WIRELESS COMMUNICATIONS AND MOBILE COMPUTING
Wirel. Commun. Mob. Comput. 2006; **6**:151–170
DOI: 10.1002/wcm.376

Medium access control in mobile *ad hoc* networks: challenges and solutions

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Summary

Mobile *ad hoc* networks (MANETs) are useful in environment where fixed network infrastructure is unavailable. To function normally, MANETs demand an efficient and distributed medium access control (MAC) protocol. However, characteristics of MANETs such as radio link vulnerability, mobility, limited power pose great challenges on MAC design. This paper surveys the recent advances in MAC design for MANETs. We first identify the challenges that are facing MAC in MANETs. Then we discuss the proposed MAC schemes according to their design goals, focusing on some critical design issues, and tradeoffs. Finally, we point out some future research directions. Copyright © 2006 John Wiley & Sons, Ltd.

KEY WORDS: medium access control (MAC); mobile *ad hoc* networks (MANETs); quality of service (QoS); fairness; energy-efficiency

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1. Introduction

With the rapid development in wireless communication technologies and the proliferation of mobile communication and computing devices like cell phones, PDAs or laptops, mobile *ad hoc* networks (MANETs) has emerged as an important part of the envisioned future ubiquitous communication because they do not require infrastructure support and can be quickly deployed with low cost. MANETs are finding a variety of applications such as disaster rescue, battlefield communications, inimical environment monitoring, and collaborative computing.

Since all the mobile nodes in MANETs use the same frequency spectrum (or physical channel), medium access control (MAC) plays an important role in coordinating channel access among the nodes so that information gets through from one node to another. Although various MAC schemes have been extensively studied in the contexts of wired networks, they cannot be directly applied to the contexts of MANETs, which have several unique characteristics that well distinguish themselves from their wired counterparts. First, wireless channels are not as reliable as wired ones, suffering from path loss, fading, and interference. Also, the usable bandwidth is limited. Second, by its name, a MANET is composed of a number of nodes that can move around. Consequently, the network topology may experience continuous change and cause frequent route breakages

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Contract/grant sponsor: U.S. Office of Naval Research; contract/grant numbers: N000140210464; N000140210554.

and re-routing activity. Third, in MANETs, mobile nodes are typically computationally limited and battery powered, which means they cannot afford complex and energy intensive computation. Last, but not least, MANETs by nature are self-organized, self-controlled, and distributed. In other words, there is no centralized controller that has perfect knowledge of all the nodes in the network. Instead, each node can only have incomplete or sometimes skewed view of the network. As a result, it has to make decisions with imperfect information. Due to all these hurdles posed by MANETs, achieving simple, efficient, fair, and energy-efficient MAC, while highly desirable, is challenging.

Recently, a tremendous number of MAC schemes have been proposed for MANETs to address various relevant issues. This paper is aimed to provide a comprehensive survey of these schemes, and discuss some critical issues and tradeoffs in designing MAC protocols to deliver good performances in MANETs.

The rest of this paper is organized as follows. Section 2 presents the challenges that are facing MAC design and discusses how they impact the performance of MANET. Next, Section 3 discusses in detail the proposed MAC schemes according to their design goals. Finally, Section 4 concludes this paper and gives several future research directions.

2. Challenges and Design Issues

While MANETs exhibit unique advantages compared to one-hop wireless networks such as cellular networks and wireless local area networks (WLANs), they do impose several challenges and design issues on MAC protocol design. The first and most serious challenge is that centralized controlling usually is not available in MANET due to the lack of infrastructure support. Without perfect coordination, collisions could take place when several nodes simultaneously access the shared medium. They may also result from transmissions that are multiple-hop away. Second, due to hardware constraints, a node cannot immediately detect collisions during its transmission, which leads to channel inefficiency. Third, as every node in the network is mobile, the network topology may change from time to time. Accordingly, each node may experience different degree of channel contention and collision. At the same time, the attendant route changes also affect the interaction between the MAC layer and higher layers. Finally, several important issues like energy efficiency, fairness, or quality of service (QoS) provision need to be carefully considered when designing MAC protocols for MANETs.

In this section, we discuss in detail the challenges from layered perspective as well as several important design issues.

2.1. Medium Access to Shared Medium

The primary goal of MAC is to coordinate the channel access among multiple nodes to achieve high channel utilization. In other words, The coordination of channel access should minimize or eliminate the incidence of collisions and maximize spatial reuse at the same time.

