Effective Interference Control in Ultra-Wideband Wireless Networks

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Abstract: *Ultra-wideband (UWB) technology is a viable candidate for next generation wireless communications, with merits such as high data rate, low power, robustness to multipath fading, and positioning capability. Multiple nearby transmissions can be supported in UWB networks, using an appropriate code assignment mechanism. Different from cellular networks, the near-far problem in UWB networks cannot be solved solely by power control at the physical layer. Instead, it should be managed jointly with the radio resource allocation at the link layer in order to achieve interference control. This article reviews possible solutions for distributed code assignment in UWB networks, and investigates two effective approaches, namely spatial exclusion and temporal exclusion, for interference control in UWB networks.*

Ultra-wideband (UWB) transmissions, with a bandwidth at least 500 MHz or 20 percent of the center frequency, have many merits, such as high data rate, low power spectrum density, and low interference to other radio systems. The ultra-wide bandwidth facilitates a fine multipath resolution, thus achieving robustness to multipath fading. In addition, UWB technology has the capability of precise positioning, benefiting from the fine time resolution in UWB transmissions which enables an accurate estimation of the time of arrival (TOA) of UWB signals. The development and deployment of commercial UWB networks have been stimulated since the Federal Communications Commission (FCC) of the United States allocated a 7.5 GHz bandwidth (3.1–10.6 GHz) for UWB applications [1]. Figure 1 illustrates a typical UWB network. Mobile devices can communicate with each other

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THE ARTICLE REVIEWS POSSIBLE SOLUTIONS FOR CODE ASSIGNMENT AT THE PHYSICAL LAYER THAT CAN BE USED IN UWB NETWORKS. IT DEMONSTRATES THAT, TO SOLVE THE NEAR-FAR PROBLEM, PHYSICAL AND LINK LAYER APPROACHES SHOULD BE JOINTLY CONSIDERED.

via peer-to-peer transmissions. A connection to a correspondence node (outside of the UWB network coverage area) can also be supported through an access point and the Internet backbone via multi-hop transmissions [2].

Generally, UWB implementation can be achieved by single-band or multiband approaches. Single-band approach is usually pulse based. Information can be transmitted by sending very short pulses. Pulse-based time hopping (TH) and pulse-based direct sequence (DS) are the two main streams of pulse-based approach for UWB modulation. On the other hand, multiband orthogonal frequency division multiplexing (MB-OFDM) is a typical scheme for multiband modulation approach. MB-OFDM is particularly useful to deal with frequency selectivity of UWB channels [3]. In this article, we focus on pulse-based UWB networks.

The inherent spread spectrum in UWB technology allows simultaneous nearby transmissions in a small local area. This is quite different from traditional wireless local area networks (WLANs) or ad hoc networks where two nearby transmissions may collide with each other. In pulse-based UWB networks, two nearby transmissions do not collide, as long as two different codes are assigned. On the other hand, even though orthogonal codes can be used in UWB transmissions, the orthogonality may not hold among multi-sender multi-receiver transmissions in UWB networks since it is difficult to synchronize the transmissions from different senders. This is different from code-division multiple access (CDMA) cellular networks where the synchronous single-sender multi-receiver transmissions in the downlink can use Walsh codes for orthogonality. Further, even if the transmissions of the mobile nodes can be synchronized, it is still difficult to achieve the orthogonality among the signals taking into account the various transmission delays from different senders to a common receiver, and the transmission delay spread in a multipath propagation environment. Thus, interference is inevitable in UWB networks. The coverage of a UWB network is typically 10–100 meters. Within the network coverage, for a target receiver receiving data from its sender that is far way, another sender close to the target receiver may generate strong interference to the target receiver, and may corrupt the desired reception at the target receiver [4]. This is the notorious near-far problem, originally raised in cellular networks. In this article, we first briefly review possible solutions for code assignment at the physical layer that can be used in UWB networks. Then we demonstrate that, to solve the near-far problem, physical and link layer approaches should be jointly considered. We propose two approaches based on spatial and temporal exclusion mechanisms, respectively, to effectively address the near-far problem and achieve resource utilization efficiency.

