HANDBOOK OF WIRELESS NETWORKS AND MOBILE COMPUTING

Edited by

Ivan Stojmenović

University of Ottawa

Universidad Nacional Autonoma de México

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CHAPTER 6

Wireless Media Access Control

ANDREW D. MYERS and STEFANO BASAGNI
Department of Computer Science, University of Texas at Dallas

6.1 INTRODUCTION

The rapid technological advances and innovations of the past few decades have pushed wireless communication from concept to reality. Advances in chip design have dramatically reduced the size and energy requirements of wireless devices, increasing their portability and convenience. These advances and innovations, combined with the freedom of movement, are among the driving forces behind the vast popularity of wireless communication. This situation is unlikely to change, especially when one considers the current push toward wireless broadband access to the Internet and multimedia content.

With predictions of near exponential growth in the number of wireless subscribers in the coming decades, pressure is mounting on government regulatory agencies to free up the RF spectrum to satisfy the growing bandwidth demands. This is especially true with regard to the next generation (3G) cellular systems that integrate voice and high-speed data access services. Given the slow reaction time of government bureaucracy and the high cost of licensing, wireless operators are typically forced to make due with limited bandwidth resources.

The aim of this chapter is to provide the reader with a comprehensive view of the role and details of the protocols that define and control access to the wireless channel, i.e., wireless media access protocols (MAC) protocols. We start by highlighting the distinguishing characteristics of wireless systems and their impact on the design and implementation of MAC protocols (Section 6.2). Section 6.3 explores the impact of the physical limitations specific to MAC protocol design. Section 6.4 lists the set of MAC techniques that form the core of most MAC protocol designs. Section 6.5 overviews channel access in cellular telephony networks and other centralized networks. Section 6.6 focuses on MAC solutions for ad hoc networks, namely, network architectures with decentralized control characterized by the mobility of possibly all the nodes. A brief summary concludes the chapter.

6.2 GENERAL CONCEPTS

In the broadest terms, a wireless network consists of nodes that communicate by exchanging "packets" via radio waves. These packets can take two forms. A unicast packet contains information that is addressed to a specific node, whereas a multicast packet distributes the information to a group of nodes. The MAC protocol simply determines when a node is allowed to transmit its packets, and typically controls all access to the physical layer. Figure 6.1 depicts the relative position of the MAC protocol within a simplified protocol stack.

The specific functions associated with a MAC protocol vary according to the system requirements and application. For example, wireless broadband networks carry data streams with stringent quality of service (QoS) requirements. This requires a complex MAC protocol that can adaptively manage the bandwidth resources in order to meet these demands. Design and complexity are also affected by the network architecture, communication model, and duplexing mechanism employed. These three elements are examined in the rest of the section.

6.2.1 Network Architecture

The architecture determines how the structure of the network is realized and where the network intelligence resides. A centralized network architecture features a specialized node, i.e., the base station, that coordinates and controls all transmissions within its coverage area, or cell. Cell boundaries are defined by the ability of nodes to receive transmissions from the base station. To increase network coverage, several base stations are interconnected by land lines that eventually tie into an existing network, such as the public switched telephone network (PTSN) or a local area network (LAN). Thus, each base station also plays the role of an intermediary between the wired and wireless domains. Figure 6.2 illustrates a simple two-cell centralized network.

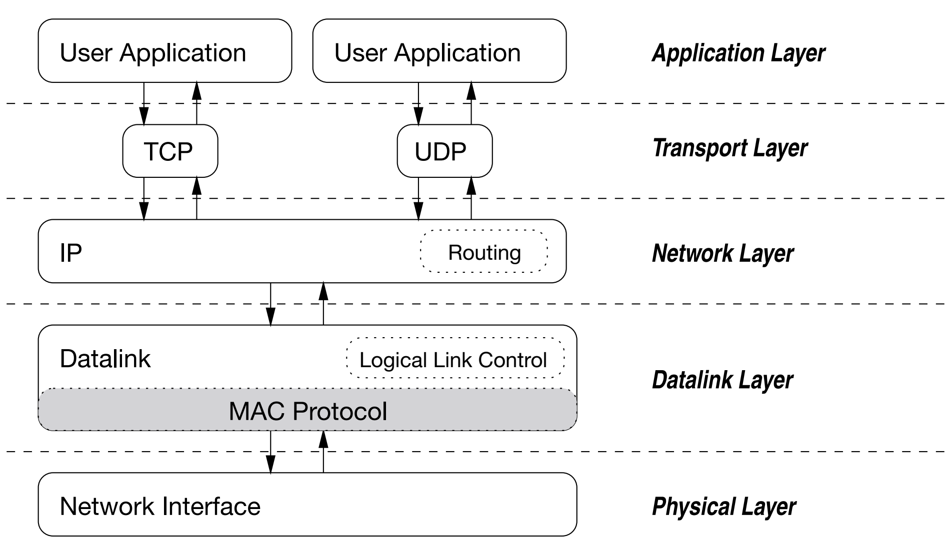

Figure 6.1 Position of the MAC protocol within a simplified protocol stack.

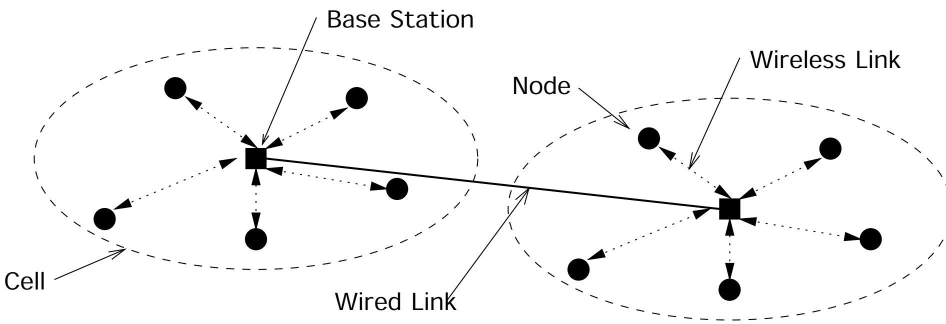

Figure 6.2 Centralized network architecture.

Communication from a base station to a node takes place on a downlink channel, and the opposite occurs on an uplink channel. Only the base station has access to a downlink channel, whereas the nodes share the uplink channels. In most cases, at least one of these uplink channels is specifically assigned to collect control information from the nodes. The base station grants access to the uplink channels in response to service requests received on the control channel. Thus, the nodes simply follow the instructions of the base station.

The concentration of intelligence at the base station leads to a greatly simplified node design that is both compact and energy efficient. The centralized control also simplifies QoS support and bandwidth management since the base station can collect the requirements and prioritize channel access accordingly. Moreover, multicast packet transmission is greatly simplified since each node maintains a single link to the base station. On the other hand, the deployment of a centralized wireless network is a difficult and slow process. The installation of new base stations requires precise placement and system configuration along with the added cost of installing new landlines to tie them into the existing system. The centralized system also presents a single point of failure, i.e., no base station equals no service.

The primary characteristic of an ad hoc network architecture is the absence of any predefined structure. Service coverage and network connectivity are defined solely by node proximity and the prevailing RF propagation characteristics. Ad hoc nodes communicate directly with one another in a peer-to-peer fashion. To facilitate communication between distant nodes, each ad hoc node also acts as a router, storing and forwarding packets on behalf of other nodes. The result is a generalized wireless network that can be rapidly deployed and dynamically reconfigured to provide on-demand networking solutions. An ad hoc architecture is also more robust in that the failure of one node is less likely to disrupt network services. Figure 6.3 illustrates a simple ad hoc network.

