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WIRELESS MEDIUM ACCESS CONTROL PROTOCOLS

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ABSTRACT

Technological advances, coupled with the flexibility and mobility of wireless systems, are the driving force behind the Anyone, Anywhere, Anytime paradigm of networking. At the same time, we see a convergence of the telephone, cable and data networks into a unified network that supports multimedia and real-time applications like voice and video in addition to data. Medium access control protocols define rules for orderly access to the shared medium and play a crucial role in the efficient and fair sharing of scarce wireless bandwidth. The nature of the wireless channel brings new issues like location-dependent carrier sensing, time varying channel and burst errors. Low power requirements and half duplex operation of the wireless systems add to the challenge. Wireless MAC protocols have been heavily researched and a plethora of protocols have been proposed. Protocols have been devised for different types of architectures, different applications and different media. This survey discusses the challenges in the design of wireless MAC protocols, classifies them based on architecture and mode of operation, and describes their relative performance and application domains in which they are best deployed.

The ability to communicate with anyone on the planet from anywhere on the planet has been mankind's dream for a long time. Wireless is the only medium that can enable such untethered communication. With the recent advances in VLSI and wireless technologies, it is now possible to build high-speed wireless systems that are cheap as well as easy to install and operate. However, the wireless medium is a broadcast medium, and therefore multiple devices can access the medium at the same time. Multiple simultaneous transmissions can result in garbled data, making communication impossible. A medium access control (MAC) protocol moderates access to the shared medium by defining rules that allow these devices to communicate with each other in an orderly and efficient manner. MAC protocols therefore play a crucial role in enabling this paradigm by ensuring efficient and fair sharing of the scare wireless bandwidth. Wireless MAC protocols have been studied extensively since the 1970s. The initial protocols were developed for data and satellite communications. We are now witnessing a convergence of the telephone, cable and data networks into a single unified network that supports multimedia and real-time applications like voice and video in addition to data. The multimedia applications require delay and jitter guarantees from the network. This demand of the network is known as the Quality of Service (QoS) guarantee. These requirements have led to novel and complex MAC protocols that can support multimedia traffic.

This article surveys the various MAC protocols that have been proposed in the literature and compares them based on architecture (MAC co-ordination, duplexing), performance (throughput, delay, stability, contention resolution algorithms and fairness) and multimedia support (scheduling, access priorities). We confine our study to systems that span relatively small areas. The article is organized as follows. First we contrast different wireless network architectures. We then bring out the issues unique to wireless MAC protocols. The performance metrics used to compare different MAC protocols are discussed later. We then present a classification of the protocols. We will present the different classes of proposed MAC protocols and compare the pros and cons of the proposed protocols.

GENERAL NETWORK CONCEPTS

A wireless network is comprised of devices with wireless adapters communicating with each other using radio waves. These wireless devices are called *nodes* in this dissertation. The signal transmitted can be received only within a certain distance from the sender, which is called the range of the node. A base station (BS) is a special node in the network that is not mobile and is located in a central location. Wireless networks differ in the duplexing mechanism and the network architecture.

Duplexing Choices

The duplexing mechanism refers to how the data transmission and the data reception channels are multiplexed. They can be multiplexed in different time slots or different frequency channels. Time division duplex (TDD) refers to multiplexing of the transmission and reception in different time periods in the same frequency band. Using different frequency bands for uplink and downlink is called the frequency division duplex (FDD) mode of operation. In FDD it is feasible for the node to transmit and receive data at the same time; this is not possible in TDD.

Network Architecture

Based on the network architecture, wireless networks can be logically divided into two classes: distributed and centralized.

Distributed Wireless Networks — Distributed wireless networks, also called ad hoc networks, are wireless terminals communicating with one another with no pre-existing infrastructure in place; therefore, they are also called infrastructure-less networks. A typical ad hoc network is illustrated in Fig. 1a. Wireless terminals have a wireless interface (RF or infrared) and exchange information between one another in a distributed manner. An ad hoc network has no central administration, thus ensuring that the network does not collapse when one of the terminals is powered down or moves away. In a distributed network all data transmission and reception has to be in the same frequency band since there are no special nodes to translate the transmission from one frequency band to another. Therefore all ad hoc networks operate in TDD mode.

Centralized Wireless Networks — Centralized wireless networks, also known as last-hop networks, are extensions to wireline networks with wireless in the last section of the network. These networks have a base station that acts as the interface between wireless and wireline networks. In centralized networks the downlink transmissions (from base station to wireless nodes) are broadcast and can be heard by all the devices on the network. The up link (from wireless terminals to the BS) is shared by all the nodes and is therefore a multiple access channel. The existence of a central node like a BS gives a great degree of flexibility in the design of MAC protocols. The BS can control the uplink transmissions by allowing access according to QoS requirements. The system architecture of a centralized network is shown in Fig. 1b. A centralized network can operate both in TDD mode or FDD mode.

Slotted Systems

The wireless channel is said to be slotted if transmission attempts can take place at discrete instants in time. A slotted system requires network-wide time synchronization, which is easy to achieve in centralized networks by using the BS as a time reference. Such synchronization is difficult in distributed networks. A slot is the basic time unit in a slotted system. It is usually large enough to carry the smallest packet, perhaps a few bytes together with packet overhead such as headers and guard band.

Wireless MAC Issues

The unique properties of the wireless medium make the design of MAC protocols very different from, and more challenging than, wireline networks. The unique properties of wireless systems and their medium are:

FIGURE 1. *System architecture alternatives: distributed and centralized wireless networks.*

Half-Duplex Operation: In wireless systems it is very difficult to receive data when the transmitter is sending data. This is because when a node is transmitting data, a large fraction of the signal energy leaks into the receive path. This is referred to as self-interference The transmitted and received power levels can differ by orders of magnitude. The leakage signal typically has much higher power than the received signal, which makes it impossible to detect a received signal while transmitting data. Hence, collision detection is not possible while sending data and so Ethernet-like protocols cannot be used. Due to the half-duplex mode of operation, the uplink and downlink need to be multiplexed in time (TDD) or frequency (FDD). As collisions cannot be detected by the sender, all proposed protocols attempt to decrease the probability of a collision using collision avoidance principles.

