MAC Protocol Design and Optimization for Multi-Hop Ultra-Wideband Networks

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***Abstract*—Ultra-wideband (UWB) communication is a promising enabling technology for future broadband wireless services. A simple, scalable, distributed, efficient medium access control (MAC) protocol is of critical importance to utilize the large bandwidth UWB channels and enable numerous new applications and services cost-effectively. In this paper, by investigating the characteristics of UWB communications, we propose a Distributed, EXclusive region (DEX) based MAC protocol. The proposed DEX protocol capitalizes on the spatial multiplexing gain of UWB networks by reserving exclusive regions (ER) surrounding the sender and receiver for data and acknowledgment (ACK) transmissions, so that users can efficiently and fairly share network resources in a distributed and asynchronous manner. We further quantify the network performance bounds and derive the optimal ER size to maximize the expected network transport throughput for a dense, multi-hop UWB network. Extensive simulation results demonstrate the efficiency and effectiveness of the DEX protocol. This work explores how to effectively utilize the wireless spatial capacity of distributed, multi-hop wireless networks by optimizing protocol parameters, instead of depending on more complicated control messages.**

***Index Terms*—Distributed MAC protocol, multi-hop, UWB, distributed exclusive region.**

I. INTRODUCTION

ULTRA-WIDEBAND (UWB) communications can achieve up to Gbps data rate with a transmission range of a few ($\leq$ 10) meters. Ubiquitous wireless access at a high data rate ($>$ 100 Mbps) are possible using multi-hop small-range UWB transmissions. As synchronization and scheduling are difficult and costly in multi-hop UWB networks, it is desirable to have a simple, scalable, robust MAC protocol that allows users to efficiently utilize wireless resources in a distributed and asynchronous manner. The IEEE 802.11 distributed coordination function (DCF) has been overwhelmingly successful due to its flexibility, robustness, and simplicity. However, the efficiency of IEEE 802.11 DCF protocol in multi-hop wireless networks is far from ideal. In a dense multi-hop network, the throughput starvation and unfairness problems become severe due to the high contention level, which lead to unsatisfactory user experiences. Thus, the 802.11 DCF protocol cannot be directly used in dense multi-hop UWB networks. On the other hand, because of the stringent power limit of UWB imposed by the FCC regulations, power adaptation for UWB transmissions is generally not feasible; but rate adaptation is supported in all UWB PHY proposals [1], [2], [3], which should be considered for MAC protocol design. Also, UWB devices have very good ranging capability, which can be utilized by MAC protocols.

Recognizing the challenges and opportunities with UWB communications, in this paper, we propose a Distributed, EXclusive region (DEX) based MAC protocol, which is compatible with the existing 802.11 DCF protocol. Without relying on complicated control messages, we propose to optimize the main protocol parameters to enhance the protocol performance for UWB networks. Compared with the legacy 802.11 DCF protocol, DEX not only improves the transmission efficiency and network transport throughput, but also enhances fairness, because it effectively exploits the spatial reuse in dense UWB networks.

Spatial reuse has been well investigated in infrastructure-based cellular systems. It is well known that a higher spatial multiplexing gain can be achieved by using smaller cells at the cost of increased system management and control complexity (e.g., handoff overheads). Here, we investigate spatial multiplexing gain in a distributed multi-hop UWB network. In the proposed DEX protocol, a sender/receiver pair will use request-to-send/clear-to-send (RTS/CTS) messages to reserve smaller spatial areas, namely exclusive regions (ERs), for transmissions. By using the precise ranging capability of UWB devices, a node can decide whether it is within the ERs of the ongoing transmissions [4]. If yes, it will refrain from transmitting concurrently with the ongoing ones, and vice versa. Since only flows within the smaller ER compete with each other for channel access, more flows can transmit concurrently, and the throughput starvation and unfairness problems can be alleviated. We further derive the optimal ER size, which is generally much smaller than the carrier sensing region, such that the expected wireless network transport throughput can be maximized using the DEX MAC protocol.

The main contributions of this paper are three-fold. First, we propose an efficient distributed MAC protocol for a dense, multi-hop, large-scale UWB network. Second, we systematically analyze the performance of the proposed protocol. The

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TABLE I
NOTATIONS

Symbol	Description
CT	concurrent transmissions
$d(s_j, r_i)$	distance between sender of flow j and receiver of flow i
$g(s_i, r_i)$	channel gain for flow i
$g(s_j, r_i)$	channel gain between sender of flow j and receiver of flow i
G_0	cross correlation between two flows
$I_i(s_j)$	interference power from sender j to receiver i
N_0	background noise power
r_i	receiver of flow i
$R(i)$	transmission data rate of flow i
s_i	sender of flow i
$P(r_i)$	received power at receiver of flow i
$P(s_i)$	transmission power by sender of flow i
W	signal bandwidth

analytical framework can be applied to other distributed MAC protocols. Third, we further investigate how to appropriately set the protocol parameters to maximize the expected network transport throughput of a randomly and densely deployed UWB network. Extensive simulations are performed to verify the accuracy of the analysis and demonstrate the effectiveness and efficiency of the proposed protocol.

The rest of the paper is organized as follows. The system model is presented in Section II. In Section III, we propose the distributed MAC protocol, DEX, analyze its performance, and derive the network performance bounds. We then propose a method to optimize the ER size to maximize the expected network throughput. Simulation results are given in Section IV. Section V discusses related works, and concluding remarks and future research issues are given in Section VI.

