UNIT-III
MAC PROTOCOLS FOR WIRELESS SENSOR NETWORKS


3.1 INTRODUCTION:
Nodes in an Ad-hoc wireless network share a common broadcast radio channel. Since the radio spectrum is limited, the bandwidth available for communication in such networks is also limited. Access to this shared medium should be controlled in such a manner that all nodes receive a fair share of the available bandwidth, and that the bandwidth is utilized efficiently. Characteristics of the wireless medium are completely different from wired medium. So a different set of protocols is required for controlling access to the shared medium in such networks. This is achieved by using Medium Access Control (MAC) protocol.

3.2 ISSUES IN DESIGNING A MAC PROTOCOL FOR AD HOC WIRELESS NETWORKS
The following are the main issues that need to be addressed while designing a MAC protocol for Ad-hoc wireless networks.

3.2.1 Bandwidth Efficiency: Since the radio spectrum is limited, the bandwidth available for communication is also very limited. The MAC protocol must be designed in such a way that to maximize this bandwidth efficiency (the ratio of the bandwidth used for actual data transmission to the total available bandwidth). That is the uncommon bandwidth is utilized in an efficient manner.

3.2.2 Quality of Service Support(QoS): Providing QoS support to data sessions in Ad-hoc networks is very difficult due to their characteristic nature of nodes mobility. Most of the time, Bandwidth reservation made at one point of time may become invalid once the node moves out of the region. The MAC protocol for Ad-hoc wireless networks that are to be used in such real-time applications must have resource reservation mechanism take care of nature of the wireless channel and the mobility of nodes.

3.2.3 Synchronization: The MAC protocol must take into consideration the synchronization between nodes in the network. Synchronization is very important for bandwidth (time slot) reservations by nodes achieved by exchange of control packets.

3.2.4 Hidden and Exposed Terminal Problems: The hidden terminal problem refers to the collision of packets at a receiving node due to the simultaneous transmission of those nodes. The exposed terminal problem refers to the inability of a node, which is blocked due to transmission by a nearby transmitting node, to transmit to another node.

3.2.5 Mobility of Nodes: This is a very important factor affecting the performance (throughput) of the protocol. The MAC protocol obviously has no role to play in influencing the mobility of the nodes.

3.2.6 Error-Prone Shared Broadcast Channel: Due to broadcast nature of the radio channel (transmissions made by a node are received by all nodes within its direct transmission range) there is a possibility of packet collisions is quite high in wireless networks. A MAC protocol should grant channel access to nodes in such a manner that collisions are minimized.

3.2.7 Distributed Nature/Lack of Central Coordination: Ad hoc wireless networks do not have centralized coordinators because nodes keep moving continuously. Therefore, nodes must be
scheduled in a distributed fashion for gaining access to the channel. The MAC protocol must make sure that the additional overhead, in terms of bandwidth consumption is not very high.

![Hidden and Exposed node problems](image)

**Figure 3.1 Hidden and Exposed node problems**

### 3.3 DESIGN GOALS OF A MAC PROTOCOL FOR AD-HOC WIRELESS NETWORKS:

The following are the important goals to be met while designing a medium access control (MAC) protocol for ad hoc wireless networks:

1. The operation of the protocol should be distributed.
2. The protocol should provide QoS support for real-time traffic.
3. The access delay, which refers to the average delay experienced by any packet to get transmitted, must be kept low.
4. The available bandwidth must be utilized efficiently.
5. The protocol should ensure fair allocation of bandwidth to nodes.
6. Control overhead must be kept as low as possible.
7. The protocol should minimize the effects of hidden and exposed terminal problems.
8. The protocol must be scalable to large networks.
9. It should have power control mechanisms.
10. The protocol should have mechanisms for adaptive data rate control.
11. It should try to use directional antennas.
12. The protocol should provide synchronization among nodes.

### 3.4 CLASSIFICATIONS OF MAC PROTOCOLS:

MAC protocols for ad hoc wireless networks can be classified into several categories based on various criteria such as initiation approach, time synchronization, and reservation approaches. Ad hoc network MAC protocols can be classified into three basic types:

a. Contention-based protocols
b. Contention-based protocols with reservation mechanisms
c. Contention-based protocols with scheduling mechanisms

Apart from these three major types, there exist other MAC protocols that cannot be classified clearly under any one of the above three types of protocols.
3.4.1 Contention-based protocols:
These protocols follow a contention-based channel access policy. Whenever it receives a packet to be transmitted, it contends with its neighbor nodes for access to the shared channel. Contention-based protocols cannot provide QoS guarantees to sessions since nodes are not guaranteed regular access to the channel. Random access protocols can be further divided into two types:
1. **Sender-initiated protocols**: Packet transmissions are initiated by the sender node.
2. **Receiver-initiated protocols**: The receiver node initiates the contention resolution protocol.
Sender-initiated protocols can be further divided into two types:
   a. **Single-channel sender-initiated protocols**: In these protocols, the total available bandwidth is used as it is, without being divided. A node that wins the contention to the channel can make use of the entire bandwidth.
   b. **Multichannel sender-initiated protocols**: In multichannel protocols, the available bandwidth is divided into multiple channels. This enables several nodes to simultaneously transmit data, each using a separate channel. Some protocols dedicate a frequency channel exclusively for transmitting control information.

