Power Allocation and Scheduling for Ultra-Wideband Wireless Networks

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***Abstract*—In this paper, power allocation and scheduling issues are studied for ultra-wideband (UWB) wireless networks. An optimization problem is first formulated to jointly maximize system spectral efficiency and minimize power consumption, taking into account advantages of UWB inherent properties (such as the capacities in supporting parallel transmissions and providing accurate positioning). For UWB networks with a stringent constraint on complexity, a margin-based power allocation scheme and an exclusive region-based scheduling scheme are then proposed. The margin-based power allocation scheme utilizes each node's own position information, and the exclusive region-based scheduling scheme takes into consideration the interaction among simultaneous transmission links. Simulation results demonstrate the effectiveness of the proposed power allocation and scheduling schemes.**

***Index Terms*—Exclusive region, power allocation, scheduling, ultra-wideband (UWB), wireless communications.**

I. Introduction

Ultra-wideband (UWB) technology is ideal for high-rate short-range (e.g., indoor) wireless communications. With a bandwidth that is larger than 500 MHz or 25% of the center frequency, UWB signals can be generated by using a short pulse without a carrier [1]–[3] or by using multiband orthogonal frequency-division multiplexing (MB-OFDM) [4], [5]. In a pulse-based UWB, bandpass pulses of extremely short duration, which are typically in the range of a fraction of a nanosecond to a few nanoseconds, are used for information transmission, whereas in MB-OFDM, hybrid frequency hopping and OFDM are used. In 2002, the Federal Communications Commission (FCC) opened the 3.1–10.6 GHz spectrum for UWB applications on an unlicensed basis [6]. The ultrawide bandwidth and ultralow transmission power consumption (−41.25 dBm/MHz for indoor applications) make UWB technology attractive for practical applications.

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Medium access control (MAC), which coordinates the transmission of the competing users in an orderly and efficient manner, is essentially important [7]. However, designing an effective and efficient MAC protocol in UWB networks is very challenging. This is due to the following: 1) the scarce radio resource and the limited transmission power; 2) the channel impairments, resulting from path loss and multiuser interference (MUI); 3) the diverse quality of service (QoS) requirements of multimedia applications in terms of throughput and bit error rate (BER); and 4) the stringent constraints on complexity and system overhead. In this paper, two important issues at the MAC layer of UWB networks, i.e., power allocation and scheduling, are studied to achieve both high spectral efficiency and low transmission power consumption.

Energy constraints on UWB devices render power allocation a critical component in designing UWB networks. The allocation of transmission power to users should be according to channel conditions and traffic load so that the total system power consumption can be reduced and the battery life of users' handsets can be prolonged. Power allocation has been extensively studied in code-division multiple-access (CDMA) systems [8] and in a general framework [9]. Although close-to-optimal solutions can be obtained, the high computational complexity prevents their applications in UWB networks. In [10] and [11], distributed power allocation schemes are proposed for *ad hoc* networks. The schemes are autonomous and can guarantee convergence. However, the iteration procedure of the distributed schemes takes a certain amount of time to converge and introduces high system overhead, which may greatly degrade the efficiency of UWB networks. An optimal power allocation algorithm is proposed for UWB networks in [12], where the transmitters either transmit with maximum power or keep silent. The optimization is based on maximizing system throughput (or maximizing utility under proportional fairness). However, when different optimization criteria are considered, e.g., maximizing spectral efficiency for given transmission rate requests, maximum power transmission may no longer be optimal [13]. In addition, maximum power transmission is not desirable in terms of power consumption since it is usually not required for most transmissions, and it may result in different channel capacity experienced by different links. How an effective but simple power allocation scheme is designed is still an open issue in UWB networks.

Scheduling is another important MAC layer technology that arranges the transmission order of different links so that minimum system resources are utilized for given transmission rate requests and that all links' QoS requirements are guaranteed.

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The scheduling defined in the IEEE 802.15.3 standard is carried out by a central controller, called the piconet coordinator (PNC), and is based on time-division multiple access (TDMA), i.e., at any time instant, only one link is allowed to transmit [14]. A more efficient way for scheduling is to allow parallel transmissions. In pure *ad hoc* networks, parallel transmissions are supported by the concept called *exclusive region* [11], [12], [15], [16], which has been proved to be beneficial for system throughput improvement [17]. By defining an exclusive region for each receiver in the network, when a desired receiver begins to receive information, all transmitters located inside the exclusive region should keep silent, while others are allowed to simultaneously transmit. Related work in this area usually assumes that 1) each transmitter either transmits with maximum transmission power or keeps silent such that the shape of the exclusive region becomes a circle centered at the desired receiver and 2) the transmitters located close to the desired receiver (i.e., the transmitters introducing larger interference) are blocked first from simultaneous transmissions. However, if power allocation is applied, since different transmitters will employ different amounts of transmission power, the exclusive region will no longer be a circle. In addition, scheduling for parallel transmissions requires the acknowledge of the interaction among all parallel transmission links. Blocking the transmitters with larger interference may not be proper, since all transmitters involved in parallel transmissions have to be located outside the respective exclusive regions of all receivers. Such interaction must be considered in parallel transmission scheduling.

A well-designed MAC layer should fully consider the network properties at the physical layer. For UWB networks, its physical layer has the following unique characteristics: 1) As an extreme form of CDMA, UWB has potential to support parallel transmissions, which can be achieved by assigning different spreading sequences (time hopping (TH) or frequency hopping) for different transmissions. For pulse-based UWB, parallel transmissions can be achieved, even though all simultaneous transmission links use the same code channel due to the very low duty cycle of the pulse transmission and the presence of different propagation delay among different links; 2) since UWB has very low transmission power, parallel transmission can also be achieved in UWB-based *ad hoc* networks if the simultaneous transmission links are sufficiently separated in space; and 3) different from the traditional narrowband and wideband networks, accurate position information of all nodes in the network can be obtained in pulse-based UWB networks [18]. All these physical layer properties should be considered in developing power allocation and scheduling schemes at the MAC layer.