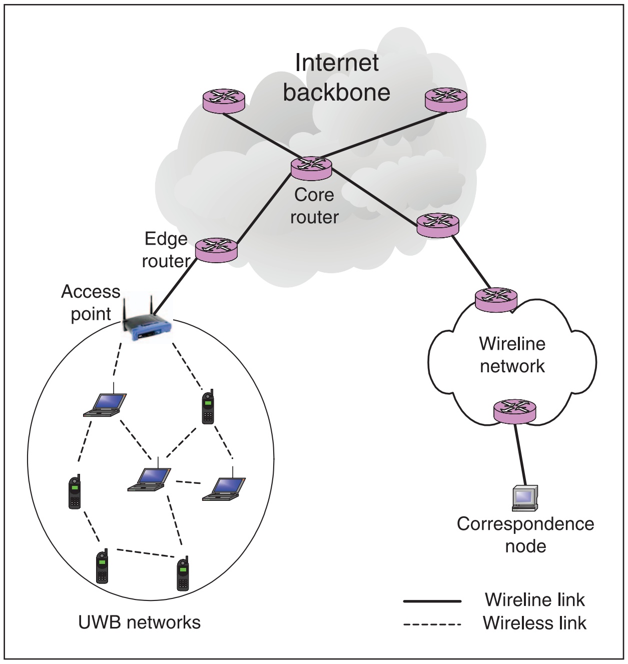

FIGURE 1 A typical UWB wireless network.

2. Code Assignment in UWB Networks

The major task of code assignment is to effectively let a sender send traffic, and a receiver monitor and receive desired signals. In cellular networks, the codes are assigned by the base station at the setup stage of a transmission. However, for UWB networks, such a centralized controller is not realistic. Thus, it is desired that code assignment is performed in a distributed manner. Similar to the CDMA-based ad hoc networks, three code assignment approaches can be applied to UWB networks: 1) common code: all transmissions are based on a common code; 2) receiver-based code: the transmission to a destination is based on the unique receiving code of the receiver; and 3) transmitter-based code: when a sender initiates a transmission, the unique transmitting code of the sender is used [5]. The common code approach may lead to a collision if there are two nearby transmissions, as the same code is used. In the receiver-base code approach, traffic monitoring is simple as each receiver only needs to monitor its own receiving code for any intended transmission. However, two transmissions from two different senders to a common receiver may still lead to a collision. For transmitter-based code approach, two transmissions will not collide if they are from different senders. However, it is not easy for the intended receiver to have information of the transmitting code of a potential sender.

To reduce the collisions, a hybrid approach may be more effective. For instance, the common-transmitter-based (C-T) approach combines common and transmitter-based codes, while the receiver-transmitter-based (R-T) approach keeps the advantages of both receiver-based and transmitter-based codes [5]. In addition, in order to reduce the duration of a possible collision, the request-to-send (RTS)/clear-to-send (CTS) dialogue in the multiple access with collision avoidance (MACA) can be adopted, thus leading to the MACA/C-T or MACA/R-T approaches [6]. In MACA/C-T, the RTS and CTS are exchanged via the common code, and if the RTS/CTS exchanges are successful, DATA transmission uses the traffic source's transmitting code. On the other hand, in MACA/R-T shown in Figure 2 (where nodes *a* and *c* send traffic to nodes *c* and *d*, respectively), the RTS is first sent through the traffic destination's receiving code, and the CTS is then sent by the traffic destination through its transmitting code. Finally the DATA frame is sent through the traffic source's transmitting code. It can be seen that the possible collision period in MACA/C-T is within the RTS/CTS exchange process because of the common code used; and the possible collision period in MACA/R-T is within the RTS exchange process, and a collision happens only if another traffic source also sends an RTS to the same traffic destination (using the same receiving code of the traffic destination). Hence, the channel is utilized more efficiently in MACA/R-T than in MACA/C-T.

