Medium Access Control in Ultra-Wideband Wireless Networks

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(Invited Paper)

***Abstract*—Ultra-wideband (UWB) transmission is an emerging wireless communication technology with unique potential merits such as high-rate, low-transmission power, immunity to multipath propagation, and capability in precise positioning. It has received significant interests for future wireless communications from both academia and industry. In UWB wireless networks, medium access control (MAC) is essential to coordinate the channel access among competing devices. The unique UWB characteristics not only pose significant challenges but also offer great opportunities in efficient UWB MAC design. This paper presents a comprehensive overview of UWB MAC development on four important aspects: multiple access, overhead reduction, resource allocation, and quality of service (QoS) provisioning, and identifies some future research issues.**

***Index Terms*—Medium access control (MAC), quality of service (QoS), resource allocation, ultra-wideband (UWB) transmission, wireless personal area network (WPAN).**

I. Introduction

ULTRA-WIDEBAND (UWB) transmission is an emerging technology for future wireless communications, although the basic idea can be tracked back to the first wireless communication system in the late 1890s [67]. Similar to spread spectrum or code division multiple access (CDMA), UWB technology was firstly used in a military environment and then introduced in the commercial market recently. Its applications have been stimulated by the Federal Communications Commission (FCC) *Notice and Inquiry* in 1998 and the *FCC Report and Order* in 2002. Today, UWB has been considered as one of the most promising candidates for both indoor and outdoor wireless communications within a short range and has been attracting more and more attentions from the research community.

Currently, a UWB system is defined as one having a -10 dB fractional bandwidth of at least 0.20 or a -10 dB bandwidth of at least 500 MHz. The FCC has allowed unlicensed use of UWB devices in the 3.1–10.6 GHz frequency band [1]. At the physical layer, the implementation of a UWB system can be achieved by using a pulse-based approach [83], [86], [90] or a multiband-orthogonal frequency-division multiplexing (MB-OFDM)-based approach [21], [73]. In a pulsed UWB system,

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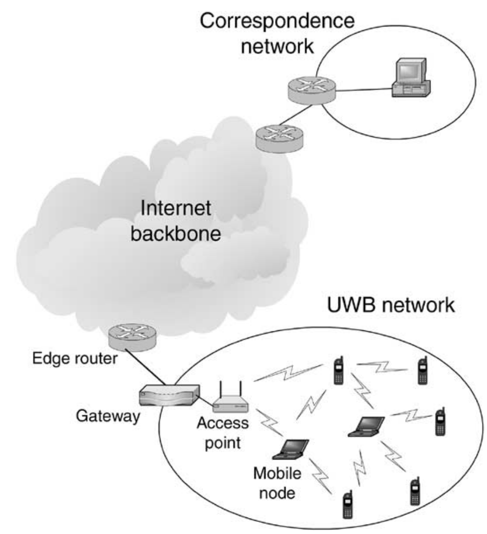

Fig. 1. UWB network architecture.

pulses of an extremely short duration, typically in the order of a nanosecond, are used for information transmission; while in MB-OFDM, hybrid frequency hopping and OFDM are applied. Each of the two leading UWB technologies has its pros and cons for communications in a multipath propagation environment. For pulse based UWB, benefiting from a simple transmitter and rich resolvable multipath components, the receiver can exploit multipath diversity effectively, while MB-OFDM offers robustness to narrowband interference, spectral flexibility, and efficiency. However, pulse based UWB needs a long channel acquisition time and requires high speed analog-to-digital converters (ADCs) for signal processing, while MB-OFDM requires a slightly complex transmitter. The large bandwidth and low transmission power density (-41.25 dBm/MHz for indoor applications) make the UWB technology attractive for high-rate (>100 Mb/s) short-range (<10 m) or low-rate (< a few Mb/s) moderate/long-range (100 to 300 m) wireless communications [67], [72]. In addition to the traditional multimedia services such as voice/video conversations, video streaming and high-rate data, UWB applications include industrial automation and control, medical monitoring, home networking, gaming, imaging, vehicular radar systems, and Department of Defense (DoD) systems, etc. As shown in Fig. 1, a typical UWB network can be constructed to provide peer-to-peer connections among mobile nodes; via an access point (AP) and a gateway, the mobile nodes can also be connected to the Internet backbone to setup a connection with a correspondence node. Each mobile node assumes a double role of terminal and router, and a mobile node is connected to the Internet probably via a multiple-hop link.

For a UWB wireless network, the medium is shared by multiple mobile nodes. Uncontrolled access to the medium can result in interference or collision, making communications low quality or impossible. The function of medium access control (MAC) is to coordinate the access among the competing nodes in an orderly and efficient manner. The major stream of the UWB MAC research includes IEEE 802.15.3 [4] and an alternative MAC specification [8] defined by multiband OFDM alliance (MBOA) [9]. However, there are still many open issues to improve and enhance UWB MAC, taking into account the unique UWB characteristics, such as large bandwidth, low-transmission power, pulse transmission, precise positioning capability, and long acquisition time, etc. This paper is to provide a comprehensive overview on the state of the art in UWB MAC design, and identify the challenges and further research issues in this area. The rest of the paper is organized as follows. Section II presents the challenges and opportunities of MAC in UWB wireless networks. The subsequent four sections devote to the four essential research topics of UWB MAC: multiple access, overhead reduction, resource allocation, and quality of service (QoS) provisioning, respectively. Conclusion remarks are given in Section VII.

II. Medium Access Control

A. Wireless Medium Access

Recent wireless MAC protocols can be classified into two main categories: centralized MAC with the aid of a central controller and distributed MAC in an *ad hoc* manner [24]. In centralized MAC, a central controller (such as the base station or the access point) determines the resource sharing manner of all the mobile nodes by polling, reservation, or demand assignment, and informs the nodes of the scheduling decisions. Random access protocols constitute the main part of distributed MAC. ALOHA [10], [11] and its slotted version [71] are the first random access protocols. The mechanisms that a node senses the channel before transmission and defers it if the channel is busy can alleviate the effect of collision in ALOHA. This principle leads to the carrier sense multiple access (CSMA) [44] based protocols. In addition, to combat the *hidden terminal* and *exposed terminal* problems, handshaking based on request-to-send/clear-to-send (RTS/CTS) is also adopted, e.g., in multiple access with collision avoidance (MACA) [43], distributed coordination function (DCF) of the IEEE 802.11 [2], and MACAW [22]. All these protocols are contention-based with a single channel. To achieve collision resolution, *backoff* and/or *persistence* mechanisms can be used. In a backoff mechanism, each station defers for a random waiting period bounded by its *contention window (CW)* prior to a transmission; while in a persistence mechanism, each node contends for the medium with a *persistence probability* when it senses the channel idle [44], [60].

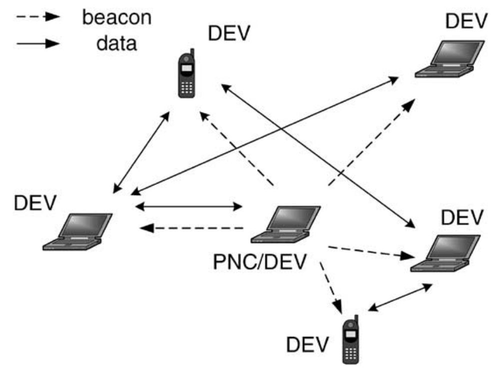

Fig. 2. IEEE 802.15.3 piconet.

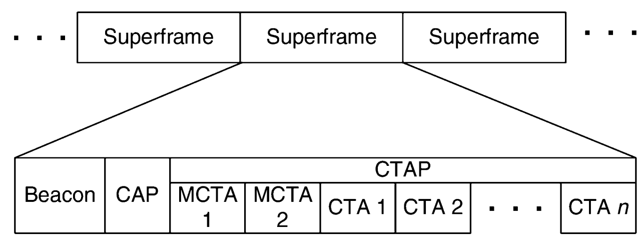

Fig. 3. IEEE 802.15.3 piconet superframes.

