MEDIUM ACCESS CONTROL PROTOCOLS FOR AD-HOC WIRELESS NETWORKS: A SURVEY

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Abstract:
Studies of ad hoc wireless networks are a relatively new field gaining more popularity for various new applications. In these networks, the Medium Access Control (MAC) protocols are responsible for coordinating the access from active nodes. These protocols are of significant importance since the wireless communication channel is inherently prone to errors and unique problems such as the hidden-terminal problem, the exposed-terminal problem, and signal fading effects. Although a lot of research has been conducted on MAC protocols, the various issues involved have mostly been presented in isolation of each other. We therefore make an attempt to present a comprehensive survey of major schemes, integrating various related issues and challenges with a view to providing a big-picture outlook to this vast area. We present a classification of MAC protocols and their brief description, based on their operating principles and underlying features. In conclusion, we present a brief summary of key ideas and a general direction for future work.

Article:
I. INTRODUCTION
Back in the 1970s, the Defense Advanced Research Projects Agency (DARPA) was involved in the development of packet radio networks for use in the battlefields. Around the same time, the ALOHA [1] project used wireless data broadcasting to create single hop radio networks. This subsequently led to development of the *multi-hop* multiple-access Packet Radio Network (PRNET), which allowed communication coverage over a wide area. The term *multi-hop* refers to the fact that data from the source needs to travel through several other intermediate nodes before it reaches the destination. One of the most attractive features of PRNET was rapid deployment.

Also, after installation, the whole system was self-initializing and self-organizing. The network consisted of mobile radio repeaters, wireless terminals and dedicated mobile stations. Packets were relayed from one repeater to the other until data reached its destination.

With the development of technology, devices have shrunk in size and they now incorporate more advanced functions. This allows a node to act as a wireless terminal as well as a repeater and still be compact enough to be mobile. A self-organizing and adaptive collection of such devices connected with wireless links is now referred to as an *Ad Hoc Network*. An ad hoc network does not need any centralized control. The network should detect any new nodes automatically and induct them seamlessly. Conversely, if any node moves out of the network, the remaining nodes should automatically reconfigure themselves to adjust to the new scenario. If nodes are mobile, the network is termed as a *MANET* (Mobile Ad hoc NETwork). The Internet Engineering Task Force (IETF) has set up a working group named MANET for encouraging research in this area [2].

Typically, there are two types of architectures in ad hoc networks: flat and hierarchical [3, 6]. Each node in an ad hoc network is equipped with a transceiver, an antenna and a power source. The characteristics of these

nodes can vary widely in terms of size, processing ability, transmission range and battery power. Some nodes lend themselves for use as servers, others as clients and yet others may be flexible enough to act as both, depending on the situation. In certain cases, each node may need to act as a router in order to convey information from one node to another [4-5].

Applications: Coupled with global roaming capabilities and seamless integration with existing infrastructure, if any, ad hoc wireless networks can be used in many new applications [6, 8]. In case of natural or other disasters, it is possible that existing communication infrastructure is rendered unusable. In such situations, an ad hoc wireless network featuring wideband capabilities can be set up almost immediately to provide *Emergency communication* in the affected region. In mobile computing environments, mobile wireless devices that have the capability to detect the presence of existing networks can be used to synchronize data with the user's conventional desktop computers automatically, and download appointment/schedule data. A user carrying a handheld Personal Digital Assistant (PDA) device can download *Context sensitive data* in a shopping mall or museum featuring such wireless networks and services. The PDA would be able to detect the presence of the network and connect itself in an ad hoc fashion. Depending on the user's movement, the PDA can poll the network for relevant information based on its current location. For instance, if the user is moving through the clothing section of the shopping mall, information on special deals or pricing can be made available. Similarly, ad hoc networks can be used in travel-related and customized household applications, telemedicine, virtual navigation, etc.

Important Issues: There are several important issues in ad hoc wireless networks [3, 6-8]. Most ad hoc wireless network applications use the Industrial, Scientific and Medical (ISM) band that is free from licensing formalities. Since wireless is a tightly controlled medium, it has '*limited channel bandwidth*' that is typically much less than that of wired networks. Besides, the wireless medium is inherently '*error prone*'. Even though a radio may have sufficient channel bandwidth, factors such as multiple access, signal fading, and noise and interference can cause the *effective throughput* in wireless networks to be significantly lower. Since wireless nodes may be mobile, the '*network topology*' can change frequently without any predictable pattern. Usually the links between nodes would be *bi-directional*, but there may be cases when differences in transmission power give rise to *unidirectional links*, which necessitate special treatment by the Medium Access Control (MAC) protocols. Ad hoc network nodes must *conserve energy* as they mostly rely on batteries as their power source. The *security* issues should be considered in the overall network design, as it is relatively easy to eavesdrop on wireless transmission. *Routing protocols* require information about the current topology, so that a route from a source to a destination may be found. However, the existing routing schemes, such as distance-vector and link-state based protocols, lead to poor route convergence and low throughput for dynamic topology. Therefore, a new set of routing schemes is needed in the ad hoc wireless context [5, 8].

MAC layer, sometimes also referred to as a sub-layer of the 'Data Link' layer, involves the functions and procedures necessary to transfer data between two or more nodes of the network. It is the responsibility of the MAC layer to perform error correction for anomalies occurring in the physical layer. The layer performs specific activities for framing, physical addressing, and flow and error controls. It is responsible for resolving conflicts among different nodes for channel access. Since the MAC layer has a direct bearing on how reliably and efficiently data can be transmitted between two nodes along the routing path in the network, it affects the Quality of Service (QoS) of the network. The design of a MAC protocol has to address issues caused by mobility of nodes and an unreliable time varying channel [6-8].

Need for Special MAC protocols: The popular Carrier Sense Multiple Access (CSMA) [9] MAC scheme and its variations such as CSMA with Collision Detection (CSMA/CD) developed for wired networks, cannot be used directly in the wireless networks, as explained below.

In CSMA-based schemes, the transmitting node first senses the medium to check whether it is idle or busy. The node defers its own transmission to prevent a collision with the existing signal, if the medium is busy. Otherwise, the node begins to transmit its data while continuing to sense the medium. However, collisions occur

at receiving nodes. Since, signal strength in the wireless medium fades in proportion to the square of distance from the transmitter, the presence of a signal at the receiver node may not be clearly detected at other sending terminals, if they are out of range. As illustrated in Fig. 1, node *B* is within the range of nodes *A* and *C*, but *A* and *C* are not in each other's range. Let us consider the case where *A* is transmitting to *B*. Node *C*, being out of *A*'s range, cannot detect carrier and may therefore send data to *B*, thus causing a collision at *B*. This is referred to as the '*hidden-terminal problem*', as nodes *A* and *C* are hidden from each other [10-11].
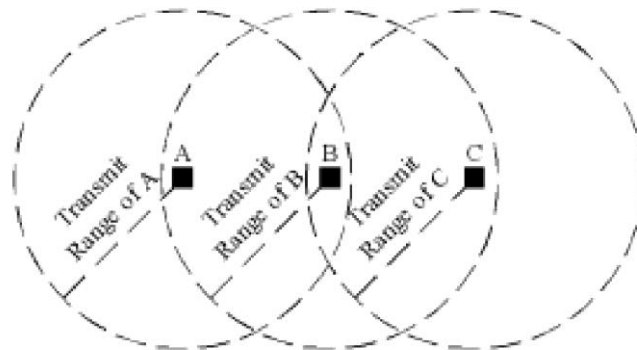

Fig. 1: Illustration of the hidden and exposed terminal problems.

Let us now consider another case where *B* is transmitting to *A*. Since *C* is within *B*'s range, it senses carrier and decides to defer its own transmission. However, this is unnecessary because there is no way *C*'s transmission can cause any collision at receiver *A*. This is referred to as the '*exposed-terminal problem*', since *B* being exposed to *C* caused the latter to needlessly defer its transmission [11]. MAC schemes are designed to overcome these problems.

The rest of the paper is organized as follows. A classification of ad hoc network MAC schemes is given in Section II. Details of various MAC schemes in each class are discussed in Sections III and IV. The summary and future research directions are described in Section V, followed by conclusion in Section VI.

(a)
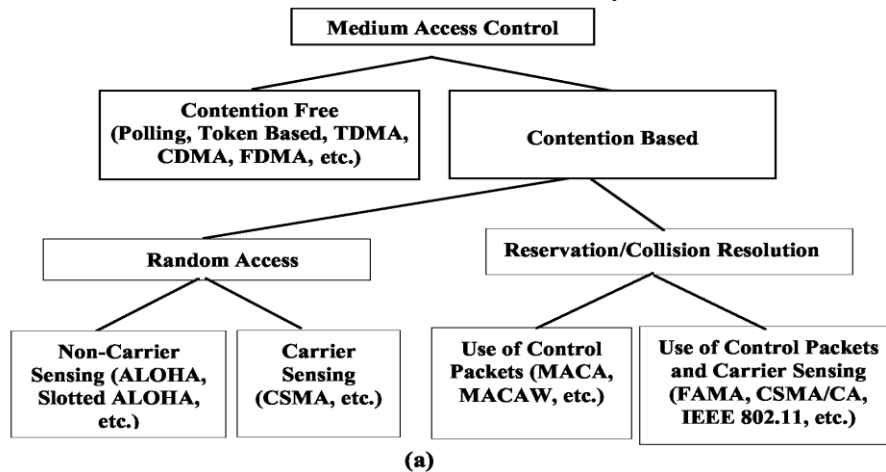
Sender vs. Receiver Initiated Protocols
- ☐ Sender initiated: most of the schemes listed below
- ☐ Receiver initiated: MACA-BI [17], RI-BTMA [18], etc.

Single Channel Protocols: MACA [13], MACAW [14], FAMA [15], etc.

Multi Channel Protocols
- ☐ Use of separate control and (single) data channels
  BTMA [9], DBTMA [20], PAMAS [27], etc.
- ☐ Use of multiple channels for data transmission
  HRMA [19], MMAC [49], DCA [51], DCA-PC [52], etc.

Power Aware Protocols
- ☐ Use of power management (i.e., alternating sleep and wake states) PAMAS [27], DPSM [32], etc.
- ☐ Use of power control (i.e., different transmit power levels) PCM [35], PCMA [36], etc.

Directional Antenna based Protocols: D-MAC [63], M-MAC [56], etc.

Unidirectional Link based Protocols: PANAMA [67], [68-69], etc.

QoS Aware Protocols
- ☐ **Synchronous Protocols:** Cluster TDMA [83, 84], Cluster token [85], SRMA/PA [86], etc.
- ☐ **Asynchronous Protocols**
  - o Use of Service Differentiation: RT-MAC [87], DCF-PC [88], EDCF [89], VMAC [75], BB [92, 93], ES-DCF and DB-DCF [94, 94]etc.
  - o Use of Reservation: MACA/PR [96], DBASE [98], [97], etc.
  - o Use of Fair Sharing: DFS [99], [102], etc.

(b)

Fig. 2: Classification of MAC schemes.

II. CLASSIFICATION

Various MAC schemes developed for wireless ad hoc networks can be classified as shown in Fig. 2. In contention-free schemes (e.g., TDMA, FDMA, CDMA), certain assignments are used to avoid contentions [6]. Contention based schemes, on the other hand, are aware of the risk of collisions of transmitted data. Since contention-free MAC schemes are more applicable to static networks and/or networks with centralized control, we shall focus on *contention-based* MAC schemes in this survey.

We can view this category as a collection of 'random access' and 'dynamic reservation/collision resolution' protocols as shown in Fig. 2(a) [12]. In *Random Access* based schemes, such as ALOHA, a node may access the channel as soon as it is ready. Naturally, more than one node may transmit at the same time, causing collisions. ALOHA is more suitable under low system loads with large number of potential senders and it offers relatively low throughput. A variation of ALOHA, termed 'Slotted ALOHA', introduces synchronized transmission time-slots similar to TDMA. Nodes can now only transmit at the beginning of any time-slot. The introduction of time slot doubles the throughput as compared to the pure ALOHA scheme, with the cost of necessary time synchronization. The CSMA-based schemes further reduce the possibility of packet collisions and improve the throughput.

In order to solve the hidden and exposed terminal problems in CSMA, researchers have come up with many protocols, which are contention based but involve some forms of *Dynamic Reservation/Collision Resolution*. Some schemes use the Request-To-Send/Clear-To-Send (RTS/CTS) control packets to prevent collisions, e.g. Multiple Access Collision Avoidance (MACA) [13] and MACA for Wireless LANs (MACAW) [14]. Yet others use a combination of carrier sensing and control packets [15, 16, 23] etc.