Time Varying Channel: Radio signals propagate according to three mechanisms: reflection, diffraction, and scattering. The signal received by a node is a superposition of time-shifted and attenuated versions of the transmitted signal. As a result, the received signal power varies as a function of time. This phenomenon is called *multipath propagation*. The rate of variation of the channel is determined by the coherence time of the channel. Coherence time is defined as time within which the received signal strength changes by 3 dB [1]. When the received signal strength drops below a certain threshold, the node is said to be in *fade*. Handshaking is a widely used strategy to mitigate time-varying link quality. When two nodes want to communicate with each other, they exchange small messages that test the wireless channel between them. A successful handshake indicates a good communication link between the two nodes.

Burst Channel Errors: As a consequence of the time-varying channel and varying signal strength, errors are more likely in wireless transmissions. In wireline networks, the bit error rates are typically less than 10^{-6} and as a result the probability of a packet error is small. In contrast, wireless channels may have bit-error rates as high as 10^{-3} or higher, resulting in a much higher probability of packet errors. In wireline networks these errors are usually due to random noise. In contrast, the errors on a wireless link occur in long bursts when the node is in fade. Packet loss due to burst errors can be minimized by using one or more of the following three techniques:

- Smaller packets.
- Forward error correcting codes.
- Retransmission methods.

A widely used strategy is to use link-layer retransmissions. Therefore, most protocols have immediate acknowledgments (ACK) to detect packet errors. If an ACK is not received at the end of a transmission, the packet is retransmitted.

Location-Dependent Carrier Sensing: It is well known that in free space, signal strength decays with the square of the

FIGURE 2. *Location-dependent sensing: hidden nodes, exposed nodes, and capture.*

path length [1]. As a result carrier sensing is a function of the position of the receiver relative to the transmitter. In the wireless medium, because of multipath propagation, signal strength decays according to a power law with distance. Only nodes within a specific radius of the transmitter can detect the carrier on the channel. This location-dependent carrier sensing results in three types of nodes in protocols that use carrier sensing.

- **Hidden Nodes**: A hidden node is one that is within the range of the intended destination but out of range of the sender [2]. Consider the case shown in Fig. 2. Node A is transmitting to node B. Node C cannot hear the transmission from A. During this transmission when C senses the channel, it falsely thinks that the channel is idle. If node C starts a transmission, it interferes with the data reception at B. In this case node C is a hidden node to node A. Hence, hidden nodes can cause collisions on data transmission.
- **Exposed Nodes**: Exposed nodes are complementary to hidden nodes. An exposed node is one that is within the range of the sender but out of range of the destination [2]. In Fig. 2, consider the case that node B is attempting to transmit to A. Node C can hear the transmission from B. When it senses the channel, it thinks that the channel is busy. However, any transmission by node C does not reach node A, and hence does not interfere with data reception at node A. In theory, C can therefore have a parallel conversation with another terminal out of range of B and in range of C. In this case, node C is an exposed node to node B. If the exposed nodes are not minimized, the bandwidth is underutilized.
- **Capture**: Capture is said to occur when a receiver can cleanly receive a transmission from one of two simultaneous transmissions, both within its range [2]. In Fig. 2, when nodes A and D transmit simultaneously to B, the signal strength received from D is much higher than that from A, and D's transmission can be decoded without errors in the presence of transmission from A. Capture can improve protocol performance, but it results in unfair sharing of bandwidth with preference given to nodes closer to the BS. Wireless MAC protocols need to ensure fairness under such conditions. Capture models are discussed in [3–5].

PERFORMANCE METRICS

Given the wide range of protocols that have been proposed, it is necessary to understand the metrics that are used to compare the MAC protocols. Delay, throughput, fairness, support for multimedia, and stability are the widely used metrics to compare MAC protocols. Robustness against fading and battery power consumption are additional metrics used to compare wireless MAC protocols. Following is a brief discussion of these metrics:

- **Delay**: Delay is defined as the average time spent by a packet in the MAC queue, i.e., from the instant it is enqueued till its transmission is complete. Delay is a function of protocol and traffic characteristics. Therefore, when comparing protocols, it is necessary to compare them based on the same traffic parameters.
- **Throughput**: Throughput is the fraction of the channel capacity used for data transmission. A MAC protocol's objective is to maximize the throughput while minimizing the access delay. If the average message size is P bits, the average time to transfer a single packet is T secs, and C b/s is the capacity of the channel, then the throughput η is given by $\eta = P/TC$.
- **Fairness**: A MAC protocol is fair if it does not exhibit preference to any single node when multiple nodes are trying to access the channel. This results in fair sharing of the bandwidth [6]. This definition can be biased when traffic with different priorities is handled. When multimedia traffic is supported, fairness is defined as being able to distribute bandwidth in proportion to their allocation.
- **Stability**: Due to overhead in the protocol, the system may be able to handle sustained source loads that are much smaller than the maximum transmission capacity of the channel. A stable system can handle instantaneous loads that are greater than the maximum sustained load when the long-term offered load is less than the maximum.
- **Robustness against Channel Fading**: The wireless channel is time-varying and error-prone. Channel fading can make the link between two nodes unusable for short periods of time. Such link failures should not result in unstable behavior.
- **Power Consumption**: Most wireless devices have limited battery power. Hence, it is important for MAC protocols to conserve power and provide some power saving features.
- **Support for Multimedia**: With the convergence of voice, video, and data networks, it is now necessary for MAC protocols to support multimedia traffic. Protocols require mechanisms to treat packets from various applications based on their delay constraints. Two common methods are access priorities and scheduling. Access priorities provide differentiated service by allowing certain nodes to get access to the network services with a higher probability than others. Scheduling can give delay and jitter guarantees.

