Exclusive-Region Based Scheduling Algorithms for UWB WPAN

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***Abstract*— With the capability of supporting very high data rate services in a short range, Ultra-Wideband (UWB) technology is appealing to multimedia applications in future wireless personal area networks (WPANs) and broadband home networks. However, the WPAN Medium Access Control (MAC) protocol in IEEE 802.15.3 standard was originally designed for narrowband communication networks, without considering any specific features of UWB. In this paper, we explore the unique characteristics of UWB communications from which a sufficient condition for scheduling concurrent transmissions in UWB networks is derived: concurrent transmissions can improve the network throughput if all senders are outside the exclusive regions of other flows. We also study the optimal exclusive region size for a UWB network where devices are densely and uniformly located. Since the optimal scheduling problem for peer-to-peer concurrent transmissions in a WPAN is NP-hard, the induced computation load for solving the problem may not be affordable to the network coordinator, commonly a normal UWB device with limited computational power. We propose two simple heuristic scheduling algorithms with polynomial time complexity. Extensive simulations with random network topology demonstrate that, by exploiting the unique characteristics of UWB communications and allowing concurrent transmissions appropriately, the proposed exclusive-region based scheduling algorithms can significantly increase the network throughput.**

***Index Terms*— Ultra-Wideband (UWB), WPAN, IEEE 802.15.3, scheduling.**

I. INTRODUCTION

RECENT advances in semiconductor technology have made Ultra-Wideband (UWB) technology ready for commercial applications [1]. Consumer UWB products and prototypes delivering high data rate ($>$ 100 Mbps) multimedia traffic over short distance ($\leq$ 10 m) with very low power consumption have been emerging. In future wireless personal area networks (WPANs) or broadband home networks, multiple UWB devices can exchange high definition multimedia traffic, or deliver high-volume data to/from the Internet. To support high data rate multimedia applications in personal/home space, it is crucial to study the performance of UWB communications in a *networked* environment.

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A WPAN reveals different features from traditional wireless networks. As specified in IEEE 802.15.3 [2], several devices can autonomously form a piconet in which one of them is selected as the piconet coordinator (PNC). Similar to the role of base stations in cellular networks or access points in wireless local area networks (WLANs), the PNC coordinates the network access and allocates radio resources according to user requirements. Unlike these centralized counterparts, users in WPANs can communicate in a peer-to-peer fashion. Thus, the PNC is no longer the traffic bottleneck but enables resource allocation to its members. In addition, a WPAN can be established in an ad hoc manner allowing flexible configurations. Such a semi-ad hoc setting can provide better Quality of Service (QoS) than a pure ad hoc network. However, it is inherently difficult to quantify throughput/capacity and fairness for WPANs, which are not only dependent on the scheduling algorithm, but also highly sensitive to network topology and user deployment. As a result, a similar structure of WPAN to cellular systems does not imply that the resource allocation techniques functioning well in cellular networks can be directly applied to WPANs, and vice versa. In addition, the existing MAC protocol in IEEE 802.15.3 standard does not consider the distinct characteristics of UWB communications, and thus it is inherently inefficient for UWB based WPANs.

Different UWB systems, such as impulse-based direct sequence (DS)-UWB [3], and multi-band orthogonal frequency division multiplexing (MB-OFDM) based UWB [4], employ different techniques to spread the signal over the UWB spectrum, but all reveal the same nature of allowing concurrent transmissions. Generally concurrent transmissions reduce the signal to interference plus noise ratio (SINR) at the receiver end due to the increased multiple user interference (MUI). If the received SINR is lower than a prescribed threshold, the receiver can not decode the information correctly and the transmission is considered to be failed. This model, known as the *physical model* [5], considers the non-adaptive rate case, while in the context of adaptive modulation and coding technique, the sender can adapt its transmission rate to the SINR level to meet the bit error rate (BER) requirement by changing the coding rate or modulation scheme. For UWB communications, the later model is more adequate since adjusting transmission rate can be readily achieved by varying the spreading gain in DS-UWB or allocating different number of subcarriers in MB-OFDM.

In this paper, we explore the physical characteristics of UWB communications and point out the inefficiency of the existing resource allocation mechanisms for UWB networks. We then derive the sufficient condition which ensures that

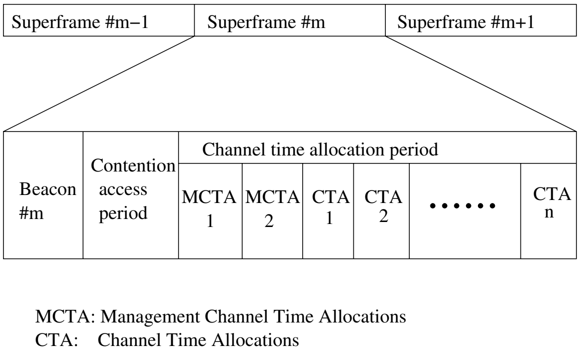

Fig. 1. Superframe structure defined in IEEE 802.15.3 MAC protocol.

concurrent transmissions are preferable in terms of network throughput improvement. Since the optimal scheduling problem for UWB networks is *NP-hard*, two simple heuristic scheduling algorithms are proposed. Extensive simulations demonstrate that, by allowing concurrent transmissions appropriately, the proposed scheduling algorithms can significantly increase the network throughput.

The remainder of this paper is organized as follows. We study the existing standard MAC protocols and discuss their pros and cons when they are applied to UWB networks in Sec. II. The system model and an asymptotic analysis of UWB network throughput are given in Sec. III. Practical MAC enhancement scheduling algorithms assigning concurrent transmissions for enlarging UWB network throughput are proposed in Sec. IV. The performance of the proposed scheduling algorithms and that of the existing scheduling algorithm used in IEEE 802.15.3 are compared in Sec. V, followed by the related work in Sec. VI. Concluding remarks and future research directions are presented in Sec. VII.

II. MAC Protocols

In IEEE 802.15.3 standard, communications among devices use a hybrid contention and contention-free MAC protocol. Since the scheduling performance is tightly coupled with the underlying MAC mechanism, we discuss the suitability of IEEE 802.15.3 MAC standard for UWB communications.

