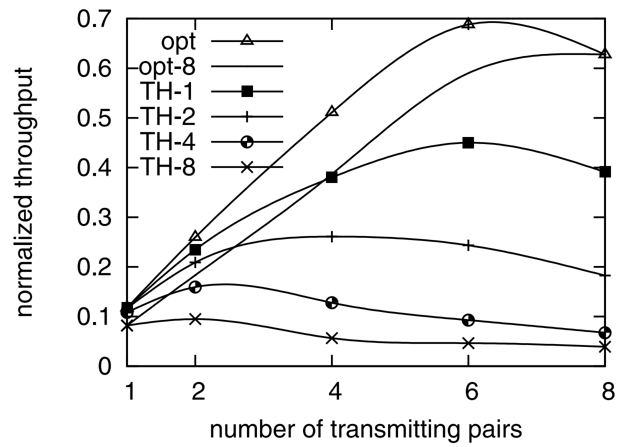

Fig. 4. System with different numbers of transmitting pairs

with $N_{TH} = 8$ (denoted as *opt-8*) does not provide any improvement in throughput performance. Conversely, if the value of N_{TH} varies according to the number of transmitting pairs in the network in an optimal code allocation scheme (denoted as *opt*), the performance of the network is always better than achieved by all other random allocation schemes.

Figure 5 illustrates the performance of the network with 8 unique source-destination pairs and varying packet sizes (which is proportional to the number of symbols transmitted per packet). The packet arrival rate τ at each source node is fixed at 5000. Here, it can be seen that the packet size has a significant effect on the throughput performance, and the throughput peaks at smaller packet sizes for larger N_{TH} values.

D. Overall Summary and Discussion

From the simulation results obtained in Section IV-B and Section IV-C, we can observe that the performance of slotted-Aloha with TH-UWB is dependent on the network density, traffic load, value of N_{TH} being used, as well as packet size.

In a large population (of up to 80 source-destination pairs), the performance of smaller N_{TH} values is better than that

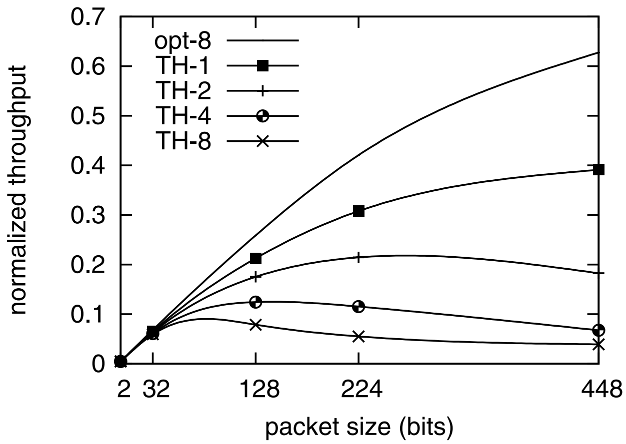

Fig. 5. System with 8 source-dest pairs and different packet sizes

for larger N_{TH} values due to more transmission opportunities within the same time interval. The advantage of lesser probability of collisions brought about by larger N_{TH} values is diminished in large populations, as the number of concurrently transmitting nodes is much greater than the number of TH codes available.

From our performance studies involving networks with a small finite population (of up to 8 source-destination pairs), it can be seen that throughput performance is dependent on traffic load, network size, as well as packet size. It appears that the performance of the network is generally poorer for large N_{TH} values if the TH codes are randomly assigned. This is due to the increased number of concurrent transmissions resulting from increased slot lengths (with larger N_{TH} values). However, if there is an optimal way to assign the TH codes to the transmitting node pairs, the overall network performance can be 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. In addition, large N_{TH} values are detrimental in very small networks as they increase slot lengths and deteriorate throughput performance.

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, network sizes, packet lengths and TH codes. Our simulation results reveal that *random* time-hopping can severely impact the throughput performance of the network. A proper and optimal assignment of TH codes to multiple users is crucial in order to exploit the advantages of concurrent transmissions among multiple nodes, which is possible with the use of TH codes.

While our result in this paper has demonstrated that random time-hopping does not provide significant throughput improvement over single-channel systems (i.e. TH-1), we believe that TH can be used to improve fairness in multi-user systems. As part of our future work, we will investigate how TH can be exploited to improve fairness in a UWB-based MAC protocol which is IEEE 802.15.4a standard-compliant.

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