II. SYSTEM MODEL

Due to the stringent transmission power limit, normally the UWB transmission power level cannot be adjusted. Instead, the sender can adjust the transmission data rate according to the received signal-to-interference-plus-noise ratio (SINR). Because of the power constraint and the wide bandwidth in the UWB system, spreading technologies in both the time domain and the frequency domain are used [1], [3]. In a distributed network, different flows can use different spreading codes to reduce the mutual interference level among concurrent transmissions. Let G_0 denote the cross correlation between two concurrent transmissions using different (pseudo-random) spreading codes. Other traffic and channel parameters are tabulated in TABLE I for easy reference. In the system model, G_0 is assumed constant. The received SINR of flow i is given by

$$SINR(i) \;=\; \frac{P(s_i)g(s_i,r_i)}{N_0+\sum_{j\neq i}P(s_j)g(s_j,r_i)G_0} \qquad (1)$$

In an additive white Gaussian noise (AWGN) channel, the data rate is upper bounded by the channel capacity $C = Wlog_2(SINR+1)$ [5]. With fine-granularity rate adaptation technologies, the achievable link data rate is approximately given by

$$R(i) \approx \eta W \log_2(SINR(i)+1) \;\; \text{bps}, \qquad (2)$$

where η is a system coefficient related to the efficiency of the transceiver design.

Due to the limited transmission range of UWB, multi-hop relay is necessary and favorable. To evaluate the protocol performance fairly in a multi-hop wireless network, transport throughput is usually used for performance evaluation, which is defined as the product of the throughput and the distance over which the information is being transferred. For MAC protocol evaluation, we focus on the transport throughput over each individual hop, i.e., the product of link throughput and distance. We will also investigate the delay and fairness (in terms of transport throughput) performance of the proposed protocol.

III. DEX PROTOCOL DESIGN AND PERFORMANCE ANALYSIS

Our protocol design principle is to choose simple and, ideally, existing building blocks for easy implementation, and to fine tune the protocol parameters for better performance. In this section, we introduce the proposed DEX-based MAC protocol, analyze its performance, and propose a method to optimize the protocol parameter.

A. DEX Protocol

Consider the employment of spreading codes for multiple access in which all nodes share a pool of spreading codes, numbered $1, 2, ..., n$. One common spreading code is chosen for control message exchange, *e.g.*, for RTS and CTS frames. Each node maintains a code table to record all the spreading codes used by the ongoing neighboring transmissions. The procedures to choose codes and initiate transmissions at the sender and receiver sides are given in Algorithm 1 and Algorithm 2, respectively.

Each node maintains a code table and a network allocation vector (NAV). The initial contention window size equals the minimum window size, i.e., $CW = CW_{\min}$, and the node sets its $retry$ counter to 0.

If node A receives data from the upper layer for transmission to node B, A will use a hash function to obtain a spreading code: $X = Hash(A+B)$ for the transmission, where A and B used in the hash function are related to their MAC addresses. A starts channel sensing when its NAV reaches zero. If the channel is sensed idle for a backoff interframe space ($BIFS$), A transmits an RTS frame to B, including the chosen code X and the transmission time $T_2 = RTS + SIFS + CTS + SIFS + DATA + ACK$. Otherwise, A enters a backoff procedure and sets a backoff counter (BC) uniformly distributed over $[0,\ CW)$ for the first transmission attempt and A freezes its BC until the channel is sensed idle for $BIFS$.

If the channel is sensed busy but A has not successfully received an RTS or CTS, A needs to continue channel sensing till the channel is idle for $BIFS$. If A overhears an RTS or CTS frame from another transmission f_i, A checks the ER condition: 1) if either the transmitter or the receiver of f_i is in A's ER region, A should postpone its own transmission until the ongoing transmission f_i completes, and A sets its NAV according to T_2; 2) if A is outside the ER of f_i, A only needs to wait until RTS times out and sets NAV according to $T_1 = RTS + SIFS + CTS$. An example of NAV setting is shown in Fig. 1, where A and B exchange RTS and CTS

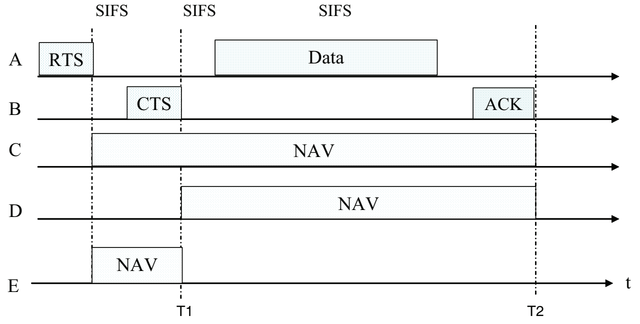


Fig. 1. Network allocation vector update.

messages, C and D are neighbors within the ER of flow AB, respectively, and E is another neighbor outside the ER of flow AB. Since A is outside the ER of f_i and concurrent transmission is allowed, A adds the spreading code used by f_i in its code table and assures that its own code X does not conflict with any record in its code table. If code collision occurs, A can hash again till there is no code collision. Each record in the code table is associated with a time to live (TTL) parameter and will be removed from the table if TTL expires.

If A successfully receives a CTS from B after an interval SIFS, implying that B is available for the transmission using the spreading code X, A starts to transmit data to B at a rate of $R(i)$ after a SIFS. For implementation simplicity, the rate $R(i)$ is not determined based on the measurement of the instantaneous interference and noise level of the tagged transmission, but on the worst case scenario that assumes the maximum number of dominant interferers. Therefore, DEX is robust against interference from neighborhood asynchronous transmissions. The detail derivation of $R(i)$ is presented in Sec. III-B. If no CTS is received successfully, implying that B is not available at this moment to receive data using code X, A will enter the backoff stage and retransmit thereafter, until the retransmission limit m is reached. The backoff procedure in DEX is the same as that in IEEE 802.11. Each time A retransmits RTS, it will also choose a different code X by repeating hash functions because the code it chose previously may not be acceptable for use at B, (although the probability of code collision at B is very low).

