Effective Packet Scheduling with Fairness Adaptation in Ultra-Wideband Wireless Networks

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***Abstract*— Ultra-wideband (UWB) transmission is an emerging wireless technology, and medium access control (MAC) with quality of service (QoS) provisioning is essential to coordinate the access among competing devices in UWB-based wireless networks. In this paper, we study the exclusive region concept (which was previously proposed) to determine the active set of senders at a time. We find out that, different from the previous work, the exclusive region for a specific link should be a system-level concept, and should depend on system factors such as interference from/to other active links. Based on the findings, two MAC packet scheduling schemes are proposed to exploit the system capacity and, at the same time, to achieve a certain level of fairness in UWB wireless networks. As the long acquisition time in UWB transmission can significantly reduce the system efficiency, the proposed schemes can be modified to alleviate the negative effect of a long acquisition time. Computer simulations demonstrate the effectiveness and efficiency of our proposed schemes.**

***Index Terms*— Ultra-wideband (UWB) transmission, medium access control (MAC), packet scheduling, quality of service (QoS), transmission power and rate, fairness.**

I. Introduction

ULTRA-WIDEBAND (UWB) transmission is an emerging wireless technology, and has been considered as one of the promising technologies to provide multimedia services in both indoor and outdoor applications. A UWB system is defined as any radio system that has the -10 dB fractional bandwidth (or -10 dB bandwidth) more than 20% (or 500 MHz). With the unique merits such as high rate, low power spectral density, capability to capture multipath energy, and ability of accurate positioning, UWB has demonstrated its potential in future multimedia applications as well as in industrial control and maintenance, medical monitoring, radar imaging, home automation, Department of Defense (DoD) systems, etc. As a significant breakthrough for R&D on UWB, the Federal Communications Commission (FCC) has allowed UWB indoor applications in the frequency band from 3.1 to 10.6 GHz on an unlicensed basis [1].

In a UWB network, the wireless medium is shared among mobile nodes. To achieve desired quality of service (QoS) (e.g., in terms of transmission accuracy, delay/jitter, throughput, fairness), the multiple access to the channel should be coordinated by a medium access control (MAC) mechanism in an effective and orderly manner. For traditional wireless local area networks (WLANs) or ad hoc networks, many MAC protocols have been developed, such as ALOHA and its slotted version, and carrier sense multiple access (CSMA)-based random access protocols. They are all contention-based with a single channel (thereby termed *single-channel* case), and hence two nearby simultaneous transmissions may collide. However, the inherent spread spectrum in UWB can support simultaneous transmissions, with an appropriate pseudorandom sequence design and effective call admission control (CAC), referred to as *multi-channel* case. In the multi-channel case, two nearby transmissions do not collide, but rather generate interference to each other, thus requiring different coordination mechanisms from those in the single-channel case. In the literature, one major stream of UWB MAC research is IEEE 802.15.3, which is designed for short-range ad hoc connectivity in wireless personal area networks (WPANs). However, it is not explicitly designed for the UWB-based multi-channel transmissions.

For multi-channel multiple access, in the limit of infinite bandwidth ($W \to \infty$), the optimal MAC scheme is to simply allow transmissions over all the links simultaneously, because interference becomes negligible [2]. However, for a practical UWB network, the bandwidth is large but finite, so that uncontrolled simultaneous transmissions are not optimal [3], [4]. Hence, it is critical to determine when, where, and how to allow simultaneous transmissions, and how to alleviate the induced interference in order to achieve desired performance. This research is to contribute to the development of such packet scheduling schemes in UWB wireless networks.

The contribution of this paper is two-fold: 1) we demonstrate that the exclusive region concept previously proposed in the literature is not optimal in terms of throughput; 2) we propose sub-optimal (in terms of throughput) packet scheduling schemes to achieve fairness and at the same time alleviate the effect of long acquisition overhead in UWB multi-channel transmissions.

The rest of this paper is organized as follows. In Section II, the system model is described. Section III reviews the concept of *exclusive region* in previous research work and presents our studies. In Section IV, we propose two MAC scheduling schemes to efficiently utilize the bandwidth, achieve a certain level of fairness among wireless links, and alleviate the effect of a long acquisition time on UWB transmissions. Section V is devoted to performance evaluation of the proposed schemes, followed by concluding remarks in Section VI.

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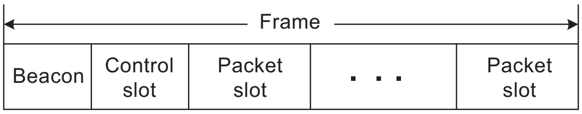

Fig. 1. Frame structure in the UWB wireless network.

II. System Model

A. Frame Architecture

We consider a UWB wireless network with a number of nodes which communicate with each other on a peer-to-peer basis. The nodes are with low mobility. Among the nodes, one is selected as the central controller. The main responsibility of the central controller is to provide timing and global information, and perform resource allocation for the active connections in the UWB network. In general, the central controller can be a node with sufficient power supply and advantageous location. The central controller can change from time to time for load distribution, or due to node arrivals/departures and user mobility.

At the physical layer, the implementation of a UWB transmission can be achieved by pulse-based time-hopping (TH) or pulse-based direct sequence (DS), or multiband orthogonal frequency division multiplexing (MB-OFDM). In the following, we use TH-UWB as an example. However, the principles can be extended to DS-UWB and MB-OFDM systems.

In the UWB network, time is partitioned into frames, each of which is further divided into a beacon, a control slot, and a number of packet slots, as shown in Fig. 1. A guard time exists between any two slots, which is not shown in the figure. The beacon is used by the central controller to provide timing and global information (such as the time hopping sequences used for channel request), and broadcast scheduling decision for the packet slots. When a node has a call arrival, it selects one of the time hopping sequences indicated in the beacon, and sends a request via this sequence in the control slot. The request is per-call based, thus having a limited overhead. The central controller monitors all the channels associated with the announced time hopping sequences. Upon correct reception of one request, in the subsequent beacon, the central controller announces whether or not the request can be admitted, and if yes, at which slots and with what power and rate levels. In other words, the central controller is responsible for an effective and efficient resource allocation with QoS provisioning in each packet slot, which is the focus of this paper. For each link, the transmission at the packet slots is via a time hopping sequence private to the source-destination pair [5].

B. Channel Model

The rich resolvable multipath components in pulse-based UWB networks determine that UWB signal reception does not suffer much from multipath fading [6]–[8]. Thus, similar to [4], we assume that there is no fast fading, and the power at the receiver is attenuated only due to path loss, i.e., the channel gain from link i's transmitter to link j's receiver can be represented as

$$h_{ij} = K \cdot d_{ij}^{-\theta} \tag{1}$$

where K and θ are constants, and d_{ij} is the distance from link i's transmitter to link j's receiver.

Since UWB systems exhibit unique physical layer characteristics such as precise positioning capability, the central controller can know the location information of all the nodes (with low mobility) [9], thus has the channel gain information of all links when multipath fading can be addressed by the RAKE receiver.