3.4.2 Contention-Based Protocols with Reservation Mechanisms
Ad hoc wireless networks sometimes may need to support real-time traffic, which requires QoS guarantees to be provided. In contention-based protocols, nodes are not guaranteed periodic access to the channel. Hence they cannot support real-time traffic. In order to support such traffic, certain protocols have mechanisms for reserving bandwidth a priori. Such protocols can provide QoS support to time-sensitive traffic sessions. These protocols can be further classified into two types:
1. **Synchronous protocols**: Synchronous protocols require time synchronization among all nodes in the network, so that reservations made by a node are known to other nodes in its neighborhood. Global time synchronization is generally difficult to achieve.
2. **Asynchronous protocols**: They do not require any global synchronization among nodes in the network. These protocols usually use relative time information for effecting reservations.
3.4.3 Contention-Based Protocols with Scheduling Mechanisms

Node scheduling is done in a manner so that all nodes are treated fairly and no node is starved of bandwidth. Scheduling-based schemes are also used for enforcing priorities among flows whose packets are queued at nodes. Some scheduling schemes also take into consideration battery characteristics, such as remaining battery power, while scheduling nodes for access to the channel.

3.4.4 Other Protocols

There are several other MAC protocols that do not strictly fall under the above categories.

3.5 CONTENTION-BASED PROTOCOLS:

These protocols follow a contention-based channel access policy. Whenever it receives a packet to be transmitted, it contends with its neighbor nodes for access to the shared channel. Contention-based protocols cannot provide QoS guarantees to sessions since nodes are not guaranteed regular access to the channel. Random access protocols can be further divided into two types:

1. **Sender-initiated protocols**: Packet transmissions are initiated by the sender node.
2. **Receiver-initiated protocols**: The receiver node initiates the contention resolution protocol.

3.5.1 Sender-initiated protocols: These are further divided into two types:

I. **Single-channel sender-initiated protocols**: In these protocols, the total available bandwidth is used as it is, without being divided. A node that wins the contention to the channel can make use of the entire bandwidth.

   *Examples*: MACAW, FAMA

a) **MACAW**: Multiple Access Collision Avoidance for Wireless

A Media Access Protocol for Wireless LANs is based on MACA Protocol.

**MACA Protocol**:

- When a node wants to transmit a data packet, it first transmits a RTS (Request To Send) frame.
- The receiver node, on receiving the RTS packet, if it is ready to receive the data packet, transmits a CTS (Clear to Send) packet.
- Once the sender receives the CTS packet without any error, it starts transmitting the data packet.
- If a packet transmitted by a node is lost, the node uses the Binary Exponential Back-off (BEB) algorithm to back-off a random interval of time before retrying. The problem is solved by MACAW.

![Figure 3.3 Packet transmission in MACA](image)
**MACA Examples:**

1. MACA avoids the problem of hidden terminals
   - A and C want to send to B
   - A sends RTS first
   - C waits after receiving CTS from B

2. MACA avoids the problem of exposed terminals
   - B wants to send to A, C to another terminal
   - Now C does not have to wait for it cannot receive CTS from A

**MACA Protocol:**
MACA for Wireless is a revision of MACA.
- **The sender** transmits a **RTS (Request To Send)** frame if no nearby station transmits a RTS.
- **The receiver** replies with a **CTS (Clear To Send)** frame.
- **Neighbors**
  - Can see CTS, then keep quiet.
  - Can see RTS but not CTS, then keep quiet until the CTS is back to the sender.
- **The receiver sends an ACK when receiving an frame.**
  - Neighbors keep silent until see ACK.
- **Collisions**
  - There is no collision detection.
  - The senders know collision when they don’t receive CTS.
  - They each wait for the exponential back-off time.

**Figure 3.4 Packet transmission in MACAW**

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**b) FAMA: Floor Acquisition Multiple Access Protocols**

The floor acquisition multiple access (FAMA) protocols are based on a channel access discipline which consists of a carrier-sensing operation and a collision-avoidance dialog between the sender and the intended receiver of a packet. Floor acquisition refers to the process of gaining control of the channel. At any given point of time, the control of the channel is assigned to only one node, and this node is guaranteed to transmit one or more data packets to different destinations without suffering from packet collisions. Carrier-sensing by the sender, followed by the RTS-CTS control packet exchange, enables the protocol to perform as efficiently as MACA in the presence of hidden terminals, and as efficiently as CSMA otherwise.
FAMA requires a node that wishes to transmit packets to first acquire the floor (channel) before starting to transmit the packets. The floor is acquired by means of exchanging control packets. Though the control packets themselves may collide with other control packets, it is ensured that data packets sent by the node that has acquired the channel are always transmitted without any collisions. Any single-channel MAC protocol that does not require a transmitting node to sense the channel can be adapted for performing floor acquisition tasks. Floor acquisition using the RTS-CTS exchange is advantageous as the mechanism also tries to provide a solution for the hidden terminal problem. There are two FAMA protocol variants are available:

- RTS-CTS exchange with no carrier sensing (MACA).
- RTS-CTS exchange with non-persistent carrier-sensing (FAMA-NTR).

**RTS-CTS exchange with no carrier sensing (MACA):** In MACA, a ready node transmits an RTS packet. A neighbor node receiving the RTS defers its transmissions for the period specified in the RTS. On receiving the RTS, the receiver node responds by sending back a CTS packet, and waits for a long enough period of time in order to receive a data packet. Neighbor nodes of the receiver which hear this CTS packet defer their transmissions for the time duration of the impending data transfer. In MACA, nodes do not sense the channel. A node defers its transmissions only if it receives an RTS or CTS packet. In MACA, data packets are prone to collisions with RTS packets.

**FAMA – Non-Persistent Transmit Request:** Before sending a packet, the sender senses the channel. If channel is busy, the sender back-off a random time and retries later. If the channel is free, the sender sends RTS and waits for a CTS packet. If the sender cannot receive a CTS, it takes a random back-off and retries later. If the sender receives a CTS, it can start transmission data packet. In order to allow the sender to send a burst of packets, the receiver is made to wait a time duration τ seconds after a packet is received.

**Multichannel sender-initiated protocols:** In multichannel protocols, the available bandwidth is divided into multiple channels. This enables several nodes to simultaneously transmit data, each using a separate channel. Some protocols dedicate a frequency channel exclusively for transmitting control information.