2.1.1. Collisions

Collisions come from two aspects in MANETs. They may occur due to simultaneous transmissions by two or more nodes in a certain range where their signals collide and interfere with each other. Obviously, the more the active nodes in the range of a transmitter-receiver pair, the more severe the collisions observed.

On the other hand, collisions can result from hidden terminals. A hidden terminal is the one that can neither sense the transmission of a transmitter nor correctly receive the reservation packet from its corresponding receiver. In the IEEE 802.11 MAC protocol [1], the reservation packet is a clear-to-send (CTS) packet, which advertises the reservation of the channel. A hidden terminal node can interfere with an ongoing transmission by transmitting at the same time. For example, in Figure 1, node D is a hidden terminal when node A is transmitting DATA packets to node B. D's transmission will interfere with B's reception because signal to noise plus interference ratio (SINR) at B is not large enough for correct decoding. Here, the *transmission range* of a transmit-

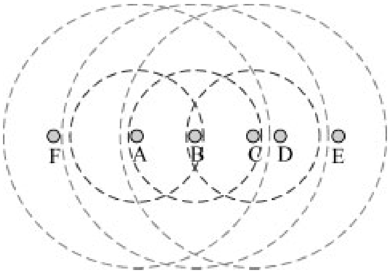

Fig. 1. Carrier sensing range and transmission range. The small and large circles denote the transmission and sensing ranges of node A, B, and C, respectively.

ter refers to a range within which any node can correctly decode the received signal if there is no interference. And the *sensing range* of a transmitter refers to a range within which any node can sense the received signal, whose power level exceeds a certain value referred to as sensing threshold.

2.1.2. Spatial reuse

To achieve high channel utilization, MAC also needs to maximize the spatial reuse. One way is to reduce the transmission power to allow more simultaneous transmissions in the networks. However, smaller transmission range means more transmission hops each packet needs to go through from source to destination. This, in turn, leads to heavier traffic at each node and could counteract the advantage of increased spatial reuse. Several papers [2,47] have already shown that there is a tradeoff between the spatial reuse and multiple forwardings in order to maximize the aggregate throughput in MANETs. In fact, the optimal transmission range depends on the number of nodes and their location and moving speed and hence is difficult to achieve due to the dynamic and distributed nature of MANETs.

Exposed terminal problem is another factor influencing the spatial reuse. An exposed terminal is the one that senses the transmission of a transmitter and cannot interfere with the reception at the receiver. However, it is not allowed to transmit simply because it senses a busy medium, which leads to bandwidth under-utilization. In Figure 1, node F is the exposed terminal of A when A is transmitting to B. F senses A's transmission and thus is forced to keep silence, even though F can transmit to other nodes outside A's sensing range without interfering B's reception.

The hidden terminal problem and exposed terminal problem are coupled with each other in multihop wireless networks. It is common that bidirectional packet exchange between a transmission pair for a DATA packet transmission, such as DATA/ACK or RTS/CTS/DATA/ACK, is used in the IEEE 802.11 MAC protocol. In the bidirectional transmission, the exposed node of one of the transmitter–receiver pair might well be the hidden node when the roles of transmitter and receiver are switched, and vice versa. For example, in Figure 1, node F is also a hidden terminal of node B when B responds to A with CTS or ACK packets, while originally F is an exposed terminal of node A when A is transmitting RTS or DATA to B. Thus these two problems can significantly lower the spatial reuse.

2.2. Physical Layer Issues

2.2.1. Capture effect

In wireless networks, in order for a node to correctly receive the transmission from another node, say node i, SINR must exceed a certain threshold β, that is,

$$\mathrm{SINR}_i = \frac{P_i}{\sum_{k \neq i} P_k + N} \geqslant \beta, \tag{1}$$

where P_i is the received signal power and β is referred to as capture threshold (when the power level of noise N is small). That is, a data packet can be received successfully if its instantaneous power is at least β times the instantaneous joint interference power. This fact is called capture effect.

Current carrier sense strategy such as that adopted in the IEEE 802.11 MAC protocol requires a node to defer its transmission whenever the channel is determined busy, despite the fact that this node's transmission may not impair some other ongoing transmissions due to the capture effect. Clearly, channel utilization will be improved if capture effect can be utilized. However, it is difficult to design MAC protocols that incorporate capture effect in MANETs because it demands careful coordination of new transmissions which would otherwise increase joint interference power and thus inviolate Equation (1).