To further improve the protocol efficiency, a transmission opportunity (TXOP) is employed, *i.e.*, a time duration T is reserved in each RTS/CTS that a transmitter can transmit a burst of data frames during T. The longer the T, the better resource utilization will be, because less overhead is involved in each transmission. But a longer T leads to a larger access delay. Therefore, T should be chosen appropriately so that the access delay is tolerable for other flows in the ER region. On the other hand, a smaller ER region allows for more concurrent transmissions, which reduces the access delay of each flow. Thus, it is possible to choose a larger T for DEX and still well maintain the desired delay and fairness performance.

At the receiver side, B is ready for channel sensing or receiving only if its $NAV = 0$. Whenever B overhears an RTS or CTS frame from its neighboring node, B will update its NAV and code table in the same way as sender A does. Upon successfully receiving an RTS from A, B sends back a CTS if X does not conflict with any record in B's code table and the channel is idle for a SIFS period. Otherwise, B keeps silent and A may retransmit an RTS and choose another code after the RTS timeout.

Algorithm 1 Sender

```
1:  if (A has data for B) then
2:      X = Hash(A + B);
3:      if X conflicts with any record in A's code table, repeat X = Hash(A+X);
4:      wait till $NAV = 0$
5:      channel sensing;
6:      if ($Channel = idle$ for BIFS) then
7:          go to Line 29
8:      else
9:          exponential random backoff;
10:     end if
11:     while ($BC > 0$) do
12:         channel sensing;
13:         if ($Channel = idle$ ) then
14:             decrease BC by 1 for each idle slot;
15:         end if
16:         if ($Channel = busy$ that A overhears an RTS/CTS) then
17:             if (the overheard sender is in A's ER region) then
18:                 $NAV$ is set according to $T_2$;
19:             else
20:                 $NAV$ is set according to $T_1$;
21:             end if
22:             Update A's code table;
23:             if X conflicts with any record in A's code table, repeat X=Hash(A+X) ;
24:             wait till $NAV = 0$;
25:         else
26:             freeze BC; wait till channel is idle;
27:         end if
28:     end while
29:     transmit RTS to B;
30:     if (receive CTS from B before timeout) then
31:         transmit DATA at rate R after SIFS;
32:     else
33:         increase $retry$ by 1;
34:         if ( $retry > m$) then
35:             drop the current frame;
36:         else
37:             if X conflicts with any record in A's code table, repeat X=Hash(A+X) ;
38:             exponential backoff, and go to Line 11;
39:         end if
40:     end if
41: end if
```

B. Protocol Performance and Parameter Setting

In this subsection, we first prove that the DEX protocol is correct, *i.e.*, for each pair of nodes that successfully exchanges RTS/CTS messages, their data transmissions can be collision-free. Here, collision-free means that the interference from other concurrent transmissions is less than the tolerable threshold. We also study the performance bounds of a dense multi-hop UWB network and propose a method to choose ER size appropriately towards the maximum network throughput in a randomly deployed network.

To evaluate the network performance, we use the log distance path loss model for signal loss in an indoor radio propagation channel, which is given by

$$PL(d) = PL_0 + 10\alpha \log_{10}(d/d_{ref}), \tag{3}$$

Algorithm 2 Receiver

```
1: if ($NAV != 0$) then
2:     wait;
3: else
4:     ready for receiving;
5: end if
6: if (overhear RTS/CTS) then
7:     if (the overheard transmitter/receiver is not in B's ER) then
8:         update B's code table;
9:         $NAV$ is set according to $T_1$; go to Line 1;
10:    else
11:        $NAV$ is set according to $T_2$; go to Line 1;
12:    end if
13: end if
14: if receive RTS targeted to itself then
15:    if (X does not conflict with any record in B's code table and
           $Channel = idle$ for SIFS) then
16:        transmit CTS; receive data; send ACK; go to Line 4;
17:    else
18:        silent; go to Line 4;
19:    end if
20: end if
```

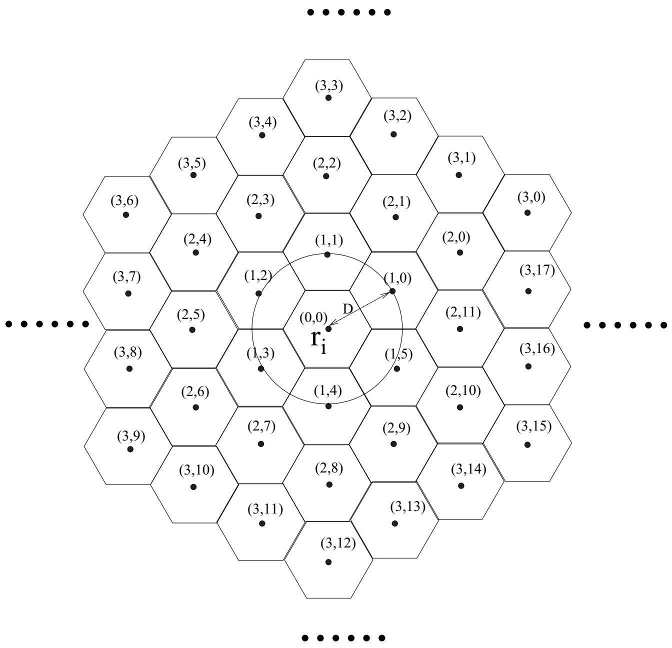


Fig. 2. Worst-case scenario with the maximum interference.

where $PL(d)$ (dB) is the total path loss at distance d, PL_0 is the path loss at the reference distance $d_{ref} = 1$ m, α is the path loss exponent. Under this channel model, the received SINR of flow i is given by

$$SINR(i) = \frac{P(s_i)d(s_i, r_i)^{-\alpha}}{N_0 + \sum_{j \neq i} P(s_j)d(s_j, r_i)^{-\alpha} G_0}, \quad (4)$$

where $P(s_i)$ is the transmission power of the sender of flow i, $d(s_j, r_i)$ is the distance between the sender of flow j and the receiver of flow i.

