Efficient MAC Protocol for Ultra-Wideband Networks

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ABSTRACT

Ultra-wideband communication is a promising enabling technology for future broadband wireless multimedia services. A simple and robust medium-access-control (MAC) protocol is of critical importance to utilize the large bandwidth of UWB channels and to enable numerous new applications and services cost effectively. In this article, we introduce an efficient MAC protocol design for both centralized and distributed multihop UWB networks, based on the exclusive region concept. By reserving a small ER surrounding the receivers to assure successful transmissions, the ER-based MAC protocol can exploit the spatial multiplexing gain of UWB networks and enable multiple users to efficiently and fairly share network resources.

INTRODUCTION

Ultra-wideband (UWB) is a promising wireless networking technology to meet the ever-increasing demand for anytime, anywhere wireless connectivity. The Federal Communications Commission (FCC) allocated the unlicensed 3.1–10.6 GHz and 57–64 GHz frequency bands for commercial use in 2002 and 2005, respectively, which opened the door for very high-data-rate, power-efficient wireless communications. Since then, prototypes and consumer products using UWB technologies have been emerging to deliver high-volume traffic over a short distance with very low-power consumption.

The salient features of UWB communication networks enable new broadband multimedia services that otherwise would be beyond what consumers might imagine today. In addition to traditional multimedia services such as voice and video streaming, UWB is considered one of the most promising candidates for health care services in medical body area networks (MBANs). The precise ranging potential of UWB technology makes it suitable for location-aware applications in IEEE 802.15.4a-based wireless sensor networks [1]. It also is anticipated that UWB will launch a new era in home consumer electronics (CE). CE manufacturers are looking for solutions to allow UWB-enabled CE devices to be connected to one another in a home network and public hotspots. For instance, in broadband hotspots like World Expo centers and soccer stadiums, consumers and business entities can use UWB CE to access high-speed Internet, view (on demand) a variety of video media, and exchange rich multimedia information locally with their neighbors. To facilitate highly dense UWB networks supporting high-volume multimedia applications, a simple and robust medium-access-control (MAC) protocol is of critical importance to utilize the large bandwidth of UWB channels and enable multiple UWB devices to efficiently and fairly share wireless resources.

In this article, we focus on efficient MAC protocol design for high-rate UWB networks. We first review the existing MAC protocols and discuss their advantages and limitations. We then study the particular physical layer characteristics of the UWB system, which provide important opportunities for MAC design. We introduce an exclusive region (ER)-based MAC protocol design for both centralized and distributed multihop UWB networks. By appropriately exploiting the spatial multiplexing capability of UWB networks, the ER-based MAC can significantly improve network performance. Some future research issues for MAC design in next-generation UWB networks are discussed.

IEEE 802.15.3 AND WIMEDIA MAC

IEEE 802.15.3 is a hybrid MAC designed to support high-rate and low-cost connectivity in wireless personal area networks (WPANs) [2]. Several wireless devices can form a piconet autonomously in which one of them is selected as the piconet coordinator (PNC) that coordinates peer-to-peer communications between the devices. Timing in IEEE 802.15.3 is based on the time-slotted, superframe structure, as shown in Fig. 1. At the beginning of a superframe, the PNC sends a beacon to all devices for synchronization, channel-time allocation, and management-information distribution. During the channel access period, devices in the piconet access the channel in a distributed manner using the carrier sense multiple access/collision avoidance (CSMA/CA) mechanism for network initiation/association, resource allocation requests, and asynchronous data transmissions. To provide quality of service (QoS) for isochronous traffic, the PNC assigns channel-time allocations (CTAs) to devices for contention-free data transmission in the CTA period