C. QoS Model

In TH-UWB, the information bit is transmitted with a train of very narrow pulses (usually in the order of a nanosecond). Multiple access in TH-UWB can be achieved by assigning unique time hopping sequences to different links. Simultaneous transmissions do not collide, but rather generate interference to each other. It has been shown in [10] that the total interference from a large number of links can be approximated as Gaussian noise. Based on this approximation, for a TH-UWB network with N active links, the achieved signal to interference-plus-noise ratio (SINR) at the receiver of link i can be represented as

$$\text{SINR}_i = \frac{P_i h_{ii}}{R_i(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j h_{ji})}, \qquad i = 1, ..., N \tag{2}$$

where P_i denotes the average transmission power of link i's transmitter, R_i bit rate of link i, η_i the background noise energy plus interference from other non-UWB systems, T_f the pulse repetition time, and σ^2 a parameter depending on the shape of the pulse [11].

QoS in MAC can be classified according to its implementation in UWB networks, based on a hierarchy of two different levels: bit-level and packet-level. Bit-level QoS is to ensure some degree of transmission accuracy, normally represented by an upper bound on bit error rate (BER). The BER guarantee can be achieved by satisfying a required SINR value γ_i for link i. For UWB transmission, the one-to-one mapping of BER to SINR depends on channel characteristics, modulation, channel coding, diversity, and receiver design. On the other hand, transmission rate (i.e., throughput), timeliness (i.e., delay and jitter), and fairness are the main consideration in packet-level QoS. In this research, the objective in QoS provisioning is to maximize system throughput with a certain level of fairness, under the constraint of the required SINR bound. That is, for each link i, the following inequality should hold

$$\frac{P_i h_{ii}}{R_i(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j h_{ji})} \geq \gamma_i. \tag{3}$$

D. Full Power Transmission

An equivalent form of inequality (3) is

$$R_i \leq \frac{P_i h_{ii}}{\gamma_i(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j h_{ji})}. \tag{4}$$

The inequality gives the maximum achievable bit rate of link i with the constraint of SINR value γ_i. This is under the assumption that adaptive rate can be achieved by changing the processing gain, e.g., via adapting the number of pulses for each symbol and/or maximum time hopping shift, or using

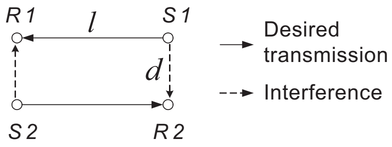

Fig. 2. The near-far scenario [5].

adaptive channel coding such as rate compatible punctured convolutional (RCPC) code [5]. To achieve link adaptation, a feedback channel is necessary. In our system, a receiver can send the feedback with low power and low rate in the control slot to the central controller or in a packet slot to its sender. For the simplicity of analysis, we omit the effect of the feedback channel. On the other hand, for each link, the maximum achieved throughput should not exceed $1/T_f$ as the processing gain should be at least 1. Hence, for link i the achievable rate is

$$\min\{\frac{1}{T_f},\ \frac{P_i h_{ii}}{\gamma_i(\eta_i + T_f\sigma^2 \sum_{j=1,j\neq i}^{N} P_j h_{ji})}\}.$$

For simplicity of presentation, in the following, when a rate appears in a format similar to $\frac{P_i h_{ii}}{\gamma_i(\eta_i + T_f\sigma^2 \sum_{j=1,j\neq i}^{N} P_j h_{ji})}$, it actually has an attached condition of the upper bound value $1/T_f$.

To maintain desired transmission quality, the traditional way is to apply power control at each link to achieve the desired SINR. However, recent research [4], [12] has shown that, for ad hoc connectivity, the optimal MAC layer should make use of the allowed maximum power at each active link, and that power control does not provide a significant gain when dynamic channel coding is used. Hence, in our research, each transmission is with the maximum allowed power, which can be determined by the emission regulation and the energy consumption of the terminals. This means that, at any moment, each sender either transmits with maximum allowed power, or does not transmit at all. At a specific packet slot, it is critical to determine the set of active links with full power transmission while the others keep silent. To address this issue, in the literature, an *exclusive region* concept was proposed [4], [5].

III. Exclusive Region Concept

A. Review of the Exclusive Region Concept

UWB transmission is generally characterized by low power and low interference. If two transmission links are separated by a large distance, the interference between them may be negligible. Thus, it is optimal (in terms of throughput) to allow the two links to transmit simultaneously. The *exclusive region* concept is one effort to define such a "large distance". When a specific link is transmitting, the concept allows simultaneous transmissions from interfering sources outside the exclusive region, while senders inside the exclusive region are required to keep silent. This means senders inside the exclusive region operate in a time-division multiple access (TDMA) mode.

To determine the exclusive region size (i.e., the minimum distance d from the interfering source to a desired receiver), in [4] d is selected so as to maximize the achieved rate at the desired receiver. However, rate maximization of a specific link may not lead to the maximization of the overall system throughput. In [5], a *near-far scenario* is used to determine d. As shown in Fig. 2, two sources $S1$ and $S2$ are intended to transmit to two destinations $R1$ and $R2$, respectively. The length of both links is l, while the distance from an interferer to the desired receiver is d. Two scheduling schemes are investigated: *All-at-Once* allows both links to send all the time, while *TDMA* permits only one link at a time, and the duty cycle of each link is 50%. Each link uses full maximum power when transmitting. The exclusive region size d is chosen as the point where TDMA performs equally with the All-at-Once scheme in terms of rate achieved by source $S1$. Indeed, this method is effective if there exist only two links in the neighborhood. However, if other UWB links exist, from the two possible transmissions $S1 \rightarrow R1$ and $S2 \rightarrow R2$, other links experience interference of one full power transmission in TDMA, but two full power transmissions in All-at-Once. Taking into account the difference in the total transmitted power levels, it can be concluded that the exclusive region size should be larger than that determined based on the method in [5]. In addition, it is not necessary to let the two links evenly share the time in the TDMA mode.

B. Discussion

Consider two target transmission links i and j in a UWB wireless network. Denote the set of other active links as $\mathcal{S}$. We also investigate two scenarios with respect to the two target links:

- All-at-Once: both links i and j transmit all the time with full maximum power.
- TDMA: links i and j transmit one by one based on round robin, with duty cycles ϕ_i and $\phi_j (= 1 - \phi_i)$ respectively.

In both scenarios, the set $\mathcal{S}$ is the same, and the processing gain and/or channel coding is adapted to the experienced interference at the receiver in order to get the maximum achievable rate.

In All-at-Once, the system throughput can be calculated as

$$\begin{aligned} T^{\text{All}} = & \frac{P_i h_{ii}}{\gamma_i[\eta_i + T_f\sigma^2(\sum_{k\in\mathcal{S}} P_k h_{ki} + P_j h_{ji})]} \\ & + \frac{P_j h_{jj}}{\gamma_j[\eta_j + T_f\sigma^2(\sum_{k\in\mathcal{S}} P_k h_{kj} + P_i h_{ij})]} \\ & + \sum_{k\in\mathcal{S}} \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S},n\neq k} P_n h_{nk} + P_i h_{ik} + P_j h_{jk})]}. \end{aligned} \tag{5}$$

On the right side of the equation, the first and the second terms are the achieved rates of links i and j, respectively, and the last term is the sum of achieved rates of all other active links.