The IEEE 802.15.3 [4] is design to support high-speed, low-power, and low-cost connectivity in wireless personal area networks (WPANs), with the *piconet* as the basic network element. As shown in Fig. 2, each piconet consists of a number of devices (DEVs), one among which is selected as the piconet coordinator (PNC). The PNC is responsible for timing (with the beacon) and resource allocation in the associated piconet. The transmission in the piconet is based on a superframe architecture, as shown in Fig. 3. Each superframe begins with a beacon, followed by a contention access period (CAP) and channel time allocation period (CTAP). The CAP employs CSMA with collision avoidance (CSMA/CA). The CTAP is composed of channel time allocations (CTAs) and management CTAs (MCTAs), and uses time-division multiple-access (TDMA)-based resource sharing.

In the traditional layered architecture of data networks, the MAC provides the upper layer with a bit pipe, and is independent of the lower physical layer. If the same approach is applied to MAC in UWB, the existing solutions typically designed for wireless networks can be directly incorporated into the design of a UWB MAC [31]. However, recent research has indicated that UWB characteristics should be taken into account in MAC to achieve more efficient system implementations. Since UWB systems exhibit unique physical layer characteristics such as the low-power condition and precise positioning capability, which are different from traditional narrowband or wideband networks, novel MAC functions should be explored for UWB communications.

B. UWB Physical Layer Characteristics

The physical layer of UWB can be divided into two major categories: pulse-based UWB and MB-OFDM, where pulse-based

UWB can be further classified as pulse-based time hopping (TH)-UWB and pulse-based direct-sequence (DS)-UWB. With a low-data rate, the IEEE 802.15.4a [7] can employ pulse-based UWB with a low-duty cycle of the pulses. DS-UWB and MB-OFDM have been included in the IEEE 802.15.3a (high date rate) proposal [5] and [6], respectively.

In pulse-based UWB, information is transmitted by sending narrow time-domain pulses. The widely used modulation schemes include pulse amplitude modulation (PAM), ON–OFF keying (OOK), and pulse position modulation (PPM). For a single-user system with binary signaling, if one pulse is used to represent one bit, the transmitted signal for these modulation schemes can be written in a general form as

$$s(t) = \sum_{n=-\infty}^{\infty} \sqrt{E_b} b_n^0 p\left(t - nT_b - \frac{\tau}{2}\left(1 - b_n^1\right)\right) \quad (1)$$

where E_b is the transmitted energy per bit, $p(t)$ is the UWB pulse, T_b denotes the bit interval, and b_n^0, b_n^1 are related to information bits. For binary PPM signals, b_n^0 is set to $1, b_n^1 \in \{-1, 1\}$, and τ is the time-shift relative to the time reference when a "-1" is transmitted. For binary PAM signaling, b_n^1 is set to 1 and $b_n^0 \in \{-1, 1\}$ carries information. For OOK signaling, $b_n^1 = 1$ and $b_n^0 \in \{0, 1\}$ carries information. To support multiuser communications, TH and DS spread spectrum schemes are normally applied. From (1), the transmitted TH signal of the ith user can be written in a general form as

$$s_i(t) = \sum_{n=-\infty}^{\infty} \sqrt{E_b} b_{i,n}^0 \sum_{j=0}^{N_s-1} p\left(t - nT_b - jT_f - h_{i,nN_s+j}T_c - \frac{\tau}{2}\left(1 - b_{i,n}^1\right)\right) \quad (2)$$

where N_s is the number of pulses used to represent one bit, T_f is the nominal pulse repetition interval, T_c is the chip (or pulse) duration, and $\{h_{i,n}\}$ is the pseudorandom hopping sequence of the ith user. For DS-UWB, the transmitted signal for the ith user is

$$s_i(t) = \sum_{n=-\infty}^{\infty} \sqrt{E_b} b_{i,n}^0 \sum_{k=0}^{N_c-1} a_{i,k} \times p\left(t - nT_b - kT_c - \frac{\tau}{2}\left(1 - b_{i,n}^1\right)\right) \quad (3)$$

where N_c is the number of chips used to represent one bit, $a_{i,k} \in \{-1, 1\}$ is the kth chip of the ith user's pseudorandom sequence [67].

The two main merits of pulse based UWB are the robustness to multipath propagation and its capability in user ranging/positioning. However, the very short pulse duration poses a significant challenge on synchronization, thus requiring a very long acquisition time. In addition, to suppress narrowband interference, notch filters should be employed. It is not attractive because additional complexity is needed to compensate the distortion of the pulses caused by the notch filters [13].

In MB-OFDM, the UWB spectrum is divided into several subbands while information is transmitted using OFDM in different frequency subbands according to a specific time-frequency code (TFC). Its desired properties are as follows: 1) multipath energy can be efficiently captured with a single RF chain; 2) narrowband interference can be suppressed by adaptive selection of the subbands, thus achieving good coexistence properties in an uncoordinated environment; and 3) the requirement of frequency-switching time is not stringent. However, using an inverse fast Fourier transformer (IFFT), the transmitter is slightly complex [16].

The unique characteristics of the UWB physical layer provide challenges but also opportunities for designing an efficient MAC layer.

C. Challenges and Opportunities

MAC design is a very challenging task in UWB networks due to the following reasons.

First of all, UWB networks have a very stringent transmission power constraint for coexistence with other narrowband networks. Very low-transmission power is also important for noncooperative UWB networks, which may operate simultaneously at a close range. The low-power requirement puts significance on power control, while provides opportunities for supporting simultaneous transmissions as long as the communication pairs are separated far enough in space.

UWB indoor networks can be designed to support very high-transmission data rate, e.g., more than 100 Mb/s. For such high data rates, any overhead time introduced by the MAC may cost a large portion of system resources and significantly degrade the system performance in terms of throughput and efficiency. Therefore, the overhead time must be suppressed to a very low level when designing MAC protocols.

Another critical issue is the acquisition in UWB transmissions [56], [65], [72], a process to synchronize the receiver's clock with the transmitter's clock to achieve bit synchronization. A long acquisition time is needed because of the high precise synchronization requirement. To obtain acquisition in a UWB system, at the beginning of each transmission, the sender may send a preamble with duration varying from tens of microseconds to tens of milliseconds (depending on the receiver design) [12]. Apparently, in each UWB transmission, a large portion of the time will be used to perform the acquisition, thus significantly degrading the efficiency of UWB transmissions, particularly for a very high rate UWB system.

One of the major applications of UWB technology is in an *ad hoc* networking environment, which is characterized by distributed control functions and nonfixed infrastructure. Since no fixed central controller exists in an *ad hoc* network, only local information is available for each node in the system, and some control mechanisms (such as power allocation) become more complicated. This should be taken into account in UWB MAC design.

On the other hand, UWB physical layer characteristics also provide new opportunities for designing an effective and efficient MAC protocol. For example, its large bandwidth and low-transmission power allow the feasibility of exclusion region concept [47], its unique pulse transmission provides more flexibility in resource allocation, and its inherent capability in positioning simplifies routing and power control. Taking

TABLE I
UWB MAC METHODOLOGY

Methodology	Objective
Multiple access	Simultaneous transmissions, channel assignment, interference mitigation, etc.
Overhead reduction	To alleviate the effect of the large overhead in UWB from control message exchanges and long acquisition time
Resource allocation	To allocate power, rate, and access time to mobile nodes
QoS provisioning	To provide QoS (in terms of bit error rate, transmission rate, delay, fairness, etc.) with efficient resource utilization

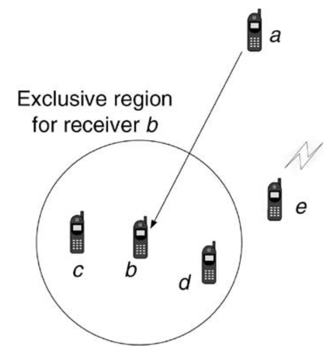

Fig. 4. Exclusive region concept.

advantages of all these opportunities facilitates effective and efficient MAC.