In this paper, the main concern is with finding a practical solution for the complex MAC design by introducing effective and efficient power allocation and scheduling schemes. By making use of the properties of the UWB in parallel transmissions and positioning, an optimization problem is first formulated to maximize system spectral efficiency with guaranteed QoS requirements. Then, a practical solution of the optimization problem is proposed by introducing a margin-based power allocation scheme and an exclusive region-based scheduling scheme. The margin-based power allocation scheme uses local information only (each link's own transmission distance) so that it is simple to implement. Furthermore, the exclusive region-based scheduling scheme jointly considers the interference introduced by other interfering transmitters to the desired receiver and the interference that results from the desired transmitter to other receivers. The scheduling scheme is further implemented using an exclusive region determination algorithm and a survival-link-based simultaneous transmission set search algorithm. Simulation results demonstrate that the proposed power allocation and scheduling schemes can achieve much better performance in terms of the number of required slots per frame and power consumption than that with the 0–MAX power allocation or the traditional exclusive region determination algorithm.

The rest of this paper is organized as follows. Section II describes the model of a UWB network from both the physical layer and the MAC layer points of view. An optimal power allocation and scheduling problem is formulated in Section III. Section IV presents the proposed margin-based power allocation scheme. The scheduling schemes without and with maximum transmission power constraints are discussed in detail in Section V. In Section VI, the performance of the proposed power allocation and scheduling schemes is evaluated via extensive simulation. Concluding remarks are given in Section VII.

II. System Model

The system model of a UWB network under consideration is depicted in Fig. 1. Our main concern is on the operation of the physical and MAC layers of the UWB network.

A. Physical Layer Model

The functional blocks of a pulse-based UWB system are shown in Fig. 1(a). Modulation is performed by pulse position modulation (PPM) and multiple access by time hopping (TH). Binary information bits from the mth transmitter, $d_m[i] \in \{0, 1\}$, are represented and transmitted by a train of ultrashort pulses $p(t)$ with pulsewidth T_p. According to PPM, an information bit "0" is represented by a sequence of pulses without any delay, whereas a bit "1" is represented by the same sequence of pulses with a delay δ relative to the time reference. Each train of pulses is further time hopped to accommodate multiple access requirements. Assuming that the pulse $p(t)$ has unit energy and the transmission power per pulse from transmitter m is P_m, the transmitted PPM UWB waveform with TH for the mth transmitter can be written as

$$s_m(t) = \sqrt{P_m} \sum_{i=-\infty}^{\infty} \sum_{j=0}^{N_s-1} p\left(t - iT_b - jT_f - c_j^m T_c - \delta d_m[i]\right) \tag{1}$$

where $\{c_j^m\}$ is a pseudorandom time-hopping sequence of length N_s, T_c is the duration of addressable time delay bins or chip duration, T_f is the nominal pulse repetition interval, and $T_b = N_s T_f$ is the symbol duration.

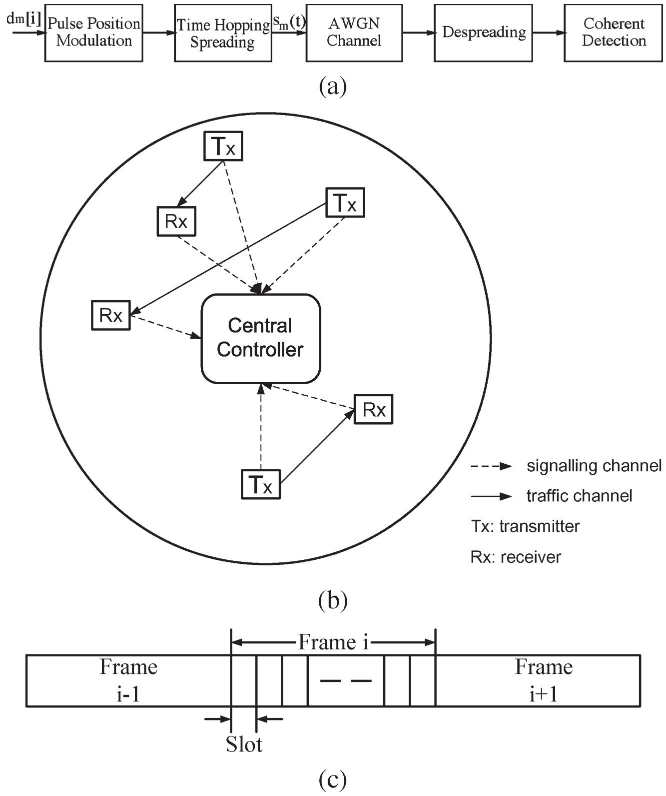

Fig. 1. System model of the UWB-based *ad hoc* network. (a) Physical layer model. (b) MAC layer model. (c) Frame structure.

The transmission channel is assumed to exhibit additive white Gaussian noise [15] with no fast fading [19]–[22] (due to the fine multipath separation and the multipath combining at the receiver end) or slow fading [12] (due to its timescale being larger than a packet transmission time). However, the transmitted signal suffers attenuation from path loss. Given the distance between the ith receiver and the jth transmitter as $d_{j,i}$, the received power $P^r_{j,i}$ from transmitter j is given by

$$P^r_{j,i} = \kappa P_j d_{j,i}^{-\gamma} \tag{2}$$

where γ is the path loss exponent, and κ is the proportional constant independent of $d_{j,i}$. Equation (2) is a commonly used attenuation model, which has been confirmed as a suitable indoor propagation model for UWB [23]. Without loss of generality, we assume $\kappa = 1$ for simplicity.