CLASSIFICATION OF MAC PROTOCOLS

Figure 3 shows a classification of wireless MAC protocols. Wireless MAC protocols can be broadly classified into two categories, distributed and centralized, according to the type of network architecture for which they are designed. Protocols can be further classified based on the mode of operation into random access protocols, guaranteed access protocols, and hybrid access protocols. In a random access protocol, nodes contend for access to the medium. When only one node makes a transmission attempt, the packet is delivered successfully. When multiple nodes make a transmission attempt, a collision results. Nodes resolve the collisions in an orderly manner according to rules defined by the contention resolution algorithm (CRA). ALOHA was the first protocol proposed for packet radio networks [7, 8], and it is a classic example of a random access protocol. The protocol operates as follows: A node that has data to send transmits it. If the transmission collides with another transmission, it retries after a random period. The maximum throughput of this protocol is 18 percent. If the medium is slotted and transmission attempts are made at the beginning of the slot, the vulnerable period of a transmission is halved, doubling the efficiency of the system [9]. This slotted version of ALOHA is called S-ALOHA.

In a guaranteed access protocol, nodes access the medium in an orderly manner, usually in a round-robin fashion. There are two ways to implement these protocols. One is to use a master-slave configuration, where the master polls each node and the node sends data in response to the poll. These protocols are called polling protocols. The second is to operate in a distributed manner by exchanging tokens. Only the station with the token can transmit data. Each station, after transmitting data, passes the token to the next station. These protocols are called token-passing protocols.

Hybrid access protocols blend the best qualities of the above two protocols to derive more efficient MAC protocols. Most hybrid access protocols are based on request-grant mechanisms. Each node sends a request to the base station indicating how much time or bandwidth is required to send the data currently resident in its buffer. The request is sent using a random access protocol. The base station then allocates an upstream time slot for the actual data transmission and sends a grant to the node indicating that time slot.

Depending on the intelligence at the BS, the hybrid access protocols can be further classified into Random Reservation Access (RRA) protocols and Demand Assignment (DA) protocols. In an RRA protocol, the BS has implicit rules for reserving upstream bandwidth. An example of a rule is: A successful request results in a periodic reservation of an upstream slot. On the other hand, in a DA protocol the BS controls upstream data transmissions according to their QoS requirements. It collects all the requests from the nodes and uses scheduling algorithms to make bandwidth allocations. Even though wireless MAC protocols handle issues very differently from wireline networks, some of the principles in hybrid access protocols are similar to the principles in the protocols developed for hybrid-fiber coax systems [10].

Hybrid access protocols and polling protocols by their mode of operation require a central node. Therefore they fall into the category of centralized MAC protocols. Random access protocols can operate in either architecture. Token passing protocols could be used as distributed protocols but are not because of robustness considerations. Due to the time varying nature of the wireless channel, token loss would be common and token recovery is a huge overhead. As a result, all proposed distributed MAC protocols are random access protocols.

FIGURE 3. *Classification of wireless MAC protocols.*

DISTRIBUTED MAC PROTOCOLS

With the exception of ALOHA, all distributed MAC protocols are based on principles of carrier sensing and collision avoidance. Carrier sensing refers to listening to the physical medium to detect any ongoing transmissions. Recall that location-dependent carrier sensing results in hidden and exposed nodes. Such nodes play a dominant role in CSMA protocols. Collisions that occur at the destination node are not necessarily heard by the sender, so the destination needs to relay feedback to the sender. Consider the example in Fig. 2 when nodes A and C transmit simultaneously to B. This results in a collision at B but not at either A or C. Therefore B has to transmit this collision information back to A and C. However, because wireless transceivers operate in half-duplex mode, nodes cannot listen while transmitting and the feedback information has to be sent using out of band signals or the node has to stop and listen for feedback. As a result most distributed MAC protocols use collision avoidance techniques wherein mechanisms are built into the protocol to minimize the probability of a collision. There are two mechanisms that can be used: the already mentioned out-of-band approach and the handshaking approach. These two approaches are described below.

COLLISION AVOIDANCE MECHANISMS

Collision Avoidance with Out-of-Band Signaling — Busy tone multiple access (BTMA) [11] is an example of a protocol that uses an out-of-band busy tone signal to prevent hidden nodes. Any node that hears an ongoing transmission transmits a busy tone; any node that hears a busy tone does not initiate a transmission. Thus, all nodes in a $2R$ radius of the transmitting node are inhibited from transmitting, where R is the range of the transmitting node. Although this solution eliminates hidden nodes, it increases the number of exposed nodes.

In *receiver initiated – busy tone multiple access* (RI–BTMA) [12], a node transmits a busy tone only after it decodes the transmission and identifies itself as the intended receiver. As a result, only the nodes within radius R of the receiving node are inhibited. In RI-BTMA the destination has to decode and match the destination address to detect a collision. As a result it takes a long time to initiate the busy tone. Therefore, the packet transmission is vulnerable to collision for a duration much longer than the round trip. This results in a higher probability of collision and hence lower throughput. RI-BTMA does not completely eliminate hidden nodes but minimizes exposed nodes.

■ **FIGURE 4.** *Four-way handshaking in DFWMAC.*

Collision Avoidance with Control Handshaking — Multiple access with collision avoidance (MACA) [13] uses a three-way handshake as a solution to the hidden node problem. A node that has data to send transmits a short Request to Send (RTS) packet. All stations within one hop of the sending node hear the RTS and defer their transmissions. The destination responds with a Clear to Send message (CTS). All nodes within one hop of the destination node hear the CTS and also defer their transmissions. On receiving the CTS the transmitting node assumes that the channel is acquired and initiates the data transmission. This handshaking mechanism does not completely solve the hidden terminal problem, but it does prevent it to a large extent. Enhancements to RTS-CTS control handshaking and more complete single-channel solutions can be found in [2, 14, 15]. In these techniques there is a tradeoff between the overhead of handshaking and the number of hidden nodes eliminated.