The UWB MAC methodology can be categorized in the avenues of multiple access, overhead reduction, resource allocation, and QoS provisioning, as shown in Table I, to be discussed in the following four sections, respectively. Multiple access is to deal with the capability of UWB to support simultaneous transmissions and the channel assignment for each transmission, and to mitigate the induced interference. Overhead reduction is to address the large overhead in UWB transmissions, such as control message exchanges and acquisition time. Resource allocation is to identify how the radio resources (e.g., power, rate, and time) can be allocated among different mobile nodes, while QoS provisioning is to meet the QoS requirements of mobile nodes with efficient resource utilization. Since traditional OFDM-based MAC mechanisms can be smoothly applied to MB-OFDM UWB networks, our focus is placed on pulse-based UWB networks.

III. MULTIPLE ACCESS

Similar to the traditional IEEE 802.11 wireless local area networks (WLANs), multiple access with a single channel can be achieved in UWB networks. In the *single channel* case, each node and its neighbors share the same channel. At the receiver, the received signals from multiple nodes may collide. However, because of the inherent spread spectrum nature in UWB transmission, simultaneous transmissions can be supported by proper pseudorandom code design and call admission control (CAC), referred to as *multichannel* case. In this section, we place our emphasis on the multichannel case, which is more relevant to UWB.

For multichannel multiple access, in the limit of infinite bandwidth $(W \to \infty)$, the optimal scheme is to simply allow transmissions over all the links simultaneously, because interference becomes negligible [61]. However, for a practical UWB network, the bandwidth is large but finite, so that uncontrolled simultaneous transmissions are not optimal [62], [69]. 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.

A. Exclusive Versus Concurrent Transmissions

In the IEEE 802.11 MAC protocols, all transmissions are in the same channel. Hence, simultaneous transmissions in a nearby neighborhood collide with each other. One effective solution to eliminate or reduce the collision is to use temporally exclusive mechanisms, e.g., collision resolution protocols [2], [22], [43], [44], time-division-based schemes [40], [58], [88], or a combination of both [4]. However, when implemented in an *ad hoc* manner, these mechanisms may suffer from a large overhead due to control message exchanges and packet (or control message) collisions.

In fact, by properly managing interference, simultaneous transmissions can be allowed in wireless communication networks, especially in *ad hoc* networks. For example, in CDMA-based networks, the simultaneous transmissions can be easily supported by using power control in a cellular system, or by hybrid power control and some exclusion mechanism in an *ad hoc* network. This is particularly true for UWB networks with low transmission power, thus providing an efficient mechanism in UWB multiple access. Since transmission power in UWB networks is very low, two transmission pairs with a large separation in space will cause negligible interference to each other and thus can work at the same time even when both of them use the same code channel. A concept, called *exclusive region* [47], is defined to clarify such large space separation. As shown in Fig. 4, when transmitter a is sending to receiver b, the transmitters c and d (within the exclusive region) either keep silence or transmit with interference mitigation technique as discussed in Section III-C when the desired receiver b begins receiving information, while transmitter e (outside the exclusive region) is allowed to transmit at the same time. Note that the exclusive region is defined for receivers only. The exclusive region approach is optimal in terms of throughput to allow interfering sources to transmit simultaneously. Finding an optimal exclusive region is a challenge which should be addressed. A small exclusive region allows more simultaneous transmissions in the desired receiver's neighborhood but may result in a large transmission error probability due to large interference, while a large exclusive region improves the transmission accuracy but may lead to inefficiency due to a less extent of frequency reuse. Although some preliminary research work has been done in this area [47], it is still an open issue to obtain optimal exclusive region. In addition, joint power allocation and exclusive region determination can lead to high-bandwidth efficiency and low-power consumption [23].

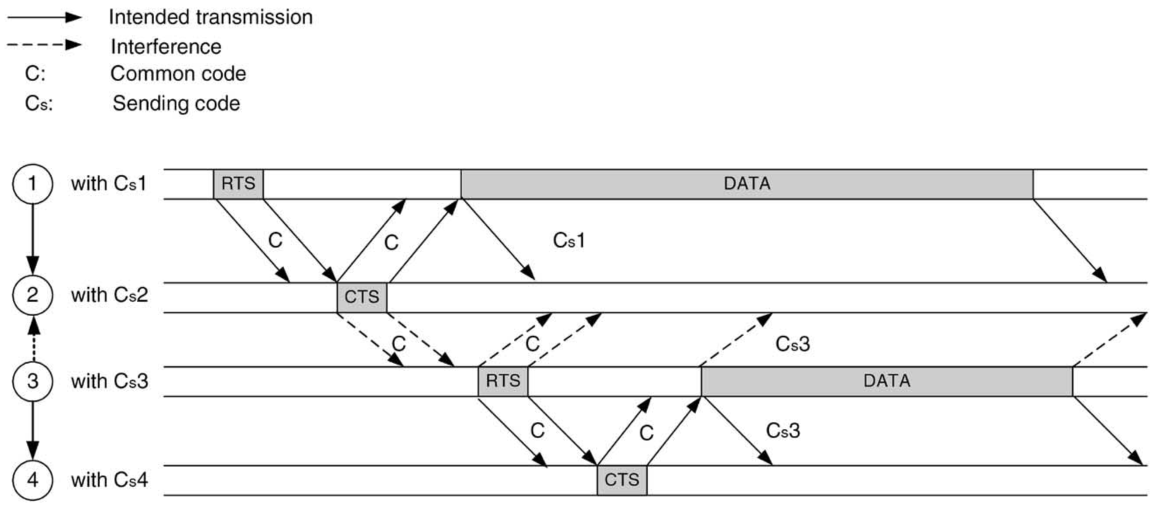

Fig. 5. MACA/C-T protocol [41].

B. Code Assignment

Both DS-UWB and TH-UWB have the potential to support concurrent transmissions. For DS-UWB, the transmission of each link is spread by a pseudorandom sequence, and the receiver despreads the received signal and recovers the original information. The spreading allows several independently coded signals to be transmitted simultaneously over the same frequency band. For TH-UWB, each link transmits one pulse per frame, based on a distinct pulse-shift pattern called a time hopping sequence (THS). Multiple access can be achieved if each link uses an independent pseudorandom THS [47]. However, for *ad hoc* networks, because there is no central controller, a code (or sequence) assignment protocol is necessary to determine the direct sequences or THSs used for traffic transmission and for monitoring any new traffic arrival over the channel. Currently, there are three basic types of code assignment protocols [77].

- Common code: All the transmissions are assigned a common code. The packet header contains the address information. Each node monitors this information for any packets intended to it. As a common code is used for all transmissions, collision may occur in case of multiple simultaneous transmissions.
- Receiver-based code: Each node is assigned a unique receiving code. The code of the destination is used for any peer-to-peer transmission. Hence, for any intended traffic arrival, each node only needs to monitor its own receiving code. The main drawback of this scheme is the possible collision when multiple senders try to send packets to the same receiver simultaneously, as the same code is used.
- Transmitter-based code: Each node is assigned a unique sending code. Each transmitter uses its sending code for transmission to any receiver. The main advantage of this scheme is that multiple transmissions from multiple senders will not collide. However, a mechanism is needed to let the intended receiver aware of an upcoming transmission.

In order to reduce the collision probability and make the handshaking procedure manageable, hybrid schemes should be more effective. For example, a combination of common code and transmitter-based code results in common-transmitter-based (C-T) protocols, while a combination of receiver-based code and transmitter-based code leads to receiver-transmitter-based (R-T) protocols [77]. However, in these schemes, as the sender transmits the data packets regardless of the reception status (i.e., collided or successfully received), the waste of bandwidth may be possible. Hence, the RTS-CTS dialogue in MACA [43] can be incorporated into C-T and R-T protocols, referred to as MACA/C-T and MACA/R-T protocols, respectively [41].