A. Contention Access Period

The IEEE 802.15.3 standard defines a superframe structure as shown in Fig. 1. Each superframe starts with a Beacon Period (BP) for network synchronization and control message broadcast. Devices then can access the channel using either the contention or contention-free mechanisms. In contention access period (CAP), devices send their resource requests to the PNC using carrier sensing multiple access/collision avoidance (CSMA/CA) in conjunction with a backoff procedure. To minimize collisions, the transmitter is required to first sense that the medium is idle for a random length of time. Only if the medium is idle after that time shall the device start its transmission.

The advantage of the contention-based MAC protocol is that it does not require a centralized controller nor synchronization between the devices and the network controller. However, according to the Federal Communications Commission's (FCC) regulation, marketing and operation of UWB devices are permitted under the conditions that the mean transmission power must not exceed -41 dBm/MHz, and the peak/mean power ratio must be less than 20 dB [18]. Consequently, the extremely low power spectral density (PSD) of UWB communications challenges the efficiency of carrier-sensing functionality that is widely used in today's WLAN[1] for detecting the channel activities. Without carrier sensing, collisions can not be avoided in contention-based access control. As UWB devices are primarily operated in dense networks, severe contentions could make the network very unstable. Moreover, the delay guarantee is difficult if not impossible using the contention-based transmissions.

Therefore, we anticipate that UWB networks will most likely deploy a contention-free MAC for high bandwidth multimedia traffic with stringent QoS requirements, and use the CAP mainly for resource request messages.

B. Contention-Free Period

Besides the BP and CAP periods, the remaining time of a superframe is occupied by the contention-free period named channel time allocation period (CTAP) using time division multiple access (TDMA). The PNC of a piconet can allocate channel time for both isochronous streams or asynchronous data traffic using the TDMA discipline. However, TDMA is very inefficient for UWB networks, which can be explained as follows. For DS-UWB communications, the acquisition time required by the high-precision synchronization usually varies from microseconds to milliseconds [19]. Taking a TDMA-based DS-UWB network with a 480 Mbps channel for example, the time to transmit a packet with 1024 bytes is only 17.06 μs. But if the acquisition time for each packet is 15 μs (the default preamble length in [3], [20]), neglecting other timing components and overheads, the transmission efficiency (the fraction of time used for actual data transmission) is reduced to only 53.2%. Similarly, for MB-UWB, considering the overhead of the physical and MAC layers, transmitting a single packet with 1024 bytes over a 480 Mbps channel, the throughput is only 195.6 Mbps [4], *i.e.,* the transmission efficiency is only 40.75%. For realtime traffic with small packet size, the efficiency is even lower. In summary, to support high-data-rate multimedia applications in densely populated UWB WPANs, there remains considerable margin of transmission efficiency to be further improved.

III. System Model and Analysis

A. Link Rate Model

A unique and interesting feature of UWB communications, for both DS-UWB and MB-UWB, is that, with an efficient transceiver design, the data rate can be adjusted *proportionally* to the received SINR. This can be explained as follows.

Let p_r denote the received signal power, R the channel capacity, and N_0 and I_0 the one-sided spectrum level of white Gaussian noise and that of Gaussian interference[2], respectively. According to the Shannon theory, $R = W \log_2(1 +$

[1] In 802.11a, the transmit PSD is 2.5 mW/MHz$\approx$ 3.98 dBm/MHz.

[2] The Gaussian approximation holds in the presence of a large number of interferers [6].

$SINR)$ bps, where $SINR = \frac{p_r}{(N_0+I_0)W}$. For the system with the ultra-wide bandwidth [21], $W \to \infty$,

$$R \approx \frac{p_r}{N_0 + I_0} \log_2 e \quad (bps). \tag{1}$$

Accordingly, the UWB sender can always adjust its data rate (by adapting its modulation and coding) according to the arbitrary SINR to maintain the BER requirement. This property holds for both DS-UWB and MB-UWB systems. On the contrary, in narrowband wireless communications, like WLANs, if the SINR falls below a certain threshold, the receiver cannot demodulate the information correctly.

For a UWB network, given a set of requests and the locations of the devices, how to allocate resource and determine the optimal transmission power, transmission rate and schedule is a very challenging issue. Previous research [7], [8] has suggested that: a) power control is beneficial to reduce power consumption, but its gain in term of total throughput in UWB networks is minor, compared to that benefits from transmission scheduling. Thus a UWB device may simply use the maximum power level permitted for transmission when it is scheduled to transmit; b) UWB devices can adjust the data rate to maintain the prescribed BER, and the achievable data rate is proportional to the SINR. Aiming at low computation overhead for practical implementation, we avoid sophisticated power control, and focus on developing our scheduling algorithms based on the strategy that all transmissions use the same transmit power p_t, which is the maximum allowed value. We have the following findings: 1) each UWB link is protected by an exclusive region in which no concurrent transmissions are allowed. The exclusive region is a circle centered at the receiver and its radius is independent of the link distance; 2) concurrent UWB communications are preferable to TDMA transmissions so long as all interferers are outside the exclusive regions of other receivers. We derive the sufficient condition that supports our arguments in the sequel.

A path-loss propagation model is assumed to estimate the average received power. For flow i, the received power is given by $p_r(i) = kp_t d_i^{-\alpha}$, where d_i is the sender-receiver distance of the i-th flow, k is the receiver processing gain and α is the path-loss exponent. We assume k and α are constants. Without loss of generality, there are n time slots to be allocated to n flows. With TDMA scheduling, the achievable data rate for the i-th flow, R_i^T, is given by

$$R_i^T = k' p_r(i)/N_0 = k' k p_t d_i^{-\alpha}/N_0, \tag{2}$$

where k' is a scaling constant. Notice that we do not consider the potential inter-piconet interference which may happen in the overlapping area covered by multiple piconets. Without the support of inter-piconet signaling, links that associate with different piconets may interfere with each other, due to the co-channel interference (CCI). This issue has been discussed in the context of Bluetooth-based piconets using frequency-hopping technique. Recently the CCI issue has also been studied for UWB-based piconets [9], [10]. How to extend our work considering CCI is underway.