As shown in Fig. 2(b), the contention-based MAC schemes can also be classified as sender-initiated vs. receiver-initiated, single-channel vs. multiple-channel, power-aware, directional antenna based, unidirectional link based and QoS aware schemes. We briefly discuss these categories in the following.

One distinguishing factor for MAC protocols is whether they rely on the sender initiating the data transfer, or the receiver requesting the same [6]. As mentioned above, the dynamic reservation approach involves the setting up of some sort of a reservation prior to data transmission. If a node that wants to send data takes the initiative of setting up this reservation, the protocol is considered to be a '*sender-initiated protocol*'. Most schemes are sender-initiated. In a '*receiver-initiated protocol*', the receiving node polls a potential transmitting

node for data. If the sending node indeed has some data for the receiver, it is allowed to transmit after being polled. The MACA – By Invitation (MACA-BI) [17] and Receiver Initiated Busy Tone Multiple Access (RI-BTMA) [18] are examples of such schemes. As we shall see later, MACA-BI is slightly more efficient in terms of transmit and receive turnaround times compared to MACA.

Another classification is based on the number of channels used for data transmission. *Single channel protocols* set up reservations for transmissions, and subsequently transmit their data using the same channel or frequency. Many MAC schemes use a single channel [1, 9, 13- 15, etc.]. *Multiple channel protocols* use more than one channel in order to coordinate connection sessions among the transmitter and receiver nodes. The FCC mandates that all radios using the ISM band must employ either DSSS or FHSS schemes. Several MAC protocols have been developed for using multiple channels through frequency-hopping techniques, e.g., Hop-Reservation Multiple Access (HRMA) scheme [19]. Some others use a special control-signal on a separate channel for protecting the actual data that is transmitted on the data channel(s) [20, 47- 53].

As mentioned earlier, it becomes important in the context of low power devices, to have energy efficient protocols at all layers of the network model. Much work has already been done for studying and developing appropriate MAC protocols that are also '*power aware*' ([27-36], etc).

Yet another class of MAC protocols uses '*directional antennas*' [56-64]. The advantage of this method is that the signals are transmitted only in one direction. The nodes in other directions are therefore no longer prone to interference or collision effects, and spatial reuse is facilitated.

Usually the links between nodes are bi-directional, but there may be cases when differences in transmission power give rise to unidirectional links, which necessitate special treatment by the MAC protocols. Prakash [66] pointed out some of the issues to be taken care of in unidirectional link networks. Several MAC schemes have been proposed for '*unidirectional*' links [10, 67-69].

With the growing popularity of ad hoc networks, it is reasonable to expect that users will demand some level of QoS from it, such as end-to-end delay, available bandwidth, probability of packet loss, etc. However, the lack of centralized control, limited bandwidth channels, node mobility, power or computational constraints and the error-prone nature of the wireless medium make it very difficult to provide effective QoS in ad hoc networks [3, 72-74]. Since the MAC layer has a direct bearing on how reliably and efficiently data can be transmitted from one node to the next along the routing path in the network, it affects the Quality of Service (QoS) of the network. Several '*QoS-aware*' MAC schemes have been reported in the literature [86-99].

Note that the above categories are not totally independent of each other. In fact, a given MAC protocol may belong to more than one category. For example, Power Aware Medium Access Control with Signaling (PAMAS) [27] is a power-aware protocol that also uses two channels. Similarly; RI-BTMA is a receiver-initiated MAC scheme that uses multiple channels.

Several representative MAC schemes for Ad Hoc Wireless Networks are briefly discussed and summarized in the following two sections. For the sake of convenience in discussion, we have broadly arranged the schemes in 'Non QoS' and 'QoS-Aware' classes. The non-QoS MAC schemes in Section III have been further divided in the following categories: general, power-aware, multiple channel, directional antenna-based, and unidirectional MAC protocols. Similarly, QoS-aware schemes (in Section IV) have been arranged in a few categories according to their properties. In the process of choosing these MAC schemes, we tended to select those that are more representative in their category.

III. REVIEW of NON-QOS MAC PROTOCOLS

In particular, we shall discuss several important contention based MAC schemes in the single channel, receiver initiated, power-aware, and multiple channel categories. Due to space limitation, we will only briefly discuss other categories. However, it should not mean that these other categories are less important.

A. General MAC Protocols

We have mostly included the single channel protocols in this sub-section. A receiver initiated MACA-BI scheme is also discussed.

A.1 Multiple Access Collision Avoidance (MACA)

The MACA protocol was proposed by Karn to overcome the hidden and exposed terminal problems in CSMA family of protocols [13]. MACA uses two short signaling packets, similar to the AppleTalk protocol [21]. In Fig. 1, if node *A* wishes to transmit to node *B*, it first sends an RTS packet to *B*, indicating the length of the data transmission that would later follow. If *B* receives this RTS packet, it returns a CTS packet to *A* that also contains the expected length of the data to be transmitted. When *A* receives the CTS, it immediately commences transmission of the actual data to *B*. The key idea of the MACA scheme is that any neighboring node that overhears an RTS packet has to defer its own transmissions until some time after the associated CTS packet would have finished, and that any node overhearing a CTS packet would defer for the length of the expected data transmission.

In a hidden terminal scenario (see Fig. 1) as explained in Section I, *C* will not hear the RTS sent by *A*, but it would hear the CTS sent by *B*. Accordingly, *C* will defer its transmission during *A*'s data transmission. Similarly, in the exposed terminal situation, *C* would hear the RTS sent by *B*, but not the CTS sent by *A*. Therefore *C* will consider itself free to transmit during B's transmission. It is apparent that this RTS-CTS exchange enables nearby nodes to reduce the collisions at the receiver, not the sender. Collisions can still occur between different RTS packets, though. If two RTS packets collide for any reason, each sending node waits for a randomly chosen interval before trying again. This process continues until one of the RTS transmissions elicits the desired CTS from the receiver.
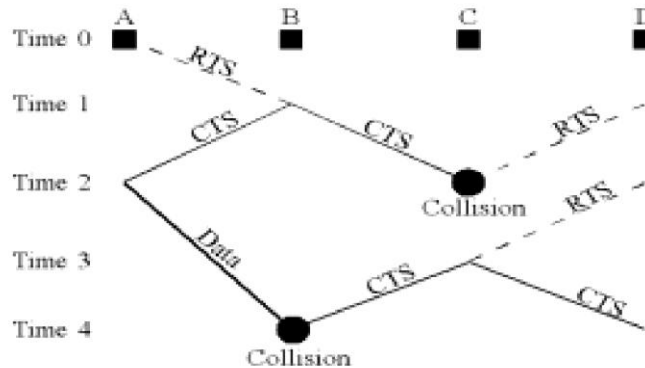

Fig. 3: Illustration of failure of RTS-CTS mechanism in solving Hidden and Exposed terminal problems.

MACA is effective because RTS and CTS packets are significantly shorter than the actual data packets, and therefore collisions among them are less expensive compared to collisions among the longer data packets. However, the RTS-CTS approach *does not always solve the hidden terminal problem completely*, and collisions can occur when different nodes send the RTS and the CTS packets. Let us consider an example with four nodes *A*, *B*, *C* and *D* in Fig. 3. Node *A* sends an RTS packet to *B*, and *B* sends a CTS packet back to *A*. At *C*, however, this CTS packet collides with an RTS packet sent by *D*. Therefore *C* has no knowledge of the subsequent data transmission from *A* to *B*. While the data packet is being transmitted, *D* sends out another RTS because it did not receive a CTS packet in its first attempt. This time, *C* replies to *D* with a CTS packet that collides with the data packet at *B*. In fact, when hidden terminals are present and the network traffic is high, the performance of MACA degenerates to that of ALOHA [20].

Another *weakness* of MACA is that it *does not* provide any *acknowledgment* of data transmissions at the data link layer. If a transmission fails for any reason, retransmission has to be initiated by the transport layer. This can cause *significant delays* in the transmission of data.

In order to overcome some of the weaknesses of MACA, Bharghavan et al. [14] proposed *MA CA for Wireless* (*MACAW*) scheme that uses a five step RTS-CTS-DS-DATA-ACK exchange. MACAW allows much faster error recovery at the data link layer by using the acknowledgment packet (ACK) that is returned from the receiving node to the sending node as soon as data reception is completed. The backoff and fairness issues among active nodes were also investigated. MACAW achieves *significantly higher throughput* compared to MACA. It however does not fully solve the hidden and exposed terminal problems [15, 20].

The *Floor Acquisition Multiple Access* (FAMA) is another MACA based scheme that requires every transmitting station to acquire control of the floor (i.e., the wireless channel) before it actually sends any data packet [15]. Unlike MACA or MACAW, FAMA requires that collision avoidance should be performed both at the sender as well as the receiver. In order to 'acquire the floor', the sending node, sends out an RTS using either non-persistent packet sensing (NPS) or non-persistent carrier sensing (NCS). The receiver responds with a CTS packet, which contains the address of the sending node. Any station overhearing this CTS packet knows about the station that has acquired the floor. The CTS packets are repeated long enough for the benefit of any hidden sender that did not register another sending node's RTS. The authors recommend the NCS variant for ad hoc networks since it addresses the hidden terminal problem effectively.

A.2 IEEE 802.11 MAC Scheme
The IEEE 802.11 specifies two modes of MAC protocol: distributed coordination function (DCF) mode (for ad hoc networks) and point coordination function (PCF) mode (for centrally coordinated infrastructure-based networks) [22-25]. The DCF in IEEE 802.11 is based on CSMA with Collision Avoidance (CSMA/CA), which can be seen as a combination of the CSMA and MACA schemes. The protocol uses the RTS-CTS-DATA-ACK sequence for data transmission. Not only does the protocol use physical carrier sensing, it also introduces the novel concept of virtual carrier sensing. This is implemented in the form of a Network Allocation Vector (NAV), which is maintained by every node. The NAV contains a time value that represents the duration up to which the wireless medium is expected to be busy because of transmissions by other nodes. Since every packet contains the duration information for the remainder of the message, every node overhearing a packet continuously updates its own NAV.
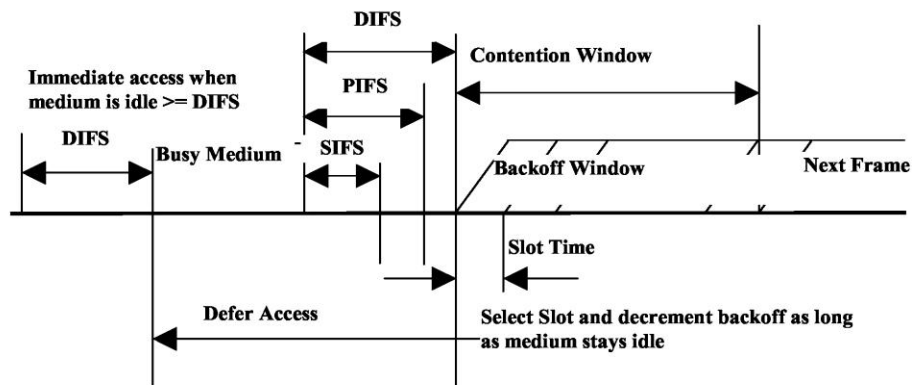

Fig. 4: IEEE 802.11 DCF channel access.

Time slots are divided into multiple frames and there are several types of inter frame spacing (IFS) slots. In increasing order of length, they are the Short IFS (SIFS), Point Coordination Function IFS (PIFS), DCF IFS (DIFS) and Extended IFS (EIFS). The node waits for the medium to be free for a combination of these different times before it actually transmits. Different types of packets can require the medium to be free for a different number or type of IFS. For instance, in ad hoc mode, if the medium is free after a node has waited for DIFS, it can transmit a queued packet. Otherwise, if the medium is still busy, a backoff timer is initiated. The initial backoff value of the timer is chosen randomly from between 0 and CW-1 where CW is the width of the contention window, in terms of time-slots. After an unsuccessful transmission attempt, another backoff is performed with a doubled size of CW as decided by binary exponential backoff (BEB) algorithm. Each time the medium is idle after DIFS, the timer is decremented. When the timer expires, the packet is transmitted. After each successful transmission, another random backoff (known as post-backoff) is performed by the

transmission-completing node. A control packet such as RTS, CTS or ACK is transmitted after the medium has been free for SIFS. Fig. 4 shows the channel access in IEEE 802.11.

IEEE 802.11 DCF is a widely used protocol for wireless LANs. Many of the MAC schemes discussed in this paper are based on it. Some other features of this protocol will be discussed along with such schemes.