Although a generic architecture certainly has its advantages, it also introduces several new challenges. All network control, including channel access, must be distributed. Each ad hoc node must be aware of what is happening in its environment and cooperate with other nodes in order to realize critical network services. Considering that most ad hoc systems are fully mobile, i.e., each node moves independently, the level of protocol sophistication and node complexity is high. Moreover, each ad hoc node must maintain a signifi-

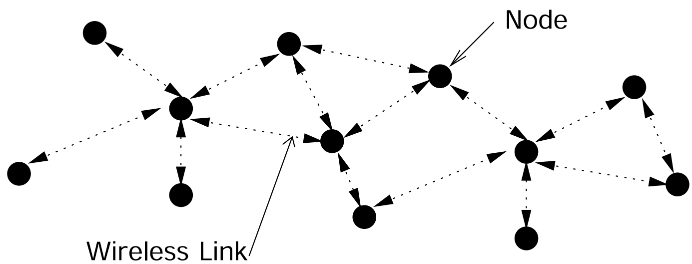

Figure 6.3 Ad hoc network architecture.

cant amount of state information to record crucial information such as the current network topology.

Given its distributed nature, channel access in an ad hoc network is achieved through the close cooperation between competing nodes. Some form of distributed negotiation is needed in order to efficiently allocate channel resources among the active nodes. The amount of overhead, both in terms of time and bandwidth resources, associated with this negotiation will be a critical factor of the overall system performance.

6.2.2 Communication Model

The communication model refers to the overall level of synchronization present in the wireless system and also determines when channel access can occur. There are different degrees of synchronization possible; however, there are only two basic communication models. The synchronous communication model features a slotted channel consisting of discrete time intervals (slots) that have the same duration. With few exceptions, these slots are then grouped into a larger time frame that is cyclically repeated. All nodes are then synchronized according to this time frame and communication occurs within the slot boundaries.

The uniformity and regularity of the synchronous model simplifies the provision of quality of service (QoS) requirements. Packet jitter, delay, and bandwidth allotment can all be controlled through careful time slot management. This characteristic establishes the synchronous communication model as an ideal choice for wireless systems that support voice and multimedia applications. However, the complexity of the synchronization process depends on the type of architecture used. In a centralized system, a base station can broadcast a beacon signal to indicate the beginning of a time frame. All nodes within the cell simply listen for these beacons to synchronize themselves with the base station. The same is not true of an ad hoc system that must rely on more sophisticated clock synchronization mechanisms, such as the timing signals present in the global positioning system (GPS).

The asynchronous communication model is much less restrictive, with communication taking place in an on-demand fashion. There are no time slots and thus no need for any global synchronization. Although this certainly reduces node complexity and simplifies communication, it also complicates QoS provisioning and bandwidth management. Thus, an asynchronous model is typically chosen for applications that have limited QoS requirements, such as file transfers and sensor networks. The reduced interdependence between nodes also makes it applicable to ad hoc network architectures.

6.2.3 Duplexing

Duplexing refers to how transmission and reception events are multiplexed together. Time division duplexing (TDD) alternates transmission and reception at different time instants on the same frequency band, whereas frequency division duplexing (FDD) separates the two into different frequency bands. TDD is simpler and requires less sophisticated hardware, but alternating between transmit and receive modes introduces additional delay overhead. With enough frequency separation, FDD allows a node to transmit and receive at the same time, which dramatically increases the rate at which feedback can be obtained. However, FDD systems require more complex hardware and frequency management.

6.3 WIRELESS ISSUES

The combination of network architecture, communication model, and duplexing mechanism define the general framework within which a MAC protocol is realized. Decisions made here will define how the entire system operates and the level of interaction between individual nodes. They will also limit what services can be offered and delineate MAC protocol design. However, the unique characteristics of wireless communication must also be taken into consideration. In this section, we explore these physical constraints and discuss their impact on protocol design and performance.

Radio waves propagate through an unguided medium that has no absolute or observable boundaries and is vulnerable to external interference. Thus, wireless links typically experience high bit error rates and exhibit asymmetric channel qualities. Techniques such as channel coding, bit interleaving, frequency/space diversity, and equalization increase the survivability of information transmitted across a wireless link. An excellent discussion on these topics can be found in Chapter 9 of [1]. However, the presence of asymmetry means that cooperation between nodes may be severely limited.

The signal strength of a radio transmission rapidly attenuates as it progresses away from the transmitter. This means that the ability to detect and receive transmissions is dependent on the distance between the transmitter and receiver. Only nodes that lie within a specific radius (the transmission range) of a transmitting node can detect the signal (carrier) on the channel. This location-dependent carrier sensing can give rise to so-called hidden and exposed nodes that can detrimentally affect channel efficiency. A hidden node is one that is within range of a receiver but not the transmitter, whereas the contrary holds true for an exposed node. Hidden nodes increase the probability of collision at a receiver, whereas exposed nodes may be denied channel access unnecessarily, thereby underutilizing the bandwidth resources.

Performance is also affected by the signal propagation delay, i.e., the amount of time needed for the transmission to reach the receiver. Protocols that rely on carrier sensing are especially sensitive to the propagation delay. With a significant propagation delay, a node may initially detect no active transmissions when, in fact, the signal has simply failed to reach it in time. Under these conditions, collisions are much more likely to occur and system performance suffers. In addition, wireless systems that use a synchronous communications model must increase the size of each time slot to accommodate propagation delay. This added overhead reduces the amount of bandwidth available for information transmission.

Even when a reliable wireless link is established, there are a number of additional hardware constraints that must also be considered. The design of most radio transceivers only allow half-duplex communication on a single frequency. When a wireless node is actively transmitting, a large fraction of the signal energy will leak into the receive path. The power level of the transmitted signal is much higher than any received signal on the same frequency, and the transmitting node will simply receive its own transmission. Thus, traditional collision detection protocols, such as Ethernet, cannot be used in a wireless environment.

This half-duplex communication model elevates the role of duplexing in a wireless system. However, protocols that utilize TDD must also consider the time needed to switch between transmission and reception modes, i.e., the hardware switching time. This switching can add significant overhead, especially for high-speed systems that operate at peak capacity [2]. Protocols that use handshaking are particularly vulnerable to this phenomenon. For example, consider the case when a source node sends a packet and then receives feedback from a destination node. In this instance, a turnaround time of 10 μs and transmission rate of 10 Mbps will result in an overhead of 100 bits of lost channel capacity. The effect is more significant for protocols that use multiple rounds of message exchanges to ensure successful packet reception, and is further amplified when traffic loads are high.

6.4 FUNDAMENTAL MAC PROTOCOLS

Despite the great diversity of wireless systems, there are a number of well-known MAC protocols whose use is universal. Some are adapted from the wired domain and others are unique to the wireless one. Most of the current MAC protocols use some subset of the following techniques.

6.4.1 Frequency Division Multiple Access (FDMA)

FDMA divides the entire channel bandwidth into M equal subchannels that are sufficiently separated (via guard bands) to prevent cochannel interference (see Figure 6.4). Ignoring the small amount of frequency lost to the guard bands, the capacity of each subchannel is C/M, where C is the capacity associated with the entire channel bandwidth. Each source node can then be assigned one (or more) of these subchannels for its own exclusive use. To receive packets from a particular source node, a destination node must be listening on the proper subchannel. The main advantage of FDMA is the ability to accommodate M simultaneous packet transmissions (one on each subchannel) without collision. However, this comes at the price of increased packet transmission times, resulting in longer packet delays. For example, the transmission time of a packet that is L bits long is $M \cdot L/C$. This is M times longer than if the packet was transmitted using the entire channel bandwidth. The

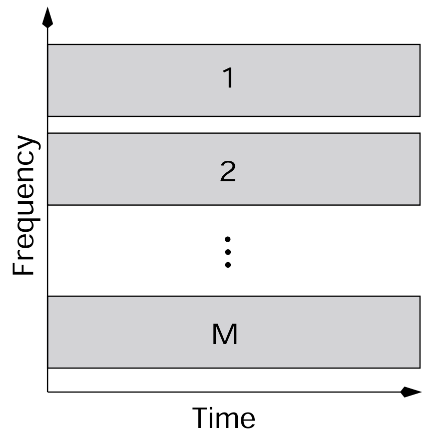

Figure 6.4 Frequency division multiple access.

exclusive nature of the channel assignment can also result in underutilized bandwidth resources when a source node momentarily lacks packets to transmit.