Let all flows transmit concurrently in n slots, the achievable data rate for the i-th flow, denoted as R_i^C, is given by

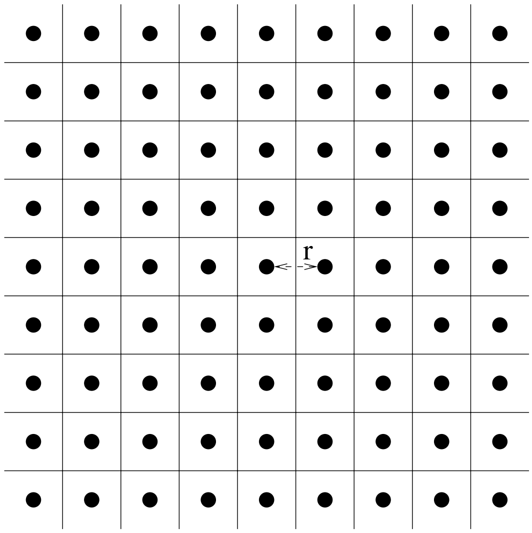

Fig. 2. The Voronoi diagram of a dense UWB network. Each point represents a transmitter except that the centric one is the tagged receiver, at least r distance away from its interferers.

$$R_i^C = \frac{nk' p_r(i)}{N_0 + \sum_{j \neq i} I_{j,i}} = \frac{nk' k p_t d_i^{-\alpha}}{N_0 + \sum_{j \neq i} I_{j,i}},$$

where $I_{j,i}$ is the interference power spectral level of the j-th sender to the i-th receiver with distance denoted by $d_{j,i}$. Let r be the distance such that $I_{j,i}$ equals N_0. If all interferers are at least r away from the receiver of the i-th flow ($d_{j,i} \geq r$), i.e., $I_{j,i} \leq N_0$ for all $j \neq i$, the resultant flow rate with concurrent transmissions becomes

$$R_i^C > \frac{nk' k p_t d_i^{-\alpha}}{N_0 + (n-1)N_0} = \frac{k' k p_t d_i^{-\alpha}}{N_0} = R_i^T. \tag{3}$$

The minimal exclusive region radius r that ensures $I_{j,i} \leq N_0$ depends on the cross-correlations of UWB communications and the background noise level, and it is independent of the sender-receiver distance. The above condition implies that scheduling concurrent UWB communications is preferable to TDMA transmissions so long as all interferers are outside the exclusive regions of other receivers.

Given the sufficient condition of $R_i^C > R_i^T$, in the following, we derive the optimal radius of exclusive region achieving the maximal total network throughput. In the analysis, it is assumed that the devices are uniformly distributed in the network. For random distributed network, we use simulations to study the impact of exclusive region in Sec. V. The analytical results can be used as a simple guideline for networks with randomly distributed topologies.

B. Asymptotic Analysis

We consider an area of size A and assume that UWB devices are densely and uniformly located in the area. Let the radius of exclusive region be r, such that, during concurrent transmissions, the shortest distance from the interferers to any receiver is r. The Voronoi diagram of all concurrent transmitters is shown in Fig. 2. For a tagged receiver, there are four interferers with distance nr, four interferers with distance $\sqrt{2}nr$, and $8(n-1)$ interferers with distance in between nr and $\sqrt{2}nr$, where $n = 1, 2, 3, \ldots$. Denote b the MUI factor, which represents the cross-correlation of the target signal and interfering signal. For the tagged receiver, the total interference from all of the other concurrent transmitters can be approximated as below:

$$\begin{aligned} I &\approx bkp_t \sum_{n=1}^{\infty}\{4[(nr)^{-\alpha} + (\sqrt{2}nr)^{-\alpha}] \\ &\quad +8(n-1)[(1+\sqrt{2})nr/2]^{-\alpha}\} \\ &= 4bkp_t r^{-\alpha}[1 + 2^{-\alpha/2} - (1+\sqrt{2})^{-\alpha}2^{1+\alpha}]\zeta(\alpha) \\ &\quad +8bkp_t(r/2)^{-\alpha}(1+\sqrt{2})^{-\alpha}\zeta(\alpha-1) \\ &= bkr^{-\alpha}C_\alpha, \end{aligned} \tag{4}$$

where the Riemann Zeta-function $\zeta(\alpha) = \sum_{i=1}^{\infty} i^{-\alpha}$, and C_α contains all the remaining terms. The Zeta-function, $\zeta(\alpha)$, converges *iff* $\alpha > 1$. Therefore, even with infinite interfering devices, the interference from them, I, is bounded *iff* $\alpha > 2$.

Since the data rate of UWB communications is proportional to SINR, the data rate of a tagged user i is

$$R_i = k' \frac{P_r(i)}{N_0 + bkC_\alpha r^{-\alpha}}. \tag{5}$$

With $n = A/(r^2)$, the throughput of concurrent transmissions is given by

$$\begin{aligned} \sum_{i=1}^{n} R_i &= \frac{k' \sum_{i=i}^{n} P_r(i)}{N_0 + bkC_\alpha r^{-\alpha}} \\ &= \frac{k' A \bar{P}}{N_0 r^2 + bkC_\alpha r^{2-\alpha}}, \end{aligned} \tag{6}$$

where $\bar{P} = 1/n \cdot \sum_{i=1}^{n} P_r(i)$. The maximum throughput can be obtained by minimizing $N_0 r^2 + bkC_\alpha r^{2-\alpha}$. Thus, the optimal radius of exclusive region r^* can be given by:

$$r^* = [\frac{(\alpha-2)bkC_\alpha}{2N_0}]^{1/\alpha}. \tag{7}$$

From (7), r^* is a function of the path-loss exponent, the background noise level, and the MUI factor. To verify (7), a dense network as shown in Fig. 2 is simulated, where $p_t = 0.05$ mW, $N_0 = 2.5 \times 10^{-8}$ mW, and $b \cdot k = 10^{-4}$. Fig. 3 shows the optimal radius of exclusive region with respect to different values of path-loss exponent obtained from (7) and from simulations. The path-loss exponent α is selected according to the measurement results indicated in [22]. In office and residential environments, α ranges from 3 to 4 for soft non-line-of-sight (NLOS) and from 4 to 7 for hard-NLOS. It can be seen the theoretical values reasonably match the simulated ones. Based on (7), the maximum throughput achieved in the area is

$$Th_{\max} = \frac{2k' A \bar{P}}{\alpha k C_\alpha (r^*)^{2-\alpha}}. \tag{8}$$

Furthermore, the ratio of per flow throughput in a time slot with the best exclusive region and its throughput if there are no concurrent transmitters is $1 - 2/\alpha$. Since we allow $A/(r^*)^2$ flows to transmit concurrently, they can be allocated $A/(r^*)^2$ slots. Therefore, during the period of $A/(r^*)^2$ slots, each of the $A/(r^*)^2$ flows has a throughput increase of $(1 - 2/\alpha)A/(r^*)^2$, compared to that they transmit one-by-one. In dense UWB networks with $A \gg (r^*)^2$ and $\alpha > 2$, the per flow throughput can be largely improved by allowing concurrent transmissions with the optimal radius of exclusive region.