1) Protocol Correctness: Considering a network with random topology and user deployment, we first consider the maximum amount of interference generated by concurrent transmissions from other nodes to the tagged receiver r_i.

The highest interference level is related to the "circle packing" problem. Each sender is located in the mid-point of an ER which is a circle. The maximum interference occurs when the non-overlapping circles are packed in the plane with highest density, which has been proved to be the hexagonal packing. Thus, the maximum interference to the receiver r_i occurs when all interferers are located in the center of each hexagon cell around r_i, as shown in Fig. 2, i.e., there are 6 interferers located in the first tier of cells of r_i, and $6k$ interferers located in the k-th tier of cells. The distance from the k-th tier interferers to r_i is no less than $\sqrt{3}kD/2$. Thus, the total interference to r_i, I_r, is bounded by

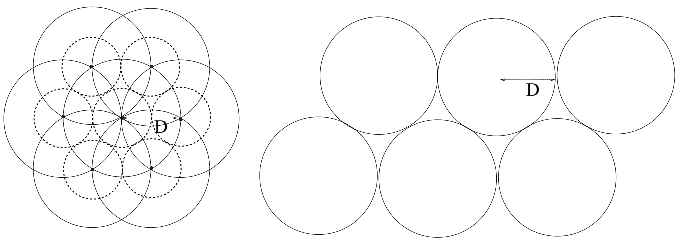
$$\begin{aligned} I_{r,D} &< \sum_{k=1}^{\infty} 6PG_0(\sqrt{3}D/2)^{-\alpha}(k)^{1-\alpha} \\ &= 6PG_0(\sqrt{3}D/2)^{-\alpha}\zeta(\alpha - 1). \end{aligned} \quad (5)$$

The above Riemann Zeta-function, $\zeta(\alpha - 1)$, converges *iff* $\alpha > 2$. Therefore, if the path loss α is a constant not larger than 2, an infinite coverage area cannot allow an infinite number of concurrent transmissions, and vice versa. Fortunately, empirical evidences from experimental field studies suggest that while path loss exponent near the transmitter is likely to be 2, at large distance, it is larger than 2, and the received power level even decays exponentially with distance if the distance is quite large. Therefore, the interference to a tagged user can be well bounded. With a random network setting, it is practical to assume that the maximum interference to r_i, $I_{r,D}$, is $6PG_0D^{-\alpha}$, because (a) the number of first tier interferers is less than six almost surely, (b) the number of interferers is finite, and (c) the path loss exponent is large for high dense wireless networks, so the value of $\zeta(\alpha - 1)$ is close to one.

Now, we can prove that the sender and receiver which successfully exchange RTS/CTS can successfully transmit without being interrupted by other users at rate $R(i) = \eta W \log_2(P(r_i)/[N + I_{r,D}] + 1)$. First, since the RTS/CTS of the pair has been successfully exchanged, all other nodes within their ER will not interrupt the tagged transmission. Second, the actual SINR should be larger than $I_{r,D}$. Thus, the transmission can be successful because the data rate chosen by the pair is more conservative than the actual achievable one.

2) Hidden terminal and exposed terminal: We examine the hidden terminal and exposed terminal problems in multi-hop wireless networks. The hidden terminal problem exists for RTS transmissions. Since DEX allows concurrent transmissions and each pair of nodes can transmit data/ACK for a comparatively long time T consecutively, the number of RTS messages exchanged is reduced, so the collisions due to hidden terminal are reduced. In addition, if we can set the carrier sensing range to be the sum of the transmission range and the interference range of RTS, we can eliminate hidden terminals.

Using 802.11 DCF, there are proposals to mitigate the hidden terminal problem, which usually leads to more severe exposed terminal problem. The nice feature of the proposed DEX protocol is that the reserved space by RTS/CTS is determined by the ER region, instead of the carrier sensing range, so it does not suffer from the exposed terminal problem as much as the IEEE 802.11 DCF protocol. Since the ER is much smaller than their carrier sensing regions, more flows



(a) (b)

Fig. 3. (a) Circle packing problem; (c) circle covering problem.

can transmit concurrently, and the spatial multiplexing gain of DEX is higher than that of 802.11 DCF.

Another issue may result in performance degradation is that the RTS message in 802.11 DCF will notify all other nodes within the carrier sensing range of the sender to refrain from contention till the end of the transmission. If the receiver cannot send CTS because it is inside the carrier sensing range of some ongoing transmissions, the reservation of the RTS is totally wasted. In addition, if both the sender and the receiver of a flow need to compete with a large number of other nodes, the flow may starve due to the low possibilities that both the sender and the receiver can successfully access the channel. With DEX, since the ER is smaller than the carrier sensing region, the chance that the receiver cannot reply to the RTS is much lower, and the starvation problem can be alleviated.

3) Network Performance Bounds: We investigate the performance of the DEX protocol and derive the performance bounds. A node's ER is a circle centered at the node with radius D. D is a key parameter, which affects the number of concurrent transmissions in an area and the interference level to a tagged user. Considering a dense network, we are interested in obtaining the optimal value of D which can maximize the expected network transport throughput. To derive the throughput, we need to know the average number of concurrent transmissions (CTs), which is very difficult to obtain because it is sensitive to the network topology and the sequence of nodes initiating transmissions. Thus, we first obtain the theoretical upper bound and lower bound of the number of CTs in a dense network.

Lemma 1: In an area of $L \times L$, for a given ER with radius D, the upper bound of the number of CTs is $2L^2/(D^2\sqrt{3})$.