6.4.2 Time Division Multiple Access (TDMA)

TDMA divides the entire channel bandwidth into M equal time slots that are then organized into a synchronous frame (see Figure 6.5). Conceptually, each slot represents one channel that has a capacity equal to C/M, where C is again the capacity of the entire channel bandwidth. Each node can then be assigned one (or more) time slots for its own exclusive use. Consequently, packet transmission in a TDMA system occurs in a serial fashion,

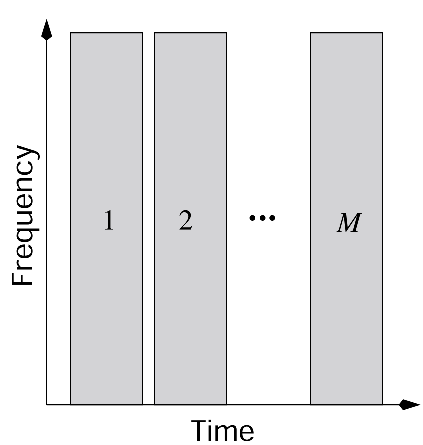

Figure 6.5 Time division multiple access.

with each node taking turns accessing the channel. Since each node has access to the entire channel bandwidth in each time slot, the time needed to transmit a L bit packet is then L/C. When we consider the case where each node is assigned only one slot per frame, however, there is a delay of $(M - 1)$ slots between successive packets from the same node. Once again, channel resources may be underutilized when a node has no packet(s) to transmit in its slot(s). On the other hand, time slots are more easily managed, allowing the possibility of dynamically adjusting the number of assigned slots and minimizing the amount of wasted resources.

6.4.3 Code Division Multiple Access (CDMA)

While FDMA and TDMA isolate transmissions into distinct frequencies or time instants, CDMA allow transmissions to occupy the channel at the same time without interference. Collisions are avoided through the use of special coding techniques that allow the information to be retrieved from the combined signal. As long as two nodes have sufficiently different (orthogonal) codes, their transmissions will not interfere with one another.

CDMA works by effectively spreading the information bits across an artificially broadened channel. This increases the frequency diversity of each transmission, making it less susceptible to fading and reducing the level of interference that might affect other systems operating in the same spectrum. It also simplifies system design and deployment since all nodes share a common frequency band. However, CDMA systems require more sophisticated and costly hardware, and are typically more difficult to manage.

There are two types of spread spectrum modulation used in CDMA systems. Direct sequence spread spectrum (DSSS) modulation modifies the original message by multiplying it with another faster rate signal, known as a pseudonoise (PN) sequence. This naturally increases the bit rate of the original signal and the amount of bandwidth that it occupies. The amount of increase is called the spreading factor. Upon reception of a DSSS modulated signal, a node multiplies the received signal by the PN sequence of the proper node. This increases the amplitude of the signal by the spreading factor relative to any interfering signals, which are diminished and treated as background noise. Thus, the spreading factor is used to raise the desired signal from the interference. This is known as the processing gain. Nevertheless, the processing gain may not be sufficient if the original information signal received is much weaker than the interfering signals. Thus, strict power control mechanisms are needed for systems with large coverage areas, such as a cellular telephony networks.

Frequency hopping spread spectrum (FHSS) modulation periodically shifts the transmission frequency according to a specified hopping sequence. The amount of time spent at each frequency is referred to as the dwell time. Thus, FHSS modulation occurs in two phases. In the first phase, the original message modulates the carrier and generates a narrowband signal. Then the frequency of the carrier is modified according to the hopping sequence and dwell time.

6.4.4 ALOHA Protocols

In contrast to the elegant solutions introduced so far, the ALOHA protocols attempt to share the channel bandwidth in a more brute force manner. The original ALOHA protocol was developed as part of the ALOHANET project at the University of Hawaii [3]. Strangely enough, the main feature of ALOHA is the lack of channel access control. When a node has a packet to transmit, it is allowed to do so immediately. Collisions are common in such a system, and some form of feedback mechanism, such as automatic repeat request (ARQ), is needed to ensure packet delivery. When a node discovers that its packet was not delivered successfully, it simply schedules the packet for retransmission.

Naturally, the channel utilization of ALOHA is quite poor due to packet vulnerability. The results presented in [4] demonstrate that the use of a synchronous communication model can dramatically improve protocol performance. This slotted ALOHA forces each node to wait until the beginning of a slot before transmitting its packet. This reduces the period during which a packet is vulnerable to collision, and effectively doubles the channel utilization of ALOHA. A variation of slotted ALOHA, known as p-persistent slotted ALOHA, uses a persistence parameter p, $0 < p < 1$, to determine the probability that a node transmits a packet in a slot. Decreasing the persistence parameter reduces the number of collisions, but increases delay at the same time.

6.4.5 Carrier Sense Multiple Access (CSMA) Protocols

There are a number of MAC protocols that utilize carrier sensing to avoid collisions with ongoing transmissions. These protocols first listen to determine whether there is activity on the channel. An idle channel prompts a packet transmission and a busy channel suppresses it. The most common CSMA protocols are presented and formally analyzed in [5].

While the channel is busy, persistent CSMA continuously listens to determine when the activity ceases. When the channel returns to an idle state, the protocol immediately transmits a packet. Collisions will occur when multiple nodes are waiting for an idle channel. Nonpersistent CSMA reduces the likelihood of such collisions by introducing randomization. Each time a busy channel is detected, a source node simply waits a random amount of time before testing the channel again. This process is repeated with an exponentially increasing random interval until the channel is found idle.

The p-persistent CSMA protocol represents a compromise between persistent and nonpersistent CSMA. In this case, the channel is considered to be slotted but time is not synchronized. The length of each slot is equal to the maximum propagation delay, and carrier sensing occurs at the beginning of each slot. If the channel is idle, the node transmits a packet with probability p, $0 < p < 1$. This procedure continues until either the packet is sent, or the channel becomes busy. A busy channel forces a source node to wait a random amount of time before starting the procedure again.

6.5 CENTRALIZED MAC PROTOCOLS

In this section, we provide an overview of two of the most prevalent centralized wireless networks. Cellular telephony is the most predominant form of wireless system in current operation. Wireless ATM is generating a lot of interest for its ability to deliver broadband multimedia services across a wireless link. Each system will be briefly highlighted and the MAC protocol will be examined.

6.5.1 Cellular Telephony

The advanced mobile phone system (AMPS) is an FDMA-based cellular system [6]. The system features 832 full-duplex channels that are grouped into control and data channels.

Each cell has a full-duplex control channel dedicated to system management, paging, and call setup. There are also 45–50 data channels that can be used for voice, fax, or data. The base station grants access to a data channel in response to a call setup request sent on the control channel. A data channel remains assigned to a specific node until it is relinquished or the node moves outside the current cell. Access to the control channel is determined using a CSMA-based MAC protocol. The base station periodically broadcasts the status of the control channel, and a node transmits its setup request (possibly in contention with other nodes) when the control channel is idle. Collisions among setup requests are resolved using randomized retransmissions.