**II. Multi-channel sender-initiated protocols:**

a) Busy Tone Multiple Access Protocols (BTMA):

The Busy Tone Multiple Access (BTMA) protocol is one of the earliest protocols proposed for overcoming the hidden terminal problem faced in wireless environments. The transmission channel is split into two: a data channel and a control channel. The data channel is used for data packet transmissions, while the control channel is used to transmit the busy tone signal.

When a node is ready for transmission, it senses the channel to check whether the busy tone is active. If not, it turns on the busy tone signal and starts data transmission; otherwise, it reschedules the packet for transmission after some random rescheduling delay. Any other node which senses the carrier on the incoming data channel also transmits the busy tone signal on the control channel. Thus, when a node is transmitting, no other node in the two-hop neighborhood of the transmitting node is permitted to simultaneously transmit. Though the probability of collisions is very low in BTMA, the bandwidth utilization is very poor. Figure 3.5 shows the worst-case scenario where the node density is very high; the dotted circle shows the region in which nodes are blocked from simultaneously transmitting when node N1 is transmitting packets.
b) Dual Busy Tone Multiple Access Protocol (DBTMAP):
It is an extension of the BTMA scheme. In this also transmission channel is split into two parts. A data channel for data packet transmissions and a control channel used for control packet transmissions (RTS and CTS packets) and also for transmitting the busy tones. In this protocol use two busy tones on the control channel, $BT_t$ and $BT_r$. Where $BT_t$ indicate that it is transmitting on the data channel and $BT_r$ indicate that it is receiving on the data channel. Two busy tone signals are two sine waves at different frequencies.
3.5.2 Receiver-initiated protocols:
a) RECEIVER INITIATED-BUSY TONE MULTIPLE ACCESS PROTOCOL (RI-BTMA):

In this RI-BTMA similar to BTMA, the available bandwidth is divided into two channels: a data channel for transmitting data packets and a control channel. The control channel is used by a node to transmit the busy tone signal. A node can transmit on the data channel only if it finds the busy tone to be absent on the control channel.

The data packet is divided into two portions: a preamble and the actual data packet. The preamble carries the identification of the intended destination node. Both the data channel and the control channel are slotted, with each slot equal to the length of the preamble. Data transmission consists of two steps. First, the preamble needs to be transmitted by the sender. Once the receiver node acknowledges the reception of this preamble by transmitting the busy tone signal on the control channel, the actual data packet is transmitted. A sender node that needs to transmit a data packet first waits for a free slot, that is, a slot in which the busy tone signal is absent on the control channel. Once it finds such a slot, it transmits the preamble packet on the data channel. If the destination node receives this preamble packet correctly without any error, it transmits the busy tone on the control channel. It continues transmitting the busy tone signal as long as it is receiving data from the sender. If preamble transmission fails, the receiver does not acknowledge with the busy tone, and the sender node waits for the next free slot and tries again.

The busy tone serves two purposes. First, it acknowledges the sender about the successful reception of the preamble. Second, it informs the nearby hidden nodes about the impending transmission so that they do not transmit at the same time.

There are two types of RI-BTMA protocols: the basic protocol and the controlled protocol. In the basic protocol, nodes do not have backlog buffers to store data packets. Hence packets that suffer collisions cannot be retransmitted. Also, when the network load increases, packets cannot be queued at the nodes. This protocol would work only when the network load is not high; when network load starts increasing, the protocol becomes unstable.

The controlled protocol overcomes this problem. This protocol is the same as the basic protocol, the only difference being the availability of backlog buffers at nodes. Therefore, packets that suffer collisions, and those that are generated during busy slots, can be queued at nodes. A node is said to be in the backlogged mode if its backlog buffer is non-empty. When a node in the backlogged mode receives a packet from its higher layers, the packet is put into the buffer and transmitted later.

![Figure 3.7 Packet transmissions in RI-BTMA](image-url)
b) MACA-By Invitation

MACA-by invitation (MACA-BI) is a receiver-initiated MAC protocol. It reduces the number of control packets used in the MACA protocol. MACA, which is a sender-initiated protocol, uses the three-way handshake mechanism, where first the RTS and CTS control packets are exchanged, followed by the actual DATA packet transmission. MACA-BI eliminates the need for the RTS packet. In MACA-BI the receiver node initiates data transmission by transmitting a Ready To Receive (RTR) control packet to the sender. If it is ready to transmit, the sender node responds by sending a DATA packet. Thus data transmission in MACA-BI occurs through a two-way handshake mechanism. The efficiency of the MACA-BI scheme is mainly dependent on the ability of the receiver node to predict accurately the arrival rates of traffic at the sender nodes.

![Figure 3.8 Packet transmissions in MACA-By](image)

**Figure 3.8 Packet transmissions in MACA-By**

![Handshake mechanism](image)

**Figure 3.9 Handshake mechanism in (a) MACA and (b) MARCH**

c) Media Access with Reduced Handshake (MARCH):

The media access with reduced handshake protocol (MARCH) is a receiver-initiated protocol. MARCH, unlike MACA-BI, does not require any traffic prediction mechanism. The protocol exploits the broadcast nature of traffic from omnidirectional antennas to reduce the number of handshakes involved in data transmission. In MACA, the RTS-CTS control packets exchange takes place before the transmission of every data packet. But in MARCH, the RTS packet is used only for the first packet of the stream. From the second packet onward, only the CTS packet is used. A node obtains information about data packet arrivals at its neighboring nodes by overhearing the CTS packets transmitted by them. It then sends a CTS packet to the concerned neighbor node for relaying data from that node.
3.6 CONTENTION-BASED PROTOCOLS WITH RESERVATION MECHANISMS:

These protocols are contention-based, contention occurs only during the resource (bandwidth) reservation phase. Once the bandwidth is reserved, the node gets exclusive access to the reserved bandwidth. Hence, QoS support can be provided for real-time traffic.