Proof: As shown in Fig. 3, in the extreme case that, for each flow, the ER region (the solid circles) of the sender and that of the receiver fully overlap, the maximum number of CTs is equivalent to the maximum number of circles with radius $D/2$ (the dashed circles) that can be packed in the area. This is the classical circle packing problem. Toth proved that the hexagonal lattice is indeed the densest of all possible plane packings [6]. Accordingly, the maximum number of CTs is $2L^2/(D^2\sqrt{3})$. ■

Remark: In a sparse network, we can improve the network throughput by increasing the node density to enlarge the number of CTs. However, according to Lemma 1, once the node density is large enough to saturate the network, further increasing the node density cannot improve the network throughput, but only increase the competition levels of all nodes within the associated ER and results in severe collisions.

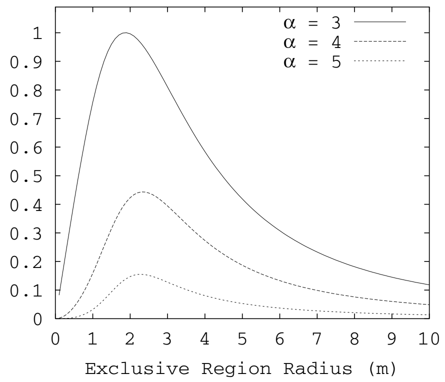


Fig. 4. Normalized expected network transport throughput.

The lower bound of the number of CTs in a sparse network can be as low as zero and it is not of our interest. In the following, we consider the lower bound of a *saturated network*. Wireless resources have three dimensions: time, frequency, and space. In a *saturated network*, we assume that if there is any unoccupied time/frequency/space to allow new collision-free transmissions, some node will initiate a transmission. As one of the main concerns for MAC protocols is to control congestion in the link layer, performance study for saturated networks can provide important insights and guidelines.

Lemma 2: Given the ER with radius D in a saturated network of size $L \times L$, the lower bound of the number of CTs is $L^2/(\sqrt{27}D^2)$.

Proof: We consider the extreme scenario that the ERs of all senders and receivers do not overlap with each other. For a given ER with radius D and a saturated network of size $L \times L$, the lower bound of the number of CTs is equivalent to half of the minimal number of circles with radius D that can cover the area. This is the classical circle covering problem. It has been derived that a lower bound for a covering using equivalent circles is $2\pi/\sqrt{27}$ [7]. Thus, the minimal number of circles covering an area equals $(2\pi/\sqrt{27})(L^2/\pi D^2) = 2L^2/(\sqrt{27}D^2)$. Given that each flow has two non-overlapping circles, the minimal number of CTs in a saturated network is $L^2/(\sqrt{27}D^2)$. ■

4) Exclusive Region Size: From Lemmas 1 and 2, for a saturated network, the upper bound of the number of CTs is six times that of the lower bound, and both are proportional to D^{-2}. The distribution of the number of CTs in a random network is very difficult if not impossible to obtain. Nevertheless, the expected number of CTs should be proportional to D^{-2}: $\mathrm{E[CT]} = \mathrm{k_1/D^2}$, where k_1 is an unknown coefficient.

As the REX sender will use $6PG_0D^{-\alpha}$ as the interference level to set the transmission rate, we then estimate the expected network transport throughput, as given by

$$\frac{k_1}{D^2}\eta W E[d]\log_2\left(1+\frac{PE[d]^{-\alpha}}{N+6PG_0D^{-\alpha}}\right), \tag{6}$$

where $E[d]$ is the expected transmission distance. As the expected transport throughput is a non-linear function of d, using $E[d]$ to get the expected transport throughput is an approximation. Simulation results show that the above approximation is acceptable. Taking the derivative of (6), we can obtain the optimal D value which maximizes the expected

TABLE II
SYSTEM PARAMETERS

W	500 MHz	BIFS	20 μs
$P(s_i)$	-41.3 dBm/MHz	SIFS	10 μs
N_0	-114 dBm/MHz	a slot time	20 μs
α	2.5-6	$CW_{\min}$	31
G_0	0.01-1	$CW_{\max}$	1023
η	0.21	maximum retry limit	7
d_{ref}	1m	RTS/CTS	20 μs
PL_0	43.9 dB	Transmission range	10 m

TABLE III
OPTIMAL EXCLUSIVE REGION SIZE (ANALYSIS)

α	$G_0 = 0.01$	$G_0 = 0.1$	$G_0 = 1$
3	1.87 m	4.03 m	8.69 m
4	2.34 m	4.15 m	7.39 m
5	2.28 m	3.61 m	5.72 m
6	2.11 m	3.10 m	4.55 m

network transport throughput.

Fig. 4 shows the normalized expected network transport throughput as a function of the exclusive region of radius D, with $G_0 = 0.01$, using the parameters listed in TABLE II. It is shown that the expected network transport throughput is a concave function of D, while fixing other parameters, including P, W, N_0, *etc.* The best value of D can be determined when the maximum expected throughput is achieved. The analytical results of optimal D under different parameter values of α and G_0 are listed in TABLE III. It is observed that the optimal D becomes larger when G_0 increases, but changes less with α. This is because the path loss exponent α affects both the received signal strength and the interference level and the corresponding SINR does not change much, while the cross correlation, G_0, determines the interference only (in the denominator of SINR). A greater G_0 means more serious interference among concurrent transmissions, and thus a larger D is required to bound the total interference level to achieve high network throughput.

In practical, the value of α may not be accurately measured or estimated, so the value of D may not be optimal. However, as shown in Fig. 4, the optimal values of D for $\alpha = 3, 4, 5$ only have small difference. Thus, even we under- or over-estimate α, the value of D chosen by the DEX protocol can still be close to the optimal value.

IV. SIMULATIONS RESULTS

In this section, we evaluate the performance of the proposed DEX protocol in terms of transport throughput, fairness, and access delay, and compare it with that of the IEEE 802.11 DCF via simulations. We choose the IEEE 802.11 DCF protocol as benchmark since it is the most popular asynchronous MAC protocol widely adopted.