The IS-136 cellular system is a digital version of the AMPS system [7]. As such, it operates within the same spectrum using the same frequency spacing of the original AMPS system. Each data channel is then slotted and a time frame of six slots is used. This allows the system to support multiple users within a single AMPS data channel. An assignment of one slot per frame can support a total of six users transmitting at a rate of 8.1 kb/s. Higher data rates can be achieved by successively doubling the number of assigned slots up to a maximum of 48.6 kb/s. Channel access remains relatively unchanged from the original AMPS system.

The IS-95 cellular system is a CDMA-based wireless network in which all the base stations share a common frequency band with individual transmissions being distinguished by their PN sequences [8]. Strict power control ensures that all transmitted signals reach the base station with the same power level. This allows a more equitable sharing of the system power resources while minimizing systemwide cochannel interference. However, the equalized power levels make it difficult to determine when a node is about to leave one cell and enter another. A node must communicate with multiple base stations simultaneously, allowing it to measure the relative signal quality of each base station. Handover is then made to the base station with the best signal characteristics. This type of system requires complex and costly hardware both within the base stations and nodes.

Cdma2000 is the third generation (3G) version of the IS-95 cellular system. Cdma2000 is backward compatible with the current system, allowing legacy users to be accommodated in future 3G systems. Many other proposed 3G cellular systems have also adopted a CDMA interface. This includes the 3G version of GSM known as the universal mobile telecommunications services (UMTS) [9].

6.5.2 Wireless ATM

Asynchronous transfer mode (ATM) is a high-performance connection-oriented switching and multiplexing technology that uses fixed-sized packets to transport a wide range of integrated services over a single network. These include voice, video, and multimedia services that have different QoS requirements. The ability to provide specific QoS services is one of the hallmarks of ATM. Wireless ATM is designed to extend these integrated services to the mobile user.

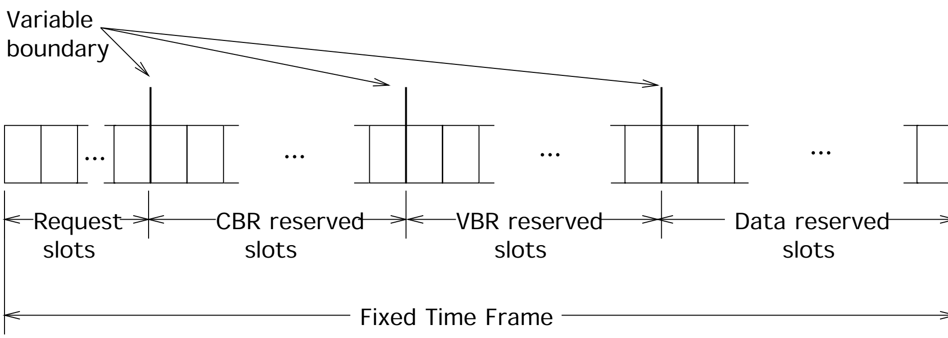

Figure 6.6 PRMA/DA protocol.

Similar to cellular systems, wireless ATM nodes send requests to the base station for service. The specific QoS requirements of an application are included in these request messages. The base station then collects these requirements and allocates the uplink and downlink channels accordingly. Thus wireless ATM MAC protocols typically follow a three-phase model. In the first phase, a request message is sent on a random access control channel, usually using a slotted ALOHA protocol. The second phase involves the base station scheduling uplink and downlink transmissions according to the QoS requirements of the current traffic mix. Preference is given to delay-sensitive data, such as voice packets, whereas datagram services must make due with any remaining capacity. The third phase involves the transmission of packets according to the schedule created in phase two.

The PRMA/DA [10] and DSA++ [11] protocols are two examples of this three-phase MAC design using FDD, whereas MASCARA [12] and DTDMA [13] use TDD. Each of these protocols are respectively illustrated in Figures 6.6 through 6.9 and Table 6.1 summarizes their relative characteristics.

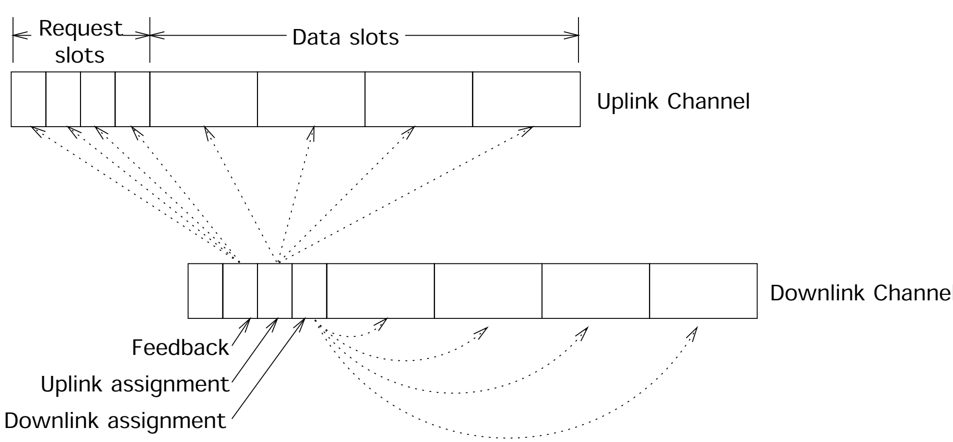

Figure 6.7 DSA++ protocol.

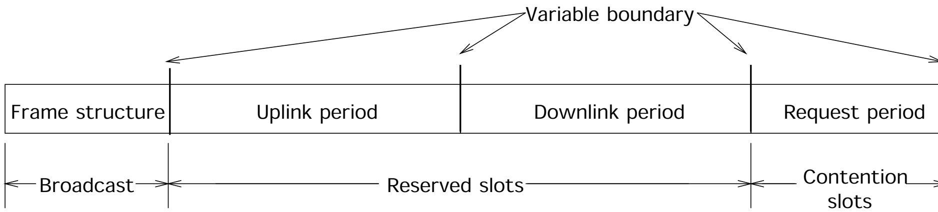

Figure 6.8 MASCARA protocol.

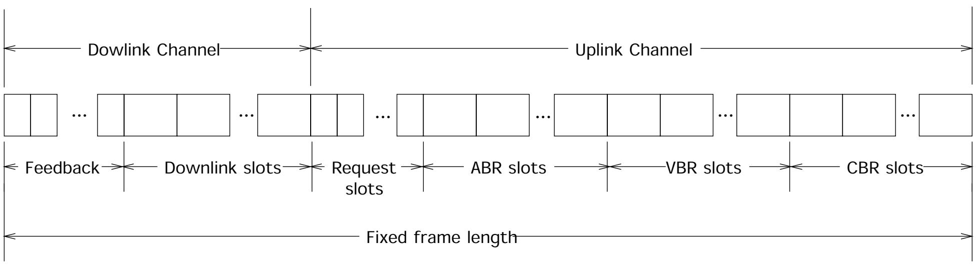

Figure 6.9 DTDMA protocol.

6.6 AD HOC MAC PROTOCOLS

Ad hoc networks do not have the benefit of predefined base stations to coordinate channel access, thus invalidating many of the assumptions held by centralized MAC designs. In this section, we focus our attention on MAC protocols that are specifically designed for ad hoc networks.

A possible taxonomy of ad hoc MAC protocols includes three broad protocol categories that differ in their channel access strategy: contention protocols, allocation protocols, and a combination of the two (hybrid protocols).

Contention protocols use direct competition to determine channel access rights, and resolve collisions through randomized retransmissions. The ALOHA and CSMA protocols

TABLE 6.1 Wireless ATM MAC protocol relative characteristics

	PRMA/DA	DSA++	MASCARA	DTDMA
Duplexing	FDD	FDD	TDD	TDD
Frame type	fixed	variable	variable	fixed
Algorithm complexity	medium	medium	high	high
Communication complexity	low	medium	high	medium
Channel utilization	medium	high	medium	high
Control overhead	medium	high	high	medium

introduced in Sections 6.4.4 and 6.4.5 are prime examples. With the exception of slotted ALOHA, most contention protocols employ an asynchronous communication model. Collision avoidance is also a key design element that is realized through some form of control signaling.

