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RESEARCH ARTICLE

UWB MAC Design Constraints and Considerations

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Abstract— In this paper, we consider the possibility of developing an optimal medium access control (MAC) layer for high data rate ultra-wideband (UWB) transmission systems that transmit minimal power. MAC in UWB wireless networks is required to coordinate channel access among competing devices. The unique UWB characteristics offer great challenges and opportunities in effective UWB MAC design. We first study the background of UWB and available MAC protocols that have been used in UWB. Secondly, we explore the constraints on UWB MAC design. Finally we present the considerations that need to be made in designing an optimal UWB MAC protocol.

Keywords— Ultra-wideband (UWB); Medium access control (MAC); Low-power consumption

I. INTRODUCTION

Ultra-wideband (UWB) has emerged as a wireless technology that offers great potential to fulfil the rising demand for low cost, high data rate, short range wireless transmission system. The need for a high-bandwidth wireless solution has increased tremendously due to the growing numbers of media-intensive devices such as mobile phones, tablets, personal computers, digital cameras, high-definition televisions and gaming systems. UWB represents a unique opportunity to be widely adopted as a radio solution for wireless personal networking technology because of the massive bandwidth available, the potential for high data rates, and the potential of miniature size and low power requirements along with low implementation cost.

UWB was originally targeted as a physical layer technology, with minimal protocol to control the communication. However, UWB has progressed dramatically so that MAC plays a significant role in UWB communication systems [1]. UWB offers huge potential for peer-to-peer and wireless ad-hoc networks. One of the main benefits in impulse radio based systems is the ability to trade data rate for link distance by differentiating concatenated pulses to define a bit. The data rate can be varied by orders of magnitude based on the system requirements without significantly altering the air interface. However, because of this, it is imperative to ensure that High Data Rate (HDR) and Low Data Rate (LDR) devices can coexist without any problem. UWB also offers the possibility of very high positional accuracy through the narrow time domain pulse. In order to acquire a position from a delay, or signal angle-of-arrival estimate, each device need to be discovered by several other devices in the network. The fact that an individual low power UWB pulse is hard to detect, coupled with these potential benefits, present several major challenges for the multiple access MAC design.

Research on UWB MAC is currently considered to be at an early stage because only few solutions that addressed the unique characteristics of UWB have been proposed in open literature [2]. Most of the proposed

solutions are based on existing standards such as IEEE 802.15.3 and ETSI HiperLAN Type 2 that allow direct peer-to-peer communications; although these standards only deal with centrally managed networks.

UWB MAC design is a challenging task because of several issues such as strict transmission power constraints, very high data rate transmission, long acquisition time between synchronising the receiver's clock with the transmitter's clock and control functions that are not centralised [3]. In addition to those issues, the physical layer characteristics of UWB such as high bandwidth and low transmission power offer new challenges when designing an optimal MAC for UWB. Resource allocation will be more flexible due of UWB's unique pulse transmission. Routing and power control also can be simplified to exploit UWB's extensive capability in positioning. It is expected that an optimal MAC can be designed to offer an efficient high-data rate, low-power UWB network by taking into all unique characteristics of UWB and also considering its deficiencies.

II. UWB MAC DESIGN

The nature of bandwidth offered by UWB systems means that many potential solutions exist on how to use the bandwidth. UWB devices may use all, or only a fraction of, the bandwidth available in the 3.1 to 10.6 GHz band. These devices will still be classed as UWB provided they use at least 500 MHz in the 7.5 GHz band. There are several major candidates for the physical layer signal structure of UWB systems, which include impulse radio, OFDM, multi-carrier and hybrid techniques. All of these possible techniques mean that different UWB devices may or may not be able to detect the presence of other devices. There are three major issues that need to be addressed by an UWB MAC; coexistence, interoperability and support for positioning and tracking [1].

A. Coexistence

Coexistence strategies need to be addressed because of the potential UWB devices with widely varying data rates and complexities. Strategies for ignoring or working around other devices of the same or different type based on physical layer properties will reflect up to the MAC layer. Highest efficiency, lowest BER and lowest complexity transceivers should be achieved through the optimisation of the UWB physical layer. The assumptions of the physical layer will have direct impacts on MAC issues such as initial search and acquisition process, channel access protocols, interference avoidance/minimisation protocols, and power adaptation protocols. The quality of the achieved channel will have implications on the link level, which may require active searching by a device for better conditions, as what occurs with other radio systems.