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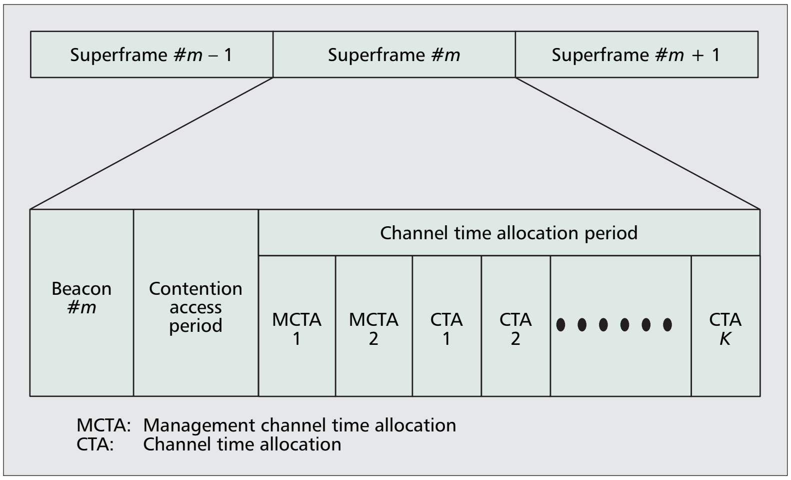
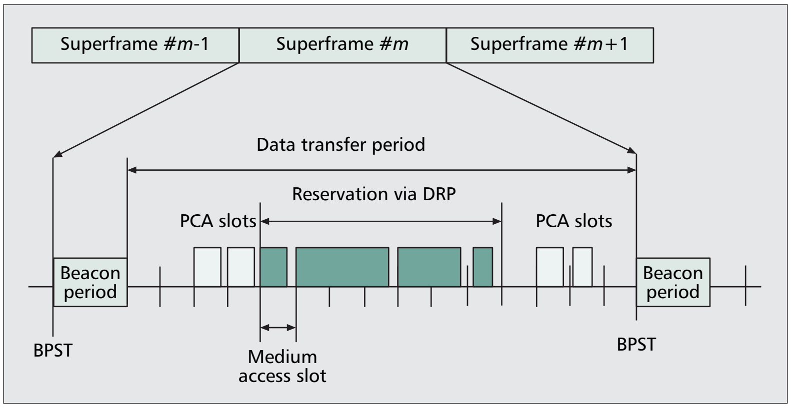


■ **Figure 1.** *IEEE 802.15.3 superframe structure.*



■ **Figure 2.** *WiMeda MAC superframe structure.*

(CTAP). Combining the best qualities of asynchronous CSMA/CA-based random access and scheduling-based guaranteed access, the hybrid IEEE 802.15.3 MAC achieves flexibility, efficiency, and QoS provisioning.

However, IEEE 802.15.3 MAC requires a centralized network architecture and suffers from a single-point-of-failure problem. Thus, IEEE 802.15.3 is more suitable for a network where a central controller usually is available, and network topology is relatively stable. In public hotspots, a large number UWB CE devices may join and leave the network at any time, and the network topology changes dynamically. If the current PNC disappears (e.g., powers off or moves away), it may take several seconds before the remaining devices reorganize and re-elect a new PNC. In addition, when multiple piconets are used in public hotspots to extend the communication coverage, it is very challenging and costly to manage the inter-piconet interference, which can degrade the network performance significantly.

To address the aforementioned problems in IEEE 802.15.3, the WiMedia alliance has specified a distributed MAC based on multiband orthogonal frequency-division multiplexing (MB-OFDM) [3, 4]. Similar to IEEE 802.15.3, timing in WiMedia MAC is based on the slotted superframe structure, as shown in Fig. 2. Each superframe starts with a beacon period (BP). First, a device senses the UWB channels for several superframes and if a beacon is received, it selects a channel for communication; otherwise, the device selects a channel and initiates a BP by itself. All devices communicating in the same channel collect the beacons from their neighbors and pick up unoccupied beacon slots to transmit their own beacon frames. Data frames are transmitted during the data transmission period (DTP), which consists of multiple medium-access slots (MASs). During the DTP, devices can access the channel in an asynchronous manner through the prioritized channel-access (PCA) protocol, which is similar to the enhanced distributed-channel access (EDCA) specified in IEEE 802.11e. The basic difference between PCA and EDCA is in the physical layer. Due to the low-power level of UWB signals, PCA uses preamble sensing instead of the energy detection-based carrier sensing in EDCA. Devices carrying isochronous traffic also can reserve multiple MASs for contention-free channel access through a distributed reservation protocol (DRP). A device first sends a reservation request to the receiver either in the beacon or using DRP or PCA. The receiver analyzes the channel-time utilization of its neighbors and responds to the sender. If the requested MASs are not available, the receiver provides additional information (e.g., available MASs in its beacon group) to the sender. Otherwise, the successful reservation is announced in the beacons so that other devices within the transmission range become aware of the reservation and defer their channel access during that period.