The contention protocols are simple and tend to perform well at low traffic loads, i.e., when there are few collision, leading to high channel utilization and low packet delay. However, protocol performance tends to degrade as the traffic loads are increased and the number of collisions rise. At very high traffic loads, a contention protocol can become unstable as the channel utilization drops. This can result in exponentially growing packet delay and network service breakdown since few, if any, packets can be successfully exchanged.

Allocation protocols employ a synchronous communication model and use a scheduling algorithm that generates a mapping of time slots to nodes. This mapping results in a transmission schedule that determines in which particular slots a node is allowed to access the channel. Most allocation protocols create collision-free transmission schedules, thus the schedule length (measured in slots) forms the basis of protocol performance. The time slots can either be allocated statically or dynamically, leading to a fixed and variable schedule length.

The allocation protocols tend to perform well at moderate to heavy traffic loads as all slots are likely to be utilized. These protocols also remain stable even when the traffic loads are extremely high. This is due to the fact that most allocation protocols ensure that each node has collision-free access to at least one time slot per frame. On the other hand, these protocols are disadvantaged at low traffic loads due to the artificial delay induced by the slotted channel. This results in significantly higher packet delays with respect to the contention protocols.

Hybrid protocols can be loosely described as any combination of two or more protocols. However, in this section, the definition of the term hybrid will be constrained to include only those protocols that combine elements of contention- and allocation-based channel access schemes in such a way as to maintain their individual advantages while avoiding their drawbacks. Thus, the performance of a hybrid protocol should approximate a contention protocol when traffic is light, and an allocation protocol during periods of high load.

6.6.1 Contention Protocols

Contention protocols can be further classified according to the type of collision avoidance mechanism employed. The ALOHA protocols make up the category of protocols that feature no collision avoidance mechanism, i.e., they simply react to collision via randomized retransmissions. Most contention protocols, however, use some form of collision avoidance mechanism.

The busy-tone multiple access (BTMA) protocol [14] divides the entire bandwidth into two separate channels. The main data channel is used for the transmission of packets, and occupies the majority of the bandwidth. The control channel is used for the transmission of a special busy-tone signal that indicates the presence of activity on the data channel. These signals are not bandwidth-intensive, thus the control channel is relatively small.

The BTMA protocol operates as follows. When a source node has a packet to transmit, it first listens for the busy-tone signal on the control channel. If the control channel is idle, i.e., no busy-tone is detected, then the node may begin transmitting its packet. Otherwise, the node reschedules the packet for transmission at some later time. Any node that detects activity on the data channel immediately begins transmitting the busy-tone on the control channel. This continues until the activity on the data channel ceases.

In this way, BTMA prevents all nodes that are two hops away from an active source node from accessing the data channel. This significantly lowers the level of hidden node interference, and therefore reduces the probability of collision. However, the number of exposed nodes is dramatically increased and this may result in a severely underutilized data channel.

The receiver-initiated busy-tone multiple access (RI-BTMA) protocol [15] attempts to minimize the number of exposed nodes by having only the destination(s) transmit the busy-tone. Rather than immediately transmitting the busy-tone upon detection of an active data channel, a node monitors the incoming data transmission to determine whether it is a destination. This determination takes a significant amount of time, especially in a noisy environment with corrupted information. During this time, the initial transmission remains vulnerable to collision. This can be particularly troublesome in high-speed systems where the packet transmission time may be short.

The wireless collision detect (WCD) protocol [2] essentially combines the BTMA and RI-BTMA protocols by using two distinct busy-tone signals on the control channel. WCD acts like BTMA when activity is first detected on the main channel, i.e., it transmits a collision detect (CD) signal on the BTC. RI-BTMA behavior takes over once a node determines it is a destination. In this case, a destination stops transmitting the CD signal and begins transmitting a feedback-tone (FT) signal. In this way, WCD minimizes the exposed nodes while still protecting the transmission from hidden node interference.

These busy-tone protocols feature simple designs that require only a minimal increase in hardware complexity. Because of its unique characteristics, the WCD protocol is the overall performance leader, followed by RI-BTMA and BTMA, respectively [2]. Furthermore, the performance of busy-tone protocols are less sensitive to the hardware switching time since it is assumed that a node can transmit and receive on the data and control channels simultaneously. However, wireless systems that have a limited amount of RF spectrum may not be able to realize a separate control and data channel. In such cases, collision avoidance using in-band signaling is necessary.

The multiple access with collision avoidance (MACA) protocol [16] uses a handshaking dialogue to alleviate hidden node interference and minimize the number of exposed nodes. This handshake consists of a request-to-send (RTS) control packet that is sent from a source node to its destination. The destination replies with a clear-to-send (CTS) control packet, thus completing the handshake. A CTS response allows the source node to transmit its packet. The absence of a CTS forces a node to reschedule the packet for transmission at some later time. Figure 6.10 illustrates the operation of the MACA protocol.

Consider the case where node *B* wishes to send a packet to node *A*. Node *B* first transmits an RTS, which reaches nodes *A*, *C*, and *D* (Figure 6.10a). Node *A* then responds by

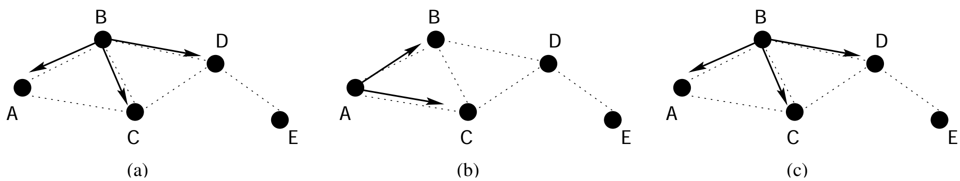

Figure 6.10 MACA protocol operation.

sending a CTS, which reaches nodes *B* and *C*, thus completing the handshake (Figure 6.10b). At this point, *B* is free to send its packet (Figure 6.10c).

Notice that a hidden node is likely to overhear the CTS packet sent by a destination node, whereas an exposed node is not. Thus, by including the time needed to receive a CTS and packet in the respective RTS and CTS packets, we reduce the likelihood of hidden node interference and the number of exposed nodes simultaneously.

The MACAW protocol [17] enhances MACA by including carrier sensing to avoid collisions among RTS packets, and a positive acknowledgement (ACK) to aid in the rapid recovery of lost packets. To protect the ACK from collision, a source node transmits a data sending (DS) control packet to alert exposed nodes of its impending arrival. Improvements are also made to the collision resolution algorithm to ensure a more equitable sharing of the channel resources.

The MACA with piggyback reservations (MACA/PR) protocol [18] enhances MACA by incorporating channel reservations. This allows the system to support QoS sensitive applications. Each node maintains a reservation table (RT) that is used to record the channel reservations made by neighboring nodes. A source node makes a reservation by first completing a RTS/CTS exchange. It then sends the first real-time packet, whose header contains the time interval specifying the interval in which the next one will be sent. The destination responds with an ACK carrying the equivalent time interval. Other nodes within range note this reservation in their RT and remain silent during the subsequent time intervals. Thus, the source node can send subsequent real-time packets without contention. To ensure proper bookkeeping, the nodes periodically exchange their RTs.