The received signal at the ith receiver is first despread and then coherently detected to recover the original transmitted signal. The analysis in [24] and [25] shows that the signal-to-interference ratio (SIR) at the output of the ith receiver's despreader is

$$\mathrm{SIR}_i = \frac{P_i d_{i,i}^{-\gamma}}{\alpha \sum_{j\in\mathbf{\Gamma}_i^s} P_j d_{j,i}^{-\gamma} + \eta} \tag{3}$$

where $\mathbf{\Gamma}_i^s$ denotes the set of transmitters that simultaneously transmit with transmitter i, η is the white Gaussian background noise power that is assumed to be identical for all links in the network, and α is the spreading factor, which is determined by the choice of system parameters, such as the transmission rate, the number of pulses in each bit, the hopping range of the TH sequence, the shape of the monocycle, etc. Note that a nonempty $\mathbf{\Gamma}_i^s$ may introduce multiuser interference (MUI). If each transmitter uses a different TH sequence, α may become very small. However, if only one code channel is shared by all active links, as defined in IEEE 802.15.3, α may be large. For α equal to 1, there is no spreading gain.

B. MAC Layer Model

As shown in Fig. 1(b), the UWB network under consideration consists of M active links. For simplicity, the transmitter and the receiver involved in the same link are represented by the same subscript, i.e., the ith transmitter communicates with the ith receiver. The network has a similar configuration as that defined in IEEE 802.15.3. A central controller is assumed available to perform the control functions, such as power allocation and scheduling, at the MAC layer. Signaling channels are established between the controller and all the other nodes in the network to exchange control messages, while data transmission is peer-to-peer through traffic channels that directly connect transmitters and receivers.

Data transmission at the MAC layer is frame-by-frame based, as shown in Fig. 1(c). Each frame is further divided into a number of equal-length slots. Although it is assumed that each active link in the network requests one slot for transmission in each frame, the proposed scheduling scheme can be easily extended to the case where each transmitter may request a different number of slots per frame. For example, a transmitter requesting N transmission slots per frame can be considered as N transmitters, each requesting only one slot per frame. With a fixed number of slots requested by each active link, the frame length with respect to the number of active links and the scheduling scheme (or the slot allocation scheme) varies with time.

Based on the system model presented in Sections II-A and B, the UWB network exhibits the following properties. 1) The application of TH indicates the possibility of parallel transmissions, which can be implemented by assigning different TH sequences to different links. 2) In UWB, T_f is much larger than T_p, which results in much smaller duty cycle. Thus, even without TH, the UWB network can still allow parallel transmission because of the propagation time difference among the links. 3) Since the duration T_p of each pulse is on the order of nanoseconds, the UWB network has very high time granularity so that it has possibility in obtaining accurate position information. 4) The existence of the controller facilitates the application of control functions at the MAC layer, but its complexity should be kept as low as possible. All these unique properties of UWB networks introduce new requirements and features for designing the MAC layer protocol. Throughout our design, these properties will be fully utilized to achieve an effective and efficient UWB network.

III. Optimal Power Allocation and Scheduling

In this section, power allocation and scheduling are optimized by maximizing the spectral efficiency (SE) under the constraints that the SIR requirements of all active links are satisfied. For homogeneous traffic with persistent transmission and transmission rate requests in each frame, maximizing spectral efficiency means that the network can support all active transmissions using a minimum number of time slots in each frame. Since scheduling is carried out at the beginning of each frame, the frame index is omitted for simplicity.

Define the scheduling function for each link as $\{A_{i,l}, i = 1, 2, \ldots, M; l = 1, 2, \ldots, L\}$, where L, a random variable, is the total number of slots required in the current frame. $A_{i,l}$ is an indicator that takes the value "0" or "1." $A_{i,l} = 1$ means that the lth slot in the current frame is allocated to transmitter i. Otherwise, $A_{i,j} = 0$. According to the definition of spectral efficiency, minimum L means maximum spectral efficiency, which depends on the slot allocation function $A_{i,l}$ and the power allocation function $P_{i,l}$ (the power allocated to the ith transmitter in the lth slot). From (3), the problem of optimal power allocation and scheduling can be written as

$$\begin{cases} \max_{\{A_{i,l}, P_{i,l}\}} SE \\ \text{subject to} \\ \frac{A_{i,l} P_{i,l} d_{i,i}^{-\gamma}}{\alpha \sum_{j=1, j\neq i}^{M} A_{j,l} P_{j,l} d_{j,i}^{-\gamma} + \eta} \geq A_{i,l}\text{SIR}_r \\ \qquad i = 1, 2, \ldots, M; \quad l = 1, 2, \ldots, L \qquad \text{(Condition I)} \\ \sum_{l=1}^{L} A_{i,l} = 1 \qquad \text{(Condition II)} \end{cases} \tag{4}$$

where SIR_r denotes the SIR requirement at the receiver. In (4), Condition I means that, at any time slot, all simultaneous transmissions must be guaranteed the required SIR at all desired receivers, and Condition II means that each active link occupies exactly one slot for transmission in each frame. Note that the equality in (4) holds in the Condition I with minimum power consumption. Equation (4) is a nonlinear integer programming problem, and exact solutions cannot be obtained by simple calculations. Since the UWB network has a stringent constraint on complexity, some simple but effective power allocation and scheduling schemes need to be developed.

Since maximizing SE is equivalent to minimizing L, in the following, a practical approach with less computational complexity to obtain a solution for (4) will be presented. The approach consists of two steps. In the first step, a margin-based power allocation is introduced, which determines the required transmission power for each link and the system capacity in each slot; in the second step, the traditional exclusive region concept is extended to ultimately determine the slot allocation for all active links.