A. Simulation Settings

The simulated network is set up in a 20 m × 20 m square room, which contains up to 100 active flows, with distinct senders and receivers uniformly distributed in the room. The simulation parameters are listed in TABLE II. The senders use the maximum transmission power and the transmission range is 10 m. The background noise power is 4×10^{-9} mW over 500 MHz signal bandwidth [1]. All N active flows contend for channel access in an asynchronous manner, with its initial arrival time uniformly chosen over $[0, 32)$ time slots. The reference distance is set as $d_{ref} = 1$ m, and the path loss at d_{ref} is 43.9 dB. Thus, the maximum data rate at 1 m is given by (2), i.e., $R = \eta W log_2(1 + SINR) = 1$ Gbps. The achievable data rate decreases with distance d, *e.g.*, given the path loss exponent $\alpha = 4$, the received $SINR$ degrades from 28.8 dB at $d_{ref} = 1$ m to 16.76 dB at $d = 2$ m and the achievable data rate at 2 m decreases to $R = 585$ Mbps. To eliminate the warming-up effects, the simulation data are collected from 10 s to 60 s. We repeat each simulation 10 times with different random seeds and calculate the average.

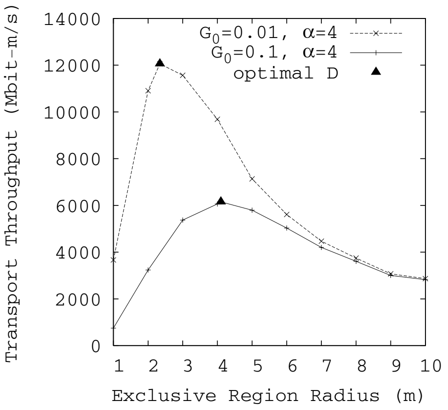


Fig. 5. Transport throughput vs ER radius.

B. Transport Throughput

The transport throughput of a dense network with 40 flows using the DEX protocol is shown in Fig. 5. The data transmission time is $T = 10$ ms. When the ER radius D is very small, more flows are likely to be outside of each other's ER to transmit concurrently; however, a smaller D results in a higher interference level that decreases the data transmission rate. It is observed in Fig. 5 that the total transport throughput of the network is maximized if the value of D is close to the optimal value obtained from the analysis. When the cross correlation G_0 is larger, the interference level among concurrent flows becomes more serious so we should enlarge the value of D accordingly. Simulation results validate the accuracy of our analysis, which demonstrate the significant spatial multiplexing gain achieved by the proposed DEX protocol.

Another observation from Fig. 5 is that, if the value of D is slightly different from the optimal, the throughput is slightly below the highest one. Combining this observation with the results shown in Fig. 4, we can claim that, even if the value of α is not accurately obtained, the protocol performance of DEX will not degrade significantly.

We then investigate the network transport throughput under various network densities, and compare the performance of the DEX protocol (with ER radius $D = 4.15$ m, $G_0 = 0.1$, $T = 10$ ms and $\alpha = 4$) with that of IEEE 802.11 DCF (with carrier sensing range of 10 m) in Fig. 6. When there are only 10 flows in a 20 m × 20 m square room, the network is relatively sparse, and the transport throughput of

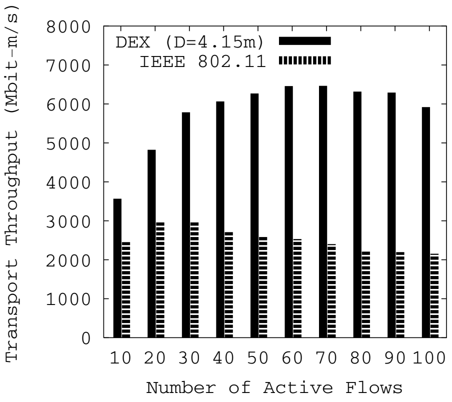


Fig. 6. Transport throughput comparison of different protocols.

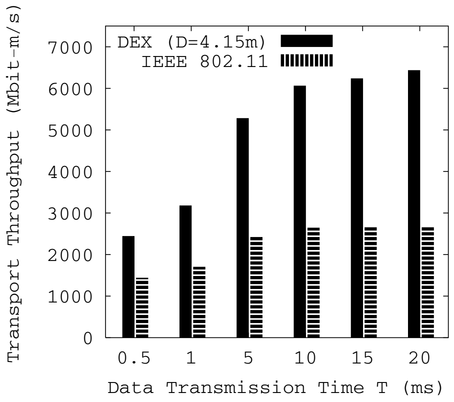


Fig. 7. Transport throughput vs data transmission time T.

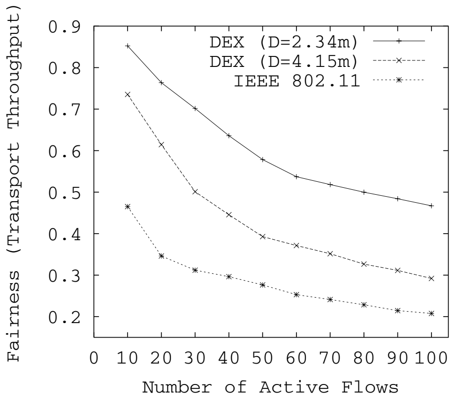


Fig. 8. Fairness (Transport throughput) comparison of different protocols.

the DEX protocol is 1.45 times that of IEEE 802.11 DCF. When the number of flows exceeds 30, the network throughput of IEEE 802.11 DCF decreases due to serious collisions among the competing flows; while with the proposed DEX, more concurrent transmissions are allowed when the number of active flows increases. The achieved transport throughput of DEX is around 2 times that of IEEE 802.11 DCF with 30 active flows, and 2.7 times with 70 active flows. It is also shown in Fig. 6 that the network transport throughput of DEX increases w.r.t. the network density until the number of active flows in the network exceeds 70, when serious collisions degrade the network performance. In all cases, the proposed DEX significantly outperforms IEEE 802.11 DCF by aggressively exploiting spatial reuse opportunities, and it is more suitable for a dense multi-hop UWB network.