The MACA by invitation (MACA-BI) protocol [19] reverses the handshaking dialogue of MACA. In this case, the destination node initiates packet transmission by sending a request-to-receive (RTR) control packet to the source node. The source node responds to this poll with a packet transmission. Thus, each node must somehow predict when neighbors have packets for it. This means that each node must maintain a list of its neighbors along with their traffic characteristics. In order to prevent collision, the nodes must also synchronize their polling mechanisms by sharing this information with their neighbors.

These MACA-based contention protocols minimize collisions by reducing the negative effect of hidden and exposed nodes through simple handshaking dialogues. However, the exchange of multiple control packets for each data packet magnifies the impact of signal propagation delay and hardware switching time. To some extent, the MACA/PR and

MACA/BI protocols alleviate these problems by reducing the amount of handshaking, yet the amount of state information maintained at each node can be substantial.

6.6.2 Allocation Protocols

There are two distinct classes of allocation protocols that differ in the way the transmission schedules are computed. Static allocation protocols use a centralized scheduling algorithm that statically assigns a fixed transmission schedule to each node prior to its operation. This type of scheduling is similar to the assignment of MAC addresses for Ethernet interface cards. Dynamic allocation protocols uses a distributed scheduling algorithm that computes transmission schedules in an on-demand fashion.

Since the transmission schedules are assigned beforehand, the scheduling algorithm of a static allocation protocol requires global system parameters as input. The classic TDMA protocol builds its schedules according to the maximum number of nodes in the network. For a network of N nodes, the protocol uses a frame length of N slots and assigns each node one unique time slot. Since each node has exclusive access to one slot per frame, there is no threat of collision for any packet type (i.e., unicast or multicast). Moreover, the channel access delay is bounded by the frame length. Because of the equivalence between system size and frame length, classic TDMA performs poorly in large-scale networks.

The time spread multiple access (TSMA) protocol [20] relaxes some of the strict requirements of classic TDMA to achieve better performance while still providing bounded access delay. The TSMA scheduling algorithm assigns each node multiple slots in a single frame, and permits a limited amount of collisions to occur. These two relaxations allow TSMA to obtain transmission schedules whose lengths scale logarithmically with respect to the number of nodes. Furthermore, TSMA guarantees the existence of a collision-free transmission slot to each neighbor within a single frame.

The source of this "magic" is the scheduling algorithm that makes use of the mathematical properties of finite fields. An excellent introduction to finite fields can be found in [21]. The scheduling algorithm is briefly outlined as follows. For a network of N nodes, the parameters q (of the form $q = p^m$, where p is a prime and m an integer) and integer k are chosen such that $q^{k+1} \geq N$ and $q \geq kD_{\max} + 1$, where $D_{\max}$ is the maximum node degree. Each node can then be assigned a unique polynomial f over the Galois field $GF(q)$. Using this polynomial, a unique TSMA transmission schedule is computed where bit $i = 1$ if $(i \bmod q) = f(\lfloor i/q \rfloor)$, otherwise $i = 0$.

As shown in [20], that this TSMA scheduling algorithm provides each node with a transmission schedule with guaranteed access in each time frame. The maximum length of this schedule is bounded by

$$L = O\left(\frac{D_{\max}^2 \log^2 N}{\log^2 D_{\max}} \right)$$

Notice that the frame length scales logarithmically with the number of nodes and quadratically with the maximum degree. For ad hoc networks consisting of thousands of nodes with a sparse topology (i.e., small $D_{\max}$), TSMA can yield transmission schedules that are much shorter than TDMA. Table 6.2 compares the frame lengths of TDMA and TSMA for

TABLE 6.2 Frame lengths of classic TDMA versus TSMA

	$D_{max} = 2$	$D_{max} = 5$	$D_{max} = 10$	$D_{max} = 15$
TDMA	1000	1000	1000	1000
TSMA	49	121	529	961

a network of $N = 1000$ nodes. For TSMA protocols a $\Omega(\log n)$ lower bound has been proved for L in [22]. We notice that there is still a gap between the TSMA upper bound and the mentioned logarithmic lower bound. Therefore, there is still room for improvement (more likely on the lower-bound side). TSMA-like protocols have also been deployed as a basis for implementing broadcast (i.e., one-to-all communication) in ad hoc networks. Upper and lower bound for deterministic and distributed TSMA-based broadcast can be found in [23, 24] and [25], respectively.

With mobile ad hoc networks, nodes may be activated and deactivated without warning, and unrestricted mobility yields a variable network topology. Consequently, global parameters, such as node population and maximum degree, are typically unavailable or difficult to predict. For this reason, protocols that use only local parameters have been developed. A local parameter refers to information that is specific to a limited region of the network, such as the number of nodes within x hops of a reference node (referred to as an x-hop neighborhood). A dynamic allocation protocol then uses these local parameters to deterministically assign transmission slots to nodes. Because local parameters are likely to vary over time, the scheduling algorithm operates in a distributed fashion and is periodically executed to adapt to network variations.

Dynamic allocation protocols typically operate in two phases. Phase one consists of a set of reservation slots in which the nodes contend for access to the subsequent transmission slots. This is similar to many of the wireless ATM protocols studied in Section 6.5. Lacking a coordinating base station, contention in this phase requires the cooperation of each individual node to determine and verify the outcome. Successful contention in phase one grants a node access to one or more transmission slots of phase two, in which packets are sent.

A great number of dynamic allocation protocols have been proposed. The protocols [26–29] are just a few excellent examples of this two-phase design. They use a contention mechanism that is based on classic TDMA. Essentially, the nodes take turns contending for slot reservations, with the earliest node succeeding. This results in a high degree of unfairness that is equalized by means of a reordering policy. Although these protocols create transmission schedules that are specific to the local network topology, they still require global parameters.

In contrast, the five-phase reservation protocol (FPRP) [29] is designed to be arbitrarily scalable, i.e., independent of the global network size. FPRP uses a complex frame structure that consists of two subframe types, namely reservation frames and information frames. As illustrated in Fig. 6.11, a reservation frame precedes a sequence of k information frames. Each reservation frame consists of ℓ reservation slots that correspond to the ℓ information slots of each information frame. Thus, if a node wants to reserve a specific information slot, it contends in the corresponding reservation slot. At the end of the reserva-

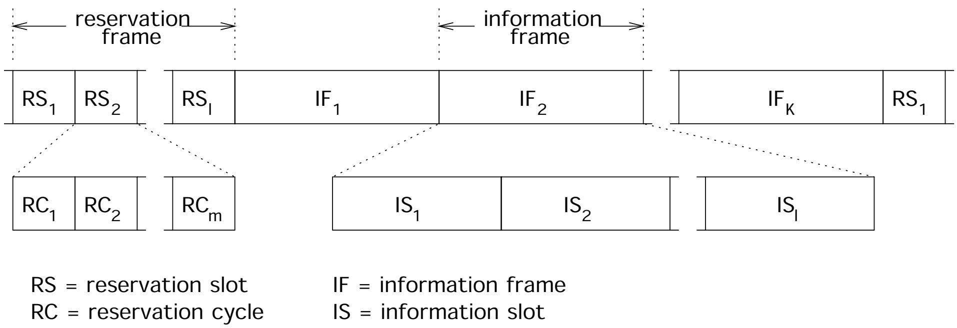

Figure 6.11 Frame and slot structure of FPRP.

tion frame, a TDMA schedule is created and used in the following k information frames. The schedule is then recomputed in the next reservation frame.

In order to accommodate contention, each reservation slot consists of m reservation cycles that contain a five-round reservation dialogue. A reservation is made in the first four rounds, whereas the fifth round is used for performance optimization. The contention is summarized as follows. A node that wishes to make a reservation sends out a request using p-persistent slotted ALOHA (round 1), and feedback is provided by the neighboring nodes (round 2). A successful request, i.e., one that did not involve a collision, allows a node to reserve the slot (round 3). All nodes within two hops of the source node are then notified of the reservation (round 4). These nodes will honor the reservation and make no further attempts to contend for the slot. Any unsuccessful reservation attempts are resolved through a pseudo-Bayesian resolution algorithm that randomizes the next reservation attempt.