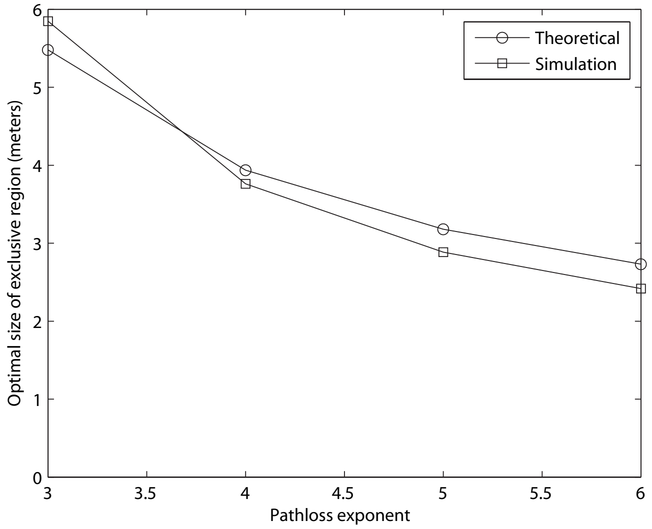

Fig. 3. Optimal radius of exclusive region with the following parameters in Eq. (7): $p_t = 0.05$ mW, $N_0 = 2.5 \times 10^{-8}$ mW, and $bk = 10^{-4}$.

IV. Fast Scheduling Algorithms

For UWB networks with random topology, how to schedule concurrent transmissions in CTAP to maximize the network throughput is a very challenging issue. The design of appropriate scheduling algorithms should consider two important requirements: (a) the complexity of the scheduling algorithm should be acceptable according to the limited computational power of PNC; (b) the magnitude of MUI should be estimated to decide the concurrent transmission groups. Concerning the complexity, since the scheduling problem for finding the optimal concurrent transmission set that maximizes the throughput is *NP-hard* (as shown in Appendix), it is not feasible to obtain the optimal solution within polynomial time. As to the requirement (b), estimating MUI for peer-to-peer communications is difficult as the PNC is not capable of acquiring instantaneous channel status of individual links. Alternately, the location/distance information obtained from accurate ranging capability of UWB can be used to estimate the link condition. By jointly considering the above requirements, we propose two heuristic scheduling algorithms with computational complexity $O(N^2)$ and $O(KN^2 \log N)$, respectively.

In the first algorithm, called proportional allocation algorithm (PaA), S_i denotes the i-th group of flows which can transmit concurrently. In addition, UA denotes the set of flows not belonging to any group yet, and ER_l the exclusive region of flow l. Assume that the number of time slots K is no less than the number of flows N. To determine the i-th group S_i, we first randomly choose a flow from UA (`Lines 2-4`). Then, we add other flows which do not conflict with any flows in S_i (`Lines 5-12`); in other words, all interferers are outside other receivers' exclusive regions. The above

Algorithm 1 Proportional Allocation Algorithm

Require: $i := 1$; $S_i := \emptyset$; $UA := \{1, \ldots, N\}$
1: **repeat**
2: **for** a flow f randomly chosen from UA **do**
3: $S_i \leftarrow S_i \cup \{f'\}$
4: $UA \leftarrow UA \backslash \{f\}$
5: **for** any flow f' other than f **do**
6: **if** $f' \notin ER_l \quad \& \quad l \notin ER_{f'} \quad \forall\, l \in S_i$ **then**
7: $S_i \leftarrow S_i \cup \{f'\}$
8: **end if**
9: **if** $f' \in UA$ **then**
10: $UA \leftarrow UA \backslash \{f'\}$
11: **end if**
12: **end for**
13: **end for**
14: $i \leftarrow i + 1$
15: **until** $(UA := \emptyset) \vee (i > K)$
16: $k \leftarrow i$
17: **for** $i = 1$ to k **do**
18: allocate $K \cdot |S_i| / \sum_{x=1}^{k} |S_x|$ to S_i
19: **end for**

procedure is repeated until UA is empty. Denote k the number of groups $(S_1, S_2, ..., S_k)$ being allocated (`Lines 15-16`). We then proportionally allocate $K \cdot |S_i| / \sum_{x=1}^{k} |S_x|$ slots to the i-th group of flows, for $1 \leq i \leq k$, where $|S_i|$ is the number of flows in the i-th group (`Lines 17-19`). The PaA has a computational complexity of $O(N^2)$. It can be observed that in PaA, 1) each flow will belong to at least one group, and will be assigned at least one slot; 2) in each group, all flows do not conflict with each others' exclusive regions; 3) the time slots allocated to each group are proportional to the number of flows that can be transmitted concurrently in that group. The rationale behind PaA is that, considering the multi-user network as a conflict graph, the maximum network throughput can be achieved when each slot allocation is a maximum weighted independent set (MWIS), where the vertex weight is set to the link throughput. In order to maximize the aggregate throughput, PaA allocates more slots to the flow group with larger size, which is hypothesized close to the MWIS.

The second algorithm is called repeating allocation algorithm (RaA). Let ϕ_f be the number of slots being allocated to flow f. For a slot i, RaA will assign it to a group of flows S_i according to the following rule. RaA first randomly chooses a flow with minimal ϕ_f, and adds it to S_i (`Lines 2-4`). Then, RaA adds other flows which do not conflict with any flows in S_i (`Lines 5-10`). This procedure repeats for all time slots. The RaA has a higher computational complexity of $O(KN^2 \log N)$, and we anticipate it should be more fair in terms of the number of slots assigned to each flow, since RaA essentially follows the max-min fairness discipline.