Similar to IEEE 802.15.3, WiMedia MAC is still a time-division multiple access (TDMA)-based MAC and requires channel-time synchronization among devices, that is, all devices communicating in the same channel must synchronize the BP starting time with each other. However, synchronization is difficult and costly in multihop UWB networks. In a densely deployed multihop network, where multiple beacon groups can overlap with each other, merging different BPs into one single common BP is not a trivial task. Another problem is when a burst of devices join in the network during one superframe, it is very likely that two or more devices can select the same beacon slot, which causes beacon collisions. A device only can determine a beacon collision or transmission error if its own device address is not included in the beacons of its neighbors for multiple, continuous superframes. In other words, it may take hundreds of milliseconds for a device to detect a beacon collision. Last but not least, both the IEEE 802.15.3 and the WiMedia MAC use TDMA to avoid collisions, which results in inefficient resource utilization in UWB networks. In contrast to a narrowband system, where simultaneous transmissions in nearby neighbors collide with each other, a UWB system can support multiple concurrent transmissions if the multi-user interference is properly managed [5, 6]. Therefore, we introduce a UWB MAC design that appropriately exploits the spatial multiplexing capability of UWB networks, taking into consideration the salient features of UWB communications.

Physical Layer Characteristics

There are several physical layer proposals for UWB networks: continuous wave UWB (C-UWB), direct sequence UWB (DS-UWB), and MB-OFDM UWB. C-UWB uses bursts of pulses and variable spreading codes to trade data rate for communication range. It is specified as an alternative physical layer in IEEE 802.15.4a [1], which also has been proposed for IEEE 802.15.3c [7]. DS-UWB and MB-OFDM UWB are two physical specifications for high-rate WPANs. DS-UWB is based on direct-sequence spread-spectrum (DSSS) technology, and MB-OFDM UWB uses a combination of frequency hopping and OFDM technologies. The performance of DS-UWB and MB-OFDM UWB has been studied extensively in the literature, and each has shown its own advantages and disadvantages. For example, DS-UWB is vulnerable to intersymbol interference (ISI) and requires a complex equalizer at the receiver, whereas MB-OFDM UWB is relatively robust to ISI but requires higher computational power for fast Fourier transform. More performance comparisons of DS-UWB and MB-OFDM UWB can be found in [8].

Generally, UWB communication is characterized by a high-data rate at a short transmission range, a low-power transmission and interference level, and high immunity against multi-user interference, and so on. The FCC power spectrum density emission limit for devices operating in the UWB band is –41.3 dBm/MHz, and the emission level can be significantly lower in other segments of the spectrum, which allows the UWB system to co-exist with other narrowband systems. Because of the stringent power constraint and the wide bandwidth in UWB communications, normally the UWB transmission power cannot be adjusted; and spreading technologies in both the time domain and the frequency domain are used to vary the data rates [3]. The inherent characteristics of spreading technology make the UWB system immune to interference. UWB can provide high-precision ranging and is ideal for real-time location systems. The next-generation UWB network, using the 57–64 GHz frequency band, usually is referred to as millimeter wave (mmWave) UWB because the wavelengths for these frequencies are about one to ten millimeters. Because mmWave communications suffer from high path loss due to oxygen absorption and atmospheric attenuation, it is highly desirable to use directional antennas to achieve high directivity and diversity gains [7]. Note that for UWB in the frequency range below 10 GHz, the emission mask must be fulfilled in all directions, and thus directional transmit antennas require a backoff of the transmit power. These physical layer characteristics provide great opportunities for designing an efficient MAC protocol to explore the spatial multiplexing in UWB networks. For example, the low power level, large bandwidth, and precise ranging allow for an ER-based approach for interference management; and the use of spreading technologies and directional antenna provides the feasibility of aggressive space reuse in wireless channels. These features facilitate the MAC design for supporting high-density, high-rate applications in UWB networks.