In TDMA, when link i is active, the system throughput is

$$\begin{aligned} T_i^{\text{TDMA}} = & \frac{P_i h_{ii}}{\gamma_i[\eta_i + T_f\sigma^2 \sum_{k\in\mathcal{S}} P_k h_{ki}]} \\ & + \sum_{k\in\mathcal{S}} \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S},n\neq k} P_n h_{nk} + P_i h_{ik})]} \end{aligned} \tag{6}$$

and when link j is active, the system throughput is

$$T_j^{\mathrm{TDMA}} = \frac{P_j h_{jj}}{\gamma_j[\eta_j + T_f\sigma^2 \sum_{k\in\mathcal{S}} P_k h_{kj}]} + \sum_{k\in\mathcal{S}} \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S},n\neq k} P_n h_{nk} + P_j h_{jk})]}. \quad (7)$$

Therefore, it can be seen that TDMA is more advantageous than All-at-Once if there exists a $\phi_i \in [0,1]$ that satisfies

$$\phi_i T_i^{\mathrm{TDMA}} + (1-\phi_i)T_j^{\mathrm{TDMA}} > T^{\mathrm{All}}. \quad (8)$$

Without loss of generality, we assume $T_i^{\mathrm{TDMA}} \geq T_j^{\mathrm{TDMA}}$. Then (8) is equivalent to

$$\phi_i > \frac{T^{\mathrm{All}} - T_j^{\mathrm{TDMA}}}{T_i^{\mathrm{TDMA}} - T_j^{\mathrm{TDMA}}}. \quad (9)$$

Taking into account $\phi_i \in [0,1]$, it can be concluded that there exists a $\phi_i \in [0,1]$ that satisfies (9) if

$$T_i^{\mathrm{TDMA}} > T^{\mathrm{All}} \quad (10)$$

or equivalently if $\max\{T_i^{\mathrm{TDMA}}, T_j^{\mathrm{TDMA}}\} > T^{\mathrm{All}}$ in general.

It can be seen that, for the two target links, it is not feasible to tell whether or not TDMA is better than All-at-Once based only on interference between them (as in the case of [5]). In contrast, as all active links in UWB wireless networks interfere with each other, a system-level consideration should be taken to determine whether or not a link should transmit when another link is transmitting. This means the exclusive region of a specific link should be a system-level concept. More specifically, the interference from/to other existing active links plays an important role in determining whether the two target links should transmit simultaneously or one by one.

IV. Proposed MAC Scheduling Schemes

Consider N links in L packet slots. For packet slot $l \in \{1,...,L\}$, $\mathbf{r}^l = \{r_1^l,...,r_N^l\} \in \mathbb{R}^N$ denotes the transmission rate vector, and $\boldsymbol{\alpha}^l = \{\alpha_1^l,...,\alpha_N^l\} \in \{0,1\}^N$ is the link activity ("1" means that the link is active with maximum allowed transmission power, and "0" means that the link keeps silent). Hence, an optimization problem can be formulated as follows

$$\begin{aligned} &\underset{\{\boldsymbol{\alpha}^1,...,\boldsymbol{\alpha}^L\}}{\text{Maximize}} \quad \sum_{l=1}^{L}\sum_{n=1}^{N} r_n^l \\ &\text{where} \quad r_n^l = \frac{\alpha_n^l P_n h_{nn}}{\gamma_n(\eta_n + T_f\sigma^2 \sum_{j\neq n}\alpha_j^l P_j h_{jn})}. \end{aligned} \quad (11)$$

High complexity is expected to solve the optimization problem. In addition, at the optimal point, it is possible that some links may starve. Hence, we propose sub-optimal approaches, based on the discussion given in the previous section, beginning with a *utility function* definition.

A. Utility Function

Recall that if $T_i^{\mathrm{TDMA}} \geq T_j^{\mathrm{TDMA}}$ and $T_i^{\mathrm{TDMA}} > T^{\mathrm{All}}$, it is better (in terms of system throughput) to let links i and j transmit by TDMA scheduling, with link i having duty cycle ϕ_i more than $\max\{0,\ (T^{\mathrm{All}} - T_j^{\mathrm{TDMA}})/(T_i^{\mathrm{TDMA}} - T_j^{\mathrm{TDMA}})\}$. Apparently, if we set $\phi_i = 1$, the system throughput achieves the maximum value, at the cost of the starvation of link j. In the following, we first show how this principle can be used in the scheduling of a UWB network to achieve maximum system throughput, then we try to take into account the fairness issue.

After some mathematical manipulation, TDMA condition (10) can be rewritten as (12) at the top of next page. By defining $\mathcal{S}' = \mathcal{S}\cup\{i\}$ (i.e., let link i be active), the inequality can be further rewritten as (13). On the other hand, for the active link set $\mathcal{S}'$ at a packet slot, if link j is also active at the packet slot, the gain obtained by link j is defined as its achieved rate, calculated by

$$G_{jj} = \frac{P_j h_{jj}}{\gamma_j(\eta_j + T_f\sigma^2 \sum_{k\in\mathcal{S}'} P_k h_{kj})} \quad (14)$$

and the cost (due to the increased interference by link j) to a link $k \in \mathcal{S}'$ is defined as the reduction of link k's achieved rate, given by

$$C_{jk} = \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2 \sum_{n\in\mathcal{S}',n\neq k} P_n h_{nk}]} - \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S}',n\neq k} P_n h_{nk} + P_j h_{jk})]}. \quad (15)$$

A utility function is defined to represent the "net gain" of link j being active in a packet slot:

$$U_j = G_{jj} - \sum_{k\in\mathcal{S}'} C_{jk}. \quad (16)$$

Note that the value of the utility function depends on the set $\mathcal{S}'$. For the same link j and packet slot, the utility may be positive for an $\mathcal{S}'$ set and negative for another.

Thus, we have an equivalent form of the condition (13) for TDMA scheduling:

$$G_{jj} - \sum_{k\in\mathcal{S}'} C_{jk} < 0. \quad (17)$$

Intuitively, at a packet slot, if the "net gain" of link j being active is negative, we should keep link j silent in order to achieve a larger system throughput. Based on this principle, we propose two MAC packet scheduling schemes for each packet slot, termed *water-draining* and *water-adding*, respectively.

B. Water-Draining and Water-Adding Packet Scheduling

The basic idea of water-draining is to first assume all the communication links are active, then remove the link (from the active set denoted by $\mathcal{S}$)[1] having a negative utility function with the maximum magnitude. This procedure is repeated until all the remaining active links are with positive utility values. On the other hand, the water-adding first assumes all the links are idle. It then randomly chooses a link to be active and, among the remaining idle links, activates the one with the largest positive utility value. This procedure is repeated until all the remaining idle links have negative utility values.