- MACA/C-T: Each node is assigned a sending code. The RTS-CTS dialogue uses the common code. If the dialogue is successfully exchanged, the subsequent data transmission is sent with the sender's sending code. As shown in Fig. 5, nodes 1 and 3 intend to send packets to nodes 2 and 4, respectively. When node 1 sends a DATA packet to node 2, it does not collide with the overheard RTS or DATA exchange from node 3 to node 4, because different codes are used. Collisions only happen when multiple RTS-CTS dialogs exist in the same region, e.g., both node 1 to 2 and node 3 to 4 pairs are in RTS-CTS exchange simultaneously in Fig. 5. Multicast and broadcast can be inherently supported in MACA/C-T as all nodes tune to the common code for the RTS-CTS dialogue and the sender's sending code is used for DATA transmission.
- MACA/R-T: Each node is assigned a sending code and a receiving code. The RTS is sent using the destination's receiving code, while CTS and DATA are transmitted by the associated sending code, respectively, or a code private to a source–destination pair [47], as shown in Fig. 6 where nodes 1 and 3 intend to transmit to nodes 2 and 4, respectively. The channel code of RTS can use the lowest possible rate so that all neighboring nodes who want to transmit to the same receiver can overhear it. In Fig. 6, multiple RTS-CTS dialogues and DATA packets can be exchanged successfully without a collision due to the different codes used. Actually, collisions only happen when multiple senders attempt to send RTS to the same receiver,

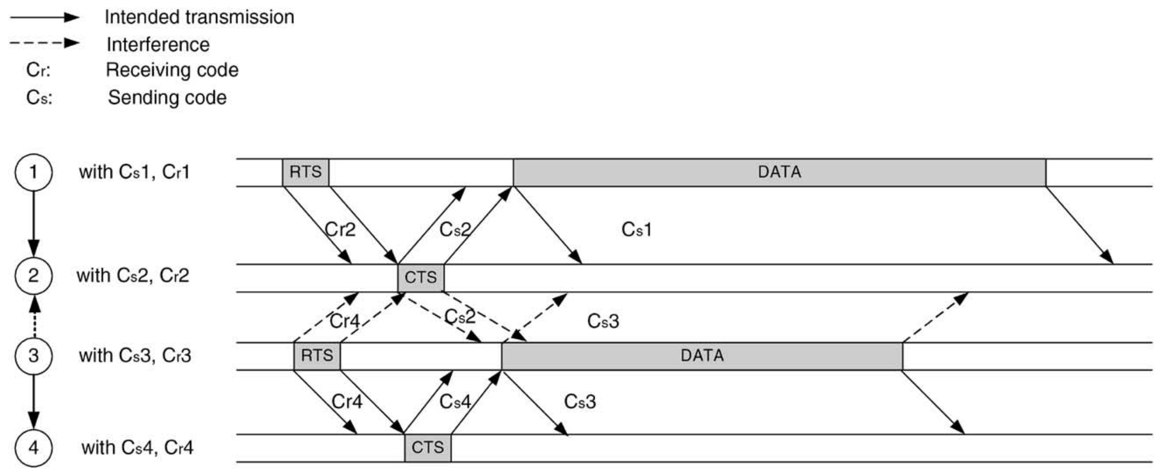

Fig. 6. MACA/R-T protocol [41].

e.g., when both nodes 1 and 3 use the same code $Cr2$ to send RTS to node 2. Therefore, MACA/R-T can achieve a higher channel throughput than that in MACA/C-T.

C. Interference Mitigation in TH-UWB

As mentioned in Section III-A, it is desired to have simultaneous transmissions with the constraint of the exclusive region. Within an exclusion region, either no simultaneous transmissions are allowed, or interference from simultaneous transmissions can be combated. The exclusion region is difficult to determine. Furthermore, coordination among nodes is needed to enforce the exclusion region, thus resulting in an information exchange overhead. If the effect of interference in an exclusion region can be mitigated, an exclusion region with a negligible size can be achieved [57]. Specifically, in addition to the traditional interference mitigation mechanisms used in conventional narrowband systems, the unique channelization in TH-UWB can be explored to implement a more flexible and efficient interference mitigation mechanism.

In TH-UWB, multiuser interference (MUI) is due to pulse collisions between the desired and interfering flows. Pulse collisions due to a near interfering node (very likely with strong interfering power at the receiver) greatly degrade the performance of the desired reception. In TH-UWB, a bit is modulated over a number (N_s) of pulses with a pseudorandom hopping sequence. At the receiver side, a matched filter is used which has the input sampled at the desired hopping interval, and generates the symbol decision variable. If one sample has a very high-power level, it is likely that there exists a collision with a strong interferer. Hence, a chip discrimination principle can be effective where an acceptance level threshold is applied to each pulse sample prior to its entering the matched filter. A pulse with a larger power level (than the threshold) is skipped, and an erasure is declared. The remaining pulses should still be able to give an accurate detection decision. A substantial bit error rate (BER) improvement can be achieved for a large near/far power ratio [52]. The loss due to the erasure can be mitigated by rate control. If the ratio of pulse erasure is recorded by the receiver, it can be fed back to the sender so that the sender can determine the minimum pulse rate per bit (i.e., N_s) to meet the required BER [53]. In addition, the loss due to pulse erasures can be recovered by channel coding, thus leading to a bit rate reduction. Dynamic channel coding can be used to improve the system throughput performance [57], similar to that discussed in Section V-B.

IV. Overhead Reduction

Overhead inevitably exists in any MAC protocol, such as frame headers, control messages, etc. Effects of overhead on the system throughput is more severe in UWB networks supporting very high-data rate, since overhead is normally transmitted at a low rate to guarantee reliable detection at the receiver. For example, the physical layer and MAC layer headers are usually transmitted at a low rate for robustness, thus requiring a relatively large bandwidth in a high-rate system. The interframe spaces also consume channel bandwidth [4], [25]. In UWB networks, one source of overhead results from the long acquisition time required by the high-precision synchronization, which usually varies from tens of microseconds to tens of milliseconds, compared to microseconds in narrowband systems. For example, consider a TDMA-based UWB network with a 50-Mb/s channel. Acquisition time is assumed to be one millisecond and packet size is 1500 bytes. Neglecting other timing components and overhead, the transmission efficiency, defined as the fraction of time used for actual data transmission, can be roughly calculated as [32]

$$\frac{1500\ \mathrm{bytes}/50\ \mathrm{Mb/s}}{1\ \mathrm{ms} + 1500\ \mathrm{bytes}/50\ \mathrm{Mb/s}} = 19\% \tag{4}$$

which is too low for an efficient MAC protocol.

The relatively large overhead and long acquisition time in UWB transmissions may limit the UWB MAC design. Therefore, it is critical to design an efficient MAC protocol which keeps the system overhead as low as possible, in order to fully explore the high-rate transmission.

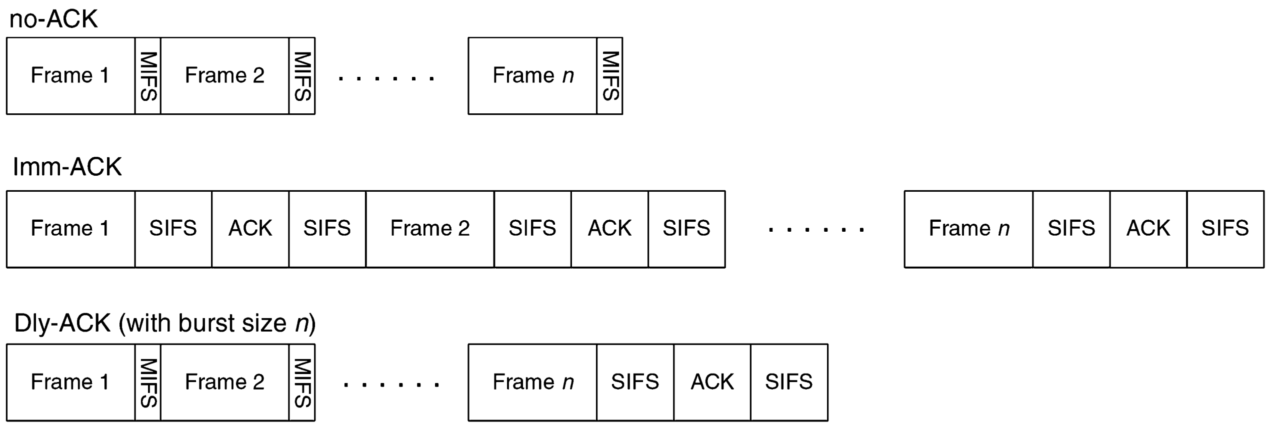

Fig. 7. No-ACK, Imm-ACK, and Dly-ACK mechanisms in IEEE 802.15.3.