3. Near-Far Problem

By an appropriate code assignment, the collision in UWB transmissions can be avoided. However, the near-far problem due to a strong interfering signal from a nearby interferer still exists. In CDMA cellular systems, power control is usually used to alleviate the near-far problem and to achieve desired transmission accuracy of all the users. For presentation clarity, consider a single service (e.g., video transmission) as a simple example. The traditional power control in cellular networks is to keep the received power from all mobile nodes at a constant level. However, the traditional power control approach cannot be applied to UWB networks for the following two reasons. First, the traditional power control is performed at a central controller with powerful computation capability, i.e., the base station. In UWB networks, such a central controller may not be available due to the ad hoc topology of UWB networks and the power consumption constraint. Second, in a cell of the cellular networks, there is a common receiver at the uplink. Thus if the received power from each mobile node is kept at a constant level, the transmission accuracy of all the links can be guaranteed as long as the number of active links does not exceed a threshold. However, in a UWB network, the receivers of the peer-to-peer transmissions are different. Even if the received power levels of desired signals at all the receivers are kept the same, the near-far problem still exists. Therefore, in UWB networks, the near-far problem cannot be solved solely by power control at the physical layer. Instead, it should be managed jointly with the radio resource allocation at the link layer, in order to control the interference at each receiver. In the following, spatial and temporal exclusion mechanisms for the interference control in UWB networks are investigated.

IN UWB NETWORKS, THE NEAR-FAR PROBLEM CANNOT BE SOLVED SOLELY BY POWER CONTROL AT THE PHYSICAL LAYER. IT SHOULD BE MANAGED JOINTLY WITH THE RADIO RESOURCE ALLOCATION AT THE LINK LAYER, IN ORDER TO CONTROL THE INTERFERENCE AT EACH RECEIVER.

4. Spatial Exclusion

The near-far problem is due to interference from nearby neighbors. Hence, a possible solution is to use spatial exclusion to eliminate nearby interferers in the vicinity of a receiver. Actually, the principle of spatial exclusion has been well adopted in single-channel networks such

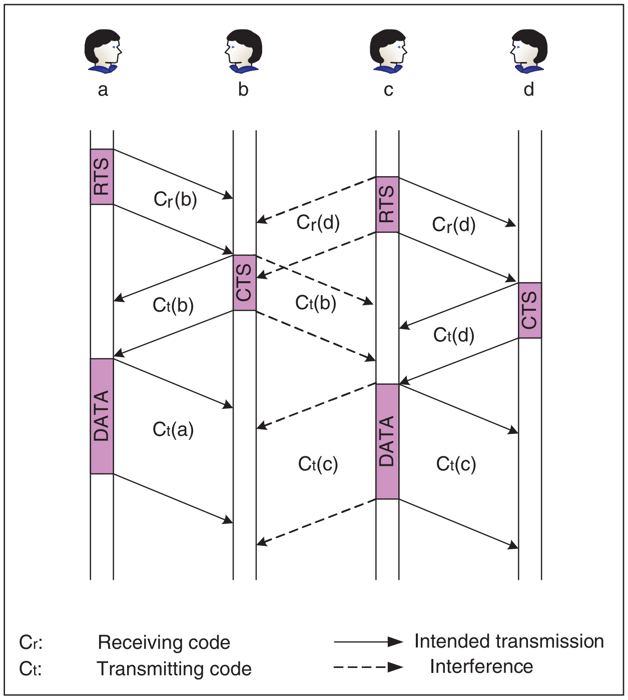

FIGURE 2 The MACA/R-T approach.

WE PROPOSE AN APPROACH FOR THE SYSTEM-WISE EXCLUSIVE REGION. TIME IS PARTITIONED INTO FIXED-DURATION FRAMES AND A CENTRAL CONTROLLER IS SELECTED FOR THE RESOURCE ALLOCATION IN EACH FRAME.

as traditional WLANs or ad hoc networks where carrier sense multiple access (CSMA) is used. Each sender senses the medium before transmission. If the medium is detected busy, the sender defers its transmission because it is likely a nearby interferer to an existing transmission. In UWB networks, the principle of spatial exclusion leads to the concept of *exclusive region* [4], [7], which targets at a maximal network throughput. The exclusive region is to determine whether an interferer is sufficiently far away so as not to generate significant interference to the desired reception. Specifically, when a target link is transmitting, simultaneous transmissions from interfering sources outside the exclusive region of the target receiver are allowed, while senders inside the exclusive region should not transmit in order not to corrupt the target reception. However, it is challenging to find an appropriate exclusive region. A small exclusive region may allow more simultaneous transmissions in the network, at the cost of a high probability of transmission corruption. On the other hand, a large exclusive region can effectively avoid significant interference, at the cost of low frequency reuse.