B. Interoperability

General requirement of MAC protocols is to support interoperability with other same-type devices. MAC protocols must be able to guarantee cooperation and information exchange between devices of different data rate, QoS class or complexity, especially with the potentially wide range of UWB devices.

C. Positioning and tracking support

Positioning is essentially linked to the MAC, which includes strategies for improving timing positioning accuracy and for exchanging timing information to produce positioning information. It is possible to approximate the arrival time of a signal from another device for any single device based on its own time reference. This single data point in relative time needs to be combined with other measurements to generate a 3D position estimate relative to some system reference. Exchange of timing information involves cooperation between devices.

For tracking purposes, each device needs to be sensed or measured at a suitable rate to allow reasonable update rate. This is relatively easy for a small number of devices, but difficult for an arbitrarily large number of devices. Information exchange between devices of timing and position estimates of neighbours in ad hoc modes requires coordination, where calculation of position needs to be done and the results fed to the information sink.

It is also important to have the received signal as unaffected by multiple access interference as possible in order to allow the best estimation of time of arrival. Every 3.3 ns error in delay estimation translates to a minimum 1m extra error in position estimation [1]

III. CONSTRAINTS ON UWB MAC DESIGN

UWB signals have unique characteristics that may be used to produce additional benefit. For example, location-aware services may be exploited by upper layers for the accurate ranging capabilities. On the other hand, some characteristics of UWB also can cause problems, which must be solved by the MAC design. For example, it is difficult to implement carrier-sensing capability if a carrier-less impulse radio system is used.

Another characteristic that affects MAC design is the relatively long synchronisation and channel acquisition time in UWB systems. This is shown in [4] where performance of the CSMA/CA protocol is evaluated for an UWB physical layer. Figure 3.1 shows packet traffic between two users in an UWB ad-hoc network where the approach uses a simple CSMA/CA protocol. Synchronisation preambles must be transmitted at the start of each

transmission burst. The receiver must first synchronise and decode the RTS packet in order to exchange data with the CSMA/CA protocol. The transmitter then needs to synchronise and decode the CTS packet, before starting transmission.

In order to achieve synchronisation for both the RTS and CTS packets, a long preamble is needed. However, a shorter preamble is possible for data transmission since synchronisation is assumed to be maintained after reception of the RTS packet. Further packets may be received with only fine corrections or tracking. Depending on the allowed length of the data packet, a longer preamble may be needed for the following ACK packet. Three preamble lengths (nominal, long, short) are proposed in [5].

The time to achieve bit synchronisation in UWB systems is typically high, in the order of few milliseconds. The impact of synchronisation acquisition on CSMA/CA-based protocols is obvious, considering that the transmission time of a 10 000 bit packet on a 100 Mbps rate is only 0.1 milliseconds. Using very long packets can minimised the efficiency loss due to acquisition time but this may impact performance in other ways. When the effects of acquisition are taken into account, simulation results show that the performance of CSMA/CA using UWB is poorer than for narrowband and even wideband systems, in terms of delay, throughput and channel utilisation [4].

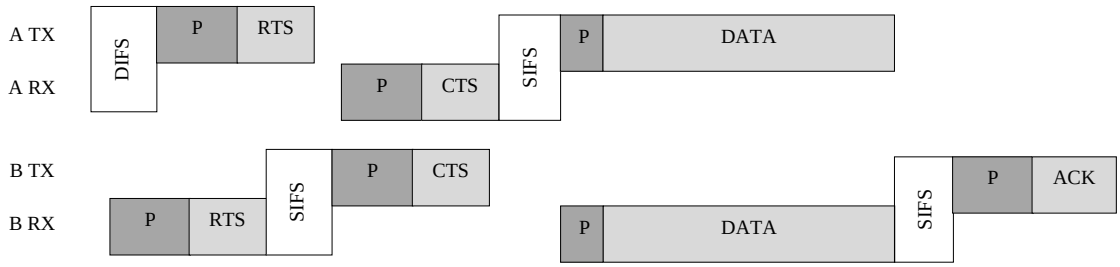

Fig. 1 Messages between sender A and destination B using CSMA/CA protocol

Acquisition preambles are typically sent with higher transmit power than data packets [6]. This impacts both the interference level and the energy consumption in highly burst traffic, so this effect must be taken into consideration when determining the efficiency of the system.