DISTRIBUTED RANDOM ACCESS PROTOCOLS

The basic operation of any CSMA protocol is as follows: A node that has data to transmit senses the channel for a certain duration before transmitting. If the channel is busy, the node waits a random period and tries to transmit at a later time. If the channel is idle, the node makes an attempt to acquire the channel. Successful acquisition is followed by transmission of the data packet. If the acquisition attempt results in a collision, the colliding nodes try to resolve the collision in an orderly manner. Each packet transmission is then acknowledged by the destination station. Two recently proposed CSMA protocols are discussed here.

Distributed Foundation Wireless MAC (DFWMAC) — DFWMAC [16] is a derivative of the MACA protocol. It is the basic access protocol in the recently standardized IEEE 802.11 wireless LAN standard. The DFWMAC protocol consists of a four-way exchange, RTS-CTS-DATA-ACK. The handshaking is illustrated in Fig. 4. When a node (sender) has data to transmit, it picks a random wait period. This wait period is decremented when the channel is idle. When this period expires, the node tries to acquire the channel by sending a RTS packet. The receiving node (destination) responds with a CTS packet indicating that it is ready to receive the data. The sender then completes the packet transmission. If this packet is received without errors, the destination node responds with an ACK. If an ACK is not received, the packet is assumed to be lost and retransmitted. If the RTS fails, the node attempts to resolve the collision by doubling the wait period. This contention resolution method is called binary exponential backoff (BEB). To give preference to a station trying to send an ACK, different waiting intervals are specified. A node needs to sense the channel idle for a *Distributed Inter-Frame Space* (DIFS) interval before making an RTS attempt and a *Short Inter-Frame Space* (SIFS) interval before sending an ACK packet. Since the SIFS interval is shorter than the DIFS interval, the station sending an ACK attempts transmission before a station attempting to send data and hence takes priority. In addition to the physical channel sensing, virtual carrier sensing is achieved by using time fields in the packets, which indicate to other nodes the duration of the current transmission. This time field is called the *Network Allocation Vector* (NAV) field, which indicates the duration of the current transmission. All nodes that hear the RTS or CTS message back off *NAV* amount of time before sensing the channel again. A detailed description of the protocol can be found in [17, 16]. Performance and stability of the protocol are discussed in [18–20]. Improvements to DFWMAC are proposed in [21].

Elimination Yield – Non-Preemptive Priority Multiple Access (EY–NPMA) — EY–NPMA [22] is the channel access protocol used in the HIPERLAN system being developed in Europe. HIPERLAN is a high-speed (24 Mb/s) wireless LAN standard for distributed networks. The protocol operates as follows: A node that has data to transmit senses the medium for a period corresponding to the time it takes to transmit 1700 bits. If no transmission is heard the channel is considered idle and the node can start transmitting its packet immediately. If the channel is busy the node synchronizes itself at the end of the current transmission interval and contends for the channel according to rules described below. The access protocol is illustrated in Fig. 5. The channel access has three phases: prioritization phase (the priority is decided), contention phase (nodes of the same priority contend and one station wins), and transmission phase (succeeding station completes the data transmission). The contention phase consists of two sub-phases: elimination phase and yield phase. In the elimination phase each node transmits for a random number of slots (the random number is picked according to a geometric distribution). At the end of the elimination phase, the node turns around and listens to the channel. If the channel is busy, it aborts its transmission attempt. If the channel is idle the node moves to the yield phase. In this phase it listens to the channel for a random number of slots. If no transmission is detected during this time, the station starts and completes its data transmission. The distributions for the random numbers are chosen such that the probability of a single transmission at the end of contention phase is very large (close to 1). The priority of a packet is derived from its *normalized MPDU residual lifetime* (NMRL). NMRL is the time that the packet has been in the queue waiting to be transmitted. The more the packet is delayed, the higher is its priority. A detailed description and analysis of the EY–NPMA protocol can be found in [19, 23–25].

CENTRALIZED MAC PROTOCOLS

Centralized MAC protocols are MAC protocols wherein the arbitration and complexity are moved into the base station. The base station has explicit control on who and when they access the medium. Because of the central location of the BS, it is assumed that all nodes can talk to and hear from the BS. Hence hidden and exposed nodes do not exist. Further, all communications must go through the base station.

FIGURE 5. *Access phase in EY-NPMA.*

CENTRALIZED RANDOM ACCESS PROTOCOLS

Idle Sense Multiple Access (ISMA) — ISMA [26] is a contention-based access protocol for a centralized wireless network. In ISMA carrier sensing and collision detection are performed by the BS. The operation of the protocol is illustrated in Fig 6. When the medium is idle, the BS broadcasts an idle signal (IS). All nodes that have data to send transmit with a probability *p*. If two or more nodes transmit, a collision results. The BS cannot decode either transmission and so it broadcasts an IS again. If a single transmission is received, the BS broadcasts an IS with acknowledgment (ISA) which serves as an acknowledgment for the previous transmission and an idle signal for the next transmission attempt.

It can be seen in Fig. 6a that in ISMA when a collision occurs a complete packet is lost, resulting in poor efficiency. Reservation ISMA [27] avoids such collisions by using reservation packets, which are very short packets. In R-ISMA (Fig. 6b) a node sends a reservation packet (RP) in response to an IS signal. If a collision occurs, a small reservation packet is lost. This can be seen in Fig. 6 where two reservation attempts are made in part (b), the same time wasted due to collision in part (a). When the BS receives a reservation request, it sends a polling signal (PS) to that node. Only the polled node is allowed to transmit a data packet. ISMA and R-ISMA time-duplex the uplink and downlink transmissions. Slotted ISMA (S-ISMA) [28, 29] is a frequency duplex version of ISMA protocol. A performance analysis of these three protocols can be found in [30–33].