A.3 Multiple Access Collision Avoidance-By Invitation (MACA-BI)

In typical sender-initiated protocols, the sending node needs to switch to receive mode (to get CTS) immediately after transmitting the RTS. Each such exchange of control packets adds to turnaround time, reducing the overall throughput. MACA-BI [17] is a receiver-initiated protocol and it reduces the number of such control packet exchanges. Instead of a sender waiting to gain access to the channel, MACA-BI requires a receiver to request the sender to send the data, by using a 'Ready-To-Receive' (RTR) packet instead of the RTS and the CTS packets. Therefore, it is a two-way exchange (RTR-DATA) as against the three-way exchange (RTS-CTS-DATA) of MACA [13].

Since the transmitter cannot send any data before being asked by the receiver, there has to be a traffic prediction algorithm built into the receiver so it can know when to request data from the sender. The efficiency of this algorithm determines the communication throughput of the system. The algorithm proposed by the authors piggybacks the information regarding packet queue length and data arrival rate at the sender in the data packet. When the receiver receives this data, it is able to predict the backlog in the transmitter and send further RTR packets accordingly. There is a provision for a transmitter to send an RTS packet if its input buffer overflows. In such a case, the system reverts to MACA.

The MACA-BI scheme works efficiently in networks with predictable traffic pattern. However, if the traffic is bursty, the performance degrades to that of MACA.

A.4 Group Allocation Multiple Access with Packet Sensing (GAMA-PS)

GAMA-PS incorporates features of contention based as well as contention free methods [26]. It divides the wireless channel into a series of cycles. Every cycle is divided in two parts for contention and group transmission. Although the group transmission period is further divided into individual transmission periods, GAMA-PS does not require clock or time synchronization among different member nodes. Nodes wishing to make a reservation for access to the channel employ the RTS-CTS exchange. However, a node will backoff only if it understands an entire packet. Carrier sensing alone is not sufficient reason for backing off.

GAMA-PS organizes nodes into transmission groups, which consist of nodes that have been allocated a transmission period. Every node in the group is expected to listen in on the channel. Therefore, there is no need of any centralized control. Every node in the group is aware of all the successful RTS-CTS exchanges and by extension, of any idle transmission periods.

Members of the transmission group take turns transmitting data, and every node is expected to send a Begin Transmission Period (BTP) packet before actual data. The BTP contains the state of the transmission group, position of the node within that group and the number of group members. A member station can transmit up to a fixed length of data, thereby increasing efficiency. The last member of the transmission group broadcasts a Transmit Request (TR) packet after it sends its data. Use of the TR shortens the maximum length of the contention period by forcing any station that might contend for group membership to do so at the start of the contention period.

GAMA-PS assumes that there are no hidden terminals. As a result, this scheme may not work well for mobile ad hoc networks. When there is not enough traffic in the network, GAMA-PS behaves almost like CSMA. However, as the load grows, it starts to mimic TDMA and allows every node to transmit once in every cycle.

B. Power Aware MAC Protocols

Since, most mobile devices in use today are powered by batteries it is crucial to conserve energy and utilize power as efficiently as possible. In fact, the issue of power conservation should be considered across all the layers of the protocol stack. The following principles may serve as general guidelines for power conservation in MAC protocols [27-30]. *First*, collisions are a major cause of expensive retransmissions and should be avoided as far as possible. *Second*, the transceivers should be kept in standby mode (or switched off) whenever possible as they consume the most energy in active mode. *Third*, instead of using the maximum power, the transmitter should switch to a lower power mode that is sufficient for the destination node to receive the transmission. Several researchers, including Goldsmith and Wicker [31], have conducted studies in this area.

As we mentioned in the context of classifying MAC protocols, some approaches implement power management by *alternating sleep and wake cycles* [27, 32-34]. Other approaches, classified as power control, use a *variation in the transmission power* [3 5, 3 6]. We now present the details of some selected schemes in both categories.

B.1 Power Aware Medium Access Control with Signaling (PAMAS)

The basic idea of PAMAS developed by Raghavendra and Singh [27] is that all the RTS-CTS exchanges are performed over the signaling channel and the data transmissions are kept separate over a data channel. While receiving a data packet, the destination node starts sending out a busy tone over the signaling channel. Nodes listen in on the signaling channel to deduce when it is optimal for them to power down their transceivers. Every node makes its own decision whether to power off or not such that there is no drop in the throughput. A node powers itself off if it has nothing to transmit and it realizes that its neighbor is transmitting. A node also powers off if at least one neighbor is transmitting and another is receiving at the same time. The authors have developed several rules to determine the length of a power-down state.

The authors also mention briefly some strategies, to use this scheme with other protocols like FAMA [15]. They have also noted that the use of ACK and transmission of multiple packets together will also enhance the performance of PAMA. However, the radio transceiver turn-around time, which might not be negligible, was not considered in the PAMAS scheme.

B.2 Dynamic Power Saving Mechanism (DPSM)

Jung and Vaidya [32] proposed DPSM based on the idea of using sleep and wake states for nodes in order to conserve power. It is a variation of the IEEE 802.11 scheme, in that it uses dynamically sized Ad hoc Traffic Indication Message (ATIM) windows to achieve longer dozing times for nodes.

The IEEE 802.11 DCF mode has a power saving mechanism, in which time is divided into beacon intervals that are used to synchronize the nodes [23]. At the beginning of each beacon interval, every node must stay awake for a fixed time called ATIM window. This window is used to announce the status of packets ready for transmission to any receiver nodes. Such announcements are made through ATIM frames, and they are acknowledged with ATIM-ACK packets during the same beacon interval. Fig. 5 illustrates the mechanism. Earlier work [33] shows that if the size of the ATIM window is kept fixed, performance suffers in terms of throughput and energy consumption.
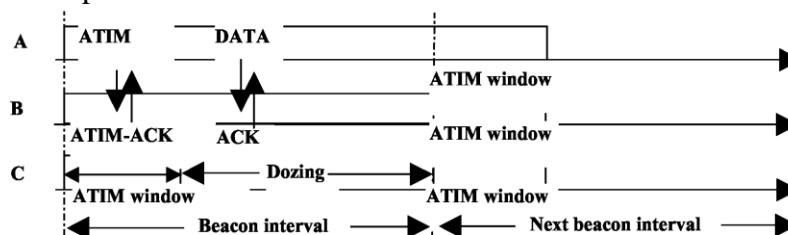

Fig. 5. Power saving mechanism for DCF: Node A announces a buffered packet for B using an ATIM frame. Node B replies by sending an ATIM-ACK, and both A and B stay awake during the entire beacon interval. The actual data transmission from A to B is completed during the beacon interval. Since C does not have any packet to send or receive, it dozes after the ATIM window [32].

In DPSM, each node dynamically and independently chooses the length of the ATIM window. As a result, every node can potentially end up having a different sized window. It allows the sender and receiver nodes to go into sleep state immediately after they have participated in the transmission of packets announced in the prior ATIM frame. Unlike the DCF mechanism, they do not even have to stay awake for the entire beacon interval. The length of the ATIM window is increased if some packets queued in the outgoing buffer are still unsent after the current window expires. Also, each data packet carries the current length of the ATIM window and any nodes that overhear such information may decide to modify their own window lengths based on the received information.

DPSM is found to be more effective than IEEE 802.11 DCF in terms of power saving and throughput. However, IEEE 802.11 and DPSM are not suitable for multi-hop ad hoc networks as they assume that the clocks of the nodes are synchronized and the network is connected. Tseng et al. [34] have proposed three variations of DPSM for multi hop MANETs that use asynchronous clocks.

B.3 Power Control Medium Access Control (PCM)

Previous approaches of power control used alternating sleep and wake states for nodes [27, 32, 34]. In PCM [35], the RTS and CTS packets are sent using the maximum available power, whereas the data and ACK packets are sent with the minimum power required to communicate between the sender and receiver.

The method for determining these lower power levels, described below, has also been used by earlier researchers in [13, 43]. An example scenario is depicted in Fig. 6. Node D sends the RTS to node E at a transmit power level P_{max}, and also includes this value in the packet. E measures the actual signal strength, say P_r, of the received RTS packet. Based on P_{max}, P_r and the noise level at its location, E then computes the minimum necessary power level (say, P_{suff}) that would actually be sufficient for use by D. Now, when E responds with the CTS packet using the maximum power it has available, it includes the value of P_{suff} that D subsequently uses for data transmission. G is able to hear this CTS packet and defers its own transmissions. E also includes the power level that it used for the transmission in the CTS packet. D then follows a similar process and calculates the minimum required power level that would get a packet from E to itself. It includes this value in the data packet so that E can use it for sending the ACK.
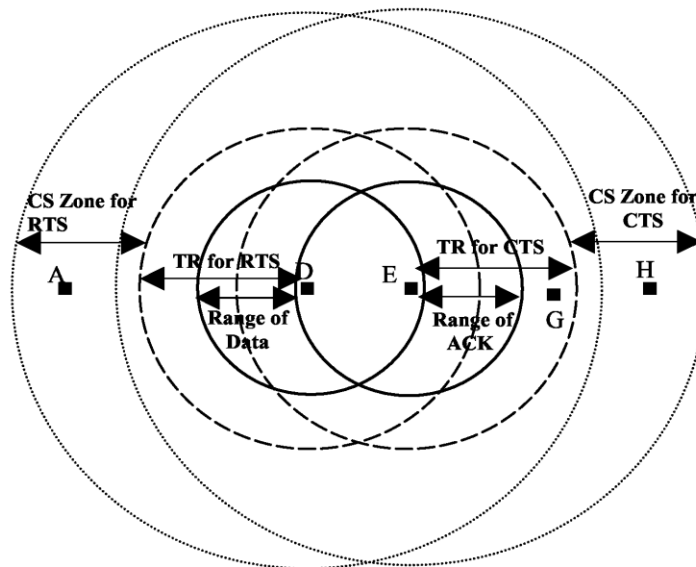

Fig. 6: Illustration of power control scheme.
CS: Carrier Sense; TR: Transmission Range

PCM also stipulates that the source node periodically transmit the DATA packet at the maximum power level, for just enough time so that nodes in the carrier sensing range, such as A may sense it. PCM thus achieves energy savings without causing throughput degradation.

The operation of the PCM scheme requires a rather accurate estimation of received packet signal strength. Therefore, the dynamics of wireless signal propagation due to fading and shadowing effect may degrade its performance. Another *drawback* of this scheme is the difficulty in implementing frequent changes in the transmit power levels.

B.4 Power Controlled Multiple Access (PCMA)

PCMA, proposed by Monks et al. [36], relies on controlling transmission power of the sender so that the intended receiver is just able to decipher the packet. This helps in avoiding interference with other neighboring nodes that are not involved in the packet exchange. PCMA uses two channels, one for sending out busy tones and the other for data and other control packets. Power control mechanism in PCMA has been used for increasing channel efficiency through spatial frequency reuse rather than only increasing battery life. Therefore, an important issue is for the transmitter and receiver pair to determine the minimum power level necessary for the receiver to decode the packet, while distinguishing it from noise/interference. Also, the receiver has to advertise its noise tolerances so that no other potential transmitter will disrupt its ongoing reception.

In the conventional methods of collision avoidance, a node is either allowed to transmit or not, depending on the result of carrier sensing. In PCMA, this method is generalized to a bounded power model. Before data transmission, the sender sends a Request Power To Send (RPTS) packet on the data channel to the receiver. The receiver responds with an Accept Power To Send (APTS) packet, also on the data channel. This RPTS-APTS exchange is used to determine the minimum transmission power level that will cause a successful packet reception at the receiver. After this exchange, the actual data is transmitted and acknowledged with an ACK packet.

In a separate channel, every receiver sets up a special busy tone as a periodic pulse. The signal strength of this busy tone advertises to the other nodes the additional noise power the receiver node can tolerate. When a sender monitors the busy tone channel, it is essentially doing something similar to carrier sensing, as in CSMA/CA model. When a receiver sends out a busy tone pulse, it is doing something similar to sending out a CTS packet. The RPTS-APTS exchange is analogous to the RTS-CTS exchange. The major difference however is that the RPTS-APTS exchange does not force other hidden transmitters to backoff. Collisions are resolved by the use of some appropriate backoff strategy.

The authors claim improvements in aggregate channel utilization by more than a factor of 2 compared to IEEE 802.11 protocol. Since carrier sensing while simultaneously transmitting is a complicated operation, there could be a problem of the ACK packet being subjected to collision. This is an issue because the noise level at the source cannot be updated during data transmission. This seems to be an open problem with all schemes that use such power control measures.