By either of the procedures, the capacity in a packet slot is maximally exploited. Apparently, if all packet slots follow the same procedure, with low mobility, some links in advantageous positions (such as with a short link distance or in a low-interference neighborhood) may obtain excessive

[1]For simplicity of presentation, we omit the slot index of $\mathcal{S}$ and other symbols in the schemes.

$$\frac{P_j h_{jj}}{\gamma_j[\eta_j + T_f\sigma^2(\sum_{k\in\mathcal{S}} P_k h_{kj} + P_i h_{ij})]} - \{\frac{P_i h_{ii}}{\gamma_i[\eta_i + T_f\sigma^2\sum_{k\in\mathcal{S}} P_k h_{ki}]} - \frac{P_i h_{ii}}{\gamma_i[\eta_i + T_f\sigma^2(\sum_{k\in\mathcal{S}} P_k h_{ki} + P_j h_{ji})]}\}$$
$$- \{\sum_{k\in\mathcal{S}} \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S},n\neq k} P_n h_{nk} + P_i h_{ik})]} - \sum_{k\in\mathcal{S}} \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S},n\neq k} P_n h_{nk} + P_i h_{ik} + P_j h_{jk})]}\} < 0. \quad (12)$$

$$\frac{P_j h_{jj}}{\gamma_j(\eta_j + T_f\sigma^2\sum_{k\in\mathcal{S}'} P_k h_{kj})} - \sum_{k\in\mathcal{S}'} \{\frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2\sum_{n\in\mathcal{S}',n\neq k} P_n h_{nk}]} - \frac{P_k h_{kk}}{\gamma_k[\eta_k + T_f\sigma^2(\sum_{n\in\mathcal{S}',n\neq k} P_n h_{nk} + P_j h_{jk})]}\} < 0. \quad (13)$$

services while others may starve. It is desired to address a certain level of fairness while at the same time exploiting the wireless capacity.

C. Fairness Adaptation

For a wireless network, the system throughput can be increased if at any instant resources are allocated to users with a good channel quality, at the cost of possible service starvation of users with a poor channel. Hence, efforts are needed to make a good compromise between the throughput and fairness. For a UWB wireless network, to achieve fairness is technically very challenging. First, the notion of fairness is quite different from that in traditional wireline networks or packet cellular networks, where fairness can be defined for a specific link with a fixed capacity. In a UWB wireless network, the links interfere with each other. The interfering relationship among links in a large area determines that the fairness in UWB should have a global definition instead of being limited to a specific link. Second, spatial channel reuse may conflict with fairness. As fairness is a global notation, it requires that the sources transmit based on a specific order. On the other hand, to take advantage of spatial channel reuse, two links with a large space separation can transmit simultaneously, which may violate the link transmission order determined by the strict fairness. Hence, a feasible tradeoff should be considered [13]. The well-know proportional fair scheduling obtains a good compromise between throughput and fairness for code-division multiple access (CDMA) cellular systems. For each time slot, the scheduler schedules the user with the highest priority value defined as the ratio of SINR to the average throughput of the user in a certain time window [14]. If a user has a low average throughput, its chance to be selected to transmit is relatively large, so as to achieve a certain level of fairness. This principle is designed for the case when only one user is scheduled at any time, thus not being able to be applied directly to wireless networks with multiple transmissions.

Here we introduce a method for a UWB wireless network to achieve a good tradeoff between system throughput and fairness. The basic idea is that users with good channel quality[2] are given priority while at the same time users with poor channel quality get an acceptable service share. Specifically, in the utility function definition (16), a *relative weight* $w_k = \frac{c_k}{T_k}$ is introduced to the gain or cost of link k, i.e.,

$$U_i = \frac{c_i}{T_i}G_{ii} - \sum_{k\in\mathcal{S}} \frac{c_k}{T_k}C_{ik} \quad (18)$$

where c_i is the pre-specified priority factor (to represent the weight in resource sharing) of link i, and T_i is the average throughput of link i over a past window of length t_w. We use an exponential weighted low-pass filter to determine T_i,

$$T_i = (1 - \frac{1}{t_w})T_i^* + \frac{1}{t_w}r_i \quad (19)$$

where T_i^* is the value of T_i in the previous packet slot, and r_i is the achieved transmission rate of link i at the current packet slot.

From (18), it can be seen that, the better the channel quality of a link, the larger its gain in calculating the utility, thus obtaining higher priority in the scheduling. On the other hand, a link that does not transmit for a long time has an increased priority due to the smaller denominator in calculating its relative weight. It is shown in Section V that, using our proposed fairness adaptation, each link's service amount is approximately proportional to its *channel quality*.

As an example, Fig. 3 shows the detailed procedure of water-adding with fairness adaptation in a packet slot l. We omit the superscript of link activity α_i^l. In the procedure, at the beginning of each packet slot, instead of randomly choosing a link to activate, the scheduler first activates the link with the largest relative weight.

D. Fairness Index

For UWB wireless networks, a fair resource allocation is not necessarily the case when each user receives the same service level. Consider a network with 3 links, where links 1 and 2 are close to each other while link 3 is far away from them. Links 1 and 2 generate large interference to each other. Hence, it is feasible not to allow them to be active simultaneously, i.e., the duty cycle of link 1 or 2 is at most 50%. However, it is not good to require link 3 to have the same duty cycle as link 1 or 2. As there is no large-interference link in link 3's neighborhood, it is better to allow link 3 to transmit all the time. This simple example shows that, to evaluate fairness, we should also take channel quality into account. However, it is challenging to evaluate the channel quality of a link in the UWB wireless network with peer-to-peer connections. It should be determined by the link's path loss and the interference level. Here we use a heuristic approach. For link i, define its *interference set* as the set of links that contribute/receive non-negligible interference to/from link i. We say link i generates non-negligible interference to link j

[2]In this paper, a user is said having good (poor) channel quality if it is in an advantageous (disadvantageous) position, such as with a short (long) link distance and/or in a low (high)-interference neighborhood.

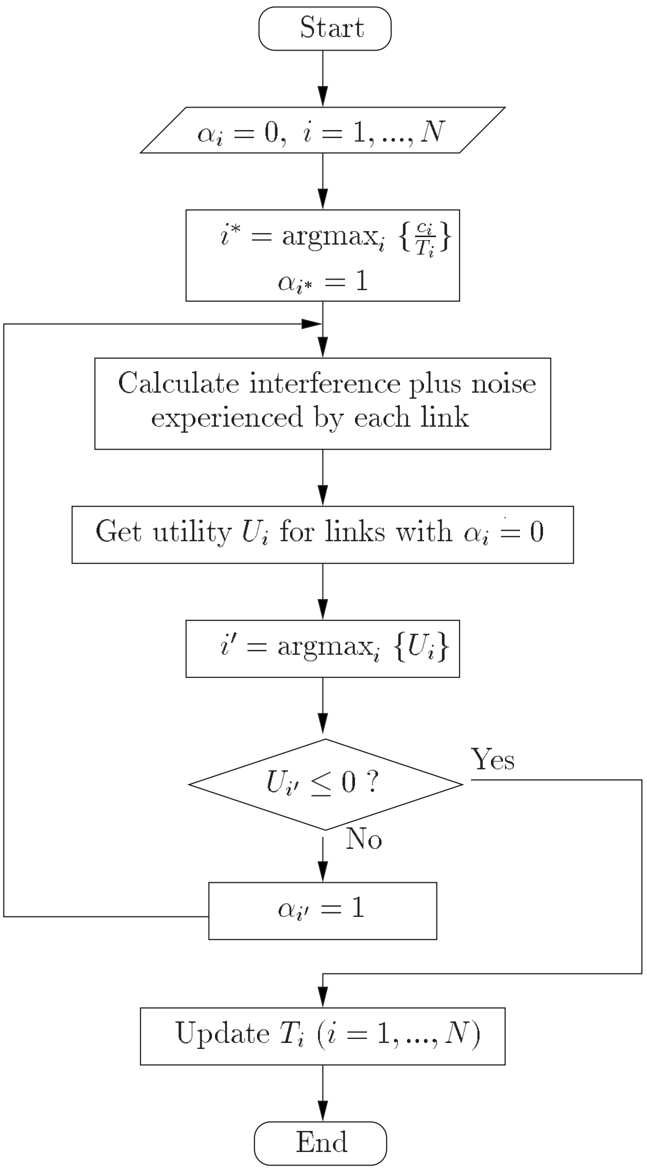

Fig. 3. The scheduling procedure (in a packet slot) of water-adding scheme with fairness adaptation.