In [29], FPRP is shown to yield transmission schedules that are collision-free; however, the protocol requires a significant amount of overhead. Each reservation cycle requires a number of hardware switches between transmitting and receiving modes. Each round of contention must also be large enough to accommodate the signal, propagation delay and physical layer overhead (e.g., synchronization and guard time). Add this together and multiply the result by m reservation cycles and ℓ reservation slots, and the end result is anything but trivial. Furthermore, the system parameters k, ℓ and m are heuristically determined through simulation and then fixed in the network. This limits the ability of FPRP to dynamically adapt its operation to suit the current network conditions, which may deviate from the simulated environment.

6.6.3 Hybrid Protocols

A protocol that integrates TDMA and CSMA is introduced in [30]. The idea is to permanently assign each node a fixed TDMA transmission schedule, yet give the nodes an opportunity to reclaim and/or reuse any idle slots through CSMA-based contention. Nodes have immediate channel access in their assigned slots, and may transmit a maximum of two data packets. Nodes wishing to transmit a packet in an unassigned slot must first determine its status through carrier sensing. If the slot is idle, each competing node attempts to transmit a single packet at some randomly chosen time instant.

As illustrated in Figure 6.12, a large portion of each idle slot is sacrificed in order to accommodate randomized channel access. Hidden nodes can also interfere with the ability of a node to successfully use its assigned slot. Thus nodes are prevented from using slots that are allocated to nodes that are exactly two hops away. Although this can be achieved in a fixed wireless system, it is unclear how this can be accomplished in a mobile environment. Furthermore, the reliability of multicast transmissions can only be assured in assigned slots.

The ADAPT protocol [31] addresses the problem of hidden node interference by integrating a CSMA-based contention protocol that uses collision avoidance handshaking into a TDMA allocation protocol. As illustrated in Figure 6.13, each time slot is subdivided into three intervals. In the priority interval, nodes announce their intentions to use their assigned slots by initiating a collision avoidance handshake with the intended destination. This ensures that all hidden nodes are aware of the impending transmission. The contention interval is used by nodes wishing to compete for channel access in an unassigned time slot. A node may compete if and only if the channel remains idle during the priority interval. The transmission interval is used for the transmission of packets. Access to the transmission interval is determined as follows. All nodes have access to the transmission interval in their assigned slots. A node that successfully completes an RTS/CTS handshake in the contention interval of an unassigned slot may access the transmission interval. Any unsuccessful handshake in the contention interval is resolved using the exponential backoff algorithm presented in [32].

Extensive simulation results demonstrate that ADAPT successfully maintains priori-

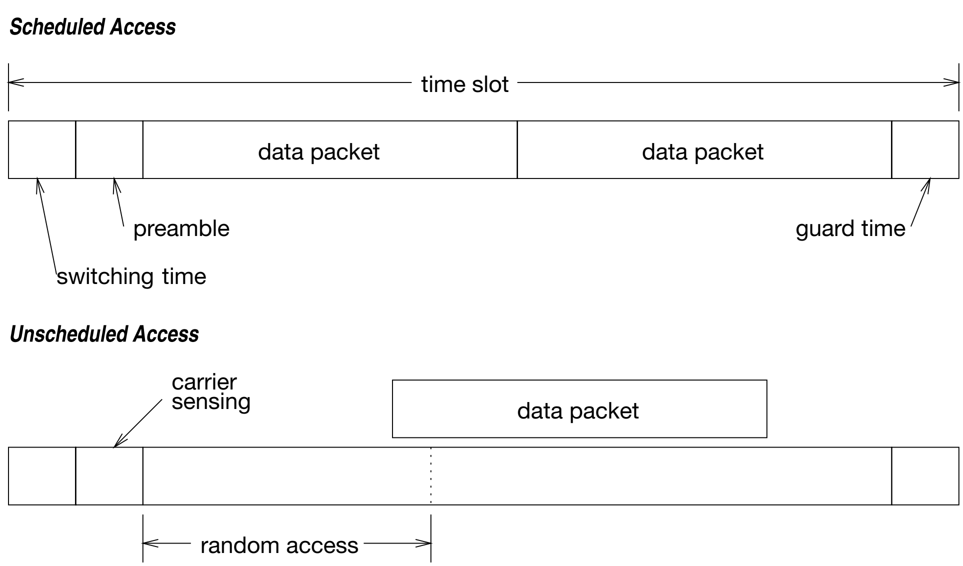

Figure 6.12 Hybrid TDMA/CSMA channel access.

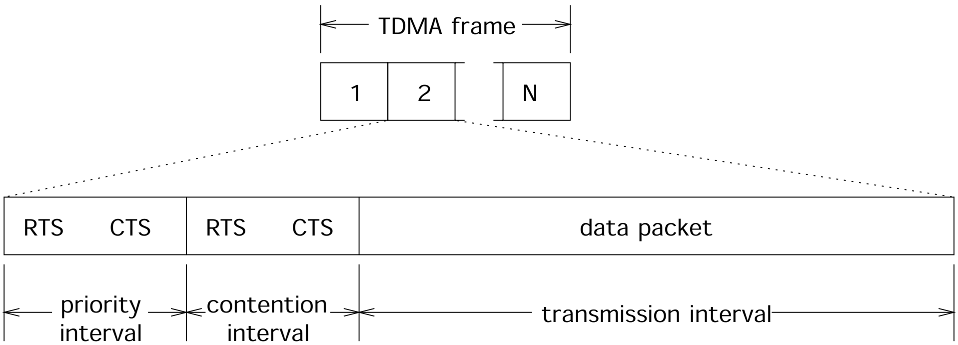

Figure 6.13 The ADAPT protocol.

tized access to assigned slots and exhibits high channel utilization in sparse network topologies [33]. However, the results do not factor in any physical constraints, such as propagation delay and hardware switch-over time, which can significantly increase overall protocol overhead. Furthermore, the handshaking mechanism employed in the contention interval does not support multicast packet transmissions.

The ABROAD protocol [34] accommodates multicast packets by altering the contention mechanism of ADAPT. The RTS/CTS signaling in the priority interval does not need to be modified since its primary purpose is to simply inform nodes of activity in an assigned slot. However, the use of a RTS/CTS dialogue fails in the contention interval due to the potential collision among the CTS responses, i.e., information implosion. ABROAD uses a form of negative feedback response to avoid this problem. Thus, a node responds with a negative CTS (NCTS) when a collision is detected in the contention interval or remains silent otherwise. There are a few cases in which this type of handshaking fails, yet simulation results and analysis demonstrate that the probability of failure is small, e.g., less than 4% in networks with low bit error rates [34].

The AGENT protocol [35] integrates the unicast capabilities of ADAPT with the multicast capabilities of ABROAD. The result is a generalized MAC protocol that is able to provide a full range of effective single-hop transmission services. AGENT uses the same frame and slot structure of ADAPT, as well as the handshaking dialogue of the priority interval. The control signaling in the contention interval is based on a combination of ADAPT and ABROAD.

Thus, to gain access to the transmission interval of a slot s, a source node i first transmits a RTS control packet. This occurs at the beginning of the priority interval in an assigned slot, or the beginning of the priority interval, otherwise. The reception of a RTS in the priority interval elicits a CTS response. On the other hand, the reception of a RTS in the contention interval generates a CTS response only when it is associated with a unicast packet. Any collision detected in the contention interval will cause a NCTS to be transmitted.

Once this initial control signaling is finished, a node can determine its eligibility to transmit its packet p in the transmission interval. If s is assigned to i, then source node i is granted permission to transmit p without restriction. Otherwise, the following rules must be applied.