IV. Margin-Based Power Allocation

In margin-based power allocation, the transmission power consists of the following two parts: 1) the power to compensate for path loss and background noise by assuming no interference from other transmitters and 2) the power margin to account for a possible MUI. Since power allocation is independent of scheduling, in this section, the slot index is omitted for simplicity. Given the distance $d_{i,j}$ for any i and j, if transmitter i is selected for transmission, its transmission power can be calculated as

$$P_i = P_{i1} + \Delta_i, \qquad i = 1, 2, \ldots, M \tag{5}$$

where $P_{i1} = \eta \text{SIR}_r d_{i,i}^{\gamma}$ is the power compensated for path loss and background noise, and Δ_i is the power margin for transmitter i. Given Δ_i, we can calculate the tolerable interference I_i of receiver i as follows. Since the power allocation requires

$$\frac{P_i d_{i,i}^{-\gamma}}{\alpha I_i + \eta} \geq \text{SIR}_r \tag{6}$$

I_i can be represented in terms of Δ_i as

$$I_i \leq \frac{\Delta_i d_{i,i}^{-\gamma}}{\alpha \text{SIR}_r}. \tag{7}$$

From (7), if a constant margin is set for all transmitters, i.e., $\Delta_i = \text{constant}$, $\forall i$, each receiver will have a different interference tolerance level because of the different propagation distances associated with each link. This is undesirable from the receiver point of view. To provide fairness, i.e., equal capacity in interference tolerance among different receivers, the power margin is set as a function of $d_{i,i}$ as follows:

$$\Delta_i = \beta d_{i,i}^{\gamma} \tag{8}$$

where β is a proportional constant, whose values represent different applied power margins. Substituting (8) into (7), we have

$$I_i \leq \frac{\beta}{\alpha \text{SIR}_r}. \tag{9}$$

V. Exclusive Region-Based Scheduling Scheme

Let $\mathbf{\Lambda}_l$, $l = 1, 2, \ldots, L$, be the set of transmitters that are scheduled for transmission in slot l. After determining the transmission power for each transmitter in the network, the scheduler tries to find $\mathbf{\Lambda}_l$ such that the total number of slots required in each frame is minimized. Since the network is quasi-static and the transmissions in previous slots will not affect the transmissions in later slots, the task of minimizing the number of slots per frame is equivalent to finding the maximum number of simultaneous transmission links in each slot. In the following, scheduling schemes with and without a maximum transmission power constraint are discussed, respectively.

A. *Scheduling Without Maximum Power Constraint*

If there is no maximum power constraint, power allocation can be carried out based on (5). Given the interference tolerance of each receiver I_i, the simultaneous transmission set $\mathbf{\Lambda}_l$ should satisfy the following condition:

$$\begin{aligned} &\sum_{j\in\mathbf{\Lambda}_l, j\neq i} P_{j,l} d_{j,i}^{-\gamma} \leq I_i \\ &\Rightarrow \sum_{j\in\mathbf{\Lambda}_l, j\neq i} \left(\eta \mathrm{SIR}_r d_{j,j}^{\gamma} + \beta d_{j,j}^{\gamma}\right) d_{j,i}^{-\gamma} \leq \frac{\beta}{\alpha \mathrm{SIR}_r} \\ &\Rightarrow \sum_{j\in\mathbf{\Lambda}_l, j\neq i} \left(\frac{d_{j,j}}{d_{j,i}}\right)^{\gamma} \leq \frac{\beta}{\alpha \mathrm{SIR}_r(\eta \mathrm{SIR}_r + \beta)} = C, \qquad \forall i \in \mathbf{\Lambda}_l \end{aligned} \tag{10}$$

where C is a systemwide constant for all receivers. Obviously, C represents the system capacity in each slot under the given power allocation scheme. Let the set of active links waiting for transmission in slot l be $\mathbf{\Lambda}_{\mathrm{active}}^l$, which contains M_l links. We can define an $M_l \times M_l$ matrix $\mathbf{G} = \{g_{i,j}\}$, $i, j \in \mathbf{\Lambda}_{\mathrm{active}}^l$, which has elements

$$g_{i,j} = \begin{cases} 0, & i = j \\ \left(\frac{d_{j,j}}{d_{j,i}}\right)^{\gamma}, & i \neq j. \end{cases} \tag{11}$$

Then, from (4) and (10), the optimal scheduling can be formulated as

$$\begin{cases} \max_{\mathbf{A}_l} \sum_{i\in\mathbf{\Lambda}_{\mathrm{active}}^l} A_{i,l} \\ \text{subject to} \\ \mathrm{diag}(\mathbf{A}_l)\mathbf{G}\mathbf{A}_l \leq \boldsymbol{\theta} \end{cases} \tag{12}$$

where the vector $\mathbf{A}_l = \{A_{i,l}, i \in \mathbf{\Lambda}_{\mathrm{active}}^l\}_{M_l\times 1}$, $\mathrm{diag}(\mathbf{X})$ denotes the diagonal matrix with diagonal elements $\mathbf{X}$, and $\boldsymbol{\theta} = [C, \ldots, C]_{1\times M_l}^T$. Equation (12) represents a nonlinear binary integer programming problem, and the exact solution is still hard to obtain. By relaxing the constraint in (12), however, an upper bound on the number of parallel transmissions can be calculated from

$$\begin{cases} \max_{\mathbf{A}_l} \sum_{i\in\mathbf{\Lambda}_{\mathrm{active}}^l} A_{i,l} \\ \text{subject to} \\ \sum_{i\in\mathbf{\Lambda}_{\mathrm{active}}^l} \sum_{j\in\mathbf{\Lambda}_{\mathrm{active}}^l} A_{i,l} A_{j,l} \left(\frac{d_{j,j}}{d_{j,i}}\right)^{\gamma} \leq \sum_{i\in\mathbf{\Lambda}_{\mathrm{active}}^l} A_{i,l} C. \end{cases} \tag{13}$$