if the *normalized interference* from link i to j (defined as the received interference from link i's transmitter normalized by the power of desired signal at link j's receiver) exceeds a threshold F. This is equivalent to $\frac{d_{ij}}{d_{jj}} < \beta$ when each active link transmits with the same maximum power, where parameter $\beta = F^{-1/\theta}$ is termed the *normalized distance threshold*. Hence, for link i, its interference set can be denoted by

$$I_i = \{j | j \neq i, \frac{d_{ij}}{d_{jj}} < \beta \text{ or } \frac{d_{ji}}{d_{ii}} < \beta\}. \tag{20}$$

The size of set I_i is denoted by $D(I_i)$. The value $q_i = \frac{1}{1+D(I_i)}$ is an indication of channel quality. In general, the smaller the size of the interference set, the better the channel quality.

Based on the channel quality indicator, the fairness is measured by the Fairness Index [15] defined as

$$\text{Fairness Index} = \frac{(\sum_{i=1}^{N} \frac{S_i}{c_i q_i})^2}{N \cdot \sum_{i=1}^{N} (\frac{S_i}{c_i q_i})^2} \tag{21}$$

where S_i is the average achieved rate of link i. The higher the Fairness Index value, the better the fairness performance. The upper bound of the Fairness Index is 1, which is achieved when $S_i/c_i q_i$ is independent of i.

E. Adaptation to Long Acquisition Time

One critical problem of UWB transmission is that the channel acquisition time can be quite long, which is a time to synchronize the receiver's clock with the transmitter's clock to achieve bit synchronization. Generally, for channel acquisition, the transmitter sends a preamble, whose duration usually varies from tens of microseconds to tens of milliseconds, as compared to microseconds in narrowband systems. This kind of overhead may greatly affect the bandwidth efficiency in high-speed UWB networks [16]. The relatively long acquisition time in UWB transmissions may also limit the UWB MAC design. Therefore, it is critical to design an efficient MAC protocol which keeps the effect of acquisition time as low as possible, in order to fully explore the high rate transmission.

For a UWB wireless network, if a link is scheduled to transmit in consecutive packet slots, the re-acquisition overhead for the packet slots following the first one can be avoided[3]. This means that it is desirable to let a link transmit continuously in terms of acquisition overhead reduction. To keep this in mind and, at the same time, to achieve acceptable system throughput and fairness performance, we modify the utility function in (18) to

$$U_i = \frac{c_i}{T_i} \cdot \big(1 - f(i) \cdot \xi\big) \cdot G_{ii} - \sum_{k \in S} \frac{c_k}{T_k} \cdot \big(1 - f(k) \cdot \xi\big) \cdot C_{ik} \tag{22}$$

where

$$f(i) = \begin{cases} 0, & \text{for link } i \text{ active at the previous packet slot} \\ 1, & \text{for link } i \text{ idle at the previous packet slot} \end{cases} \tag{23}$$

and ξ is the *acquisition overhead* (defined as the portion of time in a packet slot for acquisition, if an acquisition is needed). The modified utility function favors transmission of a link at continuous packet slots.

F. Further Discussion

In this research, throughput and fairness are the main QoS consideration. This is our first-step study to the packet scheduling in UWB wireless networks. In order to implement our research in a more practical system, other important issues need further investigations, such as QoS in terms of delay and jitter, and stability of the scheduling schemes for a system with a finite buffer size. In general, these issues can be addressed in the following directions

[3]Although there exists a guard time between two packet slots, the short duration of the guard time is unlikely to destroy the bit synchronization between the sender and the receiver.

TABLE I
THE SIMULATION PARAMETERS.

Symbol	Value	Symbol	Value
$P_{\max}$	0.5 mW	γ	10 dB
η	$4 \cdot 10^{-20}$ W/Hz	T_f	100 ns
σ^2	$1.9966 \cdot 10^{-3}$	θ	2.4
K	1/1259	t_w	8 packet slots

- A call admission control is needed to limit the calls in service, so as to guarantee the QoS requirements of the admitted calls, and to make the system work in a stability region [17].
- Rate control in higher-layer protocols can help. For example, for video transmissions over UWB wireless networks, the source coding rate can adapt to the channel capacity. Further, with the bitplane coding, a fine granularity scalability (FGS) encoder [18] is capable of achieving a continuous rate as its enhancement bit stream can be truncated anywhere to achieve the target bit-rate. The sender may truncate the bit stream to fit the channel capacity to make the queue stable. On the other hand, for data transmission, the Transmission Control Protocol (TCP) can exploit the capacity on its path by adjusting its segment sending rate based on its congestion control mechanisms, thus making the system stable.
- To achieve stability and QoS (in terms of delay and jitter), the scheduler may need to incorporate the information of the packet delay experienced at each link [19] or the queue length of each link [20].

V. PERFORMANCE EVALUATION

The performance of the proposed resource allocation schemes are evaluated via computer simulations. We consider a UWB wireless network with $N = 100$ long-lived links. Two test cases are simulated:

- Test case A: the 100 links are randomly located in a 10 m x 10 m area.
- Test case B: the 100 links are randomly located in a 40 m x 40 m area.

In each test, the selected central controller collects the location information of each node, generates a map of the UWB network, and estimates the path gain of each link. The central controller is also responsible for the resource allocation of each packet slot. When active, link i transmits with maximum power $P_i = P_{\max}$ and adapts transmission rate to the experienced interference with a required SINR value γ. We use simulation parameters similar to those in [11], [21], as listed in Table I. We only consider the overhead due to acquisition time for simplicity. For QoS provisioning, the bit-level QoS is guaranteed by adapting processing gain and/or channel coding to the experienced interference level. Hence, here we only investigate two packet-level QoS criteria: fairness and average achieved rate per link (which directly represents the system throughput).

A. Comparison with All-at-Once and Exclusive Region Schemes

Table II lists the Fairness Index, average achieved rate and normalized power consumption (with respect to $P_{\max}$) per link, and average number of active links per packet slot in All-at-Once (i.e., all links are active at all time), and in the proposed water-adding and water-draining schemes. In the simulation, the acquisition overhead ξ and normalized distance threshold β is set to 0 and 1, respectively (the effects of different acquisition overhead and normalized distance threshold value are to be discussed in Sections V-C and V-B, respectively). All links are assigned the same priority factor $c_i = 1$. It can be seen that, the average number of active links per packet slot in our schemes is around 37, a number large enough to validate the Gaussian approximation of the interference experienced by a link. Compared with the All-at-Once scheme, our proposed schemes in both tests significantly increase the Fairness Index from poor values (around 0.3 - 0.4) to acceptable ones (around 0.9); at the same time, the system throughput is also significantly increased, by approximately 30% and 70% in tests A and B, respectively. From the large Fairness Index values, it can be concluded that the achieved rate of each link is approximately proportional to its channel quality. In addition, the normalized power consumption per link in our proposed schemes is much less than that in the All-at-Once scheme, around 60% deduction in the above examples. It is preferable for UWB devices which normally have limited power supply and need to adhere to the strict emission regulation.