1. If any CTS control signaling is detected in the priority interval, then i must withhold the transmission of p to avoid collision with the owner of s.
2. If a NCTS response is received in the contention interval, then multiple source nodes are contending for s, and i must withhold the transmission of p to avoid collision.
3. If p is a unicast packet and a corresponding CTS is received, then i may transmit p in the transmission interval.
4. If p is a multicast packet and no signaling response is received, then i may transmit p in the transmission interval.

Any failure to transmit p in this manner is resolved by the backoff algorithm of ADAPT.

For example, consider the ad hoc network of Figure 6.14. The current slot is assigned to node B, which has a multicast packet addressed to nodes A and C, and node D has a unicast packet addressed to node E. Then B sends a RTS in the priority interval [Figure 6.14(a]) to which A and C respond with a CTS [Figure 6.14(b)]. Node D sends its RTS in the contention interval [Figure 6.14(c)], and E responds with a CTS [Figure 6.14(d)]. When this signaling ends, both B and D are free to transmit their respective packets.

To eliminate unnecessary control signaling, a node that is attempting to transmit a packet in an unassigned slot refrains from sending a RTS when a CTS is detected in the priority interval. There are also a number of ambiguous cases that arise when dealing with multicast packets. To ensure proper signaling behavior, a node that transmits a RTS in the priority interval also sends a jamming RTS (JAM) in the contention interval.

The analysis and simulation presented in [35] demonstrate that the performance of AGENT closely matches that of a contention protocol under light traffic loads. As the load

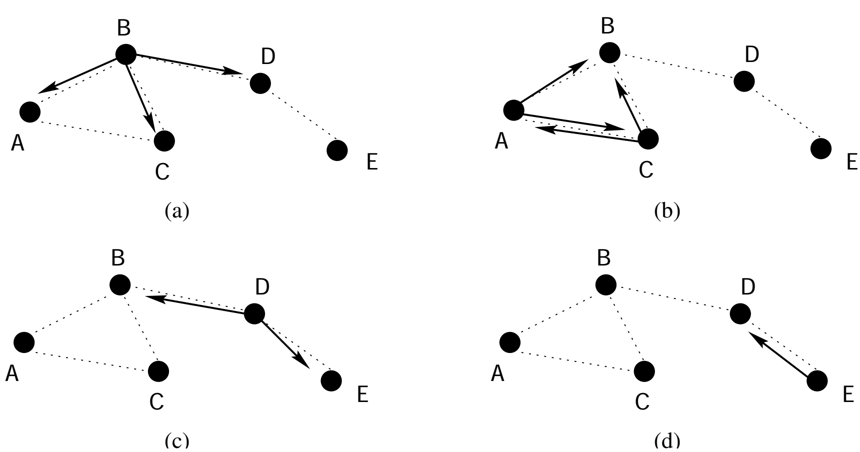

Figure 6.14 Example of AGENT signaling.

is increased, the performance of AGENT mirrors that of its underlying allocation protocol. It is further shown that AGENT is not biased toward one traffic type or another. This allows a more equitable sharing of channel resources between unicast and multicast traffic. However, the application of AGENT is somewhat limited due to the use of a TDMA scheduling algorithm. For larger networks consisting of thousands of nodes, the current AGENT protocol may no longer be a feasible alternative. Moreover, the network size is typically unknown and time-varying.

A more general framework for the integration of multiple MAC protocols is presented in [36]. This metaprotocol framework dynamically combines any set of existing MAC protocols into a single hybrid solution. This hybrid protocol essentially runs each of these component protocols in parallel. The decision of whether or not to transmit is then derived from a weighted average of the decisions made by the individual component protocols. The properties of the metaprotocol framework ensure that the hybrid protocol always matches the performance of the best component protocol without knowing in advance which protocol will match the unpredictable changes in the network conditions. This combination is entirely automatic and requires only local network feedback.

To simplify the presentation of the metaprotocol framework, we restrict our attention to slotted time and assume that immediate channel feedback is available at the end of each slot. Figure 6.15 illustrates a combination of M component protocols, $P_1, \ldots, P_M$. Each component protocol P_i is assigned a weight w_i and produces a decision $D_{i,t}$, $0 \leq D_{i,t} \leq 1$ that indicates the transmission probability in a given slot t. No assumptions are made concerning how each component protocol reaches its decision. The final decision D_t is computed as a function of the weighted average of the $D_{i,t}$ values:

$$D_t = F\left(\frac{\sum_{i=1}^{M} w_{i,t} D_{i,t}}{\sum_{i=1}^{M} w_{i,t}}\right)$$

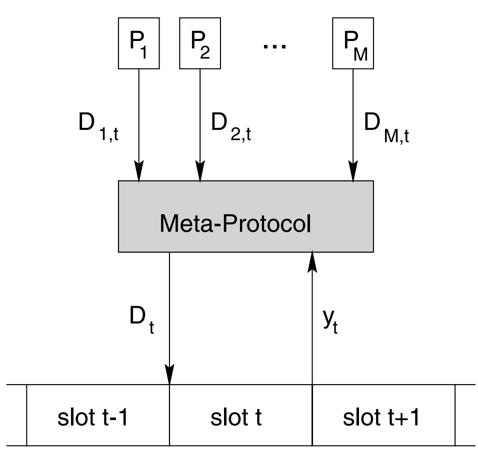

Figure 6.15 The metaprotocol framework.

The function F can be chosen in several ways, but for simplicity we will use $F(x) = x$. The value of D_t is then rounded using randomization to produce a binary decision $\tilde{D}_t$ for slot t.

At the end of each slot, the weights of the component protocols is adjusted according to the channel feedback, from which we can conclude the correctness of the final decision $\tilde{D}_t$. For example, if collision occurs, then a decision to transmit was wrong. Let y_t denote the feedback at the end of slot t, where $y_t = 1$ indicates a correct decision and $y_t = 0$ indicates the opposite. Then the correct decision z_t can be retrospectively computed as

$$z_t = \tilde{D}_t y_t + (1 - \tilde{D}_t)(1 - y_t)$$

Using z_t, the weights are updated according to the following exponential rule

$$w_{i,t+1} = w_{i,t} \cdot e^{-\eta |D_{i,t} - z_t|}$$

The term $|D_{i,t} - z_t|$ represents the deviation of protocol P_i from the correct decision z_t. If there is no deviation, then the weight remains unchanged. Otherwise, the relative weight decreases with increasing deviation. The constant $\eta > 0$ controls the magnitude of the weight change and thus greatly influences the stability and convergence of the metaprotocol. Note that the direct use of equation 6.1 will ultimately cause underflow in the weight representation since the weights decrease monotonically. This problem is easily solved in practice by renormalizing the weights when needed.

Numerous practical applications of the metaprotocol framework demonstrate its capability to dynamically optimize many of the critical parameters of MAC protocols to match the prevailing network conditions [36, 37]. Examples include the manipulation of the transmission probability of contention protocols and the transmission schedules of allocation protocols.

6.7 SUMMARY

The aim of this chapter is to provide a comprehensive view of the role of MAC protocols in wireless systems. We first described the characteristics of wireless systems that affect the design and implementation of MAC protocols. Then we presented some fundamental MAC protocols whose spirit pervades basically all the protocols used today in wireless networks. Specific protocols are then described in detail, based on the specific architecture for which they are deployed (either the centralized architecture typical of cellular systems or the distributed architecture of ad hoc networks).

Our discussion indicates that the problem of designing efficient MAC protocols is a crucial problem in the more general design, implementation, and deployment of wireless networks, in which the demand for bandwidth-greedy application is growing fast and the available RF spectrum is still very narrow.

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Index