Compared with (12), the constraint on the individual transmitter is loosened in (13) by considering the aggregated effects of all transmitters that simultaneously transmit. An optimal solution of (13) can be obtained by the following water-filling algorithm:

1) Let $\boldsymbol{\psi}_0 = \mathbf{\Lambda}_{\mathrm{active}}^l$.
2) Start with $k = 0$, and iterate

$$q = \arg\max_j \left\{ \sum_{i\in\boldsymbol{\psi}_k} \left(\frac{d_{j,j}}{d_{j,i}}\right)^{\gamma} + \sum_{i\in\boldsymbol{\psi}_k} \left(\frac{d_{i,i}}{d_{i,j}}\right)^{\gamma} \right\}$$

$$\boldsymbol{\psi}_{k+1} = \boldsymbol{\psi}_k \backslash q$$

where $\boldsymbol{\psi}_k \backslash j$ means removing the component j from $\boldsymbol{\psi}_k$ until $\sum_{i\in\boldsymbol{\psi}_k} \sum_{j\in\boldsymbol{\psi}_k} (d_{j,j}/d_{j,i})^{\gamma} \leq \sum_{i\in\boldsymbol{\psi}_k} C$ is satisfied.

3) Finally, $\boldsymbol{\psi}_{k+1}$ is the required simultaneous transmission set at slot l.

B. Scheduling With Maximum Power Constraint

If there exists a maximum transmission power constraint for each transmitter, the actual transmission power after power allocation becomes

$$P_i = \min(P_{i1} + \Delta_i, P_{\max}) \tag{14}$$

where $P_{\max}$ denotes the maximum power limitation. Then, the relationship in (10) does not exist, and the problem of optimal scheduling can be formulated from (4) as

$$\begin{cases} \max_{\mathbf{A}_l} \sum_{i\in\mathbf{\Lambda}_{\mathrm{active}}^l} A_{i,l} \\ \text{subject to} \\ \frac{A_{i,l} P_{i,l} d_{i,i}^{-\gamma}}{\alpha \sum_{j\in\mathbf{\Lambda}_{\mathrm{active}}^l, j\neq i} A_{j,l} P_{j,l} d_{j,i}^{-\gamma} + \eta} \geq A_{i,l} \mathrm{SIR}_r, \quad i, j \in \mathbf{\Lambda}_{\mathrm{active}}^l. \end{cases} \tag{15}$$

Similarly, the optimization problem (15) is a nonlinear integer programming problem, and exact solutions cannot be obtained by simple calculations. In the following, an exclusive region-based approach to solve (15) with less computational complexity will be presented. The proposed approach consists of two phases. In the first phase, an exclusive region is determined for each receiver in the network; in the second phase, a survival-link-based search algorithm is proposed to ultimately determine the simultaneous transmission set from the whole network's point of view.

1) Phase 1—Exclusive Region Determination: For each receiver, its exclusive region defines a set of potential transmitters that cannot transmit with its associate transmitter simultaneously. The determination of exclusive region should consider the following two important aspects.

1) Unlike the 0–MAX case, where each transmitter uses either maximum power or zero in transmission and the transmitters with shorter distance to the desired receiver is equivalent to the transmitters that introduce larger interference, power allocation aims at making the MUI dependent on both the distance between the interfering transmitters and the desired receiver, as well as the distance between the interfering transmitters and their own receivers. Therefore, after power allocation, the exclusive region will no longer be a circle, and the definition based on distance becomes meaningless.
2) For simultaneous transmissions, if transmitter m is outside the exclusive region of receiver i, transmitter i must be outside the exclusive region of receiver m as well. Otherwise, transmitters i and m still cannot simultaneously transmit. Thus, the determination of simultaneous transmissions depends not only on the interference introduced by other transmitters, but also, on the interference of the desired transmitter to other receivers. Including first the transmitters with larger interference in the exclusive region, which may actually be accommodated with the desired link, may block the potential simultaneous transmissions.

By taking both aspects into account, we have the following exclusive region determination scheme for each receiver.

Exclusive region determination: Instead of including the transmitter with maximum interference in the exclusive region, the transmitter, which satisfies

$$\arg\max_{j}\left\{\max\left\{a\left(\frac{d_{j,j}}{d_{j,i}}\right)^{\gamma},(1-a)\left(\frac{d_{i,i}}{d_{i,j}}\right)^{\gamma}\right\}\right\} \tag{16}$$

will be considered first.

In (16), the first term represents the interference from other transmitters, and the second term represents the interference from the desired transmitter; a is a coefficient that can take any value between 0 and 1. The parameter a is used to reflect different contributions of the two kinds of interference to the exclusive region determination. $a = 1$ means that the traditional determination scheme, i.e., the transmitter with the maximum interference to the desired receiver, will be included first, whereas $a = 0$ means that the link experiencing the most interference from the desired transmitter will be blocked first.

2) Phase 2—Simultaneous Transmission Set Determination: Define the obtained exclusive region of the ith receiver at the lth slot as $\mathbf{E}_{i,l}$, $i \in \mathbf{\Lambda}^{l}_{\text{active}}$, and its complementary set as $\bar{\mathbf{E}}_{i,l} = \mathbf{\Lambda}^{l}_{\text{active}} \backslash \mathbf{E}_{i,l}$. In this section, we show the search algorithm for the simultaneous transmission set $\mathbf{\Gamma}^{s}_{i,l}$ for any receiver i, i.e., the set of links that can be active at the same time with link i.