Randomly Addressed Polling (RAP) — RAP [34] is a contention-based access protocol. A contention attempt consists of transmitting a pseudo- random number (code) during the contention period. These codes are chosen such that they are mutually orthogonal. All the nodes transmit their chosen random numbers simultaneously. This allows the BS to decode multiple transmissions and receive all the codes that were transmitted. Therefore, RAP protocols require special hardware (CDMA receiver) to be able to decode several parallel contention requests. However, this CDMA receiver is used only during the contention phase.

The protocol is illustrated in Fig. 7a. In the contention phase, all active nodes choose a code and transmit it in the same time slot. In the example, three codes (a, c, e) are chosen. The BS identifies all the codes that were transmitted. It then sends a poll for each code that was received. All nodes that picked that particular code transmit their data packet in response to the poll. If a single node had chosen the code, the transmission is successful and the BS sends an ACK. When more than one node choses the same code, a collision occurs and a NACK message is sent. When all the received codes have been polled, the BS starts another contention phase. In the example, code a was chosen by a single node and it resulted in useful data transfer. Code c was chosen by two or more nodes, which results in a collision and the complete transmission is lost.

R-RAP [35] modifies the RAP protocol with a reservation mechanism to support stream traffic. If a node has stream traffic, and transmits successfully using the code *r*, this code is reserved for that node for the duration of the call and removed from the set of available random numbers. In RAP, each packet has to contend for the channel independently. Noting this, GRAP improves on RAP [36]. It uses a superframe consisting of $N_R + 1$ RAP frames named G_0, G_1 … G_{N_R} where N_R is the total number of codes. This is illustrated in Fig. 7b. New arrivals are allowed to transmit only in the last frame G_{N_R}. A node that used a code *r* to transmit successfully

FIGURE 6. *Operation of ISMA and r-ISMA protocols.*

FIGURE 7. *Illustration of the RAP protocol.*

in the previous super-frame transmits in frame G_r. GRAPO [37] improves the efficiency of GRAP by dynamically changing the number of groups in a super-frame $Q \leq N_R$. The R-GRAP [36] protocol allows nodes to reserve a particular code in a specific frame of the super frame. This reservation mechanism supports stream traffic.

Resource Auction Multiple Access (RAMA) — RAMA [38, 39] is a random access protocol that achieves resource assignment using a deterministic access algorithm (Fig. 8). Each node has a *b-bit ID*, and collision resolution is based on symbol-by-symbol transmission of this ID. In the contention phase, each node transmits its ID symbol-by-symbol. The BS broadcasts the symbol it heard to all the nodes. If this symbol does not match the symbol that the node transmitted, it drops out of contention. Consider an example where node A with ID 110 and node B with ID 101 are contending for access to the channel. In the first round, both A and B transmit '1' and the BS acknowledges '1'. In the second round, A transmits '1' and B transmits '0'. The channel performs an OR operation on the signals transmitted. As a result the BS receives and acknowledges '1'. As a result, B drops out of contention. This process continues till the complete ID is sent. Exactly b rounds later, the node with the highest ID always wins the contention. It then transmits the data packet.

In RAMA, if a node has data to transmit, the communication slot never goes unused. Therefore, it achieves the maximum efficiency excluding the overhead. However, the overhead can be as high as 10 percent for a 1 Mb/s channel, 53-byte ATM cell and a round trip time of 4 µs. This overhead increases as the data rate increases because of the per-symbol switching involved in collision resolution. The RAMA protocol is unfair, as the node with the highest ID *always* wins the contention. It is possible to starve other nodes of service. Random access protocols using p-persistence require *e* attempts for making a successful transmission. If *b* is greater than *e*, RAMA is less efficient than random access protocols.

The fairness problem is addressed in the F-RAMA (Fair-RAMA) [40] protocol. F-RAMA proposes that the BS select one of the received symbols randomly, instead of the highest symbol. However, due to the OR operation of the channel, it is not clear how the different symbols can be distinguished.

Summary of Random Access Protocols — Five handshaking protocols, two for ad hoc networks and three for centralized networks, have been presented. Table 1 contrasts the performance and features of these protocols. The performance results are taken from the respective references indicated in Table 1. It is important to remember that each protocol has been studied at a different data rate. The lower throughput of EY-NPMA can be attributed to its prioritized CRA. Delay refers to the average delay at 90 percent maximum throughput.

GUARANTEED ACCESS PROTOCOLS

The polling protocol is the only class of guaranteed access protocol that has been studied in the context of wireless networks. The main design goal of the polling protocols is to

FIGURE 8. *Description of the RAMA protocol.*

minimize the waste of bandwidth caused by channel outage. The channel is tested with a control handshake. A successful handshake ensures a good channel exists between the node and the BS.

Zhang's Proposal — In this protocol [41] the BS polls all the nodes in a round-robin fashion for transmission requests. The protocol operation is illustrated in Fig. 9a. A node responds with a request when it has outstanding data, or a *KEEP ALIVE* message when the queue is empty. This poll-request handshake ensures a good communication channel between the BS and node. The BS then polls nodes for data according to the requests received. Zhang proposes that all nodes be polled once every T secs, where T is the coherence time of the channel, the logic being that after a time T the channel is likely to have changed sufficiently to affect the data transmission and hence the channel needs to be re-sampled.