We further study the impact of data transmission time T on both protocols. In the DEX protocol, we use the optimal ER radius $D = 4.15$ m for $G_0 = 0.1$ and $\alpha = 4$. It is observed in Fig. 7 that the transport throughput of 40 active flows increases with the data transmission time T in both DEX and IEEE 802.11.With a larger T, the protocol overheads, including RTS/CTS, backoff time, interframe space, *etc.*, become relatively smaller, and more flows can transmit concurrently to achieve a higher spatial multiplexing gain with DEX. As shown in Fig. 7, the ratio of the achieved transport throughput using DEX at optimal D to that of IEEE 802.11 increases from 1.6 for $T = 0.5$ ms to 2.29 for $T = 10$ ms. The proposed DEX always outperforms IEEE 802.11 w.r.t. various T values. It is worth noting that a large value of T is preferable for network throughput, but it will result in unfairness problem and longer access delays for other flows in the same contention region. In the following subsections, we investigate the fairness and access delays.

C. Fairness

Fairness is evaluated using Jain's fairness index [8], in terms of the network transport throughput. We first compare the fairness performance of DEX under various D values with that of IEEE 802.11 DCF in Fig. 8. It is well known that the 802.11 DCF based MAC exhibits serious unfairness among competing flows in a multi-hop environment. Some "lucky" flows are more likely to access the channel, while other "unlucky" ones may suffer from complete throughput starvation. Starvation phenomenon becomes more severe in a denser network. As shown in Fig. 8, the fairness performance of both protocols decreases when the number of active flows increases. However, the proposed DEX with smaller ER radius D achieves better fairness than the 802.11 DCF. This is because smaller ER region can effectively reduce the flow starvation by reducing the number of competing flows, and accordingly improve the fairness performance.

The impact of T on fairness is shown in Fig. 9. We consider 40 active flows in the room. With a larger value of T, all neighbors within the ER of the tagged sender and receiver have to postpone their transmissions for a longer duration, and thus they are more likely to starve, especially when the ER radius is large and there are many competing flows in the neighborhood. As shown in Fig. 9, the fairness performance degrades significantly when the ER radius D and data transmission time T increase.

D. Delay Outage Ratio

Access delay is another important performance metric for evaluating a MAC protocol. We define the delay outage ratio as the ratio of the number of attempts with access delay exceeding the delay threshold to the total number of attempts. We set the delay threshold to 150 ms, $G_0 = 0.1$ and $\alpha = 4$. As shown in Fig. 10, the delay outage ratio increases with the number of active flows because more collisions among competing flows result in more backoff and thus longer

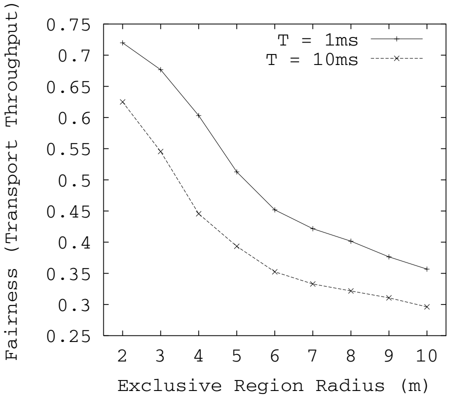


Fig. 9. Fairness (transport throughput) under various ER radius.

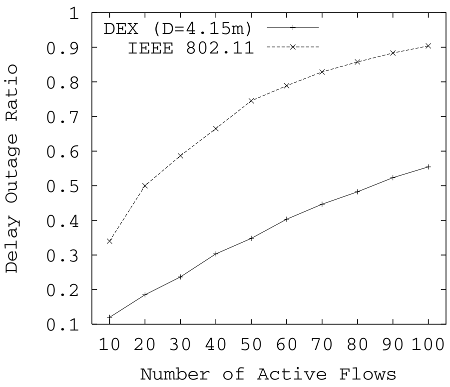


Fig. 10. Delay outage ratio comparison of different protocols.

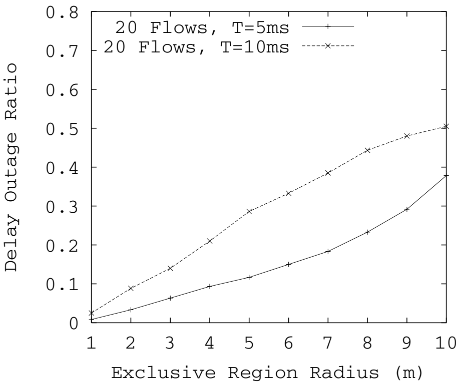


Fig. 11. Delay outage ratio vs ER radius.

access delays. However, the proposed DEX allows for more concurrent transmissions, so the average access delay of each flow is reduced when the ER radius is smaller.

For choosing the value of T, there is a tradeoff between fairness/delay and transport throughput. We can choose the maximum value of T, under the constraints that the corresponding fairness index is above certain threshold and the delay outage ratio is below certain threshold. Since the ER of DEX is much smaller than the carrier sensing region of 802.11 DCF, DEX can use a larger value of T for higher throughput and still maintain a desirable delay and fairness performance.