Woesner et al. [33] also presented the power saving techniques for IEEE 802.11 and the High Performance LAN (HIPERLAN) [46] standards. Chen et al. [37] developed a distributed algorithm called Span, wherein every node takes into account its own power reserve and the advantage to its neighbors before deciding on staying awake (or going to sleep) and acting as a coordinator node. The nodes that are awake take care of routing duties. Sivalingam et al. [29] have identified some of the ideas that can be used to conserve power at the MAC layer. They have also performed studies on some protocols in order to compare their performance vis-à-vis power efficiency. In fact, power control has also been used for network topology control in [38- 40] and to generate energy efficient spanning trees for multicasting and broadcasting in [41-42].

C. Multiple Channel Protocols

A major problem of single shared channel schemes is that the probability of collision increases with the number of nodes. It is possible to solve this problem with multi channel approaches. As seen in the classification, some multi-channel schemes use a dedicated channel for control packets (or signaling) and one separate channel for data transmissions [9, 18, 20, 27, 47]. They set up busy tones on the control channel, albeit one with small bandwidth consumption, so that nodes are aware of ongoing transmissions.

Another approach is to use multiple channels for data packet transmissions. This approach has the following advantages [52]. *First*, since the maximum throughput of a single channel scheme is limited by the bandwidth of that channel, using more channels appropriately can potentially increase the throughput. *Second*, data transmitted on different channels does not interfere with each other, and multiple transmissions can take place in the same region simultaneously. This leads to significantly fewer collisions. *Third*, it is easier to support QoS by using multiple channels. Schemes proposed in [19, 48-53] employ such an approach. In general, a multiple data-channel MAC protocol has to assign different channels to different nodes in real time. The issue of medium access still needs to be resolved. This involves deciding, for instance, the time slots at which a node would get access to a particular channel. In certain cases, it may be necessary for all the nodes to be synchronized with each other, whereas in other instances, it may be possible for the nodes to negotiate schedules among themselves.

We discuss below the details of some of the multiple channel MAC schemes.

C.1 Dual Busy Tone Multiple Access (DBTMA)
In the schemes based on the exchange of RTS/CTS dialogue, these control packets themselves are prone to collisions. Thus, in the presence of hidden terminals, there remains a risk of subsequent data packets being destroyed because of collisions. The DBTMA scheme [20] uses out-of-band signaling to effectively solve the hidden and the exposed terminal problems. Data transmission is however on the single shared wireless channel. It builds upon earlier work on the Busy Tone Multiple Access (BTMA) [9] and the Receiver Initiated-Busy Tone Multiple Access (RI-BTMA) [18] schemes.

DBTMA decentralizes the responsibility of managing access to the common medium and does not require time synchronization among the nodes. As in several schemes discussed earlier, DBMTA sends RTS packets on data channel to set up transmission requests. Subsequently, two different busy tones on a separate narrow channel are used to protect the transfer of the RTS and data packets. The sender of the RTS sets up a transmit-busy tone (BTt). Correspondingly, the receiver sets up a receive-busy tone (BTr) in order to acknowledge the RTS, without using any CTS packet.

Any node that senses an existing BTr or BTt defers from sending its own RTS over the channel. Therefore, both of these busy tones together guarantee protection from collision from other nodes in the vicinity. Through the use of the BTt and BTr in conjunction, exposed terminals are able to initiate data packet transmissions. Also, hidden terminals can reply to RTS requests as simultaneous data transmission occurs between the receiver and sender. The authors claimed a significant improvement of 140% over the MACA protocol under certain scenarios. However, the DBTMA scheme does not use ACK to acknowledge the received data packets. It also requires additional hardware complexity.

Yeh and Zhou [47] have recently proposed an RTS/OTS/CTS (*ROC*) scheme for efficiently supporting networks with devices having heterogeneous power levels and transmission ranges. This scheme uses an additional Object To Send (OTS) control packet. By the use of a separate control channel and single data channel, the proposed schemes solved problems due to hidden, exposed, moving, temporarily deaf and heterogeneous nodes. However, the authors did not present the simulation results to support their claim.

C.2 Multi Channel CSMA MAC Protocol
The multi-channel CSMA protocol proposed by Nasipuri et al. [48] divides the total available bandwidth (W) into N distinct channels of W/N bandwidth each. Here N may be lower than the number of nodes in the network. Also, the channels may be divided based on either an FDMA or CDMA. A transmitter would use carrier sensing to see if the channel it last used is free or not. It uses the last used channel if found free. Otherwise, another free channel is chosen at random. If no free channel is found, the node has to backoff and retry later. Even when traffic load is high and sufficient channels are not available, chances of collisions are somewhat reduced since each node tends to prefer its last used channel instead of simply choosing a new channel at random.

This protocol has been shown to be more efficient than single channel CSMA schemes. Interestingly, the performance of this scheme is lower than that of the single channel CSMA scheme at lower traffic load or when there are only a small number of active nodes for a long period of time. This is due to the waste of idling channels. In [50] the protocol is extended to select the best channel based on the signal power observed at the sender side.

C.3 Hop-Reservation Multiple Access (HRMA)
HRMA [19] is an efficient MAC protocol based on FHSS radios in the ISM band. Earlier protocols such as [54-55] used frequency-hopping radios to achieve effective CDMA by requiring the radio to hop frequencies in the middle of data packets. HRMA uses time-slotting properties of very-slow FHSS such that an entire packet is sent in the same hop. HRMA requires no carrier sensing, employs a common frequency hopping sequence, and allows a pair of nodes to reserve a frequency hop (through the use of an RTS-CTS exchange) for communication without interference from other nodes.

One of the N available frequencies in the network is reserved specifically for synchronization. The remaining N- 1 frequencies are divided into M = floor ((N- 1)/2) pairs of frequencies. For each pair, the first frequency is used for Hop Reservation (HR), RTS, CTS and data packets, while the second frequency is used for ACK packets. HRMA can be treated as a TDMA scheme, where each time slot is assigned a specific frequency and subdivided into four parts - synchronizing, HR, RTS and CTS periods. Fig. 7 shows an example of the HRMA frame. During the synchronization period of every time slot, all idle nodes synchronize to each other. On the other three periods, they hop together on the common frequency hops that have been assigned to the time slots.
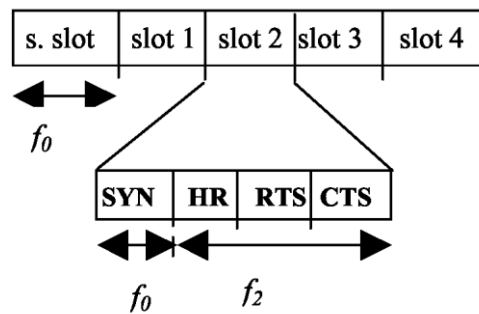

Fig. 7: Structure of HRMA slot and frame.

A sender-node first sends an RTS packet to the receiver in the RTS period of the time slot. The receiver sends a CTS packet to the sender in the CTS period of that same time slot. Now, the sender sends the data on the same frequency (at this time, the other idle nodes are synchronizing), and then hops to the acknowledgement frequency on which the receiver sends an ACK. If the data is large and requires multiple time slots, the sender indicates this in the header of the data packet. The receiver then sends an HR packet in the HR period of the next time slot, to extend the reservation of the current frequency for the sender and receiver. This tells the other nodes to skip this frequency in the hopping sequence.

The authors claim that HRMA achieves significantly higher throughput than Slotted ALOHA in FHSS channels. It uses simple half-duplex slow frequency hopping radios that are commercially available. It however requires synchronization among nodes, which is not suitable for multi-hop networks.

C.4 Multi-Channel Medium Access Control (MMAC)
So and Vaidya proposed MMAC [49], which utilizes multiple channels by switching among them dynamically. Although the IEEE 802.11 protocol has inherent support for multiple channels in its DCF, it only utilizes one channel at present [23]. The primary reason is that hosts with a single half duplex transceiver can only transmit or listen to one channel at a time.

MMAC is an adaptation to the DCF in order to use multiple channels. Similar to the DPSM scheme [32], time is divided into multiple fixed-time beacon intervals. The beginning of every interval has a small ATIM window.

During this window ATIM packets are exchanged among nodes so that they can coordinate the assignment of appropriate channels for use in the subsequent time slots of that interval. Unlike other multi-channel protocols (e.g., [51-53]), MMAC needs only one transceiver. At the beginning of every beacon interval, every node synchronizes itself to all other nodes by tuning in to a common synchronization channel on which ATIM packets are exchanged. No data packet transmission is allowed during this period of time. Further, every node maintains a preferred channel list (PCL) that stores the usage of channels within its transmission range, and also allows for marking priorities for those channels.

If a node has a data packet to send, it sends out an ATIM packet to the recipient that includes sender's PCL. The receiver in turn compares the sender's PCL with that of its own and selects an appropriate channel for use. It then responds with an ATIM-ACK packet and includes the chosen channel in it. If the chosen channel is acceptable to the sender, it responds with an ATIM-RES (Reservation) packet. Any node overhearing an ATIM-ACK or ATIM-RES packet updates its own PCL. Subsequently, the sender and receiver exchange RTS/CTS messages on the selected channel prior to data exchange. Otherwise, if the chosen channel is not suitable for the sender, it has to wait till the next beacon interval to try another channel.

The authors have shown using simulations that the performance of MMAC is better than IEEE 802.11 and DCA [5 1] in terms of throughput. Also it can be easily integrated with IEEE 802.11 PSM mode while using a simpler hardware. However, it has longer packet delay than DCA. Moreover, it is not suitable for multi hop ad hoc networks as it assume that the nodes are synchronized. It should be interesting to study its extension to multi-hop networks by using the approach proposed by Tseng et al. [34].

C.5 Dynamic Channel Assignment with Power Control (DCA-PC)
DCA-PC proposed by Tseng et al. [52] is an extension of their DCA protocol [51] that did not consider the issue of power control. DCA-PC uses concepts of power control and multiple channel medium access together in the context of MANETs. In DCA-PC, hosts are assigned channels dynamically, as and when they need them. Every node is equipped with two half-duplex transceivers and the bandwidth is divided into a control channel and multiple data channels. One transceiver operates on the control channel in order to exchange control packets (using maximum power) for reserving the data channel, and the other switches between the data channels for exchanging data and acknowledgments (with power control). When a host needs a channel to talk to another, it engages in an RTS/CTS/RES exchange, where RES is a special Reservation packet, indicating the appropriate data channel to be used.

Every node keeps a table of power levels to be used when communicating with any other node. These power levels are calculated based on the RTS/CTS exchanges on the control channel. Since every node is always listening to the control channel, it can even dynamically update the power values based on the other control exchanges happening around it. Every node maintains a list with channel usage information. In essence this list tells the node which channel its neighbor is using and the times of such usage.

DCA-PC has been shown to achieve higher throughput than DCA. However, it is observed that when the number of channels is increased beyond a point, the effect of power control is less significant due to overloading of the control channel. In summary, DCA-PC is a novel attempt at solving dynamic channel assignment and power control issues in an integrated fashion.

D. Protocols Using Directional Antennas
MAC protocols for ad hoc networks typically assume the use of omni-directional antennas, which transmit radio signals to and receives them from all directions. These MAC protocols require all other nodes in the vicinity to remain silent. With directional antennas, it is possible to achieve higher gain and restrict the transmission to a particular direction. Similarly, packet reception at a node with directional antenna is not affected by interference from other directions. As a result, it is possible that two pairs of nodes located in each other's vicinity communicate simultaneously, depending on the direction of transmission. This would lead to better spatial reuse in the other unaffected directions [56]. Using these antennas, however, is not a trivial task as the correct

direction should be provided and turned to in real time. Besides, new protocols would need to be designed for taking advantage of the new features enabled by directional antennas because the current protocols (e.g., IEEE 802.11) cannot benefit from these features. Currently, directional antenna hardware is considerably bulkier and more expensive than omni-directional antennas of comparable capabilities. Applications involving large military vehicles are however suitable candidates for wireless devices using such antenna systems. The use of higher frequency bands (e.g., ultra wide band transmission) will reduce the size of directional antennas.