3.6.1 Distributed Packet Reservation Multiple Access Protocol

The Distributed Packet Reservation Multiple Access protocol (D-PRMA) extends the earlier centralized Packet Reservation Multiple Access (PRMA) scheme into a distributed scheme that can be used in ad hoc wireless networks. PRMA was proposed for voice support in a wireless LAN with a base station, where the base station serves as the fixed entity for the MAC operation. D-PRMA extends this protocol for providing voice support in ad hoc wireless networks.

D-PRMA is a TDMA-based scheme. The channel is divided into fixed- and equal-sized frames along the time axis. Each frame is composed of s slots, and each slot consists of m mini-slots. Each mini-slot can be further divided into two control fields, RTS/BI and CTS/BI (BI stands for Busy Indication). These control fields are used for slot reservation and for overcoming the hidden terminal problem. All nodes having packets ready for transmission contend for the first mini-slot of each slot. The remaining (m - 1) mini-slots are granted to the node that wins the contention. Also, the same slot in each subsequent frame can be reserved for this winning terminal until it completes its packet transmission session.

If no node wins the first mini-slot, then the remaining mini-slots are continuously used for contention, until a contending node wins any mini-slot. Within a reserved slot, communication between the source and receiver nodes takes place by means of either Time Division Duplexing (TDD) or Frequency Division Duplexing (FDD). Any node that wants to transmit packets has to first reserve slots, if they have not been reserved already. A certain period at the beginning of each mini-slot is reserved for carrier-sensing. If a sender node detects the channel to be idle at the beginning of a slot (mini-slot 1), it transmits an RTS packet (slot reservation request) to the intended destination through the RTS/BI part of the current mini-slot. On successfully receiving this RTS packet, the receiver node responds by sending a CTS packet through the CTS/BI of the same mini-slot. If the sender node receives this CTS successfully, then it gets the reservation for the current slot and can use the remaining mini-slots, that is, mini-slots 2 to m. Otherwise, it continues the contention process through the subsequent mini-slots of the same slot.

![Figure 3.10 Frame structure in D-PRMA](image)

To prioritize voice terminals over data terminals, the Voice terminals starts contenting from mini-slot 1 with probability \( p = 1 \) while data terminals can start such content with \( p < 1 \). Both voice and data terminals can content through the extra \( (m - 1) \) mini-slots with probability \( p < 1 \). Only the
winner of a voice terminal can reserve the same slot in each subsequent frame until the end of packet transmission while the winner of a data terminal can only use one slot.

### 3.6.2 Collision Avoidance Time Allocation Protocol (CATA):

The Collision Avoidance Time Allocation protocol (CATA) is based on dynamic topology dependent transmission scheduling. Nodes contend for and reserve time slots by means of a distributed reservation and handshake mechanism. CATA supports broadcast, unicast, and multicast transmissions simultaneously. The operation of CATA is based on two basic principles:

1. The receiver(s) of a flow must inform the potential source nodes about the reserved slot on which it is currently receiving packets. Similarly, the source node must inform the potential destination node(s) about interferences in the slot.
2. Usage of negative acknowledgments for reservation requests, and control packet transmissions at the beginning of each slot, for distributing slot reservation information to senders of broadcast or multicast sessions.

Time is divided into equal-sized frames, and each frame consists of $S$ slots. Each slot is further divided into five mini-slots. The first four mini-slots are used for transmitting control packets and are called control mini-slots (CMS1, CMS2, CMS3, and CMS4). The fifth and last Mini-slot, called data mini-slot (DMS), is meant for data transmission. The data mini-slot is much longer than the control mini-slots as the control packets are much smaller in size compared to data packets.

![Frame structure in CATA](image)

Each node receives data during the DMS of current slot transmits an SR in CMS1. Every node that transmits data during the DMS of current slot transmits an RTS in CMS2. CMS3 and CMS4 are used as follows:

a. The sender of an intend reservation, if it senses the channel is idle in CMS1, transmits an RTS in CMS2.
b. Then the receiver transmits a CTS in CMS3
c. If the reservation was successful the data can transmit in current slot and the same slot in subsequent frames.
d. Once the reservation was successfully, in the next slot both the sender and receiver do not transmit anything during CMS3 and during CMS4 the sender transmits a NTS.

If a node receives an RTS for broadcast or multicast during CMS2 or it finds the channel to be free during CMS2, it remains idle during CMS3 and CMS4. Otherwise it sends a NTS packet during CMS4. A potential multicast or broadcast source node that receives the NTS packet or detecting noise during CMS4, understands that its reservation is failed. If it find the channel is free in CMS4, which implies its reservation was successful. CATA works well with simple single-channel half-duplex radios.
3.6.3 Hop Reservation Multiple Access Protocol:

HRMA is a multi-channel MAC protocol, based on half-duplex very slow frequency hopping spread spectrum (FHSS) radios. Each time slot is assigned a separate frequency channel. Assume \( L \) frequency channels, \( f_0 \) dedicated synchronized channel frequency. The remaining \( L-1 \) frequencies are divided into \( M = \frac{L-1}{2} \) frequency pairs denoted by \((f_i, f_i^*)\), \( i = 1, 2, 3, 4, \ldots, M \). Hop reservation (HR), RTS, CTS, DATA : \( f_i \) and ACK \( f_i^* \).

All idle nodes hop to the synchronizing frequency \( f_0 \) and exchange synchronization information. Synchronizing slot: used to identify the beginning of a frequency hop and the frequency to be used in the immediately following hop. Any two nodes from two disconnected networks have at least two overlapping time period of length \( \mu_s \) on the frequency \( f_0 \).