In principle, the direct search algorithm shown in the Appendix can be applied. The direct search algorithm looks for all possible simultaneous transmission sets for receiver i and chooses the one with the maximum set size as the algorithm output. Obviously, the computational complexity of the direct search algorithm increases exponentially with the size of the complementary exclusive region and will become practically infeasible when the number of active links becomes large. One observation from the direct search algorithm is that the intersection among different links' complementary sets plays an important role in each searching step. Since the links that provide a maximum intersection set have a larger chance to accommodate more simultaneous transmissions, a novel search algorithm is proposed to reduce the searching complexity, where at each step, only the link that can provide a maximum intersection set, called a survival link, remains. The pseudocode of the survival-link-based search algorithm is shown in the following.

Survival-Link-Based Search Algorithm

Let $\mathbf{\Gamma}_0 = \bar{\mathbf{E}}_{i,l}$, $\mathbf{\Gamma}^{s}_{i,l} = \{i\}$, *and* $k = 0$
while $\mathbf{\Gamma}_k \neq \phi$
  $j = \arg\max_j\{|\mathbf{\Gamma}_k \cap \bar{\mathbf{E}}_{j,l}|\}$, $j \in \mathbf{\Gamma}_k$, *where* $|\mathbf{X}|$ *denotes the size of the set* $\mathbf{X}$
  if $\mathbf{\Gamma}^{s}_{i,l} \subseteq \bar{\mathbf{E}}_{j,l}$
    $\mathbf{\Gamma}^{s}_{i,l} = \mathbf{\Gamma}^{s}_{i,l} \cup \{j\}$
    $\mathbf{\Gamma}_{k+1} = \mathbf{\Gamma}_k \cap \bar{\mathbf{E}}_{j,l}$
    $k = k + 1$
  else
    $\mathbf{\Gamma}_k = \mathbf{\Gamma}_k \backslash j$
  end
end

Since only the survival link is picked at each search step, the computational complexity of the proposed search algorithm only linearly increases with respect to the size of $\bar{\mathbf{E}}_{i,l}$ and is much less than that of the direct search algorithm.

C. Scheduling Scheme in UWB Networks

We summarize the proposed scheduling scheme as follows.

1) At the beginning of each frame, all nodes report their locations to the controller. Based on this information, the controller calculates the corresponding transmission power for each link.
2) The controller determines the exclusive region of each receiver based on the algorithm proposed in Section V-B.
3) The controller chooses the receiver with the smallest exclusive region or the maximum complementary set and carries out the simultaneous transmission set determination using the proposed survival-link-based search algorithm.
4) The controller allocates the first slot to all transmitters in the simultaneous transmission set and removes them from the active link set and all unallocated links' complementary sets.
5) The controller repeats steps 3) and 4) until every link has been allocated one slot for transmission.

VI. Simulation Results

In this section, simulation results are presented to demonstrate the performance of the proposed power allocation and scheduling schemes.

A. Simulation Parameters

Consider a UWB network [26], which covers a circular area with a radius of 50 m. There are 80 nodes that are uniformly distributed in the covered area. The transmitters and the receivers are randomly picked, which results in 40 active links. Each link requests one slot for transmission in each frame, and all transmitters always have packets waiting for transmission. The channel exhibits additive white Gaussian noise with power $\eta = 10^{-20}$ W and path loss with exponent $\gamma = 2$. The spreading factor α is set to 0.01 to account for possible spreading gain, and the target SIR for all transmissions is 10 dB. The maximum transmission power is set to $P_{\max} = 10^{-14}$ W such that the link with maximum distance (100 m in our simulation) can still be established with the target SIR without MUI. For comparison purposes, the scheduling scheme proposed in [15], with both the 0–MAX power allocation, i.e., either transmits with maximum power or keeps silent, and the margin-based power allocation (referred to as the traditional scheduling scheme), is also simulated. Equation (14) is used for power allocation to provide a fair comparison. The performance is compared in terms of the average number of slots required in each frame to satisfy 40 transmission requests, where the average is calculated by changing the nodes' locations 50 times.

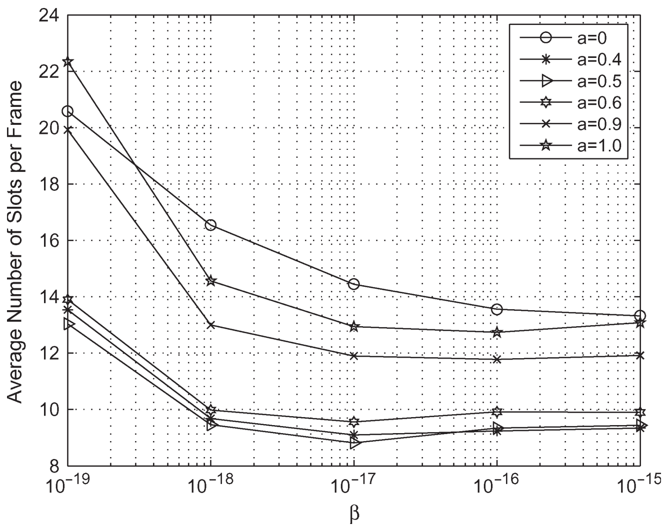

Fig. 2. Scheduling performance with respect to the different values of a; $\alpha = 0.01$.