V. Numerical Results and Discussions

In this section, performance of the proposed scheduling algorithms and that of TDMA used in IEEE 802.15.3 standard are evaluated by implementing them in a discrete-event network simulator. All simulations are repeated 10 times with different random seeds.

Algorithm 2 Repeating Allocation Algorithm

Require: $\phi_f = 0$; $S_i := \emptyset$
1: **for** $i = 1$ to K **do**
2: $f^* \leftarrow \arg\min_f \{\phi_f\}$
3: $S_i \leftarrow S_i \cup \{f^*\}$
4: $\phi_{f^*} \leftarrow \phi_{f^*} + 1$
5: **for** any flow other than f^* **do**
6: **if** $f \notin ER_l \quad \& \quad l \notin ER_f \quad \forall\, l \in S_i$ **then**
7: $S_i \leftarrow S_i \cup \{f\}$
8: $\phi_f \leftarrow \phi_f + 1$
9: **end if**
10: **end for**
11: **end for**

TABLE I
Simulation parameters

Bandwidth (BW)	1 GHz
Center frequency (f_c)	5.092 GHz
Transmitting power (P_t)	0.0397 mW
Noise power (P_N)	3.9811×10^{-9} mW
Shadowing parameter (σ_G)	4.3
Path-loss exponent (α)	4
Nakagami factor (m)	$1 \sim 6$
MUI factor (b)	$5 \times 10^{-3} \sim 5 \times 10^{-2}$

A. Large-scale UWB Channel Model

To study the impact of large-scale fading to the performance of scheduling algorithms, we use the UWB channel proposed in [23]. We assume that the network topology is fixed during each scheduling cycle. Most changes in the received signal are due to the environment changes around the receiver. Thus the large-scale UWB fading model should be adequate to model the received signal strength. A single slope model for path-loss at distance d is given by

$$PL[\text{dB}] = PL(d_0)[\text{dB}] + 10\gamma \log_{10}(\frac{d}{d_0}) \tag{9}$$

where γ is the path-loss exponent which depends on the environment, $d_0 = 1$ m is the reference distance. $PL(d_0)$ is estimated using the Friis free-space equation given by

$$PL_{FS}(d_0)[\text{dB}] = 10 \cdot \log_{10} \left(\frac{G_{tx} G_{rx} \lambda^2}{(4\pi)^2 d_0^2 L} \right), \tag{10}$$

where λ is the wavelength corresponding to the frequency f_c approximated by the geometric mean of the lower and upper band edge frequencies, L is the system loss factor, G_{tx} and G_{rx} denote the transmitter and receiver antenna gains, respectively. In simulations, the path-loss associated with each flow is generated in advance according to (9) and (10), where $L = G_{tx} = G_{rx} = 1$. Denote G the total fading power across all paths due to the shadowing. Then, the dB value of G follows a normal distribution with mean value given from (9)

$$G \sim \mathcal{N}(-PL, \sigma_G^2). \tag{11}$$

The long-term SNR is

$$\text{SNR}_{LT}[\text{dB}] = P_t - G(d) - P_N, \tag{12}$$

where P_N is the noise power. As to small-scale fading, it has been shown that the UWB fading amplitude can be well fitted by the Nakagami distribution [22]. The Nakagami fading gain g can be converted from a Ricean random variable with the conversion equations

$$K = \frac{\sqrt{m^2 - m}}{m - \sqrt{m^2 - m}},$$
$$m = \frac{(K+1)^2}{(2K+1)},$$

where $m > 1$ and $K > 0$ are the Nakagami and Rice factors, respectively. The corresponding Ricean random variable is obtained from a complex Gaussian random variable with mean $\sqrt{K/(K+1)}$ and variance $1/(2(K+1))$, where $K \geq 0$. Finally, the SNR of the received signal can be expressed as

$$\text{SNR [dB]} = 20 \cdot \log_{10} g + \text{SNR}_{LT}. \tag{13}$$

Notice that the total received energy is spread over multiple paths with different weights following a lognormal distribution. The clustering phenomenon of UWB multipath channel is not included in our simulations since we use the mean energy given by (11) to represent the average received energy. The physical parameters used in the simulations are given in Table I.

B. Network Model

There are 40 flows randomly located in a 10×10 m^2 area. The link distance is at least 1 m. All flows have an equal transmission power P_t, background noise power P_N. Depending on the characteristics of the pulse shape of transmitted signals, propagation conditions, and cross-correlation of the target signal and interfering signal, etc., the interference among concurrent transmissions may be suppressed in different levels, referred as MUI factor b in the following.

C. Scheduling Performance

In this subsection, performance of the proposed scheduling algorithms and that of TDMA scheduling are compared under different propagation environments characterized by Nakagami-m factor, and interference level characterized by MUI factor b. Two performance measures are considered: network throughput and fairness index. Given a particular network size, the network throughput measures the total bandwidth achieved by the scheduling algorithm. To demonstrate the performance gain, all results are normalized to the value obtained by TDMA scheduling. For fairness, the widely accepted Jain's fairness index [24] is used to evaluate the scheduling algorithms.