Efficient MAC Protocol Design

Exclusive Regions

The MAC layer generally uses temporally exclusive mechanisms in the time, frequency, or space domain to eliminate or reduce collisions from simultaneous transmissions. For UWB networks with very low power emission, two transmissions separated by a certain distance can cause negligible interference to each other and thus can transmit concurrently. Generally, interference and multiple access can be managed effectively through power control, rate control, or mutual exclusion. Because power control is not efficient in UWB systems, a rate control-based interference mitigation scheme is proposed in [9] to mitigate the impact of interfering pulses to the receiver in a pulsed time-hopping (TH) UWB system. If pulses from a strong interferer are larger than the erasure threshold, the scheme replaces them by erasures (i.e., skipping in the decoding process). Simulations in a symmetric topology show that a source can always send and continuously adapt its rate without mutual exclusion when the physical layer interference mitigation scheme is properly applied. Another general approach is to use an exclusive mechanism in the space domain. An ER is defined as an area surrounding the receiver such that a transmitter inside the ER causes harmful interference at the targeted receiver. Recent research indicates that an ER-based resource-management scheme is optimal in terms of throughput by exploiting the space dimension of the wireless channel to allow interfering sources to transmit concurrently [5].

The ERs are determined by the transmission and reception patterns of the antennas, that is, omni-directional (omni-) or directional antenna, as shown in Fig. 3. The omni-antenna distributes its signal energy evenly in all directions, which not only reduces the signal strength but also causes interference to other transmissions in the neighborhood. Compared to the omni-antenna, a directional antenna achieves a much higher transmission gain by radiating its energy only in the desired direction. We study four different cases. In Fig. 3a, when all transmitters and receivers use an omni-antenna, all interferers should be at least r_0 away from the receivers, and the ER is a single circle centered at a receiver with radius r_0. The ER radius is determined such that the average interfering signal strength is below a certain threshold. In Fig. 3b, the transmitters use a directional antenna with radiation angle θ, and the receiver uses an omni-antenna. If the receiver is inside the radiation angle of an interferer, the interferer should be at least r_1 away; otherwise, the interferer should be $r_2 < r_1$. Different ER radii result from different antenna gains in the mainlobes and sidelobes of the directional antenna. The higher the antenna gain, the farther the interferer should be away from the receiver. Ideally, we can ignore the sidelobe effect of a directional antenna and set $r_2 = 0$. In Fig. 3c, omni-transmitters and directional receivers are used, and the ER is a sector of a circle centered at the receiver with radius r_4 and angle θ plus a sector with radius r_3 and angle $2\pi - \theta$. Similarly, in Fig. 3d where all trans-

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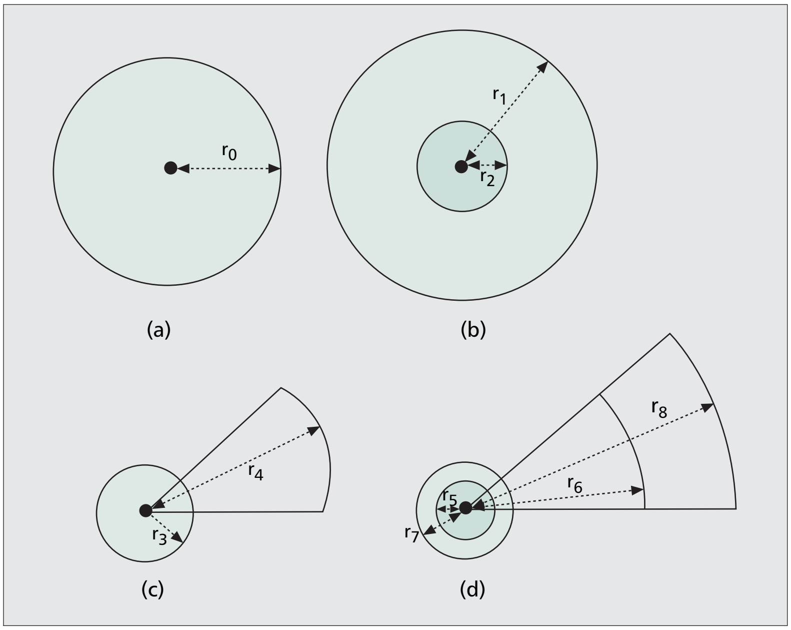


■ **Figure 3.** *Exclusive Regions: a) omni-omni; b) directional-omni; c) omni-directional; d) directional-directional.*

mitters and receivers are directional, the ER consists of four sectors [6].