Studies have been undertaken for adapting the slotted ALOHA scheme for use with packet radio networks and directional antennas [57]. Similar research on packet radio networks involving multiple and directional antennas has also been presented in [58-60]. Recently, Ramanathan [61] has discussed channel-access models, link power control and directional neighbor discovery, in the context of beam forming directional antennas. Effects such as improved connectivity and reduced latency are also discussed. Bandyopadhyay et al. [62] suggest a scheme in which every node dynamically stores some information about its neighbors and their transmission schedules through the use of special control packets. This allows a node to steer its antenna appropriately based on the on-going transmissions in the neighborhood. A method for using the directional antennas to implement a new form of link-state based routing is also proposed.

Ko et al. [63] suggest two variations of their Directional MAC (D-MAC) scheme using directional antennas. This scheme uses the familiar RTS/CTS/Data/ACK sequence where only the RTS packet is sent using a directional antenna. Every node is assumed to be equipped with several directional antennas, but only one of them is allowed to transmit at any given time, depending on the location of the intended receiver. In this scheme, every node is assumed to be aware of its own location as well as the locations of its immediate neighbors. This scheme gives better throughput than IEEE 802.11 by allowing simultaneous transmissions that are not possible in current MAC schemes.

Based on the IEEE 802.11 protocol, Nasipuri et al. [64] have proposed a relatively simple scheme, in which every node has multiple antennas. Any node that has data to send first sends out an RTS in all directions using every antenna. The intended receiver also sends out the CTS packet in all directions using all the antennas. The original sender is now able to discern which antenna picked up the strongest CTS signal and can learn the relative direction of the receiver. The data packet is sent using the corresponding directional antenna in the direction of the intended receiver. Thus, the participating nodes need not know their location information in advance.

Please note that only one radio transceiver in a node can transmit and receive at a time. Using simulation the authors have shown that this scheme can achieve up to 2 to 3 times better average throughput than CSMA/CA with RTS/CTS scheme (using omni-directional antennas).

Choudhury et al. [56] have presented a Multi-Hop RTS MAC (M-MAC) scheme for transmission on multi-hop paths. Since directional antennas have a higher gain and transmission range than omni-directional antennas, it is possible for a node to communicate directly with another node that is far away. M-MAC therefore uses multiple hops to send RTS packets to establish links between distant nodes, but the subsequent CTS, data and ACK packets are sent in a single hop. Simulation results indicate that this protocol can achieve better throughput and end-to-end delay than the basic IEEE 802.11 [23] and the D-MAC [63] schemes presented earlier. The authors however note that the performance also depends on the topology configuration and flow patterns in the system.

The use of directional antennas can introduce three new problems: new kinds of hidden terminals, higher directional interference and deafness [56]. These problems depend on the topology and flow patterns. For example, the deafness is a problem if routes of two flows share a common link. Similarly, nodes that are in a straight line witness higher directional interference. The performance of these schemes will degrade with node mobility. Some of the current protocols (e.g., [63, 64]) inaccurately assume that the gain of directional antenna is the same as that of omni-directional antenna. Similarly, none of them considers the effect of transmit power control, use of multiple channels and support for real-time traffic.

E. Unidirectional MAC Protocols

When low-power and battery-operated nodes coexist with more powerful nodes tethered to power sources in ad hoc networks, disparities in the transmission powers and asymmetric links between nodes are introduced. Such a network is therefore heterogeneous in terms of power levels. This gives rise to situations where a node *A* is able to transmit to another node *B*, but *B*'s transmission may not reach *A*. Recently, some schemes have been proposed that control the transmission range of individual node(s) to maintain optimum network topology [3 8, 40, 65]. As a result, there might be unidirectional links in these networks.

Several studies have been presented on unidirectional MAC. Prakash [66] pointed out some of the issues to be taken care of in unidirectional link networks. In a network of devices having heterogeneous power levels, when a low power node tries to reserve the channel for data transmission, it may not be heard due to higher power nodes that are close enough to disrupt its data exchange. As a result, a successful RTS-CTS exchange does not guarantee successful transmission of data. Furthermore, it is important to ensure that the MAC protocol does not favor certain higher power nodes. In order to overcome this problem, Poojary et al. [10] proposed a scheme to extend the reach of RTS/CTS exchange information in the IEEE 802.11 protocol. This ensures that all hidden higher power nodes that could otherwise interfere with the subsequent DATA transmission are made aware of the reservation of the channel. Bao et al. [67] proposed a set of collision-free channel access schemes, known as PANAMA, for ad hoc networks with unidirectional links. In each contention slot, one or multiple winners are elected deterministically to access the channel.

Agarwal et al. [68] summarized the problems caused by unidirectional links in ad-hoc wireless networks and presented some modifications of MAC and routing protocols. Ramasubramanian [69] presented a Sub Routing Layer (SRL) as a bidirectional abstraction over unidirectional links in lower layers. SRL uses different reverse links as the abstract reverse link to routing layer.

IV. QOS-AWARE MAC PROTOCOLS

With the growing popularity of ad hoc networks, it is reasonable to expect that users will demand some level of *Quality of Service* (QoS) from them. Some of the QoS related parameters that may be quantified are end-to-end delay, available bandwidth, probability of packet loss, etc. However, the lack of centralized control, limited bandwidth, error-prone wireless channels, node mobility, and power or computational constraints makes it very difficult to provide effective QoS in such networks [3, 72-74].

When the nodes join or leave an ad hoc wireless network at random, periodic topology updates are required so that every node is aware of the current network configuration. In case the topology of the network changes so rapidly that the routine updates are unable to cope up with the same, the network is not *combinatorially stable* and it may not be possible to guarantee certain levels of QoS. However, if such guarantees are maintained regardless of the changes in topology, the network is said to be '*QoS-robust*'. Otherwise, if the guarantees are maintained between any two consecutive updates to the topology, the network is said to be '*QoS-preserving*' [3]. The use of priority to realize QoS is known as '*prioritized QoS*'. Prioritized QoS lets the applications specify a higher priority for accessing network resources than other applications. A '*parameterized QoS*' involves reserving resources for the end-to-end path of the application data stream. A new stream is not admitted if enough bandwidth is not available to support it. This ensures that the already admitted flows remain unaffected. In certain situations, the concept of *soft* or *dynamic QoS* may be rather useful. In *soft-QoS* [75], after the initial connection is set up, there can be brief periods of time when there is a disruption in providing the pre-decided QoS guarantees. In *dynamic-QoS* [76], a resource reservation request specifies a range of values (i.e., the minimum level of service that the applications are willing to accept and the maximum level of service they are able to utilize), and the network makes a commitment to provide service at a specified point within this range. In such a case, allocation of resources needs to be dynamically adjusted across all layers of the network. Treating the reservations as ranges provides the flexibility needed for operation in a dynamic ad hoc network environment. Real-time consumer applications such as streaming audio/video require a reserved share of the channel capacity over relatively long durations so that QoS requirements are met. However, stringent delivery guarantees, particularly on short time scales, need not always be fulfilled for such applications. Therefore, these

applications can be satisfied by soft or dynamic QoS. Other applications such as inter-vehicle communication for safety require guaranteed delivery of short bursts of data with a bounded delay. These applications will require parameterized QoS. In fact, maintaining QoS guarantees for delay sensitive traffic is quite difficult in MANETs because obtaining a consistent network-wide distributed snapshot of the state of the queues and the channel at individual nodes at any given instant is an intractable problem.

The issues affecting support for QoS in ad hoc networks are briefly discussed below, followed by brief explanation of selected protocols.

A. ISSUES AFFECTING QoS:

Several issues, such as the service model, routing strategies, admission control, resource reservation, signaling techniques, and MAC protocols need to be considered in the context of providing QoS in ad hoc wireless networks. In fact, every layer of the network has to be made QoS aware because only when all the factors are considered together in the overall scenario can effective QoS be provided for the end-user application. We briefly discuss below the important issues across different layers.

A QoS *service model* specifies an overall architectural framework, within which certain types of services can be provided in the network. Some of the prominent service models suggested for ad hoc networks are: flexible quality of service model for MANETs (FQMM) [77], cross layer service model [78], and stateless model for wireless ad-hoc networks (SWAN) [79].

Signaling is used in order to negotiate, reserve, maintain and free up resources, and is one of the most complicated aspects of the network. It should be performed reliably (including topology changes) with minimum overhead. *Out-of-band* and *in-band* signaling are two commonly used approaches. INSIGNIA [80] and Integrated Mobile Ad-Hoc QoS (iMAQ) framework [81] are examples of signaling schemes proposed in the literature.

If the application needs to be guaranteed a certain minimum bandwidth or end-to-end delay, the *routing* algorithm needs to be QoS aware as well. Not only does the route have to be valid at the time the data is to be transported, but also all the nodes along that route need to have sufficient resources in order to support the QoS requirement of the data flow and the application. For extensive survey of routing techniques, the reader is referred to [3, 5, 72, 82]. Once a potential route is established, it is necessary to reserve and allocate the required resources in all the nodes of that route so that the demands of the application can be met. The admission control becomes important in this context.

QoS supporting components at upper layers assume the existence of a QoS-aware MAC protocol, which takes care of medium contention, supports reliable unicast communication, and provides resource reservation for *rt* traffic in a distributed environment. The MAC protocols are therefore very important for QoS support, since they have a direct bearing on how reliably and efficiently data can be transmitted from one node to the next along any path in the network. The MAC protocol should address issues caused by node mobility and unreliable time-varying channel.

B. REVIEW OF SELECTED QOS-AWARE MAC PROTOCOLS

In ad hoc networks, MAC protocols aim to solve the problem of contention by addressing the issues of hidden or exposed terminals. For applications requiring certain level of QoS, the MAC layer protocol should also support resource reservation and real time (*rt*) traffic. MAC is a lower level function and needs to be closely integrated with upper layers such as the network layer for routing. Since centralized control is not available, it is difficult to maintain information about connections and reservations.

There are two ways to avoid the use of a centralized coordinator node in QoS-aware MAC schemes. The *first approach* involves *synchronous* schemes like Cluster TDMA [83, 84], Cluster Token [85], and Soft Reservation Multiple Access with Priority Assignment (SRMA/PA) [86]. In *Cluster TDMA*, the nodes are organized into

clusters, and each cluster has a cluster head that is responsible for coordinating the activities of the nodes under its purview. Each cluster uses a different DS-Spread Spectrum code. A common, globally synchronous slotted TDM frame is defined among clusters. Slots can be reserved by *rt* traffic and free slots are used by non real-time (*nrt*) data. The *rt* traffic handling performance of the scheme is very good. However, *time synchronization* is a *resource intensive* process and should ideally be *avoided* in ad hoc networks. Similarly, the implementation of multiple codes and associated power control is non-trivial. The merits of such TDMA schemes have been discussed in [7]. In *Cluster Token* scheme, the TDM access scheme is replaced by an implicit token scheme within each cluster. Also, no synchronization is required across different clusters.

The *other option* is to use *asynchronous* approaches that do not require global time synchronization and therefore are more suitable for ad hoc networks. IEEE 802.11 DCF is a widely used asynchronous protocol that uses a best effort delivery model [22-25]. It does not support *rt* traffic as its random backoff mechanism cannot provide deterministic upper bounds on channel access delays. A number of QoS-aware MAC schemes have been proposed in the past few years and most of them are more or less based on the IEEE 802.11 DCF. No formal classification exists in the literature to group these schemes. We have attempted to classify below these schemes according to their major features: (*i*) some schemes, such as real-time MAC [87], DCF with priority classes [88] and enhanced DCF (EDCF) [89-91], use shorter inter-frame spacing and backoff contention values to meet the delay and bandwidth requirements of *rt* traffic. These schemes are relatively straightforward extensions of IEEE 802.11 DCF and can be overlaid on this protocol. (*ii*) The black burst (BB) contention [92, 93], elimination by sieving (ES-DCF) and deadline bursting (DB-DCF) [94, 95] schemes use a shorter inter-frame spacing and a different approach than the backoff window for channel contention to support bounded time delay of *rt* traffic. (*iii*) Instead of directly manipulating inter-frame spacing and contention window, another group of schemes uses reserved time slots at nodes to provide bounded delay and required bandwidth for the *rt* traffic. The *nrt* data traffic is treated exactly as in IEEE 802.11. Examples of this class of schemes are: MACA/PR [96], asynchronous QoS enabled multi-hop MAC [97] and dynamic bandwidth allocation/sharing/extension (DBASE) protocol [98]. (*iv*) The above classes of schemes may not guarantee a fair proportion of channel to different flows.

Therefore, some researchers have proposed MAC schemes (e.g., distributed fair scheduling [99]) to provide a reasonably fair channel allocation to different flows (often according to their priority).

It should be pointed out that the schemes of different classes often have some common features. We discuss below salient features of major schemes in each category.