The adoption of CSMA/CA as a distributed protocol must be jointly evaluated with the performance of the underlying UWB physical layer. In general it may not be a suitable choice for an UWB MAC unless proper synchronisation techniques are developed. One solution to this problem is the exploitation of the very low duty cycle of impulse radio where synchronisation can be maintained during silent periods by sending low power preambles for synchronisation tracking [6]. However, this approach is feasible only for communications between a single pair of nodes, which is not the case in peer-to-peer networks.

IV. UWB MAC DESIGN CONSIDERATIONS

The existing proposed wireless MAC protocols assume that simultaneous transmissions cause transmission errors and thus utilise mutual exclusion mechanisms to avoid them. Mutual exclusion is enforced either with a collision management protocol such as CSMA/CA or a variant of it [7], a time division scheme, or with a combination of both [8] where these schemes result in high practical overhead. This is because the use of RTS/CTS handshakes and the possibility of collisions will drastically influence the performance in ad-hoc environments [9].

Another element used in the design of MAC protocols is power control. To accept several transmissions simultaneously, it is crucial to have the capability to intelligently manage interference. As an example, for a CDMA networks in a purely synchronous setting such as cellular base station, multi-user interference is managed primarily by means of power control while in asynchronous settings such as ad-hoc networks, both power control and a mutual exclusion protocol [10] are employed.

Dynamic channel coding is one of the fundamentally unexploited elements in MAC design. In [11], sources transmit to a central node at full power as soon as they have something to transmit, and adapt the channel code in the presence of interfering sources to allow the central node to decode properly. Adapting the channel code will also change the source bit rate. It is shown in [12] that power control does not provide significant gains

when dynamic channel coding is used, as long as the goal is to maximise throughput, subject to power constraints. A performance analysis of ad-hoc networks in [13] shows that the optimal MAC layer should use full power when transmitting.

Scheduling is another important element that can be considered in designing optimal MAC protocol. The optimal scheduling problem for peer-to-peer concurrent transmissions in a WPAN is NP-hard [14]. Because of this, the induced computation load for solving the problem is not affordable to the network coordinator, commonly a normal UWB device with limited computation power.

A. UWB Model

To better understand the operational of UWB system, an MB-OFDM UWB model, based on proposal submitted to IEEE 802.15.3a standards group, has been developed. The proposal supports seven data rates in the range of 55 to 480 Mbit/s but the highest mandatory rate is 200 Mbit/s [15]. OFDM signals are transmitted using a frequency-hopping scheme. The model captures the end-to-end physical layer (PHY) for the highest mandatory data rate and for the mandatory frequency hopping mode.

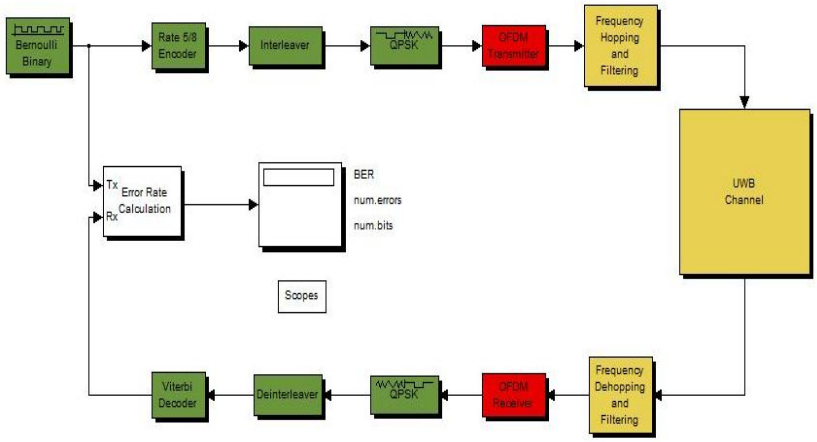

Fig. 2 MB-OFDM UWB model

Fig. 2 shows the block diagram of the MB-OFDM UWB model that has been developed. The transmitter and receiver each consist of three sections:

- Binary data processing
- Digital baseband processing
- Baseband model of the analog front-end and channel

B. Analysis of UWB Physical Model

Most of the MAC layer design for UWB was based on IEEN 802.15.3 standard since this was the first standard dedicated to WPAN [2]. Since the MAC protocol in IEEE 802.15.3 did not consider the unique characteristics of UWB, it is inefficient for UWB networks. It is essential to explore the physical characteristics of UWB communications and enhance the MAC protocol and scheduling to efficiently offer high data rate services in UWB networks.