TABLE II
TRANSMISSION TIME UNDER VARIOUS DATA RATES [25]

Data rate	Imm-ACK		5-Dly-ACK		10-Dly-ACK	
(Mb/s)	$t_m (\mu s)$	t_p/t_m	t_m	t_p/t_m	t_m	t_p/t_m
110	112.7	73.4%	90.3	91.6%	87.5	94.5%
200	80	62.5%	57.9	86.4%	55.0	90.9%
480	56.7	47.1%	34.5	77.2%	31.7	81.6%

A. ACK Mechanisms

Acknowledgement (ACK) and retransmission are usually adopted by the MAC layer to correct transmission errors. In the IEEE 802.15.3 [4], three types of ACK mechanisms are defined for MAC: no-ACK, immediate ACK (Imm-ACK), and delayed ACK (Dly-ACK), as shown in Fig. 7. Not using any acknowledgement, no-ACK is suitable for transmission not requiring reliable delivery. Two successive frames are separated by a minimum interframe space (MIFS). In the Imm-ACK mechanism, each data frame is always followed by an ACK frame from the receiver to indicate its correct reception. A short interframe space (SIFS) is used between the transmitted frame and ACK. In the Dly-ACK mechanism, instead of acknowledging each data frame, after a burst of frames are received, the whole burst is acknowledged by one ACK frame. The sender retransmits (in the next burst) the frames not ACKed in the previous ACK frames.

As shown in Fig. 7, the average total transmission time t_m of one frame for Imm-ACK and Dly-ACK can be calculated as $t_p + t_{\mathrm{ACK}} + 2t_{\mathrm{SIFS}}$ and $(nt_p + t_{\mathrm{ACK}} + (n-1)t_{\mathrm{MIFS}} + 2t_{\mathrm{SIFS}})/n$, respectively, where $t_p, t_{\mathrm{ACK}}, t_{\mathrm{SIFS}}$, and t_{MIFS} denote the transmission time of the date frame, the transmission time of the ACK frame, the SIFS, and the MIFS, respectively, and n is the burst size in Dly-ACK. The values of t_m in different ACK mechanisms are given in Table II, where 5-Dly-ACK and 10-Dly-ACK represent Dly-ACK mechanism with bust size 5 and 10, respectively [25].

It can be observed that, at a high data rate, Imm-ACK results in bandwidth inefficiency because the time to transmit the payload (i.e., t_p) is only a small portion of t_m. Therefore, Dly-ACK becomes a more suitable ACK mechanism for UWB networks, taking advantage of the reduced number of ACK frames and the associate interframe spaces (IFSs).

Traditional Dly-ACK uses a fixed burst size, which may lead to severe *local information problem* [25]. Based on the IEEE 802.15.3 specification, each MAC Service Data Unit (MSDU) is divided to one or multiple smaller parts, termed MAC Protocol Data Units (MPDUs), and all MPDUs must be delivered to the upper layer in order. In transmission, it is possible that some MPDUs with higher IDs are correctly received while those with lower IDs are not. The ordered delivery requires that such MPDUs with higher IDs must wait until all MPDUs with lower IDs have already been correctly received. However, since the receiver does not have the information of the number of retransmissions that the erroneous MPDUs have already experienced, it may keep waiting for an MPDU that has been discarded due to its exceeding the maximum retransmission time. This is the local information problem. In addition, due to the bursty nature of traffic, the source MAC queue may be empty from time to time. With a fixed burst size, when there are no enough MPDUs (due to an empty MAC queue) to trigger an ACK at the receiver, the sender cannot retransmit erroneous frames in time because it keeps waiting for additional MPDUs to fill the burst before it requests an ACK from the destination.

A possible solution to resolve the local information problem is to introduce a retransmission counter at the receiver. If an expected MPDU is not received successfully, the receiver starts a counter to count the number of the ACK frames indicating the erroneous reception of the MPDU, which is equivalently the retransmission time of the MPDU at the sender. As soon as the counter reaches a preset threshold, the MPDU is considered to be discarded and the receiver will deliver the previously received MPDUs with higher IDs to the upper layer immediately. For the fixed burst size problem, a possible solution is that the source MAC can request the Dly-ACK frame when the source MAC queue becomes empty [25].

Although Dly-ACK can achieve better bandwidth utilization (than Imm-ACK), its impact on delay performance is twofold. The total delay consists of the queueing delay at the sender, transmission delay, and reordering delay at the receiver. On one hand, the queueing delay at the sender can be reduced, as the data frames are transmitted faster. On the other hand, the reordering delay at the receiver can degrade the end-to-end delay performance. To tradeoff the two conflicting effects, there exists an optimal burst size which is heavily dependent on the input traffic volume and is insensitive to the channel error rate within a normal error rate range [26]. The end-to-end delay performance is particularly critical to real-time applications which are usually delay-sensitive.

B. Long Acquisition Time

From (4), it can be seen that the low channel utilization is due to the dominant acquisition time in the packet transmission duration. Hence, to reduce the overhead introduced by the acquisition time, an intuitive solution is to enlarge the packet size. However, as the wireless channel is usually error-prone, a large packet size leads to a high-packet error probability, thus introducing a different kind of overhead due to retransmissions of the erroneous packets and the induced delay. How to balance the tradeoff between these two effects is challenging. Furthermore, a large packet size may result in a large packetization delay, which may not be suitable for real-time applications such as voice-over-IP (VoIP) and video streaming.

A general approach of "packet packing" can be an effective way to compensate for the long acquisition time [54]. The approach consists of five policies: 1) packet classification policy, 2) buffer management policy, 3) packet assembly policy, 4) acknowledgement policy, and 5) packet error control policy. The basic idea is to assemble multiple upper-layer packets into one burst frame at the MAC layer. In each transmission, a whole burst frame is sent, rather than delivering each packet individually as in traditional approaches. Transmitting multiple packets in one frame can significantly reduce the synchronization overhead. It can be seen that, this approach tries to enlarge the transmitted payload size in each transmission. Hence, it has a similar principle as that in the "large packet size" approach discussed above, and also has the similar drawbacks.

Another possible solution to the long acquisition time is to use a link maintenance scheme [46]. The physical link is not torn down when there is no data to transmit. Rather, low-rate control packets are transmit to maintain the physical link for the lifetime of the user calls so that the re-acquisition overhead for future transmission can be reduced. This solution has its inherent drawbacks. First of all, the transmission time is enlarged, thus increasing interference to other links. The extra power consumption for the transmission of low-rate control packets is also critical for UWB devices usually with limited power supply and low power consumption requirement. In addition, for bidirectional UWB communications, a node generally cannot send and receive at the same time. To address this problem, full-duplex is achieved by blanking the receiver at a node during pulse transmissions of its transmitter. The complexity will increase significantly when a node keeps multiple full-duplex links simultaneously.

V. Resource Allocation

For UWB networks, to efficiently utilize the bandwidth and achieve desired QoS, an effective resource allocation scheme is needed to determine at what power level and rate a node can access the wireless medium. In the following, a basic power allocation mechanism is discussed in Section V-A. The unique pulse transmission in UWB networks provides flexibility in rate control, as shown in Section V-B. For resource allocation, benefits can also be obtained from cross-layer design approaches, as presented in Section V-C.