![Figure 3.12 Frame format in HRMA](image)

If \( \mu \) is the length of each slot and \( \mu_s \) is the length of the synchronization period on each slot, then the dwell time of \( f_0 \) is \( \mu + \mu_s \).

![Figure 3.13 Merging of Subnets](image)

A node ready to transmit data, it senses the HR period of the current slot, then if the channel is idle during HR period, it transmits an RTS during RTS period and waits for CTS during CTS period. If the channel is busy during HR period, it backs off for a randomly multiple slots. Suppose the sender needs to transmit data across multiple frames, it informs the receiver through the header of the data packet. The receiver node transmits an HR packet during the HR period of the same slot in next frame to informs its neighbors. The sender receiving the HR packet, it sends an RTS during the RTS period and jams other RTS packets. Then Both sender and receiver remain silent during the CTS period.
3.6.4 FPRP: Five-Phase Reservation Protocol

A single-channel TDMA based broadcast scheduling protocol. Nodes uses a contention mechanism in order to acquire time slots. The protocol assumes the availability of global time at all nodes. Time is divided into frames: reservation frame (RF) and information frame (IF). Each RF has N reservation slots (RS) and each IF has N information slots (IS). Each RS is composed of M reservation cycles (RCs). With each RC, a five-phase dialog takes place. Corresponding to IS, each node would be in one of the following three states: transmit (T), receive (R), and blocked (B).

The reservation takes five phases:
1. **Reservation request**: Send reservation request (RR) packet to dest.
2. **Collision report**: If a collision is detected by any node, that node broadcasts a CR packet
3. **Reservation confirmation**: A source node won the contention will send a RC packet to destination node if it does not receive any CR message in the previous phase
4. **Reservation acknowledgment**: Destination node acknowledge reception of RC by sending back RA message to source
5. **Packing and elimination**: Use packing packet and elimination packet.

Example:
Here nodes 1, 7, and 9 have packets ready to be transmitted to nodes 4, 8, and 10, respectively. During the reservation request phase, all three nodes transmit RR packets. Since no other node in the two-hop neighborhood of node 1 transmits simultaneously, node 1 does not receive any CR message in the collision report phase. So node 1 transmits an RC message in the next phase, for which node 4 sends back an RA message, and the reservation is established. Node 7 and node 9 both transmit the RR packet in the reservation request phase. Here node 9 is within two hops from node 7. So if both nodes 7 and 9 transmit simultaneously, their RR packets collide at common neighbor node 11. Node 11 sends a CR packet which is heard by nodes 7 and 9. On receiving the CR packet, nodes 7 and 9 stop contending for the current slot.

3.6.5 MACA/PR: MACA with Piggy-Backed Reservation

MACA/PR is used to provide real time traffic support. The main components: a MAC protocol (MACAW + non persistent CSMA), a reservation protocol, and a QoS routing protocol. Each node maintains a reservation table (RT) that records all the reserved transmit and receive slots/windows of all nodes. Non-real time packet: wait for a free slot in the RT + random time => RTS => CTS => DATA => ACK. Real time packet transmit real time packets at certain regular intervals (say CYCLE). RTS=>CTS=>DATA (carry reservation info for next data) => ACK=>… =>DATA (carry reservation info) =>ACK, Hear DATA and ACK: update their reservation table. The ACK packet serves to renew the reservation, in addition to recovering from the packet loss. Reservation fail: fail to receive ACK packets for a certain number of DATA packets.

For maintaining consistent information regarding free slots, Periodic exchange of reservation tables. Best effort and real time packet transmissions can be interleaved at nodes. When a new node joins: receive reservation tables from each of its neighbors and learns about the reservations made in the network. QoS Routing protocol: DSDV (destination sequenced distance vector). MACA/PR does not require global synchronization among nodes. Drawback is possibility of many fragmented free slots not being used at all.

![Figure 3.16 Packet transmission in MACA/PR](image-url)
### 3.6.6 RTMAC: Real Time Medium Access Control Protocol

The real-time medium access control protocol (RTMAC) provides a bandwidth reservation mechanism for supporting real-time traffic in ad hoc wireless networks. RTMAC consists of two components, a MAC layer protocol and a QoS routing protocol. The MAC layer protocol is a real-time extension of the IEEE 802.11 DCF. The QoS routing protocol is responsible for end-to-end reservation and release of bandwidth resources.

The MAC layer protocol has two parts: a medium-access protocol for best-effort traffic and a reservation protocol for real-time traffic. A separate set of control packets, consisting of ResvRTS, ResvRTSResvCTS, and ResvACK, is used for effecting bandwidth reservation for real-time packets. RTS, CTS, and ACK control packets are used for transmitting best-effort packets. In order to give higher priority for real-time packets, the wait time for transmitting a ResvRTS packet is reduced to half of DCF inter-frame space (DIFS), which is the wait time used for best-effort packets.

Time is divided into super-frames. As can be seen from Figure 6.24, the super-frame for each node may not strictly align with the other nodes. Bandwidth reservations can be made by a node by reserving variable-length time slots on super-frames, which are sufficient enough to carry the traffic generated by the node. Each super-frame consists of a number of reservation-slots (resv-slots). The time duration of each resv-slot is twice the maximum propagation delay. Data transmission normally requires a block of resv-slots. A node that needs to transmit real-time packets first reserves a set of resv-slots. The set of resv-slots reserved by a node for a connection on a superframe is called a connection-slot.

A node that has made reservations on the current super-frame makes use of the same connection-slot in the successive super-frames for transmitting packets. Each node maintains a reservation table containing information such as the sender id, receiver id, and starting and ending times of reservations that are currently active within its direct transmission range.