ER-Based Concurrent Scheduling in Centralized UWB Networks

In UWB networks, concurrent transmissions are possible and preferable to serial TDMA transmissions, as long as all interferers are sufficiently far apart, that is, outside the ERs of the receivers [6]. Using the ranging capability of UWB devices, a sender can decide whether it is within the ER or not. In a centralized IEEE 802.15.3 UWB WPAN, the central controller collects the global user information, for example, channel-time requests and the ER neighbors of each user, based on which peer-to-peer concurrent transmissions can be scheduled in each time slot, to exploit the spatial reuse opportunity of the wireless channel. Thus, the network throughput can be significantly improved by exploring the spatial multiplexing gain of UWB networks appropriately.

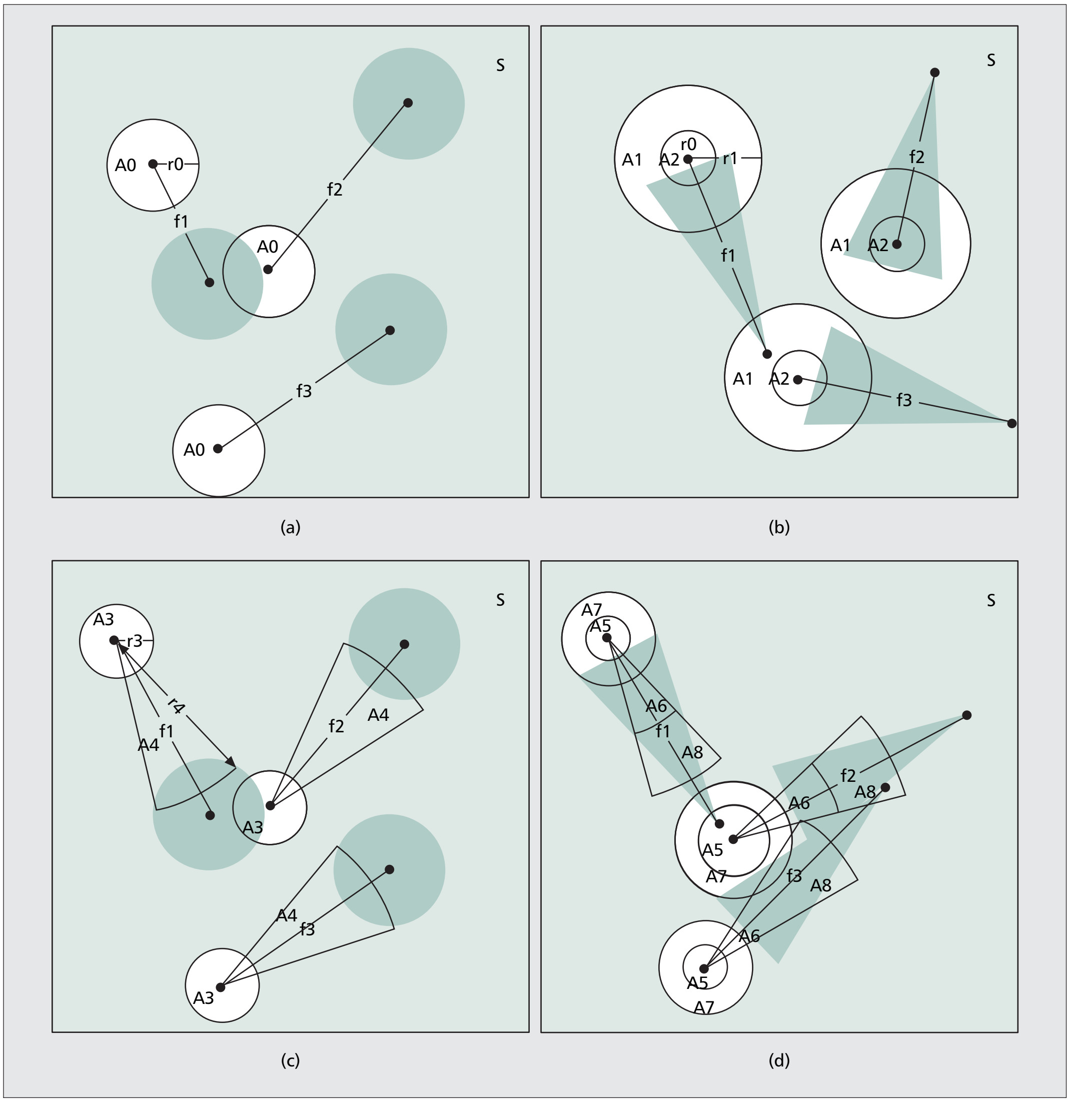
Denote the set of all active flows in an IEEE 802.15.3 UWB WPAN as S. A subset of flows $\gamma_i \subset S$ are the flows scheduled in slot i that satisfy the concurrent transmission conditions, as shown in Fig. 4. Flows are assigned with weights W, which correspond to the current service level or QoS requirement of each flow. We introduce a simple ER-based concurrent scheduling scheme with computational complexity $O(N^2 \log N)$ to allocate each slot. First, we randomly choose flow j with the highest weight W and add it into set γ_i for transmission. To explore the spatial capability of UWB networks, we check the remaining flows in $S - \gamma_i$ in descending order of W and add another flow into the set γ_i for concurrent transmission if and only if this flow does not conflict with all existing flows in set γ_i, that is, all the transmitters are outside the ER of the receivers including the new flow. We sort flows according to their current service levels and thus give flows with larger weights a higher priority to be scheduled.