1) Impact of Exclusive Region Size: The normalized network throughput resulted from different radii of exclusive region using the proposed scheduling algorithms are shown in Fig. 4, with Nakagami-$m = 4$ and MUI factor $b = 10^{-2}$. The 95% confidence interval is also plotted as error bars for each proposed algorithm. An exclusive region with radius equal to zero implies all flows can transmit concurrently, and we call this the all-at-once scheme. As the exclusive region radius increases, less flows can be allowed in concurrent transmissions. Eventually the proposed scheduling algorithms behave

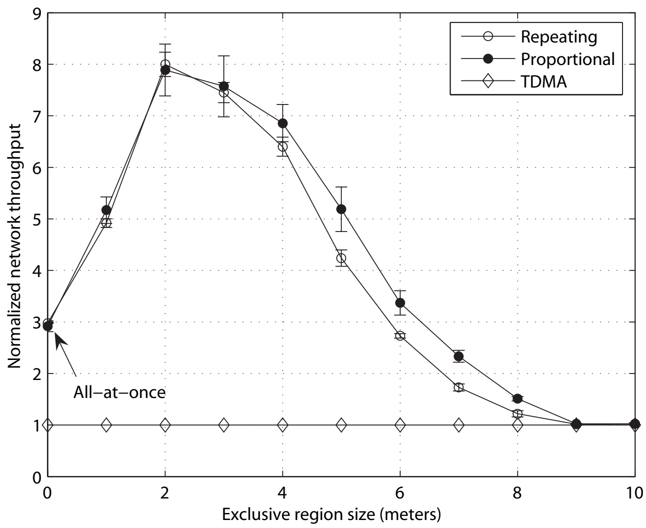

Fig. 4. Comparison of scheduling algorithms with 40 flows in 10×10 m^2; Nakagami-m=4; MUI factor b=10^{-2}. The error bars represent 95% confidence interval.

the same as TDMA when the exclusive size is sufficiently large. The simulation results show that both the proposed scheduling algorithms achieve similar network throughput. Under this setting, the radius of the optimal exclusive region is between $2 \sim 4$ m, which is close to the optimal radius r^* derived in Sec. III-B (Eq. 7). It can be seen that by properly selecting the exclusive region, the proposed PaA and RaA can achieve network throughput 768% and 830% times higher than TDMA. Our algorithms also provide 280% gain compared to the all-at-once scheme.

2) Fairness: We evaluate fairness in terms of the number of slots assigned to each flow, and the throughput achieved by each flow. The former evaluation takes less computations and suits the case when the scheduler has limited knowledge and computational power to determine the achieved throughput of each flow. Fig. 5 compares the Jain's fairness index in terms of the number of slots assigned to each flow. The resulting 95% confidence interval corresponding to each point on the x-axis is also plotted. TDMA scheduling provides good fairness since it allocates slots to all flows evenly, yet such assignment does not efficiently utilize the spectrum. As to the proposed scheduling algorithms, the general tradeoff between throughput maximization and fairness can be observed by comparing Fig. 4 and Fig. 5. The PaA shows inferior support in fair slot sharing than RaA because of the proportional rule for slot allocation.

From the viewpoint of a user, fairness is considered as the amount of throughput that one can obtain relative to other users. In Fig. 6, all scheduling algorithms being studied show poor fairness support in terms of throughput regardless the underlying exclusive region. With the objective of increasing network throughput, the proposed algorithms favor the flows with shorter communication distance and less neighboring interferers. For TDMA scheduling, the achievable rate of each link is dominated by the link quality. When each user is assigned equal number of slots, throughput fairness can not be achieved. How to make better tradeoff between efficiency and fairness will be one of our future research topics. A well-

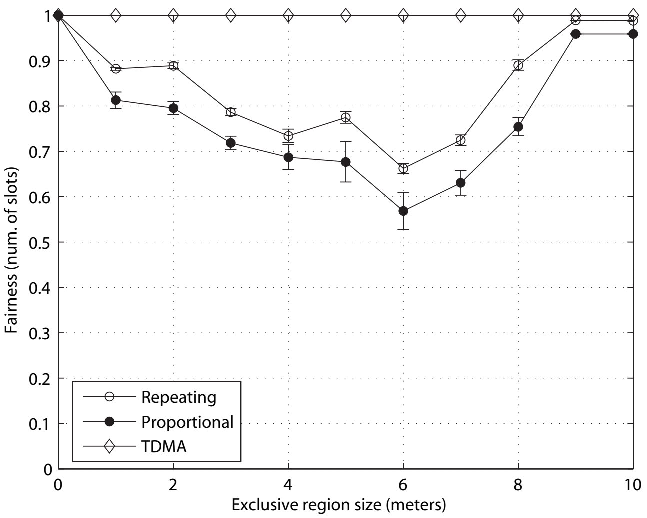

Fig. 5. Fairness comparisons w.r.t. number of slots, Nakagami-m=4. The error bars represent 95% confidence interval.

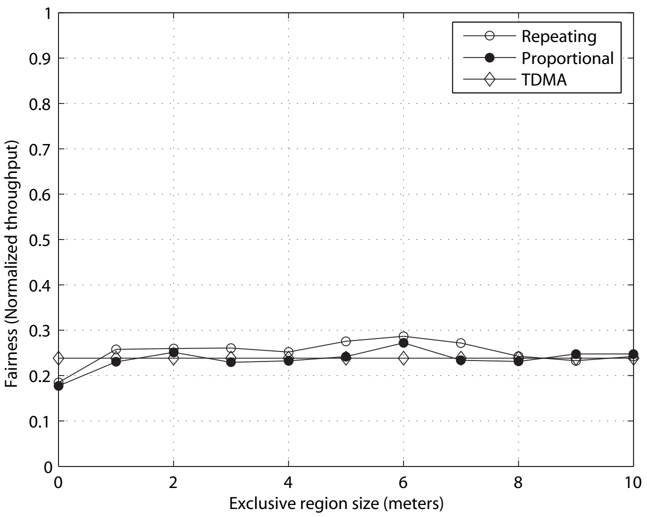

Fig. 6. Fairness comparison w.r.t. normalized throughput, Nakagami-m=4.

known solution is to define a unified cost function which tradeoffs the two objectives.

We also plot the minimum throughput among all flows in Fig. 7 using the same parameters. Sometimes a greedy scheduler aiming to maximize the throughput may favor certain flows and sacrifice others for throughput maximization. It can be seen that the proposed algorithms with an appropriate exclusive region can largely increase the minimal throughput among all competing flows, and thus more satisfactory services can be provided.