Parameter	DFWMAC [19]	EY-NPMA [19]	ISMA [31]	RAP [34]	RAMA [39]
Co-ordination	Ad-hoc	Ad-hoc	Central	Central	Central
Duplex	TDD	TDD	TDD/FDD	TDD	FDD
Throughput	0.7	0.45	0.75	0.8	0.84
Delay	10ms	20ms	10ms	5ms	–
CRA	Exponential backoff	Geometric backoff	p-persistence	Random backoff	Deterministic
Fairness	Unfair	Unfair	Fair	Fair	Unfair
Power saving	Yes	Yes	–	–	–
Hidden node	RTS-CTS	No	–	–	–
Access priority	Yes	Yes	No	No	Yes
QoS	No	Partial	No	No	No

Table 1. *Comparison of random access protocols.*

Disposable Token MAC Protocol (DTMP) — DTMP modifies this poll-request-poll-data cycle with just a poll-data cycle, thereby eliminating the need to poll all nodes within time T [42]. The operation of the protocol is shown Fig 9b. In DTMP, when the BS transmits a poll it also indicates if the BS has data for this node. If the BS indicated that it has no data for it and the node has no data to send, it remains silent. If the BS has data for it, the node sends a short message. The BS then sends the data. When the node has data in its buffers, it sends data in response to the poll. It is assumed in this protocol that the channel is reciprocal, i.e., if a node hears a poll from the BS, then the BS can also hear any transmission from that node. This is usually true in a TDD system when the time between the uplink and downlink transmission is less than the coherence time of the channel, but not necessarily true for an FDD system.

Acampora's Proposal — Recently, Acampora proposed a polling protocol for smart antenna systems [43]. As shown in Fig. 9c, the protocol operates in three phases: polling phase, request phase, and data phase. One interesting feature in this proposal is the manner in which polling is performed. The BS first identifies all active nodes by polling them with a codeword (unique to a node). The node remains silent if it has no packets to send. An active node echos this codeword back if it has data to transmit. The BS then broadcasts the codeword back so that every node knows the number and order of the active nodes. In the request phase all the active nodes send their requests in order to the BS. The BS polls the nodes for data during the data transmission phase.

Summary of Polling Protocols — The performance of the three protocols is very similar. The reported performance of the three protocols is the same for error-free channels. These protocols do not support QoS and multimedia applications.

Hybrid Access Protocols

Hybrid protocols bridge the space between statistical access with the random access protocols and deterministic access in the polling protocols by merging the best features of both types of protocol. Based on the scheduling and reservation policies imposed by the BS, these protocols can be further classified into two classes: Random Reservation Access (RRA) protocols and Demand Assignment protocols (Fig 3), both of which have been widely researched.

Random Reservation Protocols (RRA) — RRA protocols try to achieve stochastic multiplexing of data on TDMA systems and have been studied in the context of supporting data services over cellular-type networks. The uplink is a time-slotted multiple access channel that is organized into frames. Figure 10 illustrates the framing details. The length of the frame is chosen such that a single voice packet is generated per frame. Each time slot is large enough to carry one voice packet. A data packet is also one slot long. The downlink from BS to nodes is a broadcast channel.

Every RRA protocol has two components: random access and reservation. All nodes that have data to transmit use a random access protocol to make their first transmission. p-persistence and S-ALOHA are widely used random access protocols because they do not need state information. There is a second factor: reservation describes the policy enforced by the BS to reserve uplink slots for nodes that have successfully contended for the channel. The policies range from voice stream reservation to complete scheduling by the BS. RRA protocols with scheduling are similar to demand assignment protocols.

Packet Reservation Multiple Access (PRMA) — PRMA [4, 44] was proposed to multiplex speech and data on cellular networks. In PRMA a voice node with a backlogged packet transmits in a vacant slot with a probability p. A successful voice packet reserves that slot for the following packets in the stream till the end of talk spurt [45]. A data node also contends similarly. No reservation is made for a successful data node. In Fig. 10, a successful voice transmission occurs in slot 4 of frame K, and this slot is reserved for this voice traffic in the next frame. Similarly, in slot 5 a data node contends successfully but no reservation is made. To give preference to voice traffic, different access probabilities are used for voice and data [45].

Wong and Goodman [44] allow data transmissions to reserve a limited number of slots to improve efficiency and decrease contention. A maximum reservation threshold prevents long bursts from one node and avoids starving other nodes of service. Analyses of PRMA can be found in [44, 46, 47]. It was shown in [45] that the introduction of data nodes

FIGURE 9. *Description of the polling protocols.*

FIGURE 10. *Upstream frame structure of PRMA and its operation.*

in a voice-only system decreases the performance of PRMA. Frame reservation multiple access (FRMA) [48] separates the voice and data subsystems. A frame contains voice slots and data slots. Only voice nodes are allowed to contend for the voice slots and data nodes for data slots. The ratio of the number of data and voice slots is dynamically adjusted from frame to frame, under the constraint of bounding the voice packet dropping probability by one percent.

In PRMA, the request and data channel are the same. When a large number of nodes are contending and a large fraction of slots are reserved, little bandwidth is left for contention, which makes the protocol unstable. *PRMA++* separates the request and data channels [49]. In an uplink frame, a few slots are designated as request slots and the rest are information slots. All nodes contend in request slots using S-ALOHA. The BS queues the successful requests and provides a grant in an information slot. Mitrou [50] pointed out that using a full slot to make a reservation is wasteful and proposed sub-dividing a request slot into mini-slots to increase the efficiency of contention. Centralized PRMA (C-PRMA) uses scheduling to give QoS guarantees [51]. Nodes use the random access slots to send their QoS requirements to the BS. The BS schedules the uplink transmissions, taking into account different traffic rates and delay constraints. The

FIGURE 11. *Details of the DQRUMA protocol.*

scheduling algorithm grants the next transmission opportunity to the node that has the closest deadline. This is also called earliest due date (EDD) scheduling. Even though C-PRMA is an extension to the PRMA protocol, it is a demand assignment protocol because of the scheduling functionality.