Comparisons are also carried out between our proposed schemes and the exclusive region scheme with a fixed exclusive region size (as used in [4], [5]). As it is not easy to select an appropriate exclusive region size, we test the exclusive region size ranging from 0–10 meters in test A, and 0–40 meters in test B. To achieve a certain level of fairness, the exclusive region scheme operates as follows:

Step 1 : All links are set as active.
Step 2 : Set the target link (indexed by i) as the one with the largest relative weight c_i/T_i.
Step 3 : Mark the target link i as "checked".
Step 4 : Set idle the remaining active and un-checked links with transmitters located in the exclusive region of target link i.
Step 5 : If all links are checked or idle, finish; otherwise, continue to Step 6.
Step 6 : From the remaining active and un-checked links, set the target link i as the one with the largest relative weight, and continue to Step 3.

We also assume that each transmitter can adapt the processing gain and/or channel coding to the interference at the receiver so that the maximum achievable rate under the interference environment can be obtained. Note that when the exclusive region size is 0, it is equivalent to the All-at-Once scheme, and when the exclusive region size is the size of the UWB wireless network, it is equivalent to Total-Exclusion scheme (i.e., only one link can transmit at any time).

In Figs. 4 – 7, we present the fairness and system throughput performance of the exclusive region scheme and our pro-

TABLE II

FAIRNESS INDEX, AVERAGE ACHIEVED RATE AND NORMALIZED POWER CONSUMPTION PER LINK, AND AVERAGE NUMBER OF ACTIVE LINKS PER PACKET SLOT IN TESTS A AND B.

Test	Packet scheduling scheme	Fairness Index	Achieved rate per link (Mbps)	Normalized power consumption per link	Number of active links per slot
A	All-at-Once	0.39	2.16	1	100
	Water-adding	0.96	2.83	0.37	37.07
	Water-draining	0.91	2.92	0.37	37.23
B	All-at-Once	0.33	1.61	1	100
	Water-adding	0.96	2.76	0.37	36.75
	Water-draining	0.88	2.87	0.36	36.03

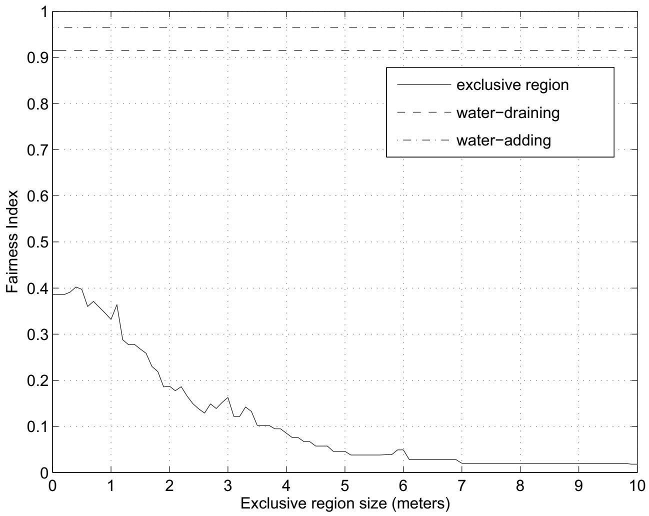

Fig. 4. Fairness Index of the exclusive region scheme and the proposed schemes in test A.

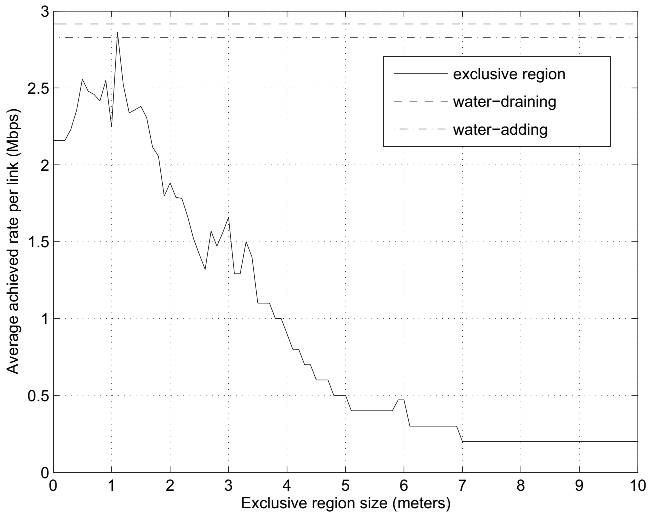

Fig. 5. Average achieved rate per link of the exclusive region scheme and the proposed schemes in test A.

posed schemes in tests A and B. In both tests, the fairness performance of our proposed schemes is much better than that of the exclusive region scheme. In terms of system throughput, it can be seen that, for most exclusive region size values (except the neighborhood of 1 meter in test A), the achieved system throughput in our proposed schemes is much larger than that in the exclusive region scheme. The reason is that, different from the fixed-size exclusive region scheme, our schemes are dynamic ones, adapting to the different interference environment of each link. Next, we investigate the optimal exclusive region size in the exclusive region scheme. For test A, it seems that the exclusive region should be set to around 1.1 meter. However, from Fig. 5, it is also observed that the system throughput is very sensitive to the exclusive region size around the optimal point, i.e., a small variation of the exclusive region size results in a large system throughput reduction. For test B, it is difficult to tell what is an appropriate exclusive region size, as there are several local maxima with a similar system throughput. The large fluctuations near the local maxima determine that it is not feasible to apply the exclusive region concept here. Furthermore, as the same maximum transmit power constraint is applied in both tests A and B, it can be concluded that the exclusive region should not depend only on the transmit power constraint, which is different from the claim in [4] that the size of exclusive region depends only on the power constraint of the source.

B. Effects of Normalized Distance Threshold β

The normalized distance threshold β is critical to evaluate the fairness performance of the proposed water-adding and water-draining schemes. Originally used to evaluate the channel quality of a link, β should be set properly. Intuitively, it should not be very small, otherwise the estimated channel quality q_i cannot properly indicate the actual situation of link i. In our simulation, we calculate the Fairness Index values in tests A and B for different β values, shown in Fig. 8. It can be seen that, the Fairness Index value is not sensitive to β when $\beta > 0.3$. The calculated Fairness Index value decreases when β decreases from 0.3 to 0.1. This is because such small β values cannot lead to a relatively accurate evaluation of the channel quality.