V. RELATED WORK AND EXISTING PROTOCOLS

Generally, MAC protocols can be classified into two categories: centralized and distributed MAC. Extensive research has been conducted on developing efficient centralized MAC protocols for wireless networks, with dedicated or randomly chosen coordinators [9]. A centralized MAC protocol usually provides more reliable and predictable services than distributed MAC at the expense of control overheads. The order-optimal wireless capacity with ideal scheduling in the MAC layer was investigated in [10]. The optimal throughput and delay tradeoff in static wireless networks was studied in [11]. It was claimed in [12] that in wideband systems, it is optimal to have an ER around the receiver. Based on the ER concept proposed in [12], the capacity of the infrastructure-based UWB networks with the dedicated resource allocation scheme and the random access MAC were studied in [13] and [14], respectively. The optimal resource management was formulated as a utility maximization problem in [15], based on the global user information at the central controller.

However, a centralized solution may not be desirable for large-scale, multi-hop wireless networks for the following reasons: a) Centralized schemes normally have significant communication and computational overheads. With high data rate (up to Gbps) UWB communication technologies, the transmission time is usually on the order of μs, so any packet-level scheduler with complexity more than $O(1)$ becomes less desirable. On the other hand, the traffic of many applications, *e.g.*, data and video traffic, are bursty in nature, thus it is difficult to reserve an appropriate amount of resources for these traffic flows; b) tight synchronization among devices is costly, especially in dense UWB networks; c) centralized architecture is less scalable, and it may suffer the single-point-of-failure problem; d) when a hierarchical structure is used to divide the entire network into multiple small piconets, coordination among piconets is not an easy task.

The WiMedia Alliance has launched PHY and MAC layer specifications based on the Multi-band Orthogonal Frequency Division Multiplexing (MB-OFDM) UWB technology [3]. The WiMedia MAC specification uses a combination of CSMA and TDMA mechanisms to provide a certain level of quality of service for isochronous traffic in a distributed manner. In [16], a contention based distributed algorithm, RCAMA, is proposed, using a physical interference model. However, both RCAMA and WiMedia MAC are based on a time-slot frame structure, which still requires tight synchronization. The maximum throughput region attained by a distributed scheduling strategy under arbitrary network topology and interference models was given in [17]. A distributed maximal matching scheduling strategy was presented in [18] to guarantee a certain fraction of the optimal throughput region. In [19], a distributed greedy scheduling scheme based on a more general interference model was proposed, and a lower bound on the capacity region was also investigated. However, to guarantee the throughput performance, the schemes in [17], [18], [19] may require many rounds of computation and control message exchanges, and thus are not scalable because the overheads increase with the network size.

These works mainly focused on proposing new protocols or algorithms with more complicated control messages and computations to improve the resource utilization. In addition, the rate adaptive characteristics of the UWB communication technologies were not considered. A joint PHY/MAC architecture for impulse-based time-hopping UWB was proposed in [20], considering power control, rate adaptation, and mutual exclusive region. The approach mainly focused on effective physical layer modulation schemes to cancel the interfering energy, and effective MAC protocol design still remains an open issue.

On the other hand, several recent works have been proposed to adaptively adjust the carrier sensing range of the transmitters to improve the spatial reuse performance of IEEE 802.11 DCF [21], [22], [23], [24], [25]. In [22], the relationship between transmission power and the carrier sense threshold was studied, assuming a perfect MAC protocol that all communication channels are fully utilized. The impact of the carrier sensing threshold on the network capacity was investigated in [23]. The optimal carrier sensing threshold that maximizes spatial reuse for several regular topologies was obtained in [24]. It was found in [25] that the optimal carrier sensing range of 802.11 DCF MAC should consider the tradeoff between the spatial reuse and the packet collision probability, and that an optimal carrier sensing range can be obtained based on a reward formulation. However, all the previous works use a simple collision model (A collision occurs if two or more stations within their transmission ranges transmit simultaneously.) in a WLAN environment, where the signal and interference levels are much higher than those in UWB networks. Due to the stringent power emission regulation and the wide bandwidth of UWB communications, spreading technologies are usually employed to allow multiple concurrent transmissions [1], [3]. Thus, the simple collision model used in WLANs does not hold in UWB systems. In addition, adjusting the carrier sensing range of the transmitters can only reduce possible collisions among those transmitters within their carrier sensing ranges, but cannot guarantee successful receptions at the receivers. Therefore, instead of adjusting sensing ranges around the transmitters, we define exclusive regions around the receivers to assure that the ongoing transmission to the tagged receiver will not be interrupted by other interferers. To the best of our knowledge, little work has been done for asynchronous distributed MAC design and optimization for multi-hop UWB wireless networks, considering the characteristics of UWB communication technologies. Thus motivated, we propose the DEX MAC protocol to efficiently exploit the spatial capacity of multi-hop UWB networks.

VI. CONCLUSION AND FUTURE WORK

In this paper, we have proposed a distributed MAC protocol, referred to as DEX, for multi-hop UWB networks. With the derived optimal ER size, DEX can effectively and efficiently utilize network resources in an asynchronous and distributed manner. Our work suggests a new direction of future MAC protocol design for high data rate, dense networks. Instead of depending on more complicated control messages, we have investigated the protocol parameters and improve the protocol performance significantly by fine tuning them. An important future research issue is to study the performance of the proposed DEX protocol in the presence of fast fading and shadowing in the UWB channel. Another possible way to implement the DEX protocol is to use the average received signal strength instead of the geometry distance to determine the exclusive region. In this case, how to promptly obtain accurate signal strength of UWB communications requires further investigation.

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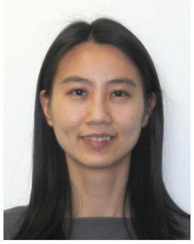

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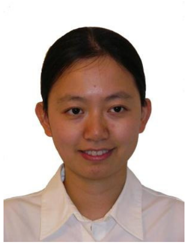

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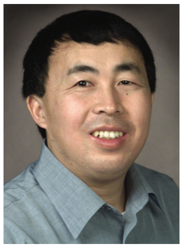

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