Random Reservation Access – Independent Stations Algorithm (RRA–ISA) — RRA-ISA proposes a different access policy, using *Independent Stations Algorithm* [52, 53]. This algorithm tries to distribute access rights (i.e., the right to transmit in a slot) among nodes so as to maximize the throughput from slot to slot. This algorithm can be thought of as the BS polling a subset of nodes, where the subset is chosen such that the probability of a single transmission in a slot is maximized. Using the past channel history, the

Parameter	PRMA [4]	RRA-ISA [53]	C-PRMA [51]	FRMA [48]
MAC co-ordination	Central	Central	Central	Central
Duplex operation	FDD	TDD/FDD	FDD	TDD
Voice calls	38	41	44	36
Data delay	1.6s	32ms	–	40ms
CRA	p-persistence	Group polling	S-ALOHA	p-persistence
Priority in access	Yes	Yes	No	Yes
QoS	No	Parital	Yes	Voice only
Multimedia data	Voice	Voice	Voice	Voice
Scheduling algorithm	None	None	EDD like	None

Table 2. *Comparison of random reservation protocols.*

Parameter	DQRUMA [54]	MASCARA [55]	DSA++ [56]
MAC co-ordination	Central	Central	Central
Duplex operation	FDD	TDD	FDD
Maximum throughput	0.92	0.78	0.82
Average delay	10 slots	300 slots	10 slots
CRA	Binary stack algo	Slotted aloha	Ternary splitting
QoS	Yes	Yes	Yes
Multimedia data	Any	Any	Any
Scheduling algorithm	GBMD	PRADOS	Hueristic

Table 3. *Comparison of the demand assignment protocols.*

BS computes the probability that a node has a packet to transmit and uses the probability to come up with the set of users to poll. If the upstream traffic can be well characterized, the BS can make a good prediction as to which nodes are likely to have traffic and can poll these nodes. As a result, the capacity wasted due to collisions can be minimized and efficiency can be improved.

Summary of RRA Protocols — Table 2 contrasts the different RRA protocols that have been proposed. The performance of these protocols is compared based on the number of voice calls that can be supported on a 720 kb/s upstream channel. This has been a common metric to compare RRA protocols. The voice source model is modeled as a two-state Markov model and includes features such as silence suppression. The delay shown in the table is the delay experienced by data traffic, when the number of calls is 90 percent of the maximum that can be supported by that particular protocol. FRMA and C-PRMA are modifications to PRMA and they perform better. The RRA-ISA protocol performs better than PRMA when the number of nodes is small. As the number of nodes increases, the performance is very similar to PRMA.

Demand Assignment Protocols — Demand assignment protocols try to allocate bandwidth to nodes according to their QoS requirements. Wireless ATM, where end-to-end QoS is an important design goal, has been the motivation for these protocols. However these principles are valid for any centralized packet radio network. It is difficult to satisfy QoS requirements of delay-sensitive real-time applications with random access protocols, because every packet has to contend for access. The time required to resolve collisions is a function of the load on the network, and bounded delay and jitter are difficult to guarantee. Such guarantees can be typically achieved by having a central node collect the requirements and schedule transmissions for each node so as to match the requirements against available resources.

There are three phases to a demand assignment protocol: request, scheduling, and data transmission. The request channel, which is typically a random access channel, is used by the nodes to send the node's QoS requirements to the BS. Additional requests can be piggy-backed with data transmissions. This reduces the contention on the request channel. Using these requests, the BS schedules uplink transmissions using a scheduling algorithm. The nodes transmit their data, contention-free, in the scheduled transmission slot.

Distributed-Queuing Request Update Multiple Access (DQRUMA) — In DQRUMA [54] the uplink and downlink are frequency duplexed. Protocol details are illustrated in Fig. 11a. The uplink consists of a request channel and a packet-transmission channel. The request channel is used to send contention requests; the data channel to send data. The data channel is also used to piggyback additional requests when the buffers are non-empty. The downlink slot carries three messages. The ACK message acknowledges the contention request in the current uplink slot. The transmit-permission carries a grant for the node that is allowed to use the next uplink slot. The third message is data from the BS to one of the nodes.

When a node receives a packet, it sends a request to the BS on the request channel using a random access protocol. The BS receives the request and adds it to a list of outstanding requests. It acknowledges the receipt of the request by broadcasting the ID of the node on the downlink ACK channel in the immediate downlink slot. A node knows the result of the contention request in the current slot before the beginning of the next slot (Fig. 11a). If a collision occurs, it shall attempt to send the request again after waiting a random period. After the request is successful, the node listens to the downlink for a permission to transmit. When transmitting data, the node sets the piggybacking bit to indicate that it has more packets in its buffer. The BS adds the piggyback to its list of outstanding requests. It is shown in [54] that DQRUMA has better performance than RAMA and PRMA with guaranteed bandwidth and minimum delay (GBMD) scheduling.

Mobile Access Scheme based on Contention and Reservation for ATM (MASCARA) — MASCARA [55] is the MAC protocol designed for the MAGIC Wireless ATM Network Demonstrator project. MASCARA uses variable-length time frames. Each variable-length time frame consists of three periods: broadcast, reserved, and contention. This is shown in Fig. 11b. The broadcast period is used to tell all nodes the structure of the current time frame and the scheduled uplink transmissions. The reserved periods consists of a down-period in

	RA	RRA	DA	Polling
Infrastructure	Last hop/ad-hoc	Last hop	Last hop	Last hop
Number of nodes supported	Large	Medium	Medium	Small
Performance Delay@low loads	Good	Medium	Medium	Medium
Delay@high load	Medium	Medium	Good	Medium
Message size	Variable	Fixed	Fixesd	Variable
Multimedia support	Priorities	Priorities	Scheduling	No
Power saving	Yes	Yes	Yes	Possible
Link state information	Yes	No	No	Yes
Complexity	Low	Low	High	Low