![Figure 3.17 Reservation mechanism in RTMAC](image-url)
3.7 CONTENTION-BASED MAC PROTOCOLS WITH SCHEDULING MECHANISMS:

Protocols in this category focus on packet scheduling at the nodes and transmission scheduling of the nodes. The factors that affect scheduling decisions are Delay targets of packets, Traffic load at nodes and Battery power.

3.7.1 Distributed Priority Scheduling and Medium Access in Ad Hoc Networks:

Distributed priority scheduling and medium access in Ad Hoc Networks present two mechanisms for providing quality of service (QoS). They are Distributed priority scheduling (DPS) – Piggy-backs the priority tag of a node’s current and head-of-line packets to the control and data packets and Multi-hop coordination – Extends the DPS scheme to carry out scheduling over multi-hop paths.

The distributed priority scheduling scheme (DPS) is based on the IEEE 802.11 distributed coordination function. DPS uses the same basic RTS-CTS-DATA-ACK packet exchange mechanism. The RTS packet transmitted by a ready node carries the priority tag/priority index for the current DATA packet to be transmitted. The priority tag can be the delay target for the DATA packet. On receiving the RTS packet, the intended receiver node responds with a CTS packet. The receiver node copies the priority tag from the received RTS packet and piggybacks it along with the source node id, on the CTS packet. Neighbor nodes receiving the RTS or CTS packets (including the hidden nodes) retrieve the piggy-backed priority tag information and make a corresponding entry for the packet to be transmitted, in their scheduling tables (STs).

Figure 3.18 Piggy-backing and scheduling table update mechanism in DPS
3.7.2 Distributed Wireless Ordering Protocol (DWOP)

The distributed wireless ordering protocol (DWOP) consists of a media access scheme along with a scheduling mechanism. It is based on the distributed priority scheduling scheme. DWOP ensures that packets access the medium according to the order specified by an ideal reference scheduler such as first-in-first-out (FIFO), virtual clock, or earliest deadline first. In this discussion, FIFO is chosen as the reference scheduler. In FIFO, packet priority indices are set to the arrival times of packets. Similar to DPS, control packets are used in DWOP to piggy-back priority information regarding head-of-line packets of nodes.

Example:

1. Information asymmetry: A transmitting node might not be aware of the arrival times of packets queued at another node which is not within its transmission range. The Solution is a receiver find that the sender is transmitting out of order, an out-of-order notification is piggy-backed by the receiver on the control packet (CTS/ACK).

2. Perceived collisions: The ACK packet collides at the node, the corresponding entry in the ST will never be removed. The Solution is when a node observes that its rank remains fixed while packets whose PR are below the priority of its packet are being transmitted, it deletes the oldest entry from its ST.

In summary, DWOP tries to ensure that packets get access to the channel according to the order defined by a reference scheduler. The above discussion was with respect to the FIFO scheduler. Though the actual schedule deviates from the ideal FIFO schedule due to information asymmetry and stale information in STs, the receiver participation and the stale entry elimination mechanisms try to keep the actual schedule as close as possible to the ideal schedule.

3.7.3 Distributed Laxity-Based Priority Scheduling Scheme:

The distributed laxity-based priority scheduling (DLPS) scheme is a packet scheduling scheme, where scheduling decisions are made taking into consideration the states of neighboring nodes and the feedback from destination nodes regarding packet losses. Packets are reordered based on their uniform laxity budgets (ULBs) and the packet delivery ratios of the flows to which they belong.
Each node maintains two tables: scheduling table (ST) and packet delivery ratio table (PDT). The ST contains information about packets to be transmitted by the node and packets overheard by the node, sorted according to their priority index values. Priority index expresses the priority of a packet. The lower the priority index, the higher the packet’s priority. The PDT contains the count of packets transmitted and the count of acknowledgment (ACK) packets received for every flow passing through the node. This information is used for calculating current packet delivery ratio of flows.

3.8 MAC PROTOCOLS THAT USE DIRECTIONAL ANTENNAS:

MAC protocols that use directional antennas for transmissions have several advantages over those that use omnidirectional transmissions. The advantages include reduced signal interference, increase in the system throughput, and improved channel reuse that leads to an increase in the overall capacity of the channel.

A directional antenna or beam antenna is an antenna which radiates or receives greater power in specific directions allowing for increased performance and reduced interference from unwanted sources.

3.8.1 MAC Protocol Using Directional Antennas

The MAC protocol for mobile ad hoc networks using directional antennas makes use to improve the throughput in ad hoc wireless networks. The mobile nodes do not have any location information by means of which the direction of the receiver and sender nodes could be determined. The protocol makes use of an RTS/CTS exchange mechanism, which is similar to the one used in MACA. The nodes use directional antennas for transmitting and receiving data packets, thereby reducing their interference to other neighbor nodes. This leads to an increase in the throughput of the system. Each node is assumed to have only one radio transceiver, which can transmit and receive only one packet at any given time. The transceiver is assumed to be equipped with M directional antennas, each antenna having a conical radiation pattern, spanning an angle of $2\pi/M$ radians.

Figure 3.20 Radiation patterns of directional antennas
3.8.2 Directional Busy Tone-Based MAC Protocol:

The directional busy tone-based MAC protocol adapts the DBTMA protocol for use with directional antennas. It uses directional antennas for transmitting the RTS, CTS, and data frames, as well as the busy tones. By doing so, collisions are reduced significantly. Also, spatial reuse of the channel improves, thereby increasing the capacity of the channel. Each node has a directional antenna which consists of \( N \) antenna elements, each covering a fixed sector spanning an angle of \((360/N)\) degrees. For a unicast transmission, only a single antenna element is used. For broadcast transmission, all the \( N \) antenna elements transmit simultaneously.
most of the time. It is assumed that the orientation of sectors of each antenna element remains fixed. The protocol uses the same two busy tones BTt and BTr used in the DBTMA protocol. A node that receives a data packet for transmission first transmits an RTS destined to the intended receiver in all directions (omnidirectional transmission). On receiving this RTS, the receiver node determines the antenna element on which the RTS is received with maximum gain. This will observe in figure 3.22(b). This protocol is not guaranteed to be collision free see Fig. 3.23(b).