The ER radius is the key parameter for an ER-based scheduling scheme. In a UWB network, a smaller ER achieves a larger spatial multiplexing gain by allowing more concurrent transmissions that may cause a higher mutual-interference level and degrade the throughput of each flow. A larger ER allows fewer concurrent transmissions, but each flow achieves a higher transmission rate due to the reduced multi-user interference. Thus, it is critical to determine the optimal ER size to maximize the network throughput. Given a random network topology, an analytical framework was developed in [10] to study the performance of a UWB WPAN using an ER-based scheduling scheme in terms of the expected number of concurrent transmissions, the average per-flow throughput and network throughput, and so on. The relationship of the normalized network throughput and the ER radius is shown in Fig. 5. There are 40 flows randomly deployed in a 10 m $\times$ 10 m area. The transmission power is 0.1 mW, and the background noise level is –76 dBm/MHZ. The cross correlation among concurrent transmissions is 10^{-4}. As shown in Fig. 5, the network throughput is a concave curve with different ER radii, and the optimal ER radius is obtained when the maximum network throughput is achieved.

ER-Based Asynchronous Distributed MAC in Multihop UWB Networks

Because UWB communication achieves a very high data rate with a short transmission range, multihop relay usually is required for ubiquitous high-rate wireless connections. MAC protocol plays a key role in coordinating channel access among multiple competing users. Because global synchronization and scheduling are difficult and costly in multihop UWB networks, we are motivated to design an asynchronous distributed MAC protocol to efficiently utilize the wireless resources in densely deployed, multihop UWB networks. In the recent past, the IEEE 802.11 distributed coordination function (DCF) has been overwhelmingly successful supporting asynchronous data transmissions due to its flexibility, robustness, and simplicity. To provide QoS for delay-sensitive applications, such as voice and streaming multimedia, IEEE 802.11e uses EDCA for service differentiation. In EDCA, high-priority traffic has a higher probability to access the channel than low-priority traffic by using smaller arbitrary interframe spaces (AIFSs) and/or contention windows (CWs). However, the efficiency of CSMA/CA-based IEEE 802.11(e) MAC in multihop wireless networks is far from ideal. In a densely deployed multihop network, the throughput starvation and unfairness problems resulting from hidden/exposed terminals become severe because of the contention nature of the protocol, which leads to unsatisfactory user experiences and becomes a major barrier for the future growth of wireless networks.

Recognizing the unique characteristics of UWB communications, we employ the concept of ER in the design of an asynchronous, fully distributed MAC for a multihop UWB network. Instead of designing a new protocol from scratch,



■ **Figure 4.** *Concurrent transmissions: a) omni-omni; b) directional-omni; c) omni-directional; d) directional-directional.*

In the DEX protocol, a pool of spreading codes are shared among all users, one of which is chosen as the common spreading code for control-message exchange, for example, for RTS and CTS frames, and other codes are used for data transmissions.