A. Power Allocation

For multichannel UWB networks, code assignment can deal with the primary collisions due to the same code being used in simultaneous transmissions. However, the well-known near-far problem may induce the secondary collisions because of the intolerable interference experienced from simultaneous transmissions (spread by different codes), i.e., MUI in the vicinity [59]. The transmission power of each link should be managed to make the network stable and to achieve desired system performance.

For TH-UWB transmission, the combined MUI can be approximated by additive white Gaussian noise in a multiuser environment, if the number of users is large and different terminals use independent pseudorandom codes [82], [83]. In the following, a power allocation strategy for TH-UWB is discussed [29], and the similar principle can be applied to DS-UWB networks as well.

Consider a UWB network with N active links. The achieved signal-to-interference-plus-noise ratio (SINR) at the receiver of the ith link is

$$\mathrm{SINR}_i = \frac{P_i h_{ii}}{R_i\left(\eta_i + T_f\sigma^2\sum_{j=1,j\neq i}^{N} P_j h_{ji}\right)}, \quad i=1,\ldots,N \tag{5}$$

where P_i denotes the average transmission power of link i's transmitter, h_{ij} the path gain from link i's transmitter to link j's receiver, R_i the ith link bit rate, 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.

It is interesting that, if only best-effort service is considered, each sender should either transmit with the allowed maximum power level, or not transmit at all. From the view point of a transmission link i, an increase in transmission power leads to a higher SINR at the receiver side, therefore resulting in a higher achievable rate. It also increases interference level to other simultaneous links. However, the loss in other links can be compensated by the gain obtained by link i [29], [69].

On the other hand, for services with QoS requirements, generally the physical layer should provide an upper bound of the BER, which can be translated into a prespecified SINR threshold, say γ_i for link i. In addition, each transmitter should maintain an upper bound of average power level, say $P_{\max}$. The $P_{\max}$ value can be determined by the emission regulation and the energy consumption of the terminals. Thus the power levels of the N active links should comply with the following constraints:

$$\begin{cases} \frac{P_i h_{ii}}{R_i\left(\eta_i + T_f\sigma^2\sum_{j=1,j\neq i}^{N} P_j h_{ji}\right)} \geq \gamma_i, & i=1,\ldots,N \\ 0 \leq P_i \leq P_{\max}, & i=1,\ldots,N. \end{cases}$$

To meet the constraints, a centralized power allocation controller (if available) can take the advantage of system-level information such as the transmission power level of every node and the path gain of every link. Combined with rate allocation, the power allocation issue can lead to a joint optimization problem, to optimize network metrics such as system throughput or energy consumption [29].

For centralized resource allocation in UWB, the system level information exchange usually imposes heavy signaling overhead, and a central controller (maybe a selected node) is necessary to a) broadcast synchronization information; b) collect the traffic request of every node and status of every link; and c) determine active links with the allowed power levels, their transmission time duration and transmission rates. However, a centralized controller may not always be available, especially in *ad hoc* networks. A suboptimal but distributed power/rate allocation scheme is more realistic for UWB networks.

For a distributed power/rate allocation scheme, each node performs admission decision for each request and determines the transmission power and rate if the request is admitted, according to its local measurements of the system and information obtained from the control message exchanges. In order to avoid the frequent power reconfiguration after each new request is admitted, each link keeps an interference margin, also referred to as maximum sustainable interference (MSI), denoting the additional tolerable interference while not violating the SINR requirement. For link i

$$\frac{P_i h_{ii}}{R_i\left(\eta_i + T_f\sigma^2\sum_{j=1,j\neq i}^{N} P_j h_{ji} + \mathrm{MSI}_i\right)} = \gamma_i \tag{6}$$

that leads to

$$\mathrm{MSI}_i = \frac{P_i h_{ii}}{\gamma_i R_i} - \eta_i - T_f\sigma^2 \sum_{j=1,j\neq i}^{N} P_j h_{ji}. \tag{7}$$

The MSIs of all the links should be nonnegative.

Each active link periodically announces its MSI over a control channel. When a new call request arrives at one node, according to local measurements of interference and noise levels, and MSI information of other links, the node determines whether or not it is feasible to assign a power level and a rate such that: a) its own MSI is nonnegative and b) the interference (due to the new transmission if admitted) to any other existing active link does not exceed its MSI [28], [29].

B. Rate Control

Although power control is usually considered as an effective way in CDMA based systems to combat MUI, guarantee the required SINR at the receiver, and lengthen the battery life, it is not always true, or at least not efficient under some conditions. For example, when a link experiences deep fading, power control significantly increases its transmission power to keep the same SINR at the receiver. This large transmission power introduces large interference to other links and may reduce the interference-limited system capacity. As an extreme case of CDMA, UWB encounters the similar problem. Rate control is effective to compensate for such shortcomings in the power control. Instead of changing the transmission power, rate control adapts the data transmission rate such that more or less redundancy is introduced for compensating channel fading and interference. In UWB networks, rate control can be achieved by adapting the channel coding rate as discussed in Section V-B1. On the other hand, collocated UWB WPANs interfere with each other. For TH-UWB, an effective way to reduce such interference is to control the "pulse rate" (i.e., the number of pulses transmitted per second) in each WPAN, as discussed in Section V-B2.

1) Adaptive Channel Coding: Channel encoder is a basic component of a wireless system to overcome channel errors at the receiver by inserting some redundancy at the transmitter. The selection of the channel code is determined by the tradeoff between the error correction capacity and the introduced transmission overhead. Since a wireless channel is time variant due to user mobility, an adaptive channel encoder should be more efficient in such an environment. Research in [68]–[70], [78] also indicates that 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. Basically, adaptive channel encoding at the transmitter should consist of following four steps:

- based on channel statistics, a channel code is selected at the sender side;
- after adding a cyclic redundancy check (CRC) and encoding, the sender transmits the encoded packet;
- at the receiver side, CRC is checked and ACK (positive or negative) is fed back to the sender;
- based on the ACK feedback, the channel coding rate is adjusted such that a lower (higher) rate channel code is used for next transmission if the channel becomes worse (better).

From the practical implementation point of view, a new channel code with different coding rate can be transmitted at each adaptation step. In order to reduce the overhead and the transmission delay, a more efficient way, called *incremental redundancy* [47], can be applied. In incremental redundancy, a special channel coding scheme is adopted such that a high-rate code is the subset of the lower rate codes. In transmission, if the current channel code cannot provide sufficient protection for decoding at the receiver end, only the redundant bits (which are the different bits between the current channel code and the lower rate code) are transmitted. In other words, none of the already transmitted coded bits are transmitted again.

Many convolutional codes have been developed to provide variable encoding rates as well as incremental redundancy [66], [81]. One example of such codes is Rate Compatible Punctured Convolutional (RCPC) code [34], [35], [47], [57]. In RCPC codes, a high-rate code is created by puncturing coded bits from the lowest rate block of coded bits. It is easy to prove that RCPC codes have compatibility property. For instance, given a set of codes with rates $R_0 = 1 > R_1 > R_2 > \cdots > R_N$ (where "1" means uncoded case and R_N represents the lowest coding rate), the code with rate R_n is the subset of the code with rate R_{n+1}. In addition, since the encoder only needs to generate the code with the lowest coding rate, one encoder/decoder pair is enough for encoding and decoding the coded bits with all coding rates, thus further reducing the system complexity [47].

To implement adaptive channel coding, it is critical to determine the initial highest code rate for reliable transmission. For RCPC codes, as an example, the initial highest code rate can be determined by the following procedure [47].

- At the beginning, the first packet is coded using the most powerful code, i.e., the lowest rate code.
- At the receiver, the decoding is carried out by step-wise traversal of the trellis of the Viterbi decoder. If the outcome of a decoding step for a higher rate code differs from that of the actual code, the higher rate codes are eliminated.
- The remaining highest rate code is the code powerful enough for decoding.