A distinctive and attractive feature of UWB communications, for both pulse-based, direct spread (DS) and MB-OFDM-based approach, is that, with efficient transceiver design, data rate can be adjusted proportionally to signal to noise and interference ratio (SNIR) at the receiver end. To explain this, let P denote the received signal power, r the channel capacity, and N0 and I0 the one-sided spectrum level of white Gaussian noise and that of Gaussian interference, respectively. According to the Shannon theory:

$$r = W \log_2 (1 + SNIR) \text{ bps} \tag{1}$$

where $SNIR = \dfrac{P}{(N_0 + I_0)W}$. For the system with the ultra-wide bandwidth where $W \to \infty$:

$$R \approx \frac{P}{N_0 + I_0} \log_2 e \text{ bps} \tag{2}$$

The transmitter can always modify its data rate according to the arbitrary SNIR to maintain the bit error rate (BER) requirement by adapting its coding. This is true for both DS and MB-OFDM UWB systems. This is different in narrowband wireless communications where the receiver cannot receive any meaningful data if the SNIR falls below certain threshold.

Given a set of requests in a UWB network, allocation of resources is a very demanding issue. Resources are allocated by determining the optimal transmission power, transmission rate and schedule. Previous research has recommended that when a UWB device should operate at the maximum power level permitted for transmission to achieve optimal performance [13]. UWB devices can also adjust the transmission rate to sustain the prescribed transmission BER, and the possible data rate is proportional to the SNIR. Two main observations when all UWB devices transmitting using the maximum power level permitted are:

- Each UWB receiver has an exclusive region and no other UWB device inside the region should transmit. The exclusive region is depending on the background noise level and cross-correlation of concurrent transmissions
- Simultaneous UWB communications are preferable to TDMA transmissions as long as all interferers are outside the exclusive regions of other receivers

Consider n flows requesting transmission time in a superframe with n time slots. The sender-receiver distance for the i-th flow is d_i, and the distance from the j-th sender to the i-th receiver is $d_{j,i}$. The transmission power of the i-th flow is $p_t(i)$, and the receiving power of the i-th flow $p_r(i)=kp_t(i)d_i^{-\alpha}$, where k is the receiver processing gain and α is the path loss exponent. α depends on the environment and usually takes the value between 2 to 6. We assume both k and α are constant. If the n flows are transmitted in a TDMA fashion, each slot is assigned to one flow. The achievable data rate for the i-th flow, r_i^T, is given by:

$$r_i^T = k' p_r(i)/N_0 = k' k p_t(i) d_i^{-\alpha}/N_0 \tag{3}$$

where k' is a constant. If all flows are transmitted simultaneously for n slots, the achievable data rate for the i-th flow, r_i^C is given by:

$$r_i^C = \frac{nk' p_r(i)}{N_0 + \sum_{j \neq i} I_{j,i}} = \frac{nk' k p_t(i) d_i^{-\alpha}}{N_0 + \sum_{j \neq i} I_{j,i}} \tag{4}$$

where $I_{j,i}$ is the interference power spectrum level of the j-th sender to the i-th receiver, which is proportional to $d_{j,i}^{-\alpha}$. Assume the cross correlations between any two UWB transmissions is a constant. The distance, d, such that $I_{j,i}$ equals N_0 to can be obtained. If all interferers are at least d away from the receiver of the i-th flow ($d_{j,I} \geq d$), we have $I_{j,i} \leq N_0$ for all $j \neq 1$. Therefore:

$$r_i^C > \frac{nk' k p_t(i) d_i^{-\alpha}}{N_0 + (n-1)N_0} = \frac{k' k p_t(i) d_i^{-\alpha}}{N_0} = r_i^T \tag{5}$$

Put differently, each receiver have an exclusive region, which is a circle centered at the receiver with radius of at least d. This radius depends on the cross-correlations of UWB communications and the background noise level but it is not dependent on the distance between sender and receiver.