3) Impact of MUI: The impact of MUI is shown in Fig. 8 with Nakagami-$m = 4$. Take DS-UWB for example, UWB networks may employ different pseudo-random codes for multiple-access. The MUI factor b can be interpreted as the cross-correlation among different spreading code sequences. Because of the multipath effect and the correlations among user spreading codes that are generated locally, the cross-correlation factor is generally modeled by non-zero positive values. A smaller value of b means less correlation among users and thus stronger suppression of MUI. The robustness

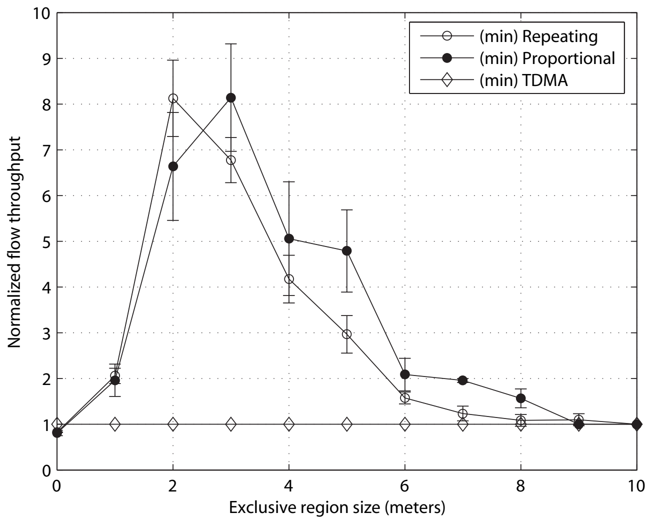

Fig. 7. The minimum flow rate achieved by each algorithm. with 40 flows in 10×10 m^2; Nakagami-m=4; MUI factor b=10^{-2}. The error bars represent 95% confidence interval.

of MUI depends on the system parameters such as monocycle shape in DS-UWB systems. It has been reported that using a higher-order monocycle can increase the robustness against MUI given the fixed pulse width [25], while the complexity and susceptibility to timing jitter in the receiver are also increased. When b is sufficiently small (e.g., $b < 10^{-2}$ in Fig. 8), the MUI is significantly reduced such that the all-at-once scheme (i.e., zero exclusive region) yields higher network throughput than that of TDMA. Since a UWB system is limited to certain capability of MUI suppression, the simple all-at-once rule may be even worse than TDMA; for instance, with $b = 5\times10^{-2}$. On the other hand, the proposed scheduling algorithms can guarantee higher network throughput than TDMA by deploying proper exclusive region size. The optimal size of exclusive region leading to the maximum network throughput shown in Fig. 8 is between $2 \sim 4$ meters, which is close to that estimated by Eq. (7). Finally, we observe the relationship between exclusive region radius and the MUI factor. With less protection against MUI (i.e., larger b), a larger exclusive region radius is required to achieve the maximum network throughput. Thus the optimal exclusive region radius can also be seen as a function of MUI factor, as we have analyzed in Sec. III-B.

4) Impact of Nakagami Fading: To study the effect of Nakagami fading parameter m, Fig. 9 shows the network throughput versus m ($m = 1 \sim 6$ [23]). For the sake of presentation conciseness, only the network throughput achieved by the RaA in the exclusive region radius of 2 m is shown. Generally, the Nakagami parameter m characterizes the severity of fading condition. A larger value of m represents less fading and a stronger line-of-sign path. Therefore the network throughput is an increasing function with respect to m.

D. Remarks on Implementation Issues

For practical implementations, the scheduling cycle can be predetermined considering the computation overhead and traffic arrival rate. In our simulations, each scheduling algorithm

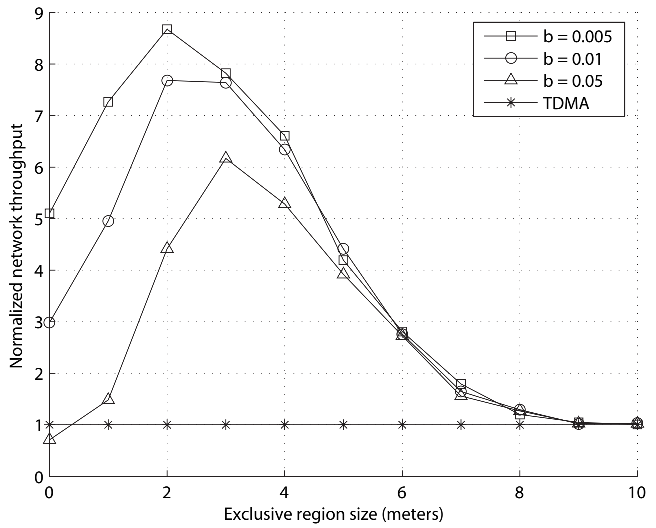

Fig. 8. Normalized network throughput due to different MUI factor b with 40 flows in $10 \times 10\ \mathrm{m}^2$, Nakagami-$m$=4. In this setting the optimal exclusive size is between $2 \sim 4$ m.

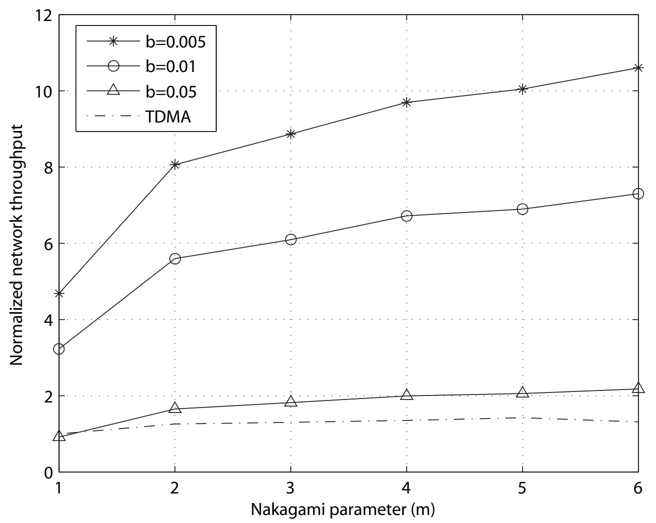

Fig. 9. Nakagami parameter m with different MUI factor b; 40 flows in $10 \times 10\ \mathrm{m}^2$.

is coded in C language and executed on a Pentium-4 2.8 GHz CPU. The execution time for RaA is 0.58 ms and 0.11 ms for PaA on average when there are 40 flows and 80 slots. Since the PaA has lower complexity, less execution time can be expected. Referring to the maximum superframe length of 65 ms specified in the standard, running our algorithms per superframe is still affordable to the scheduler.