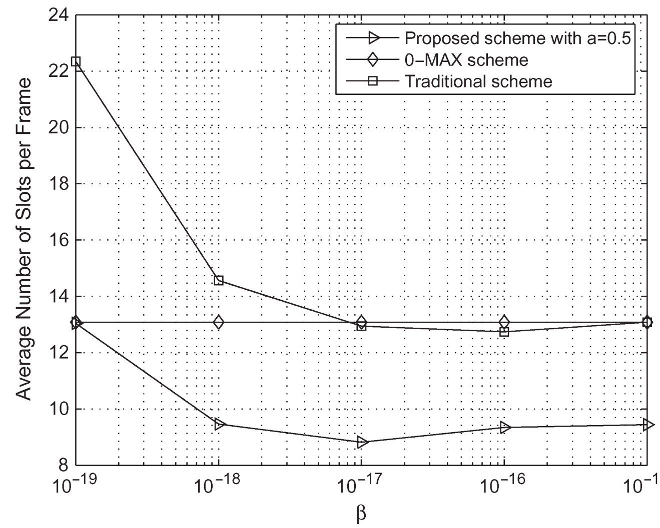

Fig. 3. Scheduling performance comparison among three scheduling schemes; $\alpha = 0.01$.

TABLE I
AVERAGE POWER CONSUMPTION BETWEEN THE 0–MAX AND THE MARGIN-BASED POWER ALLOCATION SCHEMES

	Power Margin (β)			
	10^{-18}	10^{-17}	10^{-16}	10^{-15}
0-MAX power allocation ($\times 10^{-14}$)	1	1	1	1
margin based power allocation ($\times 10^{-14}$)	0.2527	0.7947	0.9758	0.9826

B. Simulation Results and Discussions

Fig. 2 shows the effects of the parameter a in (16) on the performance of the proposed scheduling scheme. Different values of a reflect different contribution of two kinds of interference on exclusive region determination. The parameter β in (8) is varied to represent different power margins applied. From the figure, it can be observed that the parameter a significantly affects the ultimate performance of the proposed scheduling scheme. Both cases with $a = 0$ (only the interference introduced by the desired link to other receivers is considered) and $a = 1$ (only the interference that results from the other transmitters to the desired receiver is considered) cannot give optimal performance. Jointly considering two kinds of interference, therefore, becomes necessary in determining a proper exclusive region for each receiver. In our simulation, the best scheduling performance is achieved at $\beta = 10^{-17}$ and $a = 0.5$, i.e., equally considering both kinds of interference in the exclusive region determination.

Performance comparison of the proposed scheme with respect to the 0–MAX power allocation scheme and the traditional scheduling scheme is shown in Fig. 3. It can be observed that the proposed power allocation and scheduling schemes outperform both the 0–MAX power allocation scheme and the traditional scheduling scheme over all the power margins considered. Compared with the 0–MAX power allocation scheme, at power margin $\beta = 10^{-17}$, the proposed scheduling scheme requires only 8.8 slots per frame on the average, which is 32.56% less than the 0–MAX power allocation scheme. Since UWB networks usually support transmission rates that are higher than 100 Mb/s, the 32% performance improvement indicates a 32-Mb/s improvement in spectral efficiency. In addition, by observing the average power consumption shown in Table I with respect to different power margin, for $\beta = 10^{-17}$, 20% less power consumption is applied in the proposed scheme than that in the 0–MAX power allocation scheme. As mentioned in previous sections, the savings in power consumption are quite important for UWB networks.

In addition, by comparing the performance of 0–MAX power allocation and traditional scheduling in Fig. 3, it can be observed that there is no significant improvement resulting from power allocation. This indicates that simply introducing power allocation in the UWB network may not improve the scheduling performance, which further highlights the importance of optimal power allocation and scheduling, as formulated and solved in this paper.

Fig. 3 also demonstrates the effects of power margin on the scheduling performance. It can be observed that the performance of the traditional scheme is worse than that of the 0–MAX power allocation scheme at small power margins, while it approaches the optimal point at power margin $\beta = 10^{-16}$ and merges with the performance of the 0–MAX power allocation scheme for large values of β. This is because when the power margin is relatively small, according to (9), each receiver has little interference tolerance. When the power margin equals zero, no interference tolerance exists. Under this situation, no parallel transmissions are allowed, and the required number of slots equals the number of active links. On the contrary, if the power margin is sufficiently large such that all transmitters work at the maximum transmission power, no performance difference exists between the traditional scheduling scheme and the 0–MAX power allocation scheme.

To investigate the effects of the spreading factor α on the scheduling performance in terms of the average number of slots

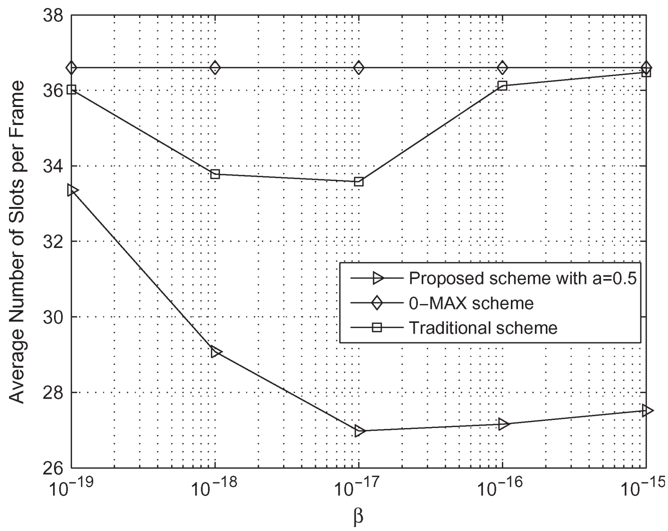

Fig. 4. Scheduling performance comparison among three scheduling schemes; $\alpha = 0.1$.