2) TH Sequence Parameters Adaptation: Based on the IEEE 802.15.3, WPANs work in both coordinated and uncoordinated ways. A well designed MAC protocol can coordinate multiple transmissions within each WPAN by using contention-free techniques, random-access, or a combination of both. In addition, adapting the parameters of TH in each WPAN is effective to combat the mutual interference among uncoordinated WPANs. One way to achieve rate control is to adapt TH sequence parameters such that the spreading gain is changed with respect to the channel and interference variance [45]. Such parameters include number of pulses for each bit (N_s), maximum time hopping shift (N_h), and time hopping unit (T_c). It is a unique control method inherent in UWB networks.

Effects of TH parameters on system performance in terms of throughput and BER have been studied in [87] through simulation. Consider the case when time hopping is allowed over the whole frame time T_f, i.e., $T_f = N_h T_c$. The basic observation is that N_h should be increased with the number of WPANs in order to reduce the amount of generated interference and therefore reduce collisions. This *hard link adaptation* changes the TH sequence used and requires explicit information exchanges. To avoid the overhead, a *soft link adaptation* scheme can be applied, which varies the values of N_h and N_s, while keeps $N_h \cdot N_s$ constant such that the bit rate remains unchanged. Let h_0 denote the possible minimum value of N_h. For the soft link adaptation, the TH sequence with parameter h_0 is firstly generated. Since $T_b = N_h N_s T_c$, for a fixed chip duration T_c, the maximum processing gain is $N_s^{\max} = (T_b)/(h_0 T_c)$. Define a probability parameter q. The different value of N_h can be achieved by so called "chip puncturing": If a pulse should be transmitted in a certain chip, the node transmits a pulse with probability q and keeps silent with probability $1 - q$ in that chip interval. After chip puncturing, the average number of pulses transmitted per bit is $q \cdot N_s^{\max}$ such that each chip of the TH sequence can hop on a wider range, i.e., a virtually larger N_h. Since the chip puncturing does not need to be coordinated with the receiver, it can be applied autonomously by the sender in the WPAN without the overhead of control packet exchanges. By chip puncturing, the transmitted pulse rate is reduced, thus generating less interference to neighboring WPANs, at the cost of a smaller processing gain. It is still an open issue how to determine a proper probability q to achieve the best tradeoff between the gain from less inter-WPAN interference and the loss due to a smaller processing gain.

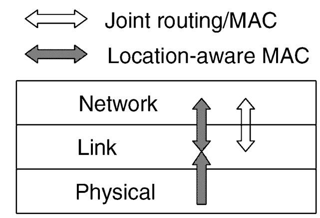

Fig. 8. Cross-layer design for UWB MAC.

C. Cross-Layer Design

A UWB wireless system performance should benefit from cross-layer design approaches, taking advantage of information exchanges across the protocol layers which may not be available in the traditional layering architecture, i.e., the open system interconnection (OSI) protocol stack. Specifically, designing efficient MAC protocol can utilize information from both the physical layer and the network layer, such as channel status, location information, and routing information, as shown in Fig. 8.

1) Joint Routing/MAC in Multihop UWB Transmissions: In multihop UWB networks, more challenges will be encountered than those in the single-hop case as follows. a) An optimal route should be chosen appropriately by considering the traffic load distribution, power consumption, and system overhead. b) MAC parameters in each link should be determined, such as rate and power, and how to control them with a fluctuating interference/contention level. c) Most importantly, routing and MAC interact with each other. Therefore, designers need to determine how the routing and MAC should interact, and jointly design them accordingly. Generally, joint routing/MAC design can achieve performance improvement at the cost of complexity [17]. Although MAC protocol in UWB networks has been shown insensitive to route selection strategies for best-effort services [69], further research efforts are needed to investigate how routing and MAC interact for multimedia traffic with various QoS requirements.

2) Location-Aware MAC: One advantage of UWB technology is its potential to provide accurate distance information. In addition, nodes in UWB indoor networks usually have low mobility. If distance information is exchanged among nodes (with limited overhead due to low mobility), a node may know the (accurate or coarse) location information of other nodes [19], [27], [49]. All of these can be beneficial to the MAC design.

- Routing in UWB networks can benefit greatly from location information. Signaling overhead can be reduced significantly. In search for a route from a source node (say a) to the destination node (say b), instead of the flooding used in traditional approaches, a smaller forwarding zone can be selected based on location information of nodes a and b [19], [30], [48], [50], [79]. In addition, based on location information of the nodes, the geographic area can be divided into *grids*, each with a grid leader. The grid mechanism can offer efficient route discovery and resilient route maintenance [50]. With an effective routing mechanism, complexity can be reduced in the joint routing/MAC design.

- Power/rate control can take advantage of the location information. Based on the location information of the communication pair and a signal propagation model, power level or the UWB channelization parameters (such as TH sequence parameters, or variable spreading factors) can be selected appropriately, to achieve the required SINR [36].
- The exclusion region can be implemented more conveniently with the help of location information.
- Given location information, each node may estimate the traffic density in its vicinity. A node in a sparse area can use different parameters (e.g., power levels and backoff parameters) in its transmission from those of a node in a dense neighborhood [38].

VI. QoS Provisioning

For UWB MAC design, one major challenge is the QoS provisioning with efficient resource utilization. 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. The transmission accuracy, transmission rate (i.e., throughput), timeliness (i.e., delay and jitter), and fairness are the main consideration in this classification.

- Bit-level QoS—To ensure some degree of transmission accuracy, an upper bound on BER for each traffic flow is required.
- Packet-level QoS—As real-time applications (such as voice or video conversations) are delay-sensitive, each packet should be transmitted within delay and delay jitter bounds. On the other hand, data applications are usually delay-tolerant, and throughput is a better QoS requirement. Each traffic type can also have a packet loss rate (PLR) requirement.

If a centralized controller is available for a UWB network, to guarantee the bit-level and packet-level QoS requirements at each node, an effective centralized packet scheduler with appropriate power allocation is desired. Specifically, the power levels at different receiving nodes are managed in such a way that each flow achieves the required SINR, and the transmissions from/to all the nodes are controlled by the scheduler to meet the delay, jitter, throughput, and PLR requirements. The order of packet transmissions for multimedia traffic has a great impact on the system efficiency and performance. The design of a packet scheduler involves balancing a number of conflicting objectives. For different types of multimedia traffic, different scheduling policies can be applied, focusing on the corresponding main QoS criteria of the traffic types [14], [28], [37], [39].

On the other hand, if no centralized controller is available, the QoS provisioning in distributed MAC is much more challenging due to the following reasons [55].

- Location-dependent contention/interference: One flow's contending/interfering flow set may be different from that of another flow. QoS support for one flow will affect QoS of its contending/interfering flows. In addition, for two flows without a direct contending/interfering relationship, it is still possible that their QoS indirectly affects each other through their common contending/interfering flows.
- Incomplete information: Unlike a centralized scheduler where global system information may be available, in a distributed case, only local information and limited information of other flows are available at each node.
- Spatial channel reuse: For two flows not contending/interfering with each other, the same channel can be used by them simultaneously. This spatial channel reuse can improve the system performance. However, it also increases complexity in resource allocation.

Given the statistics of the UWB channel, spread spectrum and modulation scheme, RAKE receiver structure and diversity combining technology, the bit-level QoS (i.e., transmission accuracy) can be mapped one-to-one to the required SINR and guaranteed by power and rate allocation. As discussed in Section V-A, when transmitting a packet, each node determines its transmission power and rate according to its local measurements and interference margin levels of other active flows. On the other hand, packet-level QoS needs more complex coordination among neighboring nodes, taking into account the various requirements such as delay/jitter, throughput and packet loss rate. Although originally proposed for WLAN, the contention-based enhanced distributed channel access (EDCA) in IEEE 802.11e [3], [84], [85] can be a good candidate for relative QoS provisioning in UWB networks. However, it is designed for networks with a single channel. For the scenario where multiple simultaneous transmissions are allowed (e.g., in the multichannel case), EDCA loses its potential. In the following, other packet-level QoS mechanisms are discussed, with a certain level of QoS guarantee.