B.1 Real-Time MAC (RT-MAC)
In IEEE 802.11 protocol, packets that have missed their deadlines are still retransmitted, even though they are not useful any more. This causes bandwidth and resources to be wasted. Baldwin et al. [87] proposed a variation of the IEEE 802.11 protocol called RT-MAC that supports *rt* traffic by avoiding packet collisions and the transmission of already expired packets. To achieve this, RT-MAC scheme uses a packet transmission deadline and an 'enhanced collision avoidance' scheme to determine the transmission station's next backoff value. When an *rt* packet is queued for transmission, a timestamp is recorded locally in the node indicating the time by when the packet should be transmitted. The sending node checks whether a packet has expired at three points: before sending the packet, when its backoff timer expires and when a transmission goes unacknowledged. An expired packet is immediately dropped from the transmission queue. When the packet is actually about to be sent out, the sending node chooses the next backoff value and records it in the packet header. Any node that overhears this packet then ensures that it chooses a different backoff value. This eliminates the possibility of collision. The range of values (i.e., contention window, *CW*) from which the backoff value is chosen, is made a function of the number of nodes in the system. Therefore, the number of nodes should be known or at least estimated in this scheme.

RT-MAC scheme has been shown to achieve drastic reductions in mean packet delay, missed deadlines, and packet collisions as compared to IEEE 802.11. However, the contention window may typically become quite

large in a network with large number of nodes. This will result in wasted bandwidth when the network load is light.

B.2 DCF with Priority Classes

Deng et al. [88] proposed another variation of the IEEE 802.11 protocol (henceforth called DCF- PC) that supports priority based access for different classes of data. The basic idea is to use a combination of shorter IFS or waiting times and shorter backoff time values (i.e., maximum allowable size of contention window) for higher priority data (i.e., *rt* traffic). As already mentioned, some different IFS intervals specified in the IEEE 802.11 protocol are SIFS, PIFS and DIFS [23-25]. While normal nodes wait for the channel to remain idle after DIFS interval before they transmit data, a higher priority node waits for only PIFS. However, if the chosen backoff value happens to be longer, the higher priority node can still lose out to another node that has a larger IFS but a shorter random backoff value. In order to solve this problem, the authors have proposed two different formulae for generating the random backoff values so that the higher priority nodes are assigned shorter backoff time.

Using simulations, the authors have demonstrated that this scheme has better performance than 802.11 DCF, in terms of throughput, access delay and frame loss probability for higher priority (*rt*) traffic. It can support more than 2 traffic priorities. However, this scheme lacks the ability to provide *deterministic* delay bounds for *rt* traffic. Moreover, normal data traffic suffers *higher delay* due to a longer backoff time even when no higher priority node is transmitting. Channel bandwidth is also wasted in such cases.

B.3 Enhanced DCF

IEEE 802.11 DCF is designed to provide a channel access with equal probabilities to all the contending nodes in a distributed manner. EDCF enhances the DCF protocol to provide differentiated channel access according to the frame priorities. It has been developed as a part of the hybrid coordination function (HCF) of IEEE 802.11 e [89-9 1]. We discuss below its working principle, independent of the details of IEEE 802.11e HCF.

Each data frame is assigned a traffic class (TC) in the MAC header, based on its priority as determined in the higher layers. During the contention process, EDCF uses AIFS[TC], CW_{min}[TC] and $CW_{max[TC]}$ instead of DIFS, CW_{min} ^{and} CW_{max} of the DCF, respectively, for a frame belonging to a particular TC. Here AIFS (Arbitration Inter Frame Space) duration is at least DIFS, and can be enlarged individually for each TC. The CW_{min} of the backoff mechanism is set differently for different priority classes. EDCF thus combines two measures to provide service differentiation. Fig. 8 illustrates the EDCF channel access.
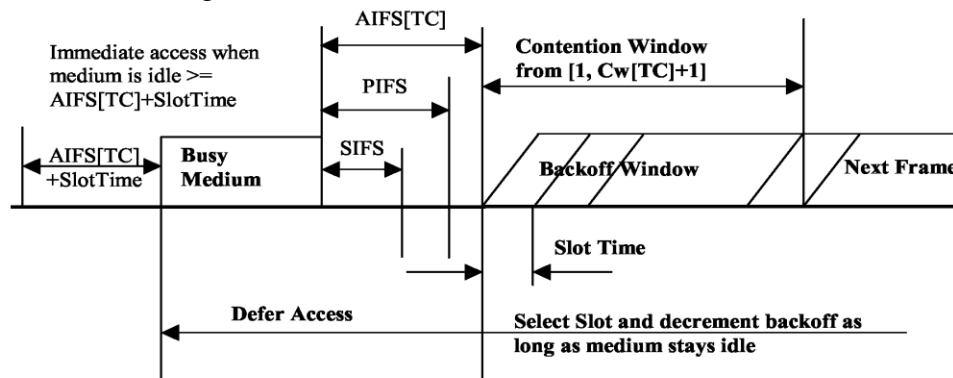
Fig. 8: The EDCF channel access scheme.

Based on the analysis of delay incurred by IEEE 802.11 DCF, Veres et al. [75] proposed a fully distributed *Virtual MAC* (VMAC) scheme that supports service differentiation, radio monitoring, and admission control for delay-sensitive and best-effort traffic. VMAC passively monitors the radio channel and estimates locally achievable service levels. It also estimates key MAC-level QoS statistics, such as delay, delay variation, packet collision, and packet loss.

B.4 Black Burst (BB) Contention

Sobrinho and Krishnakumar introduced BB contention scheme in [92, 93]. This scheme is distributed, can be overlaid on the IEEE 802.11 standard and relies on carrier sensing. The scheme operates as follows: Normal data nodes use a longer inter-frame spacing than *rt* nodes. This automatically biases the system in favor of the *rt* nodes. Instead of sending their packets when the channel becomes idle for a predetermined amount of time, *rt* nodes jam the channel with pulses of energy (which are termed the black bursts) whose length is proportional to the contention delay experienced by the node. This delay is measured from the instant an attempt is made to access the channel until the BB transmission is started.

To uniquely identify all the BB pulses sent by different *rt* nodes, they all differ in length by at least one black slot. Following each BB transmission, a node senses the channel for an observation period to determine whether its own BB was the longest or not. If so, the node goes ahead with its data transmission. Otherwise it has to wait for the channel to be idle before it can send another BB. In essence, the scheme seems to achieve a dynamic TDM transmission structure without explicit slot assignments or synchronization. It guarantees that *rt* packets are transmitted without collisions and with a higher priority over others. It has also been shown that BB contention enforces a round robin discipline among *rt* nodes (if there is more than one) and achieves bounded *rt* delays.

The BB contention scheme thus provides some *QoS guarantees* to *rt* multimedia traffic as compared to simple carrier sense networks. Applications considered are those like voice and video that require more or less periodic access to the channel during long periods of time denominated sessions. One of the main considerations in such applications is the end-to-end delay. This translates to requiring a bounded packet delay at the data link layer. However, this scheme does not consider *hidden terminal problem*.

B.5 Elimination by Sieving (ES-DCF) and Deadline Bursting (DB-DCF)

Pal et al. [94, 95] proposed two variants of the IEEE 802.11 DCF that offer guaranteed time bound delivery for *rt* traffic, by using deterministic collision resolution algorithms. Interestingly, they also employ black burst features.

The ES-DCF has three phases of operation – elimination, channel acquisition and collision resolution. In elimination phase, every node is assigned a grade based on the deadlines and priority of its packets as in [88]. A closer deadline results in a lower numerical grade, which translates to lower than DIFS channel-free wait times. Therefore, the grade of the packet improves if it remains in the queue for a longer time. In the channel acquisition phase, the node transmits RTS packet to initiate the channel acquisition, when the channel has been free for the requisite amount of time, as decided by the grade of its data packet. If it receives a CTS packet in return, the channel is considered acquired successfully. Otherwise, the third phase of collision resolution is initiated by sending out a BB (as in [92, 93]). The length of the BB corresponds to the node identification (Id) number. Higher Id numbers are given to the nodes that generate a lot of *rt* data. The node that sends out the longest burst accesses the channel at the subsequent attempt.

In the DB-DCF, the first phase is for BB contention wherein the lengths of the BB packets are proportional to the urgency (i.e., relative deadlines) of the *rt* packet. This is followed by phases for channel acquisition and collision resolution, which are similar to the corresponding phases in ES-DCF.

Both schemes assign channel-free wait time longer than DIFS for *nrt* nodes, such that these nodes are allowed to transmit only when the other *rt* nodes have no data waiting to be sent. However, the results of the simulations carried out by the authors indicate that ES-DCF is more useful when hard *rt* traffic is involved, and DB-DCF performs better in the case of nodes with soft *rt* packets. Due to the use of BB and longer (than DIFS) channel-free wait time for *nrt* traffic, these schemes cannot be directly overlaid on any existing IEEE 802.11 DCF implementation.

B.6 Multiple Access Collision Avoidance with Piggyback Reservations (MACA/PR)

Lin and Gerla proposed MACA/PR architecture to provide efficient *rt* multimedia support over ad hoc networks [96]. MACA/PR is an extension of IEEE 802.11 [23-25] and FAMA [15]. The architecture includes a MAC protocol, a reservation protocol for setting up *rt* connections and a QoS aware routing scheme. We will discuss only the MAC protocol here.

In MACA/PR, nodes maintain a special reservation table that tells them when a packet is due to be transmitted. The first data packet in an *rt* data stream sets up reservations along the entire path by using the standard RTS-CTS approach. Both these control packets contain the expected length of the data packet. As soon as the first packet makes such a reservation on a link, a transmission slot is allocated at the sender and the next receiver node at appropriate time intervals (usually in the next time cycle) for the subsequent packet of that stream. The sender also piggybacks the reservation information for the subsequent data packet in the current data packet. The receiver notes this reservation in its reservation table, and also confirms this through the ACK packet. Neighboring nodes overhearing the data and ACK packets, become aware of the subsequent packet transmission schedule, and back off accordingly. The ACK only serves to renew the reservation, as the data packet is not retransmitted even if the ACK is lost due to collision. If the sender consecutively fails to receive ACK N times, it assumes that the link cannot satisfy the bandwidth requirement and notifies the upper layer (i.e., QoS routing protocol). Since there is no RTS-CTS exchange after the first data packet, collision prevention of *rt* packets is through the use of the reservation tables. For *nrt* data packet, MACA/PR uses IEEE 802.11 DCF.

Using simulations, the authors have demonstrated that this *asynchronous* scheme is able to achieve a *lower end-to-end delay* than other schemes that require time synchronization such as Cluster Token and Cluster TDMA. However, since the cluster based schemes use code separation, they can achieve higher aggregate throughput efficiency. Another reason for lower throughput achieved by MACA/PR is that multiple reservation tables need to be kept current at all times so that the sending node can consult them before transmission. This introduces an overhead on the network as the tables are exchanged frequently among neighbors.

B.7 Asynchronous QoS Enabled Multi-Hop MAC

Ying et al. [97] proposed an *asynchronous* protocol based on the IEEE 802.11 DCF, that supports constant bit-rate (CBR) and variable bit rate (VBR) *rt* traffic, and regular *nrt* datagram traffic. In the case of an *nrt* data transmission, the regular RTS-CTS-DATA-ACK sequence is employed between the sender and the receiver. The acknowledgments sent in response to *nrt* and *rt* packets are called D-ACK and R-ACK, respectively. Similarly, the *nrt* and *rt* data packets are termed as D-PKT and R-PKT, respectively. In the case of *rt* traffic, though, there is no RTS-CTS exchange for the data packets sent after the first R-PKT (similar to the MACA/PR scheme [96]). In other words, the R-ACK packet reserves the transmission slot for the next *rt* data packet. The scheme requires every node to maintain two reservation tables, Rx RT and Tx RT. The former (latter) informs the node when neighbors expect incoming (to transmit) *rt* traffic. These estimates are recorded in the corresponding tables based on the overhearing of R-PKT and R-ACK packets. In essence, before sending any RTS, nodes look for a common free slot based on the entries in the reservation tables so as not to interfere with *rt* transmissions already in the queue in the neighborhood. Similarly, if a node receives an RTS, it performs the same checks before responding with a CTS packet. After a successful RTS-CTS exchange, data is sent out, and an ACK is expected. If an ACK is missed, the node starts to backoff (using BEB) and uses the IEEE 802.11 contention windows for the same.