As the first attempt to determine an appropriate exclusive region size (i.e., the minimum distance d from an interfering source to a desired receiver), it is suggested that the size be selected to maximize the achieved rate at a desired receiver [7]. However, local rate maximization of a target link may not be able to achieve overall throughput maximization. Another attempt to determine the exclusive region size is based on the *near-far scenario* [4], as illustrated in Figure 3. There are two links: from A to B, and from C to D. The transmission power of the senders is the same. The distance from a sender to the intended receiver is l, while the distance from an interferer to a receiver is d. Consider two scheduling approaches: 1) all-at-once where the two links are active all the time; and 2) time-division multiple access (TDMA) where only one link is active at a time, and each link has a duty cycle 50% based on round robin. When d is very small, TDMA outperforms all-at-once in terms of system throughput due to the dominant effect of interference in the all-at-once mode. When d increases, the interference in all-at-once gradually decreases, and the throughput increases. The throughput of TDMA does not change with d. The exclusive region size is selected as the value of d when the all-at-once and TDMA approaches achieve the same system throughput. Indeed, this heuristic selection method is effective in selecting an appropriate exclusive region size when there are only two links in a network. However, the selection method may lose its effectiveness when there are more active links in the neighborhood, as it does not address the interference generated by the two target links' senders to other active links. From the two links $A \to B$ and $C \to D$, both of them generate interference to other existing links in the all-at-once mode, while only one of them generates interference in the TDMA mode. Hence, the actual exclusive region size should be larger than that determined above. In summary, in a UWB network with possible multiple (larger than two) simultaneous transmissions, each link generates/receives interference to/from other links. Thus, to determine whether two target links should transmit one by one or simultaneously, system-wise information such as interference from/to other existing active links and achievable rates at other links is needed. In the following, we propose an approach for the system-wise exclusive region. Time is partitioned into fixed-duration frames. And a central controller is selected for the resource allocation in each frame.

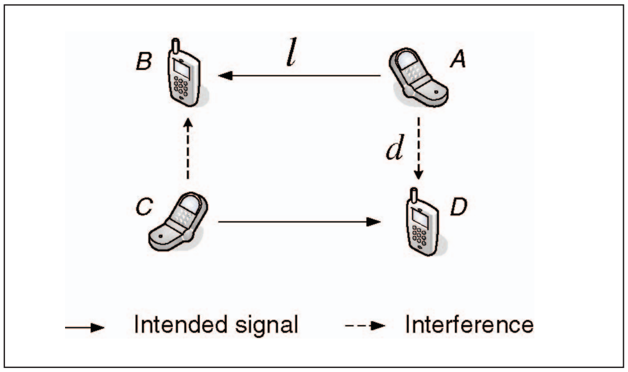

FIGURE 3 The near-far scenario [4].

As the status of a target link changes from inactive to active, other active links experience more interference and, hence, have smaller achievable transmission rates. Thus, for each target link, we estimate the interference levels experienced by other active links in the cases when the target link is active and inactive, respectively, and calculate the reduced rates of other active links because of the active target link. A utility function is defined as the transmission rate of the target link minus the total reduced rate of other active links because of the active target link. We first consider all links are active; that is, the set of active links (referred to as active set) contains all the links. Then we remove the link (from the active set) that has a negative utility value with the maximum magnitude. This procedure is repeated until all the remaining active links are with positive utility values. To achieve fairness, in the utility calculation of a target link, a lagging link (i.e., a link that received less service than others) is assigned a relatively large weight (e.g., inversely proportional to the achieved throughput in previous frames) to its reduced rate.