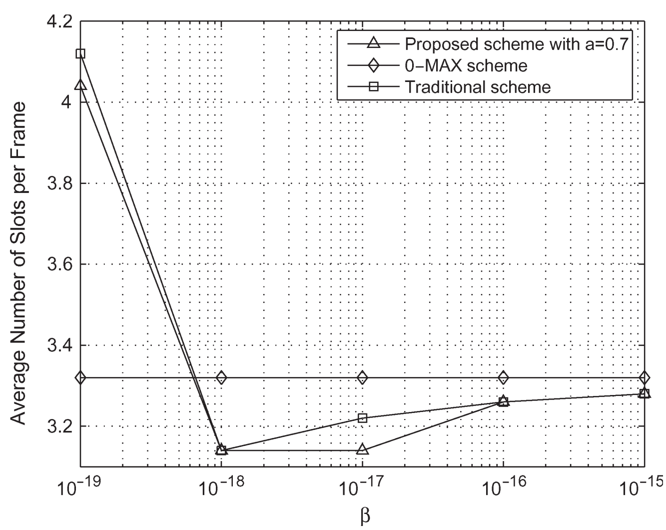

Fig. 5. Scheduling performance comparison among three scheduling schemes; $\alpha = 0.001$.

per frame, we ran the same simulation for different α with optimal values of a, i.e., $\{\alpha = 0.1, a = 0.5\}$ and $\{\alpha = 0.001, a = 0.7\}$, and the results are shown in Figs. 4 and 5, respectively. Compared with the $\alpha = 0.01$ case in Fig. 3, similar observations can be made. One additional observation from Fig. 5 is that the optimal value of a equals 0.7, i.e., the optimal value of a increases as α decreases.

Fig. 6 shows the scheduling performance with different α's and a fixed β ($\beta = 10^{-17}$). It can be observed that when α decreases, the performance improvement of the proposed scheme over the other two schemes decreases accordingly. This is because a smaller value of α introduces less MUI. When α tends to zero, MUI vanishes for parallel transmissions, and the three schemes need only one slot for supporting all active links. However, by considering the power allocation mechanism, the proposed scheme can still outperform the 0–MAX power allocation scheme in terms of power consumption.

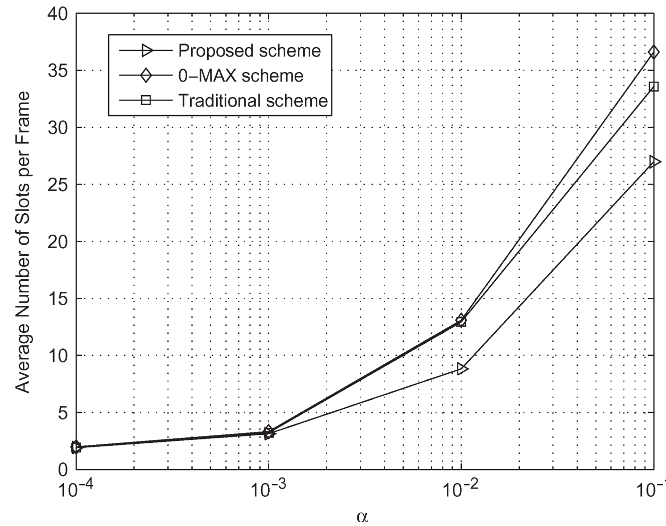

Fig. 6. Scheduling performance with respect to the different values of α; $\beta = 10^{-17}$.

VII. Conclusion

In this paper, power allocation and scheduling schemes have been proposed for UWB networks. By making use of the UWB properties, the proposed schemes can improve system spectral efficiency and, at the same time, reduce the required power consumption. To keep the system complexity at a relatively low level, a margin-based power allocation algorithm, an exclusive region determination algorithm, and a survival-link-based simultaneous transmission set search algorithm have been proposed. Through simulation, it is shown that the proposed schemes can achieve better performance in terms of the average number of slots per frame and the transmission power saving over the 0–MAX power allocation scheme and the traditional scheduling scheme. It is conjectured that the proposed power allocation and scheduling schemes are beneficial for future development of efficient UWB networks.

Appendix
Direct Search Algorithm

Let $\mathbf{\Gamma}^s_{i,l} = \{i\}$ *(initialize the simultaneous transmission set)*
for all $j \in \bar{\mathbf{E}}_{i,l}$ *(consider all transmitters in the ith receiver's complementary exclusive region)*
if $i \in \bar{\mathbf{E}}_{j,l}$ *(determine whether transmitter* i *is located outside the exclusive region of receiver* j*)*
$\mathbf{\Gamma}^s_{i,l} = \mathbf{\Gamma}^s_{i,l} \cup \{j\}$ *(put transmitter* j *in the simultaneous transmission set)*
$\mathbf{\Gamma}_1 = \bar{\mathbf{E}}_{i,l} \cap \bar{\mathbf{E}}_{j,l}$ *(the left potential parallel transmitters exist in the intersection of* $\bar{\mathbf{E}}_{i,l}$ *and* $\bar{\mathbf{E}}_{j,l}$*)*
if $\mathbf{\Gamma}_1 \neq \phi$ *(*ϕ *denotes an empty set)*
for all $k \in \mathbf{\Gamma}_1$ *(consider all potential transmitters)*
if $\mathbf{\Gamma}^s_{i,l} \subseteq \bar{\mathbf{E}}_{k,l}$ *(determine whether the simultaneous transmission set is located outside the exclusive region of transmitter* k*)*
$\mathbf{\Gamma}^s_{i,l} = \mathbf{\Gamma}^s_{i,l} \cup \{k\}$ *(put transmitter* k *in the simultaneous transmission set)*

$\mathbf{\Gamma}_2 = \mathbf{\Gamma}_1 \cap \bar{\mathbf{E}}_{k,l}$ *(update the potential transmitter set)*

if $\mathbf{\Gamma}_2 \neq \phi$
for all $n \in \mathbf{\Gamma}_2$
$\vdots$
end
end
end
end
end
end
end
end
end

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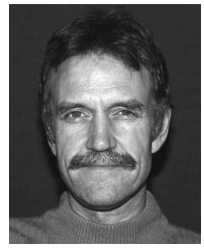

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