C. Enhancing MAC scheduling algorithms

IEEE 802.15.3 states that the PNC schedules the channel times of channel time allocation period (CTAP) for all flows. During CTAP, devices communicate in a peer-to-peer mode. Packets between devices or between devices and the PNC can either be exchanged directly or through multi-hop. Normally, MAC and routing protocols are closely coupled. By assuming that the routes of all traffic in the UWB network are known, attention is focused on the scheduling algorithm of the MAC protocol [14].

The optimal scheduling problem for peer-to-peer simultaneous transmissions can be converted to a maximum weighted independent set problem [16], which is *NP -hard*. Exhaustive searching induces a computational complexity of $O(2^{NK})$, where N is the number of flows requesting transmission and K is the number of time slots to be scheduled. Two heuristic scheduling algorithms are proposed with computational complexity $O(N^2)$ and $O(KN^2 \log N)$, respectively.

In Algorithm 1, multiple flows can share the same slot, where S_i denotes the i-th group of flows, which can transmit simultaneously. Assume the number of slots K is larger than the number of flows N. Let UA represent

the set of flows not belonging to any group yet, and ER_l the exclusive region of low l. To determine the i-th group S_i, a flow is randomly chosen in UA. Other flows that do not conflict with any flows in S_i are then added. In other words, all interferers are outside the other receivers' exclusive regions.

Require: $i := 1;\ S_i := \emptyset\ UA := \{1,\ldots, N\}$
repeat
  for a flow f randomly chosen from UA **do**
    $S_i \leftarrow S_i \cup \{f'\};\ UA \leftarrow UA \setminus \{f\}$
    for any flow f' other than f **do**
      if $f' \notin ER_l\ \ \forall l \in S_i$ **then**
        $S_i \leftarrow S_i \cup \{f'\}$
      end if
      if $f' \in UA$ **then**
        $UA \leftarrow UA \setminus \{f'\}$
      end if
    end for
  end for
  $i \leftarrow i + 1$
until (UA is empty) $\vee (i > K)$
$k \leftarrow i$
for $i = 1$ to k **do**
  allocate $K \cdot |S_i| \big/ \sum_{x=1}^{k} |S_x|$ to S_i
end for

Algorithm 1. Proportional allocation

Once UA is empty, k groups of flows $(S_1, S_2,\ldots,S_k)$ are obtained. $K \cdot |S_i| \big/ \sum_{x=1}^{k} |S_x|$ slots are allocated to the i-th group of flows, for $1 \le i \le k$, where $|S_i|$ is the number of flows in the i-th group. This algorithm has a low computational complexity of $O(N^2)$. The basic plan of this algorithm is that each flow will belong to at least one group, and thus will be assigned at least one slot. In each group, all flows will not conflict with each other where no sender will be in the exclusive regions of other receivers. The time slots allocated to each group are proportional to the number of flows that can be transmitted concurrently in that group.

Require: $\phi_f := 0;\ S_i := \emptyset$
for $i = 1$ to K **do**
  $f^* \leftarrow \arg\min_f \{\phi_f\}$
  $S_i \leftarrow S_i \cup \{f^*\}$
  $\phi_{f^*} \leftarrow \phi_{f^*} + 1$
  for any flow f other than f^* **do**
    if $f \notin ER_l\ \ \forall l \notin S_i$ **then**
      $S_i \leftarrow S_i \cup \{f\};\ \phi_f \leftarrow \phi_f + 1$
    end if
  end for
end for

Algorithm 2. Repeating allocation

In Algorithm 2, □f represent the number of slots being allocated to flow f. For a slot i, it will be assigned to a group of flows S_i. First, a flow with minimal □f is randomly chosen and it is added to S_i. Subsequently, other flows that do not conflict with any flows in S_i are added. This process is repeated for all time slots.

The repeating allocation algorithm has a higher computational complexity of $O(KN^2 \log N)$, and it is expected to be more fair in terms of the number of slots assigned to each flow, since flows with less assigned time slots are given a higher priority.