Table 4. *Comparison of different classes of protocols.*

Metric/ protocol	Network architecture	Duplexing	CRA	Robust-ness	Stable	Fair	Power saving	Hidden nodes	Mutlimedia support
DFWMAC	Distributed	TDD	BEB	Good	Yes	No	Yes	Solve	Access priority
EY-NPMA	Distributed	TDD	Geometric	Medium	Yes	No	Yes	Not addressed	Access priority
R-ISMA	Centralized	TDD	p-persistence	Medium	No	Yes	No	N/A	None
RAP	Centralized	TDD/FDD	S-ALOHA	Good	No	Yes	No	N/A	Reservation
RAMA	Centralized	TDD	Deterministic	Good	No	Yes	No	N/A	Access priority
PRMA	Centralized	TDD/FDD	S-ALOHA	Good	No	No	No	N/A	Access priority
RRA-ISA	Centralized	TDD/FDD	None	Good	Yes	Yes	No	N/A	Group polling
DQRUMA	Centralized	TDD/FDD	S-ALOHA	Good	Yes	Yes	No	N/A	Scheduling
MASCARA	Centralized	TDD	S-ALOHA	Medium	Yes	Yes	No	N/A	Scheduling
DTMP	Centralized	FDD	None	Good	Yes	Yes	No	N/A	None

Table 5. *Summary of wireless MAC protocols.*

which the BS transmits the downlink data and an up-period when the nodes transmit packets in the order as defined by the BS at the start of the frame. The contention period is used to send new requests to the BS. The length of each period can be adjusted dynamically. Nodes use S-ALOHA to send the bandwidth requests to the BS. The BS collects all the requests and makes slot assignments using the Prioritized Regulated Allocation Delay-oriented Scheduling (PRADOS) algorithm, which is based on the leaky bucket token scheme [55].

Dynamic Slot Assignment ++ (DSA++) — Mobile broadband systems are being developed for wideband radio communications in the 60 GHz band using DSA++ [56]. The MAC on the uplink is based on a fixed TDMA structure, as shown in Fig. 11c. Uplink and downlink are slotted. An uplink slot carries ATM cells. Each downlink slot contains a data portion and a MAC message. The MAC message in the current slot (k) contains an acknowledgment for the transmission in the previous uplink slot (k–1) and a reservation for the next uplink slot (k+1). Some of the slots are marked as contention slots. A contention slot is a data slot sub-divided into contention mini-slots. The BS collects all the requests and schedules uplink transmissions. For determination of the slot assignments, the BS must take into account the connection-specific parameters such as mean data rate and peak data rate, as well as the short-term and dynamically-changing parameters such as current queue length and waiting period of the first cell in the input queue. The transmissions are scheduled using a heuristic algorithm. This algorithm prioritizes the requests and assigns the next slot to the node with the highest priority.

Summary of Demand Assignment Protocols — Demand assignment protocols outperform other protocols and support multimedia traffic. Table 3 compares the performance and features of the three demand assignment protocols discussed above. DQRUMA has the best throughput. The higher delay shown by the MASCARA protocol is due the TDD mode of operation. Both DQRUMA and DSA++ assume fixed size messages. The rigid framing structure and the tight coupling between the uplink and downlink timing prevents the use of these protocols in variable-length packet systems. MASCARA, on the other hand, does not have such limitations.

COMPARISON

It is difficult to compare the different MAC protocols. Each has been developed with a different architecture and application in mind. Here we summarize the advantages and disadvantages of the different classes of protocols. This comparison is shown in Table 4. The choice of a particular protocol is a function of network architecture, number of nodes, type of service required, and physical-layer constraints. Two different approaches have been followed to support multimedia traffic. In the first case, traffic is separated into classes and each class of traffic is treated separately by assigning different priorities. In the second approach, which is applicable only to centralized networks which have a controlling node such as a base station, QoS guarantees are given by careful admission control and scheduling of uplink transmissions. Demand assignment protocols are best suited for supporting multimedia with QoS. These protocols have the overhead of connection establishment and call admission. The BS needs to be robust as it is the single point of failure and should also be powerful enough to schedule a large set of requests with diverse constraints in real-time. Such scheduling is computation-intensive. Random access protocols are robust and can multiplex a large number of nodes. With access priorities, partial QoS can be given, which might be acceptable for many multimedia applications. However, unbounded delay and jitter might prohibit some applications. RRA protocols are halfway between random and demand assignment protocols and can support voice efficiently. Polling protocols are efficient when the size of the network is small. These protocols also have advantages when used with smart antenna arrays. Since we know *a priori* which node would be transmitting, the antenna coefficients can be used to point a beam toward that node. The poll response can be used for channel equalization and training the array [43]. The polling protocols proposed do not support multimedia data and QoS. If we were to compare the performance of the protocols at higher data rates, all TDD protocols perform poorly because of the constant switching (between transmit mode and listen mode) times in wireless transceivers [57]. Table 5 summarizes the features present in different protocols. Different protocols proposed have been tabulated based on the performance metrics discussed earlier, namely: network architecture, duplexing, contention resolution algorithms, robustness, fairness, power saving features, and how they support multimedia applications.

CONCLUSIONS

Wireless medium access control protocols have been extensively studied since the 1970s. The design of these protocols must take into consideration issues such as time-varying channel, bursty errors, and localized carrier sensing, which makes it a challenging problem. We have classified the protocols first on the basis of their network architecture into distributed and centralized MAC protocols. These protocols can be further classified into random access, guaranteed access, and hybrid protocols based on the mode of operation. Random access protocols are very efficient in multiplexing a large number of bursty sources. Hybrid protocols can give network guarantees and can support multimedia applications.

Most MAC protocols have been analyzed assuming error-free channels. It is interesting to study the performance of different MAC protocols in fading-channel and bursty-error environments. The design of high-speed distributed wireless protocols is another area that needs significant research. It is an additional challenge to provide Quality of Service in these networks.

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