the proposed distributed EXclusive (DEX) region-based MAC uses control messages similar to those in the IEEE 802.11(e) MAC protocol [11]. That is, prior to data transmission, devices exchange request-to-send/clear-to-send (RTS/CTS) frames to reserve the medium for the subsequent data transmissions. Similar to the IEEE 802.11 DCF, each device monitors the medium before attempting transmissions. If the medium is sensed busy, the device enters the back-off phase after the medium is sensed idle for a period of time. The back-off counter decreases by one for every idle slot and freezes when the medium is busy. The device can transmit only when the back-off counter reaches zero. If the transmission fails due to strong interference from other concurrent transmissions, the device doubles the back-off window until the maximum value is reached and reschedules the RTS transmission following the same process. After each successful transmission, the back-off counter is reset to its minimum value. The retransmitted frame is dropped when the retry limit is reached. In contrast to IEEE 802.11 DCF, DEX also uses the RTS/CTS exchange to reserve small ERs around the sender and receiver for data and acknowledgment (ACK) transmissions and thus, can effectively explore the spatial multiplexing gain of UWB networks and enable users to efficiently and fairly share network resources in a distributed manner. By using the ranging service, a sender can decide if it is within the ER of the ongoing transmissions. If yes, it refrains from transmitting concurrently with the ongoing ones and vice versa. Because 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. To fairly evaluate the protocol performance in a multihop environment, transport throughput is used for performance evaluation, which is defined as the product of the throughput and the distance over which the information is being transferred. In addition, finding the optimal ER that maximizes the network transport throughput also is an interesting issue.

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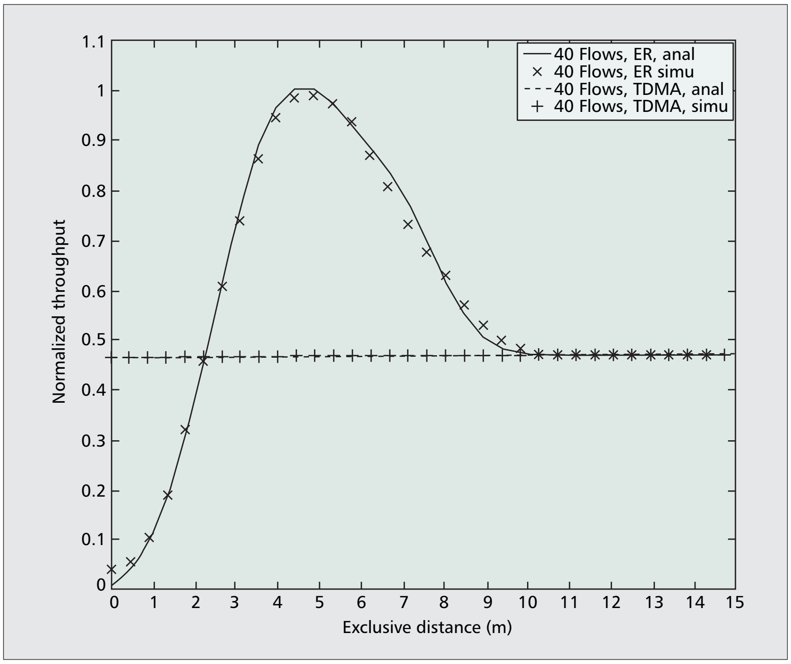

Figure 5. *Network throughput under various ER sizes.*

chosen as the common spreading code for control-message exchange, for example, for RTS and CTS frames, and other codes are used for data transmissions. Each user maintains a code table to record all the spreading codes used by the ongoing neighboring transmissions. If user A has data for user B, A uses a hash function to obtain a spreading code, $X = H(A, B)$, where A and B can use their MAC addresses in the hash function. A starts channel sensing when its network allocation vector (NAV) reaches zero. If the channel is sensed idle for a back-off 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 back-off procedure and sets a back-off counter (BC) uniformly distributed over $[0, CW)$ for the first transmission attempt; and A freezes its BC until the channel is sensed idle for a $BIFS$. If A overhears an RTS or CTS frame from another transmission f_i, A checks the ER condition:

- If A is within the ER of either the transmitter or the receiver of f_i, A should postpone its own transmission until the ongoing transmission completes, and A sets its $NAV = T_2$.
- If A is outside the ER of f_i, A is able to concurrently transmit with f_i; A sets $NAV = T_1 = RTS + SIFS + CTS$ and adds the spreading code used by f_i in its code table.