C. Effects of Acquisition Time

Simulations are carried out to check whether our proposed schemes can maintain efficiency with a relatively large acquisition overhead ξ. In the simulations, we ignore other

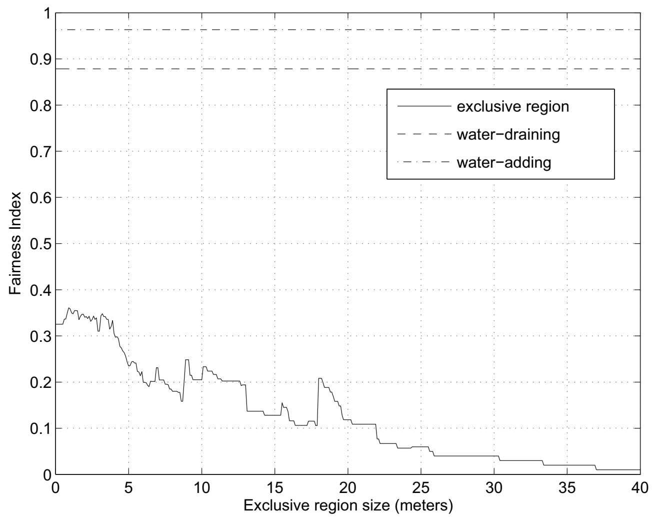

Fig. 6. Fairness Index of the exclusive region scheme and the proposed schemes in test B.

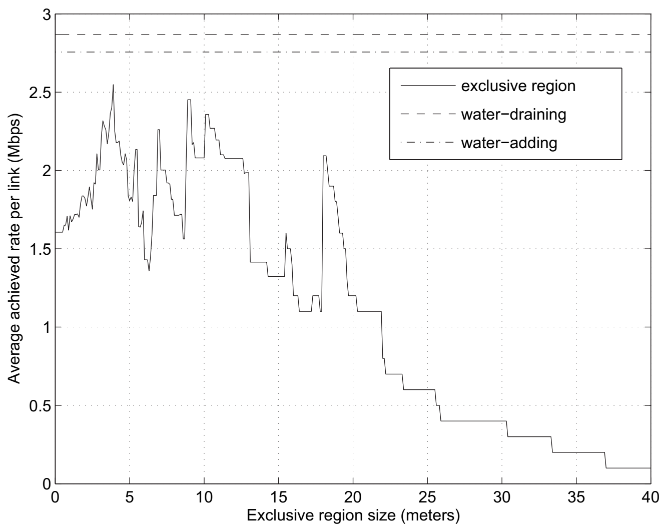

Fig. 7. Average achieved rate per link of the exclusive region scheme and the proposed schemes in test B.

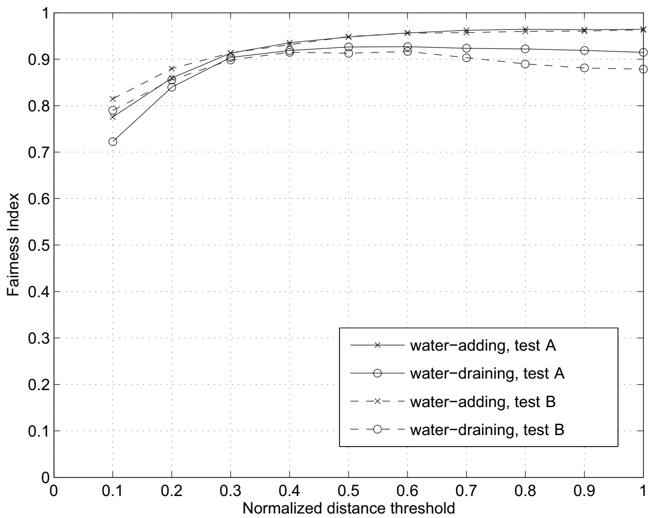

Fig. 8. Fairness Index versus normalized distance threshold β.

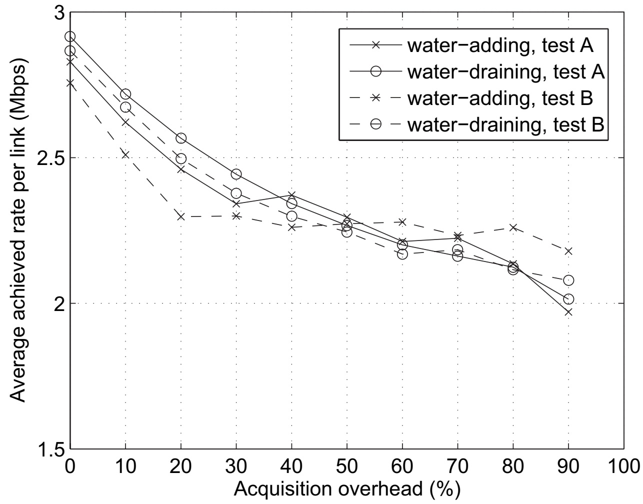

Fig. 9. Average achieved rate versus acquisition overhead ξ.

overheads and vary the acquisition overhead from 0 to 90 percent[4]. Figs. 9–11 show the average achieved rate per link, the Fairness Index, the average normalized power consumption (with respect to $P_{\max}$) per link, and the acquisition-necessary probability, respectively. Here the *acquisition-necessary probability* is defined as the probability that, when a link transmits at a packet slot, an acquisition is needed (i.e., the link is idle at the preceding packet slot). From Fig. 10, we can see that the average power consumption decreases slightly with the increase of acquisition overhead. This is because, when the acquisition overhead increases, the gain to include one link in a packet slot may not compensate for the loss of other links. Hence, the average active link number in a packet slot decreases accordingly, thus leading to a low average power consumption. From Fig. 9, it is interesting that, when the acquisition overhead increases from 0 to 90% (i.e., the system efficiency significantly decreases from 100% to 10% when an acquisition is needed), the average achieved rate per link only decreases by approximately 30%. This is because, with a large acquisition overhead, our proposed schemes can automatically favor transmission of a link at consecutive packet slots. This can also be seen from Fig. 11, where the acquisition-necessary probability decreases from values around 0.8 (at the acquisition overhead equal to 0) to approximately 0.2 (at the acquisition overhead equal to 90%). In addition, the fairness performance of our proposed schemes is not affected by different acquisition overhead values, as shown in Fig. 10. The simulation results demonstrate that our proposed schemes are robust to the relatively long acquisition time in UWB networks.

[4]The 90 percent may be an extreme case. We use it here to demonstrate the performance of our proposed schemes under severe conditions.

D. Effects of Shadowing

In this research, a UWB network with low mobility is considered. We assume that there is no fast fading, due to the rich resolvable multipath components in UWB transmissions. However, it is not easy to compensate for signal attenuation due to shadowing. In this subsection, we evaluate the effect

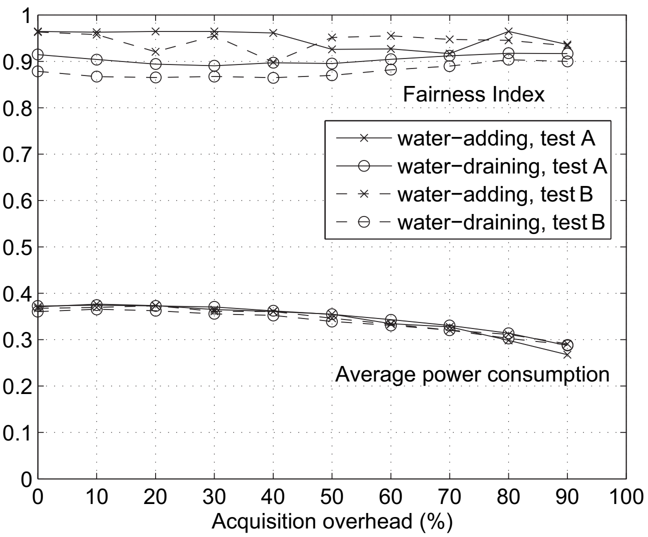

Fig. 10. Fairness Index and average normalized power consumption (with respect to $P_{\max}$) per link versus acquisition overhead ξ.