V. NUMERICAL RESULTS

The proposed scheduling algorithms are implemented in OMNeT++ and compared to TDMA scheduling used in IEEE 802.15.3 [14]. The network simulation contains 40 flows with transmitters and receivers located randomly in a 10 × 10 m^2 area. All flows have an equal transmission power of −41 dBm/MHz, background noise power of −114 dBm/MHz over 500 MHz frequency bandwidth, and the cross-correlations among different users' spreading codes of 0.1. The radius of exclusive region d = 2.96 m and the throughput is calculated by Equation 4.

The transmitters are saturated so that they always have data to send. The scheduler operating TDMA scheduling evenly allocates time slots to all flows. For the schedulers using the proposed scheduling algorithms, different radii of the exclusive region from 0 to 10d are used. The total throughput of all flows in all slots is normalized.

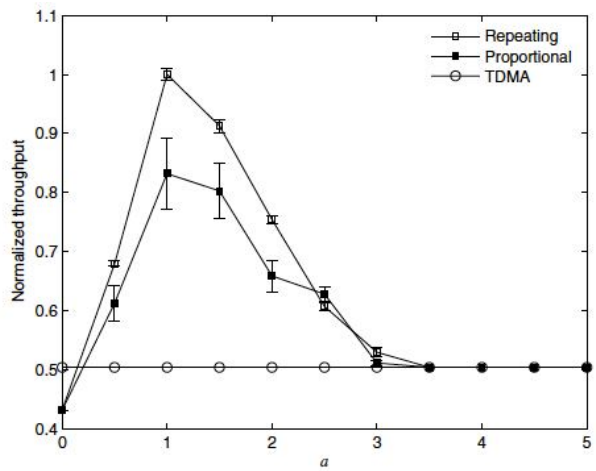

Fig. 3 Impact of size of exclusive region to network throughput for network size 10 x 10m^2

Fig. 3 shows the impact of the size of exclusive region to the network throughput for network size of 10 x 10 m^2. The figure compares the normalized throughputs of the proposed scheduling algorithms with the TDMA algorithm. The x-axis, a represents the radius of the exclusive region used in the proposed scheduling algorithms with unit d m, so the radius of the exclusive region equals a.d m. The y-axis represents the normalized throughput, which is the throughput over the maximum throughput achieved in all simulations. When a = 0, all flows can transmit simultaneously and it is observed that the resultant throughput is lower than that of TDMA. Simultaneous transmissions achieves higher throughput than TDMA when the magnitude of multi-user interference is less than the aggregate background noise level where $I_{j,i} \leq (N-1)N_0$. This condition may not always hold, for example if a = 0. However, when a is sufficiently large to prevent any simultaneous transmissions, the proposed scheduling algorithms behave the same as the TDMA algorithm.

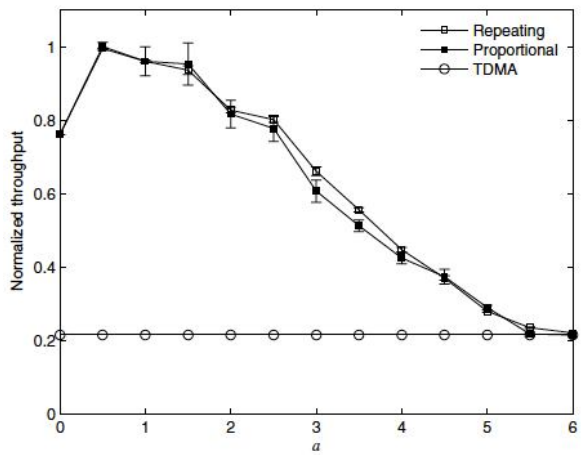

Fig. 4 Impact of size of exclusive region to network throughput for network size 20 x 20m^2

Fig. 4 illustrates another example where 40 flows are redistributed within a larger area with size 20 x 20 m^2. In this case, the condition $I_{j,i} \leq (N-1)N_0$ holds for all values of *d*. Therefore simultaneous transmissions always achieved higher throughput than TDMA. The simulation results prove that if the appropriate size of exclusive region is chosen, the throughput of the proposed algorithms can be improved. Comparing the proposed algorithms, in most cases, repeating allocation algorithm performs slightly better than proportional allocation algorithm.