![Diagram](image)

**Figure 3.23 Directional DBTMA(Example-2)**

### 3.8.3 Directional MAC Protocols for Ad-Hoc Wireless Networks:

1. D-MAC: assume each node knows about the location of neighbors
2. In the first directional MAC scheme (DMAC-1)
b. May increase the probability of control packet collisions
c. See Figure 3.24 (if node E send a packet to node A, it will collide the OCTS or DACK)

3. In the second directional MAC scheme (DMAC-2)
   a. Both the Directional RTS (DRTS) and Omni-directional RTS (ORTS) transmissions are used.
   b. Reduced control packet collisions

4. Rules for using DRTS and ORTS:
   a. ORTS: None of the directional antennas are blocked
   b. DRTS: Otherwise.
   c. Another packet called directional wait-to-send (DWTS) is used in this scheme (See Figure 3.25)

![Figure 3.25 Operation of D-MAC Protocol](image)

3.9 OTHER MAC PROTOCOLS:
There are several other MAC protocols that do not strictly fall under the three contention based protocol categories.

3.9.1 Multichannel MAC Protocol:
The multichannel MAC protocol (MMAC) [24] uses multiple channels for data transmission. There is no dedicated control channel. N channels that have enough spectral separation between each other are available for data transmission. Each node maintains a data structure called Preferable Channel List (PCL). The usage of the channels within the transmission range of the node is maintained in the PCL. Based on their usage, channels can be classified into three types.

1. **High preference channel (HIGH):** The channel has been selected by the current node and is being used by the node in the current beacon interval (beacon interval mechanism will be explained later). Since a node has only one transceiver, there can be only one HIGH channel at a time.

2. **Medium preference channel (MID):** A channel which is free and is not being currently used in the transmission range of the node is said to be a medium preference channel. If there is no HIGH channel available, a MID channel would get the next preference.
3. **Low preference channel (LOW):** Such a channel is already being used in the transmission range of the node by other neighboring nodes. A counter is associated with each LOW state channel. For each LOW state channel, the count of source-destination pairs which have chosen the channel for data transmission in the current beacon interval is maintained.

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**Figure 3.26 ATIM Window**

Power saving mechanism for DCF: Node A announces a buffered frame for B using an ATIM frame. Node B replies by sending an ATIM-ACK, and both A and B stay awake during the entire beacon interval. The actual data transmission from A to B is completed during the beacon interval. Since C does not have any frame to send or receive, it dozes after the ATIM window.

**Figure 3.27 Operation of MMAC Protocol**
Time is divided into beacon intervals and every node is synchronized by periodic beacon transmissions. ATIM messages such as ATIM, ATIM-ACK (ATIM-acknowledgment), and ATIM-RES (ATIM-reservation) are used for this negotiation. The exchange of ATIM messages takes place on a particular channel called the default channel. The default channel is one of the multiple available channels. This channel is used for sending DATA packets outside the ATIM window, like any other channel. The ATIM message carries the PCL of the transmitting node. The destination node, upon receiving the packet, uses the PCL carried on the packet and its own PCL to select a channel. The ATIM packets themselves may be lost due to collisions; in order to prevent this, each node waits for a randomly chosen back-off period before transmitting the ATIM packet.

Channel selection mechanism:
1. If a HIGH state channel exists in node R’s PCL then that channel is selected.
2. Else if there exists a HIGH state channel in the PCL of node S then this channel is selected.
3. Else if there exists a common MID state channel in the PCLs of both node S and node R then that channel is selected.
4. Else if there exists a MID state at only one of the two nodes then that channel is selected.
5. If all channels in both PCLs are in LOW state the channel with the least count is selected.

MMAC uses simple hardware. It requires only a single transceiver. It does not have any dedicated control channel. The throughput of MMAC is higher than that of IEEE 802.11 when the network load is high. This higher throughput is in spite of the fact that in MMAC only a single transceiver is used at each node. Unlike other protocols, the packet size in MMAC need not be increased in order to take advantage of the presence of an increased number of channels.

3.9.2 Multichannel CSMAMAC Protocol:
In the multichannel CSMA MAC protocol (MCSMA), the available bandwidth is divided into several channels. A node with a packet to be transmitted selects an idle channel randomly. The protocol also employs the notion of soft channel reservation, where preference is given to the channel that was used for the previous successful transmission. Though the principle used in MCSMA is similar to the frequency division multiple access (FDMA) schemes used in cellular networks, the major difference here is that there is no centralized infrastructure available, and channel assignment is done in a distributed fashion using carrier-sensing.

The total available bandwidth is divided into N non-overlapping channels. Where N is independent of the number of hosts in the network, each having a bandwidth of \((W/N)\), where \(W\) is the total bandwidth available for communication. The channels may be created in the frequency domain (FDMA) or in the code domain (CDMA). Since global synchronization between nodes is not available in ad hoc wireless networks, channel division in the time domain (TDMA) is not used.

When the number of channels \(N\) is sufficiently large, each node tends to reserve a channel for itself. This is because a node prefers the channel used in its last successful transmission for its next transmission also. This reduces the probability of two contending nodes choosing the same channel for transmission. Even at high traffic loads, due to the tendency of every node to choose a reserved channel for itself, the chances of collisions are greatly reduced. The number of channels into which the available bandwidth is split is a very important factor affecting the performance of the protocol. If the number of channels is very large, then the protocol results in very high packet transmission times.
3.9.3 Power Control MAC Protocol for Ad Hoc Networks:

The power control MAC protocol (PCM) allows nodes to vary their transmission power levels on a per-packet basis. In the BASIC scheme, the RTS and CTS packets are transmitted with maximum power $P_{\text{MAX}}$. The RTS-CTS handshake is used for deciding upon the transmission power for the subsequent DATA and ACK packet transmissions. This can be done using two methods.