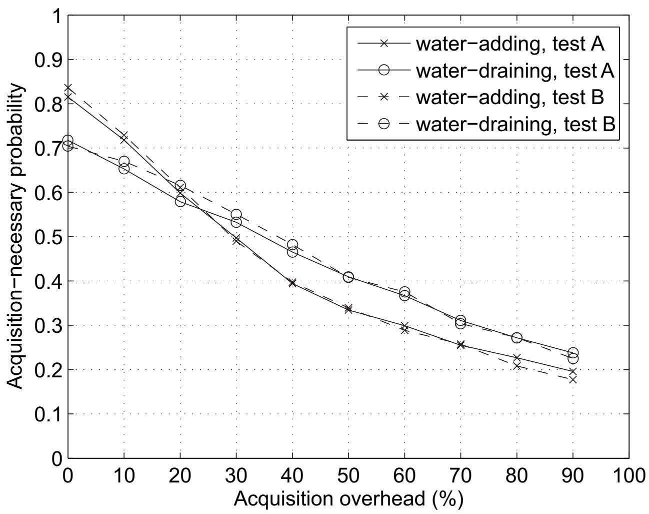

Fig. 11. Acquisition-necessary probability versus acquisition overhead ξ.

of shadowing on throughput and fairness performance of the proposed packet scheduling schemes.

When lognormal shadowing is considered, the channel gain from link i's transmitter to link j's receiver in (1) should be rewritten as

$$h_{ij} = K \cdot d_{ij}^{-\theta} \cdot 10^{\chi_{ij}/10} \tag{24}$$

where χ_{ij} (the dB attenuation due to shadowing) is a zero-mean Gaussian random variable with variance σ_χ^2. To the best of our knowledge, so far there is no research result in the open literature on correlation property of UWB channel shadowing. At a first step, we use the first-order autoregressive process [22] (used for a narrowband channel) to model UWB channel shadowing. Let $\chi_{ij}(l)$ denote the χ_{ij} value at the lth packet slot. The random process $\chi_{ij}(l)$ can be modeled by

$$\chi_{ij}(l) = \zeta^{v \cdot t_{\rm slot}} \cdot \chi_{ij}(l-1) + (1 - \zeta^{v \cdot t_{\rm slot}}) \cdot n(l) \tag{25}$$

where ζ is the correlation between two points separated by one meter, v is the moving velocity, $t_{\rm slot}$ is the duration of a packet slot, and $n(l)$'s for different l values are i.i.d. Gaussian random variables with zero mean and standard deviation $\sigma_\chi \sqrt{\frac{1+\zeta^{v \cdot t_{\rm slot}}}{1-\zeta^{v \cdot t_{\rm slot}}}}$.

In the system, each transmitter/receiver pair adjusts the transmission rate according to the received desired signal power and interference level. The transmitter/receiver pair informs the central controller their location, the channel gain, interference level, and actually received service amount after every M packet slots. The value of M is determined experimentally.

We set $\xi = 10\%$, $\beta = 1$, $\sigma_\chi = 4$ dB, $\zeta = 0.9$, $t_{\rm slot} = 5$ ms in the simulation. Test case B with the water-adding scheme is used as an example. The velocity v varies from 0.2 m/s, 2 m/s, to 10 m/s[5]. All the senders are moving with velocity v, while the receivers are static. Each sender chooses a new moving direction randomly in [0, 2π) at the end of each second. Table III shows the average achieved rate per link and fairness performance with different v and M value in test B with the water-adding scheme. For comparison, the performance with no mobility/shadowing is also given. When $v = 0.2$ m/s, the throughput and fairness performance with mobility/shadowing is degraded slightly from that with no mobility/shadowing. This is because of the very low variance in shadowing. It is also observed that the throughput and fairness performance is not very sensitive to the selection of the M value. Thus, a relative large M value (e.g., 1000) can be used. When $v = 2$ m/s, we can see that it is better to select $M = 200$. For the extreme case $v = 10$ m/s, $M = 50$ is appropriate.

E. Implementation and Discussion

Our proposed schemes dynamically allocate resources to the transmission links according to their channel quality and average received services. They can achieve desired QoS requirements at the cost of certain computation complexity at each packet slot. However, the complexity of our proposed schemes can be reduced in a practical system. For the resource allocation, time can be partitioned into *cycles*. Each cycle consists of one or several frames, as long as the number of packet slots in a cycle is large enough to achieve the required fairness level. The resource allocation remains the same from cycle to cycle, until the central controller announces a new resource allocation decision due to call arrivals/departures or user mobility. When the central controller detects a significant distance update of the users, it re-allocates the resources for each cycle, and broadcasts the allocation results to the users. With low mobility, the re-allocation frequency is not high, thus not leading to a large computation burden to the central controller.

VI. CONCLUSIONS

For UWB wireless networks, the exclusive region for specific links should be a system-level concept, taking into account interference from/to other existing active links. From the point of view, we propose the water-draining and water-adding scheduling schemes to achieve a good compromise

[5]The 10 m/s velocity may be too large for a low-mobility UWB wireless network in a small area. We use it here to demonstrate the performance of our proposed schemes under extreme conditions.

TABLE III
THE AVERAGE ACHIEVED RATE PER LINK AND FAIRNESS INDEX IN TEST B COMPARED WITH NO-MOBILITY/SHADOWING CASE IN THE WATER-ADDING SCHEME.

M		1	10	50	100	200	1000	No-mobility/shadowing
Rate (Mbps)	$v = 0.2$ m/s	2.3754	2.3705	2.3692	2.3781	2.3716	2.3865	2.4569
	$v = 2$ m/s	2.0342	1.9827	2.0099	1.9814	1.9705	1.8770	
	$v = 10$ m/s	1.9531	1.9806	1.9508	1.8561	1.7620	1.3693	
Fairness Index	$v = 0.2$ m/s	0.8831	0.8891	0.8913	0.8870	0.8881	0.8798	0.9386
	$v = 2$ m/s	0.8738	0.9110	0.8929	0.8849	0.9111	0.8546	
	$v = 10$ m/s	0.9323	0.9162	0.9442	0.9124	0.9224	0.7583	

between throughput and fairness. Each link's achieved rate is approximately proportional to its channel quality level. Via computer simulations, we have shown that our proposed schemes outperform the All-at-Once scheme and the exclusive region scheme with a fixed exclusive region size. To develop an effective and efficient MAC for UWB wireless networks, further research efforts are necessary in call admission control with QoS guarantees, resource allocation with delay and stability consideration, and cross-layer design between the link layer packet scheduling and high-layer rate control mechanisms, etc.

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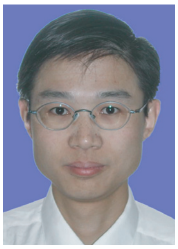

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