This scheme allows for bounded delays in *rt* traffic but depends on the overhearing of R-PKT and R-ACK packets within each node's transmission range to avoid hidden node problem. Both the receiver and transmitter nodes check their own tables, thereby eliminating the overhead of exchanging table information. Using simulations, the authors have demonstrated that this scheme achieves lower delays for *rt* traffic than BB Contention, MACA/PR and DFS [99] schemes. The packet loss rates are also relatively small.

Sheu et al. [98] have proposed the *Dynamic Bandwidth Allocation/Sharing/Extension* (*DBASE*) protocol that also uses a reservation table for supporting *rt* traffic. A unique feature of this scheme is that bandwidth allocation can change dynamically over time, which allows efficient support of CBR as well as VBR traffic. The scheme achieves very high throughput and low packet loss probability for *rt*-packets even at heavy traffic load, and outperforms the IEEE 802.11 DCF [23-25] and DFS [99] schemes. DBASE, however, assumes that all the nodes can hear one another and it may be difficult to extend it to the (multi hop) ad hoc networks with hidden terminals. Overall, DBASE is a quite different scheme than the other two (previously discussed) reservation based schemes.

B.8 Distributed Fair Scheduling (DFS)

Vaidya et al. [99] proposed the DFS scheme to ensure that different flows sharing a common wireless channel are assigned appropriate bandwidth corresponding to their weights or priorities. DFS is derived from the IEEE 802.11 DCF and requires no central coordinator to regulate access to the medium. The fundamental idea of DFS is that each packet is associated with start and finish timestamps. A higher priority packet is assigned a smaller 'finish-tag' and shorter backoff periods. This approach ensures that any flow that has packets of higher priority will consistently have shorter backoff times, thereby achieving a higher throughput.

In DFS, the start and finish times for packets are calculated on the basis of the Self-Clocked Fair Queuing (SCFQ) algorithm proposed by Golestani [100]. Following the idea of SCFQ, every node also maintains a local virtual clock. DFS does not, however, REMOVE short-term unfairness in certain cases. The authors observe that the use of collision resolution schemes such as those proposed in [101] can resolve this anomaly. In order to calculate backoff intervals, the authors have proposed two alternate approaches: linear mapping and exponential mapping. A disadvantage of the linear mapping scheme is that if many packet flows have low priorities, all of them are assigned large backoff intervals. As a result, the system remains idle for long periods of time. The exponential mapping approach is proposed as one solution to this problem.

Using simulations, the authors have shown that DFS obtains a higher throughput than IEEE 802.11. Also, they have verified that use of exponential mapping technique for calculating backoff intervals leads to higher throughput than linear mapping. However, the DFS does not consider the hidden terminal problem and delay bound of *rt* packets [98]. Nandagopal et al. [102] have also proposed a general analytical framework for modeling the fairness.

V. SUMMARY AND FUTURE DIRECTIONS

Due to space constraints and the large number of MAC schemes reviewed in this paper, it is difficult to compare their quantitative performance. We briefly discuss below qualitative performance of some of these schemes.

The CSMA based MAC schemes are not suitable in ad hoc networks due to multi-hop transmission and hidden/exposed terminal problems. The MACA scheme [13] was proposed to solve these problems with the help of two relatively short RTS/CTS control packets. The MACAW scheme [14] adds an ACK packet to the transmission sequence, providing quicker response to data packet loss at the MAC layer. The MACAW scheme also includes techniques to solve the congestion and unfairness problems at the MAC layer. Although schemes like MACA and MACAW are based on the RTS-CTS dialog and abandon the Carrier Sensing mechanism in order to reduce performance degradation caused by hidden terminals, they are only partially successful, since the control packets are themselves subject to collisions.

A combination of control packets (e.g., RTS/CTS/ACK) and carrier sensing (i.e., CSMA) has been found to reduce the probability of collisions caused by hidden terminals. Such a strategy has been used by FAMA-NCS [15] with a mechanism to provide "CTS dominance". This solves the hidden terminal problem since the data packets can never collide with CTS packets. The exposed terminal problem is still unsolved, though. Similar to the FAMA scheme, the IEEE 802.11 DCF standard combines the CSMA and the RTS/CTS message exchange. While IEEE 802.11 DCF works well in Wireless LAN environment, it is not particularly suitable for multi-hop ad hoc networks with mobile nodes [71, 104].

In spite of the use of RTS/CTS/ACK and NAV in IEEE 802.11, some packets are still vulnerable to collisions as explained below. The transmission range of a node in which it can successfully decode the packet is determined by the received signal strength. Let *RX_Th* and *CS_Th* denote the minimum received signal power for receiving a valid packet and sensing a carrier, respectively. The received signal is discarded as noise if its strength is lower than *CS_Th*. If the received signal strength is in between *RX_Th* and *CS_Th*, the node cannot decode the packet but can sense the transmission. This is referred to as interference range. A node that is out of interference range of receiver (sender) but is within the interference range of sender (receiver) cannot sense ACK (data packet). As a result, the ACK and data packets are vulnerable to collisions from these nodes. Collisions in ACK packets are particularly troublesome as their loss results in retransmission of long data packets. Extended IFS (EIFS) is used in IEEE 802.11 DCF to prevent collisions with ACK receptions at sender [35, 104]. However, most of the other MAC schemes consider that the transmission range is equal to the interference range.

Due to the use of BEB algorithm in IEEE 802.11 DCF, the contention window size quickly increases for the nodes whose data suffers collisions. On the other hand, the contention window is set to the minimum value *CW_{min}* for each new packet even when the previous packet was not delivered successfully and the network area is congested. This contention and backoff strategy is *unfair* to the already existing nodes that are backing off due to collisions, especially under the heavy traffic conditions. Bhargavan et al. [14] attempted to improve the situation by using the multiplicative increase and linear decrease (MILD) algorithm in MACAW. This scheme however reduces throughput in light traffic conditions. Weinmiller et al. [105] proposed to divide the slots in a contention cycle in two parts such that the newly arriving traffic is assigned slots after the traffic that has suffered collisions. Cali et al. [106] proposed another scheme (to achieve fair channel access and reduce the probability of collisions) in which the contention window for a node is dynamically set depending on the traffic in its vicinity.

Multiple simultaneous transmissions can take place amongst different nodes that are out of transmission/interference range in a multi-hop network. Multi-hop networks experience more collisions compared to the one-hop case as the nodes are overlapped successively in space. As a result, congestion in one area may also affect the neighboring areas and can even propagate to other areas. The end-to-end throughput of IEEE 802.11 DCF decreases considerably in multi-hop networks due to collisions at intermediate forwarding nodes [71]. The throughput can be improved by resolving the exposed terminal problem (as in DBTMA [20] and using power control (as in PCMA [36]) and directional antenna [56-64] based schemes.

As devices shrink in size, their ability to carry larger battery packs will diminish. The power-aware schemes across all layers of the network can maximize performance and battery life. Both the *power management* (using sleep and wake cycles for various nodes) and *power control* (changing power level in the nodes) approaches used in power-aware MAC schemes have their advantages and disadvantages in data communication, as briefly discussed below.

Power management based MAC schemes such as PAMAS [27] achieve significant power savings by powering down nodes at the appropriate times. Interestingly, even though the nodes follow alternating sleep and wake cycles, throughput is not affected since a node sleeps only when it cannot actually transmit or receive. PAMAS however lacks provisioning of acknowledgment at the MAC layer. If an enhancement, such as the one in MACAW [14], is made at the link layer, energy efficiency can be improved as the higher layer retransmissions become unnecessary. Power management yields significant savings but reduces the network capacity when only a small number of nodes are active. It may also introduce long route establishment delays, since sleeping nodes might need to be woken up for packet transmission.

Power control based MAC schemes improve the network capacity through spatial reuse, but it also increases the end-to-end delay for packet delivery due to the need for large number of short hops in a multi-hop path. The PCM [35] protocol uses the concept of power control by regulating transmission power levels according to the factors such as the distance between the nodes. This is a rather practical approach and it should be easy to

merge this technique with the power management schemes (similar to PAMAS [27]). When nodes wake up from their sleep state, they can initiate RTS and CTS transmissions to deduce the required power level for subsequent transmissions. We have seen that the IEEE 802.11 standard also lends itself to some provisioning for power saving, but this needs to be explored further and improved. As explained in [10], there is a need to find a balance between power savings and control traffic overhead. This is important in the context of scalability, which is an important issue in ad hoc networks.

Ebert et al. [44] observed that using lower power levels to transmit data packets can result in higher bit error rates and expensive retransmissions. Using power control with IEEE 802.11 protocol, Feeney et al. [45] found that small packets usually have disproportionately high energy-costs due to the large overheads of channel acquisition. They also observed that the ad-hoc mode is more expensive than the centralized base station mode.

An ad hoc network may comprise heterogeneous devices with diverse power sources such as low power transducers, PDAs, handheld computer and other devices that may be tethered to a power supply. These devices will vary in their transmit power capabilities. This gives rise to *asymmetric links* between devices with widely different power sources. It is important to ensure that low power node(s) in the neighborhood of more powerful nodes are not denied channel access. Most of the power aware schemes in the literature do not consider the heterogeneous nodes, fairness properties, node mobility and multi-hop networks [10].

The performance (e.g., throughput) of single channel MAC schemes degrades significantly due to higher collisions when the number of mobile nodes increases. Use of power control schemes and directional antenna to increase channel reuse can improve the performance. Another option is to use *multiple channels* where a channel could be a code (in CDMA) or a frequency band (in FDMA). The advantages of multi-channel schemes were discussed in Section III.C. Of course some multi-channel schemes such as DBTMA [20] use only single data channel. DBTMA addresses the hidden and exposed terminal problems by using separate channels to set up busy tones. However, DBTMA requires relatively more complex hardware, i.e., two narrow-bandwidth transmitters for setting up separate busy tones. Even so, the significant performance benefit obtained by the scheme over others like MACA and FAMA-NCS can justify the required extra hardware complexity for some applications. Some other MAC schemes also solve the hidden-terminal and the exposed-terminal problems using different approaches, e.g., HRMA [19] solves these problems with multiple FHSS channels.

For using the multiple data channel, the mobile hosts can either have a single transceiver (capable of switching from one channel to another) or multiple transceivers (capable of accessing multiple channels simultaneously). Use of multiple transceivers requires complex hardware and higher cost. Moreover, hardware with the ability to synchronize transceivers for using different frequencies may not be feasible in miniature devices.

A *multi-channel* scheme typically needs to address the issues of channel assignment (for multiple data channels) and medium access. The number of channels chosen by a scheme should be independent of network degree [5 1]. Multi-channel CSMA [48] is a degree independent scheme. However, it requires each node to listen to all the channels while there is only one transmitter hopping from one channel to another. This will increase the hardware cost due to need for multiple transceivers. Also it suffers from the hidden terminal problem due to lack of RTS/CTS like reservation mechanism. HRMA scheme [19] is also a degree independent scheme using single transceiver, but it requires clock synchronization, which is difficult when the network is dispersed in a large area. Similarly, IEEE 802.11 based MMAC scheme requires single transceiver, but it needs node synchronization. DCA [51] scheme uses on-demand channel assignment (with single transceiver) and does not require clock synchronization. Jain et al. [53] have proposed a scheme that is similar to DCA in having one control and N data channels. However, the best channel is selected according to the channel condition at the receiver side. While most of the schemes use either power saving or multiple channels, the DCA-PC scheme addresses the channel assignment, medium access and power control issues in an integrated manner, in order to exploit the advantages of power saving as well as multiple channels.

We have already seen that almost all the schemes rely on some control packets and the amount of overhead caused by these packets will grow as the number of nodes in the network increases. Transmission of each control packet requires resources to be used. As a result, there is a need to investigate the relationship between the number of nodes and the control packet overhead. Instead of relying on flat networks, it may be useful to employ clustering schemes at higher layers like routing, although a detailed survey of those methods is beyond the scope of this study.

In the previous section, we briefly discussed major *QoS-aware* MAC schemes and identified their features and weaknesses. In particular, we looked at issues of providing guaranteed bandwidth and bounded delays for *rt* traffic. Most of these schemes are based on the widely used IEEE 802.11 DCF protocol. As mentioned earlier, IEEE 802.11 DCF protocol does not support QoS features such as bounded delay, guaranteed bandwidth, different user (or flow) priorities, and fair resource allocation.