A should choose its own code X that 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 is 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 after a SIFS. To ensure that ongoing transmissions are not interrupted by the concurrent transmissions, the transmission rate R is not determined based on the measurement of the instantaneous interference and noise level of the tagged transmission, but on the worst case scenario with the maximum number of dominant interferers. Therefore, DEX is robust against interference from neighborhood asynchronous transmissions. If no CTS is received successfully, implying that B is not available to receive data using code X at this moment, A enters the back-off stage and retransmits thereafter until the retransmission limit m is reached. The back-off procedure in DEX is the same as that in IEEE 802.11(e). In other words, different CW and $AIFS$ values also can be employed in DEX for service differentiation.

At the receiver side, B is ready for channel sensing or receiving when its $NAV = 0$. Whenever B overhears an RTS or CTS frame from its neighboring node, B updates 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 can retransmit an RTS and choose another code after the RTS timeout.

The network transport throughputs of the DEX protocol and IEEE 802.11 MAC are compared in Fig. 6. Under the obtained optimal ER radius, the DEX protocol significantly outperforms IEEE 802.11 by effectively exploiting the spatial reuse opportunities in a dense multihop network [11]. By reserving two smaller ERs for each pair, DEX does not suffer from the exposed terminal problem as much as the IEEE 802.11 MAC and can achieve a higher spatial multiplexing gain. Because DEX allows concurrent transmissions, and each sender/receiver pair can transmit data/ACK for a comparatively long time T, consecutively, the number of RTS initiations in the neighborhood of a sender can be reduced significantly. A larger T results in a higher resource utilization with less involved overhead but can cause longer access delays of neighboring users. On the other hand, a smaller ER allows for more concurrent transmissions, which in turn reduces the access delay of each flow. Thus, in the DEX protocol, it is possible to choose a larger T and to well maintain the desired delay and fairness performance.

Conclusion and Future Research

In this article, we introduce an ER-based approach in the MAC protocol design for both centralized and distributed multihop UWB networks. Considering the salient features of UWB communications and using the concept of ER to properly manage the potential multi-user interference, the protocols can efficiently exploit the spatial multiplexing gain of UWB networks and significantly improve the network performance. Designing and optimizing a distributed MAC for emerging mmWave UWB is challenging because of the inefficiency in neighbor discovery with directional antenna. Further research to investigate cooperative communications in UWB networks in the presence of fast fading and shadowing will be pursued.

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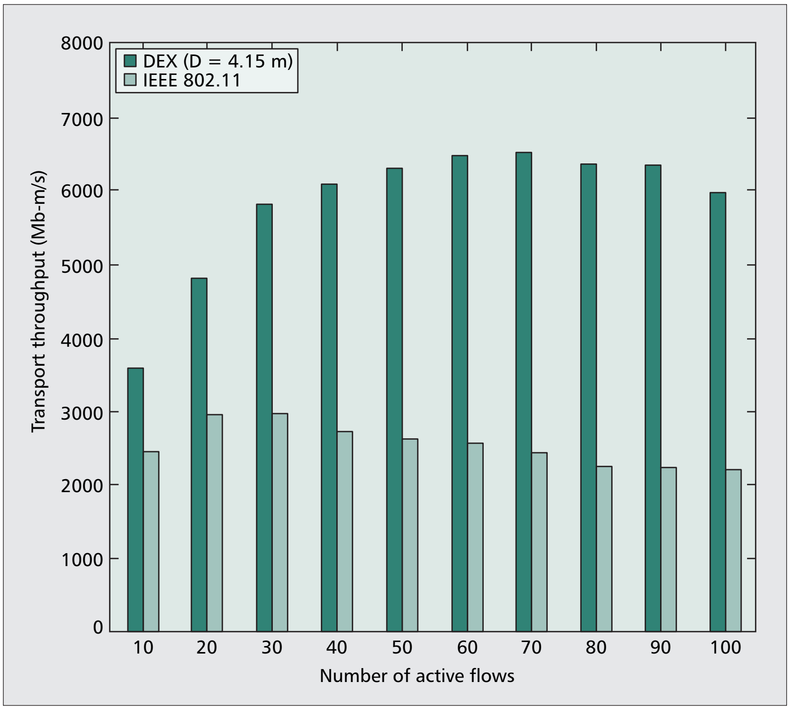

Figure 6. *Network transport throughput comparison.*

BIOGRAPHIES

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