A. Rate Guarantee

For multiple access in a multichannel case, if a flow's interference margin is honored by all the neighboring flows, its transmission rate can be guaranteed. Consider a UWB network with N active flows with rate requirements from R_1 to R_N, respectively. Upon a new transmission flow request i with required rate R_i, the following procedure can be implemented [28], [29]:

- Step 1) Calculate
$$P_i = \min\left\{P_{\max}, \min_{1\le j\le N}\left\{\frac{\mathrm{MSI}_j}{T_f\sigma^2 h_{ij}}\right\}\right\}. \quad (8)$$
If $P_i = 0$, reject the flow request; otherwise, continue to the next step;
- Step 2) Check whether or not
$$\frac{P_i h_{ii}}{\gamma_i R_i} - \eta_i - T_f\sigma^2\sum_{j=1}^{N} P_j h_{ji} \ge 0. \quad (9)$$
If it is true, assign power P_i and rate R_i; otherwise, reject the flow request.

The first step is to guarantee that the interference margins of all the existing flows are honored, while the second step is to guarantee that a newly admitted flow can obtain a nonnegative interference margin. It can be seen that this rate mechanism is similar to the circuit-switching channel reservation in cellular networks. It is not efficient to meet the different QoS requirements of various traffic types in a packet-switching environment.

B. Fairness

For distributed UWB MAC, fairness is an important metric, and is with respect to end-to-end traffic flows. Hence, per-flow fairness instead of per-node fairness should be used. In the following, fairness mechanisms in single channel UWB networks are discussed.

For a single-hop (i.e., all nodes are neighbors) UWB network, the access to the common medium by each node can be controlled by the evolution of its backoff timer, which is bounded by the CW. Thus distributed fair scheduling can be achieved by adjusting the CW or backoff timer according to the difference between expected and actually obtained services [18], [20], [80], [89].

However, for a multiple-hop case, to achieve fairness is much more 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. For example, in the well-known generalized processor sharing (GPS) discipline [63], [64], the scheduler for an output link assigns a fixed weight to each session, and allocates bandwidth for all the sessions according to their weights and traffic load. In a multihop UWB network, each node needs to contend for resources with its neighbors, and a node's neighbor set is location-dependent. The direct or indirect contention relationship among flows 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 flows transmit based on a specific order. On the other hand, to take advantage of spatial channel reuse, two flows can transmit simultaneously if they do not collide with each other, which may violate the flow transmission order determined by the strict fairness. In addition, allocating resources to a flow with high contention results in low spatial reuse. Hence, a feasible tradeoff should be considered. Third, to achieve fairness in a global sense, global information needs to be exchanged among nodes. Inconsistent information may be kept in different nodes [55], [60].

An effective way to achieve flow-based fairness in a multi-hop UWB network is to use self-coordinating localized fair queueing where flows self-coordinate their scheduling decisions to collectively obtain fairness. Each flow calculates a service tag of itself and, when transmitting a packet, piggybacks the service tag in the handshaking messages. Each flow keeps all the current service tag values for all of its contending flows. If a flow's service tag is smaller than those of all its contending flows, it will transmit; otherwise, back off with a timer set to the number of contending flows with smaller (than its own) service tags. If the channel is sensed clear until the timer expires, the node can transmit although it is not with the minimum service tag among its contending flows, for the purpose of spatial channel reuse. With consistent information, a minimum fair service share is guaranteed for each flow. However, to implement such a distributed fair queueing, information is maintained for contending flows, i.e., for two-hop neighboring nodes. Thus, service tag information of contending flows should be kept and retrieved from both the sender and receiver of a specific flow [55]. On the other hand, the fairness model (such as weighted fairness, proportional fairness, and max-min fairness) can be represented by a utility function. Based on a *resource contention graph*, the fairness model can be translated into a contention resolution algorithm, where each flow adjusts a persistence probability according to its collision status. Fairness can be achieved without explicit global coordination [60].

Notice that all the above-discussed fairness approaches are for single channel UWB MAC. For a UWB network supporting multiple simultaneous transmissions, i.e., in a multichannel case, a node cannot monitor all other nodes' transmissions. Thus, an information exchange mechanism by "overhearing" may not work well. To achieve fairness in such networks, an effective and efficient message-exchange approach is necessary, and power/rate allocation should be jointly considered due to the interference-limited environment in multichannel UWB.

C. Real-Time Traffic Support

One main requirement for real-time service is delay guarantee, as packets with a large delay may be considered useless and discarded. Although there have been extensive researches on real-time traffic (voice and video) over *ad hoc* MAC [15], [40], [42], [51], [74]–[76], very limited work takes into account the characteristics of UWB. Specifically, for voice traffic, each arrival packet is relatively small, thus resulting in a very small bandwidth efficiency due to the channel acquisition time. The "packet packing" scheme does not work well as it may induce a large "packing" delay. Keeping sustained link also has its inherent disadvantage, as discussed in Section IV-B. For video traffic, the traffic arrival rate is time varying, thus posing more challenges on the distributed resource allocation. An automatic-repeat-request (ARQ) mechanism with limited retransmission is an effective way to overcome channel errors for real-time traffic. How the channel acquisition time affects ARQ performance needs further investigation.

D. Distributed CAC for Multimedia Traffic

Traffic arrival pattern and characteristics, to some extent, significantly affect the system performance. Hence, an effective CAC mechanism is essential for QoS guarantee in MAC mechanisms. However, for distributed UWB networks without a central controller, CAC becomes an extremely challenging issue due to the lack of global information. So far, some R&D efforts based on measurements have been devoted to this issue [28], [29], [85]. However, these efforts only address coarse QoS, and cannot make use of different features of various applications. The remaining open issues are given as follows.

- Depending on the applications, the call-level QoS requirements of a connection may be new call-blocking probability and handoff call-dropping probability. An effective mechanism is necessary to meet such requirements, either based on measurements or by analytical approaches.

- CAC should be designed to support heterogeneous traffic. Specifically, different classes of traffic with various packet-level QoS requirements should be differentiated.
- For packet-switching UWB systems, CAC needs to ensure QoS provisioning at the network, link, and physical layers. The capacity calculation in the previous work for continuous transmission [33] needs to be extended to discrete packet transmission, taking into account the packet data traffic characteristics.
- Although CAC is conducted in a distributed manner, limited global information is still needed. The tradeoff between the overhead for the information exchange and bandwidth utilization efficiency should be carefully considered. Moreover, the exchange messages may also be lost, thus leading to an incomplete view of the system, and this effect should be taken into account and should be manageable.
- CAC largely depends on the channel access method. TH versus DS and single channel versus multichannel UWB networks should have different admission principles. Hence, CAC should be jointly designed with the MAC mechanisms for more effective and efficient control at both link and network layers.

VII. Conclusion

Medium access control plays a very important role in UWB wireless networks to support effective and efficient communications. Unique characteristics of the UWB physical layer and network layer provide both challenges and opportunities for the MAC layer design. More flexibility can be obtained from the inherent support of simultaneous transmissions in UWB technologies, but it also leads to a relatively complex MAC protocol in terms of power and rate allocation, interference control, and fairness mechanism in a distributed manner. The relatively large overhead is a significant challenge in UWB transmissions, and should be suppressed to a level as low as possible. For pulse transmissions in UWB, its unique channelization features can benefit rate control and interference control. Moreover, the cross-layer approach should be exploited in UWB system design for better performance.

This paper has provided a comprehensive overview of the state-of-the-art research in UWB MAC design, in the avenues of four major research topics, namely, multiple access, overhead reduction, resource allocation, and QoS provisioning. Although some work has been done in these areas, many research issues remain open, including distributed admission control, overhead suppression, real-time service support, effective cross-layer design for multimedia traffic, and fairness for multichannel scenarios. These important research issues should be tackled in the future.

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