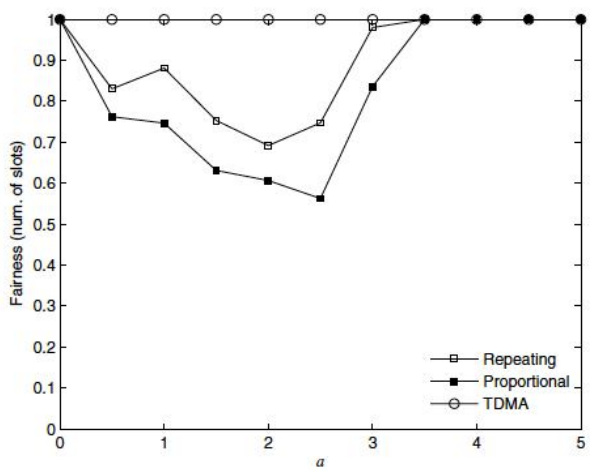

Fig. 5 Comparison of fairness based on number of slots

Next is the analysis of the fairness in the proposed scheduling algorithms. Fairness is determined through the throughput achieved by each flow and the number of slots assigned to each flow. While throughput is commonly defined to achieve strict per user fairness, the scheduler is needed to estimate the achievable rate of each flow. Normally the scheduler has limited computational power and the knowledge of per channel status. Because of that, it may simply use the number of slots assigned to each flow to measure fairness. Fig. 5 compares the Jain's fairness index [17] in terms of the number of slots assigned to each flow. TDMA scheduling provides good fairness because it allocates slots to all flows evenly. However, it does not efficiently utilize the spectrum. For proposed algorithms, the proportional algorithm shows slightly inferior support in fair slot sharing since the proportional rule prefers flows being allocated higher numbers of slots after the first scheduling iteration. As *a* increases, the proposed algorithms gradually becoming comparable to TDMA.

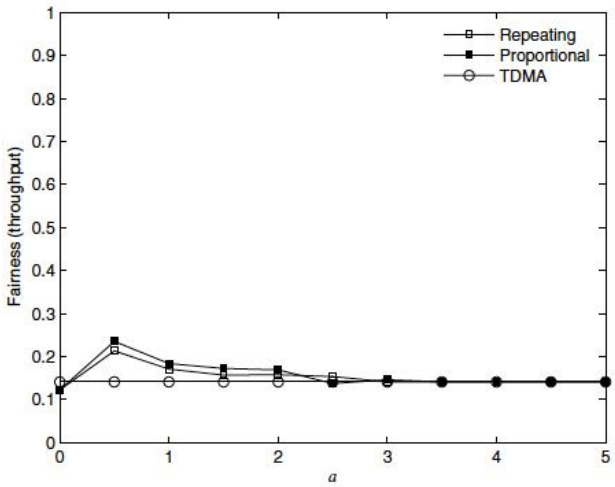

Fig. 6 Comparison of fairness based on normalized throughput

From a user point of view, fairness is considered as the amount of bandwidth that can be obtained compared to other users. Fig. 6 shows Jain's fairness index in terms of per flow throughput. It can be observed that all the scheduling algorithms being studied demonstrate inferior fairness support based on throughput regardless the underlying exclusive region. The proposed algorithms favour the flows with shorter communication distance and higher throughput with the main objective of increasing network throughput. Although time slots can be assigned evenly in TDMA scheduling, its fairness index based on throughput is also very low. It is important to find a better trade-off between efficiency and fairness that will greatly improve the performance of UWB communication system.

VI. CONCLUSION

In this paper, we have presented an overview of UWB, the basics of UWB MAC design, its constraints and considerations. MAC plays a very significant role in UWB networks to ensure efficient communications, and it is essential to coordinate channel access among devices. The distinctive UWB characteristics present great challenges and opportunities in efficient UWB MAC design and this is shown in the proposed protocols. The two scheduling algorithms take the initial step toward an efficient UWB MAC protocol. There are still many issues that need further exploration such as how to define the optimal exclusive region, how to attain optimal scheduling with reasonable computation complexity, how to combine PHY/MAC/routing to maximize the system throughput and how to make proper trade-off between throughput and fairness.

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