Computer simulations are carried out to evaluate the performance of the traditional exclusive region approach and the proposed spatial exclusion approach. Consider a TH-UWB wireless network with 100 long-lived links whose senders and receivers are randomly located in a 20 m × 20 m area. The pulse repetition time (T_f) is 100 ns. Thus, for each link, the maximum achieved rate is $R_{\max} = 1/T_f = 10$ Mbps as the processing gain should be at least 1. For traditional exclusive region approach, it is not an easy task to select an appropriate exclusive region size. In the simulations, sampled values ranging from 0 to $20\sqrt{2}$ meters (the network coverage) are tested. When the exclusive region size is 0, all links are allowed to transmit simultaneously, equivalent to the all-at-once approach; and when the exclusive region size is $20\sqrt{2}$, at most one link is allowed to transmit at any time. The exclusive region approach operates in the following steps for resource allocation in each time frame:

1) Assume set Ω contains all the links. Denote the active set as Θ. So initially, Θ is a null set.
2) To achieve some level of fairness, choose link i from Ω with the smallest achieve throughput (in previous time frames), and include link i in the active set Θ.
3) For each link k in Ω, remove it from Ω if its transmitter is located in the exclusive region of link i (i.e., the distance from link k's transmitter to link i's receiver is less than the exclusive region size), and/or link i's transmitter is located in the exclusive region of link k.
4) Remove link i from Ω.
5) If Ω becomes a null set, the links in Θ can be active simultaneously because the distance from a link's transmitter to another link's receiver is at least the exclusive region size; otherwise, continue to Step 2.

Figure 4 shows the normalized (with respect to $R_{\max}$) achieved rates per link using the traditional exclusive region approach and the proposed approach, respectively. It can be seen that the proposed approach outperforms the traditional approach. For the traditional approach, it is difficult to tell what an appropriate exclusive region size should be, as there are several local maxima with a similar system throughput. The large fluctuations near the local maxima imply the sensitivity of the system performance to the exclusive region size in the traditional exclusive region approach.

5. Temporal Exclusion

In order to avoid a strong interferer corrupting desired reception of a target link, the target link and the interferer's link can be allowed to transmit in different time slots, based on a frame structure. In each slot, to achieve interference control, a solution is to allocate the minimal transmission power to a link which is sufficient to ensure the transmission accuracy as in cellular networks. However, this is not practical for a UWB network without a central controller having strong computational capability. Actually, even if such a central controller exists, it is challenging to monitor all the peer-to-peer connections. It becomes worse in a distributed UWB network. When there is a call arrival/departure, power levels of all the existing links should be reconfigured. A procedure is necessary to effectively exchange control messages among the nodes, which is a challenging task, and the associated overhead can be very high.

5.1 Interference Margin (IM)

To keep the signaling overhead at a low level, a possible solution is the incremental approach, where a new call arrival or departure does not affect the existing power level assignment [8]. Following this principle, an interference margin (IM)-based approach has been proposed [2], [9]. The interference margin, also referred to as maximum sustainable interference (MSI), is the additional tolerable interference while not violating the required signal to noise-plus-interference ratio (SINR), denoted by γ_i for link i. Consider a TH-UWB network with N links as an example. For link i, we have

$$\frac{P_i g_{ii}}{R_i\left(\eta_i + T_f \sigma^2 \sum_{j=1, j\neq i}^{N} P_j g_{ji} + IM_i\right)} = \gamma_i$$

where P_i and R_i denote the transmission power and rate of link i, respectively, g_{ij} the channel gain from link i's transmitter to link j's receiver, η_i the background noise energy, σ^2 a parameter depending on the shape of the pulse, and IM_i the interference margin value of link i.