VI. Related Work

Considerable research work on UWB medium access control has been conducted in [7], [8], [11], [12]. In [7], the cross-layer design issue for UWB ad hoc networks was investigated. Aiming at maximizing the logarithmic flow rates, the cross-layer optimization problem was explored based on simple network topologies. Their work suggested that by implementing an exclusive region around each receiver, the optimal flow rate can be attained, and the radius of exclusive region is relevant to the achievable flow rate. However, how to determine a proper exclusive region size has not been reported. Concentrating on single-hop communications, a joint scheduling and power allocation for centralized setting was investigated in [8]. It has been shown that for UWB networks, the throughput improvement resulted from power allocation is very limited, although the implementation of power allocation is beneficial to manage interference and reduce power consumption. Indeed, the very low transmission power of UWB has been regulated by the strict emission mask. Thus power allocation may not be necessary if the design objective is to maximize the network capacity. A framework aiming at max-min scheduling for centralized UWB networks was considered in [11], where the emission power constraint of UWB transmissions is transformed to the PSD limit. Such transformation is shown to result in a simple algorithm variation. By considering the frequency bands as the wireless resources to be allocated, their solution can be applied to multi-band UWB. Another scheduling solution for multi-band UWB was presented in [12] for inter-piconets resource allocation, while we deal with the resource allocation problem inside a piconet. Different from the previous work where certain power control/allocation mechanisms have been deployed to reduce power consumption and interference, our work focuses on increasing the network throughput and maintains the processing load of PNC as low as possible. Thus, we seek the solution when transmission power is regulated by a simple rule: either zero or the maximum allowable level. Although our strategy does not directly reduce power consumption, by easing the load of PNC which often equips with limited processing capability, the proposed algorithm can significantly improve network throughput and is more practical. In addition, we derive the optimal exclusive region which can be easily determined according to the underlying propagation environment. The results can be used as a simple guideline for fast UWB network planning. How to extend our work considering multiple piconets will be an important future research issue.

The extremely wide bandwidth of UWB inherently allows multiple concurrent transmissions. This physical property has been extensively studied at signal level [6], [13], but not well explored from the networking aspect. It has been shown that the average packet error rate in DS-UWB is a function of UWB monocycle and channel behavior [14]. With a properly selected format of monocycle, the nature of time-hopping (TH) impulse radio, one of the variations of UWB systems, allows several users to access to the network at the same time without the need of user synchronization. This property facilitates ad hoc networking where distributed channel access can be implemented at each node according to the locally monitored multi-access interference level in the vicinity [14], [15]. Under this principle, techniques such as adaptive coding [16] and chip discrimination [17] have been proposed to further improve the system capacity. However, the aggregated throughput may be even worse than one-by-one transmission if the density of UWB devices is too large or the cross-correlation among users' spreading codes is not sufficiently low. Thus, an effective scheduling algorithm is required to control interference, which is the main focus of this paper.

Due to the rate adaptiveness feature of UWB communications, the physical and protocol models used in the classic network capacity analysis [5] are not directly applicable. The physical model in [5] assumes that the transmission rate is fixed if the received SINR is above certain threshold and the transmission fails otherwise; the protocol model defines an exclusive region with the radius proportional to the distance between the transmitter and the receiver. For UWB networks, our findings reveal that the sufficient condition to allow concurrent transmission is to define an exclusive region with the radius independent of the transceiver's distance. The asymptotic analysis in this paper leads a step toward further understanding the UWB network capacity. It beckons more in-depth investigation in this new area.

VII. Conclusions

Considering the unique characteristics of UWB communications, we have proposed the enhancement for IEEE 802.15.3 MAC protocol by allowing concurrent transmissions appropriately. The proposed exclusive region based concurrent transmission algorithms can achieve much higher network throughput and efficiency without compromising the throughput of any single flow. The proposed research work takes the first-step toward an efficient MAC protocol design for UWB WPANs. Many open issues beckon for further investigations. For instance, how to determine the optimal exclusive region for arbitrary network topology, how to achieve near-optimal scheduling with affordable computation complexity, couple PHY/MAC/routing to maximize the system throughput, make appropriate tradeoff between throughput and fairness, *etc*. How to guarantee the strict delay requirement for supporting real-time traffic in UWB networks should be further investigated.

Appendix
NP Hardness of Optimal Concurrent Scheduling

We show that the optimal scheduling for concurrent transmissions that optimizes throughput is NP-hard using the notion of conflict graph [26]. Consider a UWB peer-to-peer network as a directed graph $G = (V, E)$ where the nodes correspond to the UWB devices and the links correspond to the peer-to-peer links between the devices (e.g., a directed link l_{ij} from device i to j). We use the terms "node" and "link" in reference to the directed graph G, and reserve the terms "vertex" and "edge" for the *conflict graph* H. Under graph G, the conflict graph H is defined such that a vertex corresponds to the link in the graph G. An edge, denoted as (l_{ij}, l_{pq}), is drawn if the links l_{ij} and l_{pq} can not be scheduled concurrently. According to the exclusive region with radius r, there is an edge between vertex l_{ij} and l_{pq} if either $d_{iq} \le r$ or $d_{pj} \le r$. Given the conflict graph H, an independent set is a set of vertices, such that there is no edge between any two of the vertices. In other words, an independent set consists of the links that can be scheduled concurrently. If each link has identical capacity, the problem of finding the largest independent set in H, known as NP-hard, can be reduced to the throughput maximization problem. Since the link throughput depends on the propagation distance and shadowing effect and thus is not identical, the optimal scheduling leading to maximum throughput can be seen as a weighted version of the aforementioned throughput optimization problem. This results in the hardness of optimal scheduling problem in peer-to-peer UWB networks.

To solve the maximum weighted independent set problem, several approximation algorithms based on greedy strategy have been proposed [27], [28]. In [28], the proposed greedy algorithms can achieve $1/\triangle(H)$ of the weight of the maximum independent set, where $\triangle(H)$ is the maximum degree of the graph. However such approximation may be loose for a dense network. In addition, these methods rely on iteratively configuring the graph until it is empty and thus is considered computation-expensive for complete graphs in our case.

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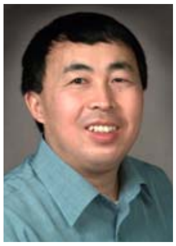

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