The IEEE 802.11 DCF specifies different IFS slots, and because of the modular nature of the DCF, these slots can be easily exploited to provide service differentiation. Higher priority (or *rt*) nodes in a number of MAC schemes wait for the wireless medium to be free for shorter IFS than other (*nrt*) nodes [87-89]. Similarly, the backoff contention mechanism of IEEE 802.11 DCF has been widely used for service differentiation in [87-89]. These schemes successfully provide a relatively shorter average delay for higher priority (i.e., *rt*) traffic. However, a larger fraction of the packets suffer much longer delay at high loads. Aad and Castelluccia [103] have observed that the flows in IEEE 802.11 using the maximum frame size and frame fragmentation get higher throughput in case of error free channel. This is used for providing service differentiation in combination with IFS and backoff schemes. However, longer packets are more likely to get corrupted than the shorter frames in the presence of noise. In fact, the service differentiation by using backoff and maximum frame length does not work well in noisy environment, while the performance of shorter inter frame spacing remains unchanged. The most MAC schemes do not consider the effect of channel errors.

Another alternative approach to contention was used in BB-based scheme [92, 93]. The primary strength of this scheme is the use of black-burst signals to disseminate degree-of-urgency information to other nodes in the network. It guarantees bounded and typically very small *rt* delays. However, it imposes extra requirements (such as constant access intervals) on high priority stations. A major limitation of this scheme is that it is optimized for the service needs of isochronous traffic sources and may not work well with VBR sources. Similarly, it is not well suited if a node has only single or a few urgent packets to be delivered. Moreover the hidden terminals were not expressly considered in this approach. It may be possible to improve this by adding the carrier sensing and busy tones.

The above mentioned schemes may not ensure end-to-end delay required for *rt* traffic (CBR as well as VBR) over multi hop ad hoc networks. For this, reservation based schemes (i.e., MACA-PR [96] and its variant in [97]; DBASE does not suit multi-hop networks) have been proposed that entail significant changes in IEEE 802.11 DCF. The end-to-end delay in these schemes is lower as a packet need not wait to access the channel at intermediate nodes. Rather it can immediately access the free available slot. However, neighboring nodes in MACA/PR are required to periodically exchange reservation tables (RT). The resulting overhead increases with the frequency of RT exchange. An infrequent exchange, on the other hand, increases chances of collision. The variant of MACA/PR in [97] has better performance, as it does not require RT exchange. Both of these schemes have been shown to achieve lower average and maximum delays for *rt* traffic, and smaller packet loss rates than BB Contention and DFS [99] schemes.

Most of the above mentioned schemes (including service differentiation based schemes) may not provide *fair sharing* between *rt* traffic and datagram. The lower priority traffic often suffers from starvation in the presence of heavy *rt* traffic. The DFS scheme also uses the backoff mechanism of IEEE 802.11. The service differentiation is achieved by choosing the backoff interval inversely proportional to the priority of the node. On the other hand, fairness is achieved by making the interval proportional to the packet size. It does not, however,

provide bounded delay required by *rt* traffic. Moreover, the backoff intervals for lower priority flows can become quite large, which could be undesirable if the flow is already backlogged.

So far, we looked at some of the ideas proposed in the literature for incorporating explicit support for *rt* traffic into the MAC layer protocols. The use of asynchronous access, smaller channel-free wait times, need for determinism in collision resolution, dissemination of urgency information, dropping expired packets, fairness, etc. were some of the important aspects of the protocols.

Future Directions:

The MAC schemes reported in the technical literature have addressed, some successfully while others partially, a broad range of problems in ad hoc networks, including the well-known hidden/exposed terminal problems and QoS provisioning. However, several important issues still need to be addressed:

Hidden/Exposed Terminal Problems: In fact, while it is well-known that the transmission from a hidden terminal may destroy the packet reception at the receiver, the transmission from exposed terminals should be allowed on the same channel to maximize overall spatial reuse. Most of the MAC schemes addressing the hidden terminal problem do not effectively treat the exposed terminal problem. In fact, introduction of ACK packet on the MAC layer prohibits the exposed terminals from reusing the channel. Eliminating the ACK packets may solve the problem. However, the sender then has no way to be sure of its data packet being received successfully. Some researchers have attempted to use busy tones and multiple channels to solve these problems (e.g., DBTMA [20]). The balance and trade-off between these two conflicting design issues need to be studied.

As explained in the previous section, the ACK and data packets are vulnerable to collisions from the interfering nodes. Collisions in ACK packets are particularly troublesome as their loss results in retransmission of long data packets. However, most of the other MAC schemes consider that the transmission range is equal to the interference range.

Interference-Limited Model: Most of the proposed MAC schemes, if not all, use an overly-simplified packet collision model, i.e., the circular step-function collision model. The transmission range of each node is usually assumed to be the same. The node will always overhear all transmissions sent within this range. If two transmissions in this range overlap over time, packet collisions occur. While this collision model simplifies protocol design and its theoretical analysis, it may provide vastly inaccurate information on how certain operations may be performed. For example, there could be two senders, both of which are outside of the transmission (reception) range of a common receiver. The concurrent transmissions of these two nodes may affect any reception at this node. Therefore, interference should be considered instead of the simple Cartesian distance.

Energy Conservation: Power conservation is another challenging aspect in ad hoc networks with mobile and battery operated devices (i.e., nodes). Apart from technological advances in developing miniature power sources, the research on developing energy efficient MAC protocols will be critical. As discussed earlier, both the power management and power saving approaches have their drawbacks in terms of throughput, protocol overhead, asymmetric links, sensitivity to channel errors, etc.

Single Channel vs. Multiple Channels: Many MAC schemes employ certain control packets (such as RTS/CTS in MACA, FAMA, IEEE 802.11) to negotiate the use of the channel before the data packet transmission starts. Since these control packets may collide with data packets, some MAC schemes transmit control packets on a separate control channel. Data packets are then transmitted on the data channel(s) after negotiations are performed successfully on the control channel.

The real issue with regard to such arrangement is whether it actually improves the efficiency of channel usage. Thorough studies are necessary to understand the relationship of different ratios of control/data channel data

rates, as this affects the relative time to transmit control packets and hence the overall throughput. The overall benefit of using multiple channels instead of a single channel is still unclear.

Multi-hop Networks: Most of the MAC schemes for wireless ad hoc networks do not result in optimum transmission pattern, which should provide maximum network utilization, when used in multi-hop networks. In order to provide an optimum transmission pattern or structure, the schedule or queue of all active nodes in the entire network should be known. Given the dynamic and distributed nature of ad hoc networks, the information of the entire network is usually unknown before decisions can be made to start accessing the channel. However, the information in the local area may be available due to the limited speed and quasi-static traffic pattern over a period of time. How to use this limited information and instruct the active nodes to access the channel in an orderly and effective manner can be an interesting area of study for MAC schemes in wireless ad hoc networks.

Fairness Among Competing Nodes: Fair channel access to the competing active nodes is an important issue in a MAC scheme. An extreme example is to always allow one node to use the shared channel, while keeping all other nodes waiting. The throughput and delay performance of such an unfair scheme may be better than other MAC schemes. For example, schemes such as DFS that provide fair access to competing nodes do not support time bounded delay for *rt* traffic.

Directional Antennas: In the future, applications are likely to require more and more bandwidth, and these ad hoc networks may well be part of our daily lives. Smart antennas based on directional control may need to evolve and robust methods of effectively utilizing them will be required. As of now, relatively little work has been done in this area, and further research will have to be conducted as the actual hardware development takes place.

QoS Issues: With the widespread availability of portable computing devices, more and more applications are being designed for mobile use. Although at present, cellular connectivity is a popular choice, there is no doubt that ad hoc networks will become increasingly popular. As multimedia applications are developed and deployed over such ad hoc networks, QoS parameters and issues become even more important. The MAC layer plays an important role in the performance of the overall system, affecting other layers (in particular the network layer). Effective MAC protocols should find a good balance between the added complexity of offering service guarantees for multiple service classes, efficient use of available resources, and the ability to react promptly to failed transmissions. For this, close integration among resource reservation schemes, MAC protocols, and routing approaches needs to be achieved in order to satisfy the overall QoS requirements.

The main sources of *dynamics* in ad hoc networks are: variable link characteristics and mobile nodes. Variable application demand can also be considered another source of dynamics. Most schemes consider the wireless links between networks nodes as having constant characteristics (e.g., bandwidth and error rate). However these links are subject to variations in their transmission quality (i.e., bit error rate, BER) due to factors such as interferences and fading. If the link layer does not detect or respond to the changes in BER, an increase in BER will result in more packet losses at the network layer. It would be difficult for the network layer to distinguish whether packet losses are due to congestion or link layer corruption. As a result, network layer will not be able to correctly determine the current available bandwidth, which is a key parameter in any resource reservation-based QoS mechanism. The automatic repeat request (ARQ) is therefore used at the link layer that increases the number of packet retransmissions when transmission quality degrades. A sophisticated link layer could also use adaptive error correction (e.g., forward error correction) mechanism or change the modulation. These measures usually lead to decrease in effective throughput at the network layer, while packet loss due to corruption remains low [76].

The projected deadlines of the contending packets should be considered in the channel access mechanism. This is particularly important when some packets have experienced increased delay in the network. Similarly, the degree of urgency information (usually for the *rt* packets) should be broadcasted by each contending node in the network, as in the BB scheme. On the other hand, dropping of expired packets at various points during the

channel access (as in RT-MAC [87]) is also important for improving the network performance. In order to guarantee delay bounds for *rt* traffic, the collision resolution mechanism should terminate in a finite time. No new traffic should be allowed to contend for the channel when collision among two or more nodes is being resolved. Many of the current schemes do not consider this feature. The starvation of some flows (or complete denial of service to some nodes) should be avoided by ensuring fair sharing of resources among nodes, within the bounds of deadline-based delivery requirements.

Widely varying QoS requirements will be needed in future. Bandwidth allocation, admission control, and traffic policing all need to be considered together to satisfy various QoS flows. Some form of admission control for the *rt* traffic may be required to avoid the starvation of low priority traffic for schemes that provide absolute QoS for *rt* traffic.

Unfortunately, some issues that need to be resolved appear to be contradictory to each other in nature. For instance, in order to provide certain levels of QoS, it is sometimes necessary to include provisions for acknowledging successful data packet reception. This, however, requires heavier control-packet overhead. On the other hand, acknowledgment of the *rt* packets may not be needed, as newer *rt* packets are generated continuously. In fact, the emphasis should be on transmitting the newly arrived packets, instead of the un-acknowledged packet.

Most of the existing MAC schemes focus on only a subset of QoS features with a simple network topology, while ignoring the issues of end to end packet delay in multi hop networks, channel errors, power control, heterogeneous nodes, node mobility, etc. Furthermore, they consider one flow per node where all the packets have same priority. In multi hop ad hoc network, a node may be forwarding packets belonging to different flows, which may have very different bandwidth, delay bounds and priority. Similarly, different packets of a flow can have different priorities due to delay variation and packet importance (e.g., header packets). Simulation results usually consider simple random errors; the effect of channel fading, bursty and location-dependent noise models on the performance is not considered. Similarly the effects of broken or dynamically varying network topologies are also not considered in most protocols. It should however be pointed out that IEEE 802.11 DCF has some degree of built-in resilience to fading and burst noise due to the use of BEB and packet fragmentation.

However, there is no single approach that can be claimed as the most appropriate one for all applications. Indeed, there is no silver bullet. At best, one can hope to make intelligent compromises depending on the identified priorities.

VI. CONCLUSION

This study has presented a broad overview of the research work conducted in the field of ad hoc wireless networks with respect to MAC protocols. We have discussed many schemes and identified their salient features. In particular, we have looked at issues of collision resolution, power conservation, multiple channels, advantages of using directional antennas and QoS.

We have discussed the characteristics and operating principles of several MAC schemes. While some of them are general-purpose protocols (such as MACA [13], MACAW [14], etc), others focus on specific features such as power control (PAMAS [27], PCM [35], etc) or the use of specialized technology like directional antennas (D-MAC [63], Multi-Hop RTS MAC [56], etc). Most of these schemes, however, are not designed specially for networks with mobile nodes. On the other hand, the transaction time at the MAC layer is relatively short. The effect of mobility will become less significant as the available channel bandwidth continue to grow.

Several international standards exist for MANETs, such as IEEE 802.11 a, b, and g, HIPERNET, and Bluetooth. It is worth mentioning here that several new standards are still being developed. In particular, the IEEE 802.15 Personal Area Network (PAN) [107] and the IEEE 802.16 Metropolitan Area Network (MAN) [108] standards are targeted towards small and large-scale wireless networks, respectively. The PAN working

group is working on standards to allow devices such as PDAs, cell phones, pagers, etc. to be linked together. The MAN group, on the other hand, is developing standards for the development and deployment of fixed broadband wireless access systems.

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