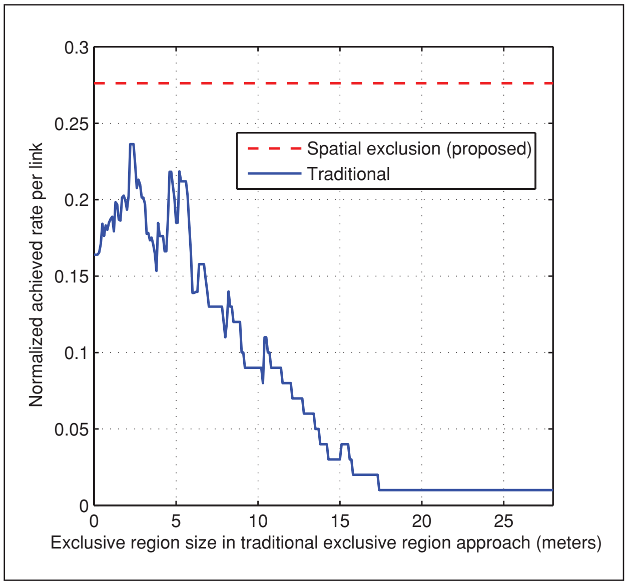

FIGURE 4 System throughputs with the exclusive region approaches.

TO ENHANCE THE IM-BASED INTERFERENCE CONTROL WITH A TEMPORAL EXCLUSION MECHANISM, WE PROPOSE A CONSTANT-DURATION FRAME PARTITIONED INTO A NUMBER OF TIME SLOTS.

In order to ensure the transmission accuracy of all the N links, their IMs should be kept non-negative. When a new call request for link k with required rate R_k arrives, its transmitter first checks whether it can be assigned a power level while not violating non-negative IM requirements of all the existing links, i.e., it calculates

$$P_k = \min\left\{P_{\max}, \min_{1 \le j \le N}\left\{\frac{IM_j}{T_f \sigma^2 g_{jk}}\right\}\right\}$$

where is the $P_{\max}$ maximum allowed transmission power in the UWB network. If $P_k = 0$, the call request should be rejected as otherwise it will corrupt the reception of an existing link. If $P_k > 0$, link k's transmitter checks whether it can keep a non-negative IM if admitted, i.e., whether

$$\frac{P_k g_{kk}}{\gamma_k R_k} - \eta_k - T_f \sigma^2 \sum_{j=1}^{N} P_j g_{jk} \ge 0.$$

If it is true, link k's transmitter determines that its call can be admitted with power P_k and rate R_k; otherwise, its call should be rejected [2], [9].

The principle of the IM-based approach is a kind of circuit-switching channel reservation. A code channel is reserved for a link, and the transmission quality of existing links should not be violated by a new call. However, the approach has both implementation and near-far problems, as explained in the following.

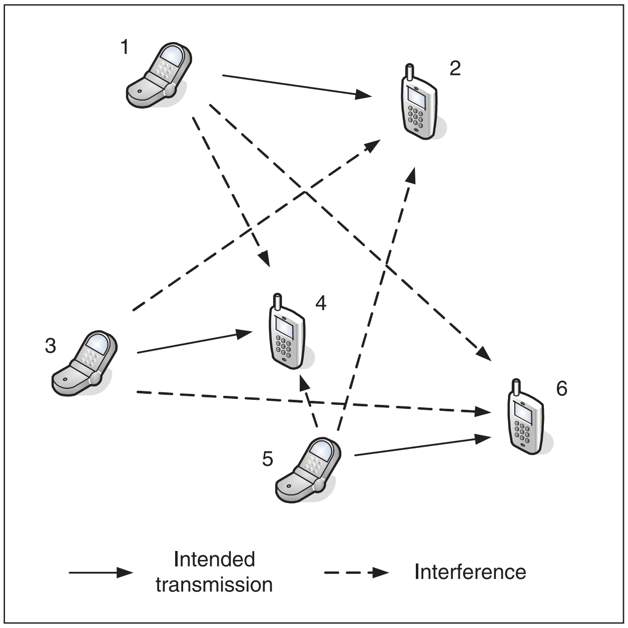

FIGURE 5 The near-far problem in the IM-based approach.

1) The IM value, the power level, and the location information of each active link need to be broadcast to the whole network. Upon a new call admission or call completion, each active node needs to update and broadcast its IM value. A control channel is suggested in [2]. However, it is very likely that the broadcast messages may collide with each other since all the broadcast messages are approximately "synchronized" with the call arrival/departure moment. Furthermore, when a new call request arrives, it has to wait for a long time in order to collect the broadcast information from all the existing links. The incomplete and out-of-date information may degrade the system performance.
2) A near-far problem exists, which is a variant of the traditional near-far problem. Consider the scenario illustrated in Figure 5, where the calls over links 1→2 and 3→4 are admitted into the network first. Then the call over link 5→6 is admitted. All the senders, i.e., nodes 1, 3, and 5, transmit with power $P_{\max}$. The IM of link 3→4 is much smaller than those of the other two links, because it has a nearby interferer, i.e., node 5. Therefore, when a new call request arrives, it is likely to be rejected because of no sufficient IM at link 3→4, although the other two existing links have large IMs.