In the first method, source node A transmits the RTS with maximum power $P_{\text{MAX}}$. This RTS is received at the receiver with signal level $P_R$. The receiver node B can calculate the minimum required transmission power level $P_{\text{DESIRED}}$ for the DATA packet, based on the received power level $P_R$, the transmitted power level $P_{\text{MAX}}$, and the noise level at receiver B. Node B then specifies this $P_{\text{DESIRED}}$ in the CTS packet it transmits to node A.

In the second method, when the receiver node B receives an RTS packet, it responds with a CTS packet at the usual maximum power level $P_{\text{MAX}}$. When the source node receives this CTS packet, it calculates $P_{\text{DESIRED}}$ based on the received power level $P_R$ and transmitted power level $P_{\text{MAX}}$ as

$$ P_{\text{DESIRED}} = \frac{P_{\text{MAX}}}{P_R} \times R_{x\text{Thr}} \times C \quad \text{...............(1)} $$

where $R_{x\text{Thr}}$ is the minimum necessary received signal strength and $C$ is a constant.

The main drawback in this protocol basic scheme is may possibility of collision, that will be observed in figure 3.28.

Figure 3.28 Packet transmission in BASIC scheme.

PCM modifies this scheme so as to minimize the probability of collisions. The source and receiver nodes transmit the RTS and CTS packets, as usual, with maximum power $P_{\text{MAX}}$. Nodes in the carrier-sensing zones of the source and receiver nodes set their NAVs (Network Allocation Vector) for EIFS (Extended Inter-Frame Space) duration when they sense the signal but are not able to decode it. In order to avoid collisions with packets transmitted by the nodes in its carrier-sensing zone, the source node transmits the DATA packet at maximum power level $P_{\text{MAX}}$ periodically. The
power level changes for RTS-CTS-DATA-ACK transmissions are shown in Figure 3.29. Hence with the above simple modification, the PCM protocol overcomes the problems faced in the BASIC scheme. PCM achieves throughput very close to that of the 802.11 protocol while using much less energy.

![Diagram](image)

**Figure 3.29 Packet transmission in PCM**

### 3.9.4 Receiver-Based AutoRate Protocol:

The Receiver-Based AutoRate Protocol (RBAR) uses a novel rate adaptation approach. The rate adaptation mechanism is at the receiver node instead of being located at the sender. Rate adaptation is the process of dynamically switching data rates in order to match the channel conditions so that optimum throughput for the given channel conditions is achieved. Rate adaptation consists of two processes, namely, channel quality estimation and rate selection. The accuracy of the channel quality estimates significantly influences the effectiveness of the rate adaptation process. Therefore, it is important that the best available channel quality estimates are used for rate selection.

Rate selection is done at the receiver on a per-packet basis during the RTS-CTS packet exchange. Since rate selection is done during the RTS-CTS exchange, the channel quality estimates are very close to the actual transmission times of the data packets. This improves the effectiveness of the rate selection process. The RTS and CTS packets carry the chosen modulation rate and the size of the data packet, instead of carrying the duration of the reservation.

The sender node chooses a data rate based on some heuristic and inserts the chosen data rate and the size of the data packet into the RTS. When a neighbor node receives this RTS, it calculates the duration of the reservation $D_{RTS}$ using the data rate and packet size carried on the RTS. The neighbor node then updates its NAV accordingly to reflect the reservation. Neighbor nodes receiving the CTS calculate the expected duration of the transmission and update their NAVs accordingly. The source node, on receiving the CTS packet, responds by transmitting the data packet at the rate chosen by the receiver node.

If the rates chosen by the sender and receiver are different, then the reservation Duration $D_{RTS}$ calculated by the neighbor nodes of the sender would not be valid. DRTS time period, which is calculated based on the information carried initially by the RTS packet, is referred to as *Tentative Reservation*. In order to overcome this problem, the sender node sends the data packet with a special MAC header containing a *Reservation Sub Header (RSH)*.
3.9.5 **Interleaved Carrier-Sense Multiple Access Protocol (ICSMA):**

The interleaved carrier-sense multiple access protocol (ICSMA) efficiently overcomes the exposed terminal problem faced in ad hoc wireless networks. The inability of a source node to transmit, even though its transmission may not affect other ongoing transmissions, is referred to as the exposed terminal problem. For example, consider the topology shown in Figure 3.31. Here, when a transmission is going from node A to node B, nodes C and F would not be permitted to transmit to nodes D and E, respectively. Node C is called a sender-exposed node, and node E is called a receiver-exposed node. The exposed terminal problem reduces the bandwidth efficiency of the system.

![Figure 3.30 Packet transmission in RBAR](image)

![Figure 3.31 Exposed terminal problem](image)

Each node maintains a structure called extended network allocation vector (E-NAV):

1. Two linked lists of blocks (SEList and REList):
2. List looks like $s_1, f_1; s_2, f_2; \ldots; s_k, f_k$, where $s_i$ denotes start time of the $i$-th block list and $f_i$ denotes finish time of the $i$-th block.
3. SEList: the node would be sender-exposed in the future such that $s_j < t < f_j$
4. REList: the node would be receiver-exposed in the future such that $s_j < t < f_j$
5. Both lists are updated when RTS and CTS packets are received by the node.
ICSMA is a simple two-channel MAC protocol for ad hoc wireless networks that reduces the number of exposed terminals and tries to maximize the number of simultaneous sessions.