Temporal exclusion mechanisms can be effective to address the near-far problem in the preceding example. If links 3→4 and 5→6 are allowed to transmit in different time durations, the insufficient IM at link 3→4 due to the nearby interferer can be avoided.

5.2 Interference Control with Temporal Exclusion

To enhance the IM-based interference control with a temporal exclusion mechanism, we propose a frame structure as shown in Figure 6. A constant-duration frame is partitioned into a number of time slots. Data transmissions and/or control message exchanges can be accommodated in a time slot. Among all the active senders in a slot, one acts as the *slot leader*. The leader collects information of the slot and broadcasts to potential new call senders during its period of duty. For call admission, a control message exchange procedure exists which includes three phases:

1) Request phase: If a potential call sender intends to transmit at a slot, it issues a request at the request phase of the slot, using a pre-specified request common code. If the transmission of the request fails or collides with others (i.e., the sender does not receive a confirmation in the confirmation phase), the sender re-sends the request at the same slot of the next frame with a probability p.
2) Confirmation phase: If the slot leader receives a new call request, it issues a request confirmation via the receiving code of the call sender.

3) Broadcast phase: Using a pre-specified broadcast common code, the leader broadcasts the IM, location, and transmission power information of the existing links at a slot.

It is required that the broadcast message be heard by all the nodes, and the request and the confirmation be heard by the slot leader and the requester, respectively. To achieve this in a small-area UWB network, a solution is to use higher transmission power or more powerful channel codes for these transmissions.

For a potential sender with a new call request, it first monitors the broadcast channel in all the slots, and collects the IM, location, and transmission power information of every active link at every slot. If there exists an idle slot (i.e., no broadcast message is monitored in a slot), the sender acts as the leader, and the new call request is automatically admitted to the idle slot. If no idle slot exists, the sender decides whether its call can be admitted, and if yes, selects the slot in which a utility function is maximized. The admission control and slot selection are performed by the call sender in a distributed manner. The detailed procedure is omitted due to mathematics complexity. Interested readers can refer to [10]. After a slot is selected, the potential sender sends a request to the leader at the request phase of the slot. After the slot leader receives the request, it sends a request confirmation at the confirmation phase. Then the new call request is admitted to the slot, and its sender becomes the new slot leader. No handover command is needed for the slot leader handover, as the new leader can obtain all required information through the previous broadcast messages from the old leader. Another advantage of the slot leader handover is to distribute the computation burden and the power consumption of the slot leader, which is particularly important to UWB devices with limited power supply and computation capacity. On the other hand, if there exists another call sender which also issues a request at the same slot, the requests of the two senders will collide, and the leader will not issue a confirmation. When the expected confirmation does not arrive, a target sender monitors the broadcast phase of the slot. If the slot leader is changed (which means a new call is admitted into the slot), the call sender will choose a new target slot. If the slot leader is not changed, the call sender re-sends the request at the slot of the following frames with a probability p until success.

It is possible that the rate requirement of the new call is large, thus the requirement cannot be fully satisfied at a single slot. Then the call sender will continue to send requests in other slots. As long as a call is admitted to a slot, its sender can transmit at the same slot of subsequent frames until the call is completed. Thus, reservation is made at each slot.

IT CAN BE SEEN THAT THE CONTROL MESSAGE EXCHANGE PROBLEM OF THE INTERFERENCE MARGIN BASED INTERFERENCE CONTROL APPROACH CAN BE ADDRESSED EFFECTIVELY IN THE PROPOSED APPROACH, WITH THE AID OF THE SLOT LEADERS.

When a call is completed, the call sender will send a CALL_FINISH message to inform its slot leader(s) that the reserved resources are not needed anymore. The message is sent at the request phase(s) of the call sender's serving slot(s), in the same manner as sending a call request. If a slot leader receives the message, it will update the broadcast IM information. If the call sender is the leader of a slot, it only needs to update broadcast IM information, and continues to act as the leader until a slot leader handover happens (i.e., a new call is admitted into the slot).

It can be seen that, the aforementioned control message exchange problem of the IM-based interference control approach can be addressed effectively in our proposed approach, with the aid of the slot leaders. Through an appropriate slot selection algorithm, links

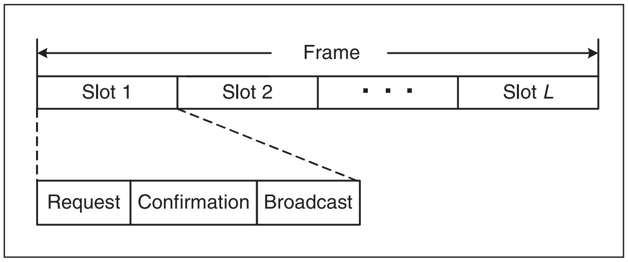

FIGURE 6 The proposed frame structure.

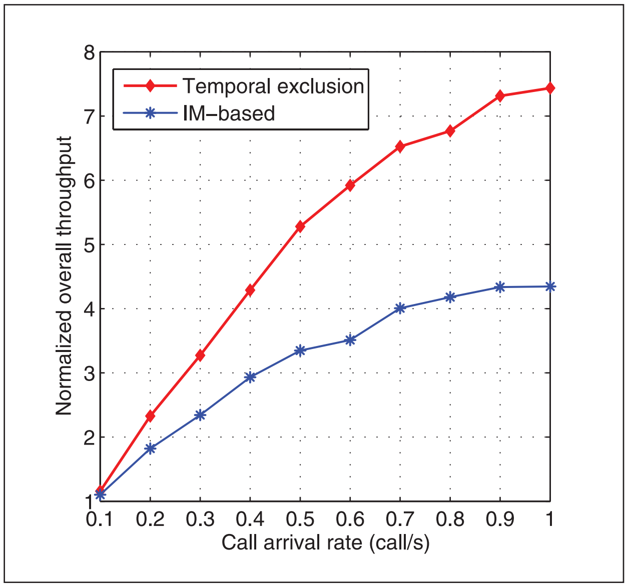

FIGURE 7 System throughput versus the call arrival rate.

with large mutual interference are accommodated in different slots, thus the near-far problem can be effectively addressed.

Computer simulations are carried out to evaluate the performance of our proposed temporal exclusion approach and compare it with the IM-based approach [2]. Consider a UWB network covering a 100 m × 100 m square. Call arrivals follow a Poisson process with rate λ. Each call duration is exponentially distributed with mean value of 60 seconds. The sender and receiver of each arrived call are randomly and independently located in the square. The link layer time frame length is 30 ms, which includes 5 slots, as shown in Figure 6. For the IM-based approach, there is only one slot in each frame. We simulate different λ values, and obtain the normalized (with respect to $R_{\max}$) system throughput by averaging over 2,000 calls for each simulation result. Figure 7 shows the normalized system throughput versus the call arrival rate λ. It can be seen that our approach performs much better than the IM-based approach, especially as λ increases. The reason is that the temporal exclusion mechanism in our approach can avoid allocating links with large mutual interference at the same slot. Hence, more call arrivals can be admitted into the system with our proposed approach, achieving a higher system throughput.

6. Conclusions

The unique merits of UWB make it promising for 4G wireless communications. One big challenge in UWB communications is the near-far problem which is quite different from that in cellular networks. To address the near-far problem in UWB networks, we have investigated the spatial exclusion and temporal exclusion approaches to achieve effective interference control. For the spatial exclusion approach, it is difficult to select a constant exclusive region size for a UWB network. Rather, a system-wise exclusive region concept is more appropriate. On the other hand, the temporal exclusion can be jointly designed with the IM-based approach to avoid large interferers transmitting at the same time slot as that of target transmissions.

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