2.2.2. Variable channel condition

Unlike wired channels that are stationary and predictable, wireless channels are time-varying, depending on the spatial location of transmitting and receiving nodes, the characteristics of surrounding environment, and movements of surrounding objects as well as mobile nodes. Wireless channels are also location dependent. For instance, the channel gain is different for each transmitter and receiver pair as long as the stations are not extremely close to each other.

Since the received power signal strength is determined by channel gain as well as transmission power, given the bit error rate, the maximum achievable channel bit rate also varies with time. Consequently, corresponding to variable channel conditions, variable transmission data rate can be used. To maximize the channel utilization, MAC protocols need to exploit the channel adaptive transmission. Typically, when SINR is sufficiently high, higher data rates than the base rate should be used for transmission and otherwise lower data rate should be used.

2.2.3. *New physical layer techniques*

The recent advancement of wireless communications, such as directional antenna, multiple input multiple output (MIMO) systems, and space time coding, offers a variety of advantages such as low transmission power and high data rate. In response, MAC mechanisms are supposed to take advantage of these new techniques to further improve efficiency or reduce transmission power. For example, directional transmission results in less interference to other transmissions and hence makes it possible to enhance the spatial reuse. However, it is worth noting that MAC protocols have to be elaborately designed to make sure that directional transmission does not affect efficient negotiations for successful transmission between a transmitter and a receiver as required in an *ad hoc* environment.

2.3. Interactions With Higher Layers

The interaction between the MAC layer and higher layers in *ad hoc* networks are much more complicated than in wired networks mainly for two reasons. First, current routing algorithms in *ad hoc* networks determine a broken link whenever the (re)transmissions continuously fail over this link for a certain number of times. However, transmission failures may well result from MAC collisions that are very common in a contention-based MANET. False reports of link/route failures, in turn, require routing algorithms to conduct an unnecessary re-routing process, which will interrupt the ongoing traffic flow and greatly degrade the end-to-end throughput. Second, network congestion and medium contentions are closely coupled in MANETs. In wired networks, when congestion happens and packets build up in the queue, the data rate of the link between an upstream node and its downstream node is not affected. However, this is not the case in MANETs. Since the channel is shared by all nodes in a neighborhood, the congestion is not only a phenomenon related to one pair of transmitting-receiving nodes, but also one to all nodes in the neighborhood. When congestion happens and queues build up, contentions and collisions will become severe, leading to significant decrease in the data rate for any transmission pair in the neighborhood and the aggregate data rate. Worse yet, the decreased throughput further aggravate congestion. Thus, when designing MAC protocols, one should bear in mind the undesirable interaction between MAC and congestion control algorithms [88,89], such as TCP end-to-end congestion control mechanism.

2.4. Energy Efficiency

In wireless networks, energy efficiency is always a critical issue due to a limited battery life. First, MAC protocols should reduce the number of collided packets as many as possible, and hence reduce the power consumption wasted in collisions. Second, only just enough power should be used to achieve a certain data rate for each transmission while maintaining good coordination among all the nodes. In addition, less transmission power can also reduce interference to other ongoing transmissions and improve the spatial reuse.

2.5. Fairness

Unfairness could result from different opportunities of channel access. In MANETs, there are two major sources for unequal channel access opportunities: the backoff mechanism and location. While the backoff mechanism is widely used in MAC protocols for MANETs to reduce collisions and achieve high channel efficiency, it always favors the node that just successfully seized the channel. As a result, different nodes may use different backoff window, leading to different transmission probabilities and consequently short-term unfairness as well as long-term unfairness. Meanwhile, since nodes' location and traffic might not be uniformly distributed in MANETs, a node's location also influence its channel access opportunity. Nodes with less channel contention from their neighboring nodes can seize the channel more likely than others. Note that to achieve fairness among all nodes, the network's aggregate throughput, namely, efficiency, often has to be sacrificed.

2.6. Quality of Service (QoS)

With the proliferation of Internet multimedia services, such as voice over IP and streaming video, mobile devices in MAENTs are expected to support these multimedia services with QoS guarantee. Since multimedia services typically have strict end-to-end delay and delay variation requirements, QoS provisioning will not be easy given that MANETs are characterized by their distributed and bandwidth-limited channel access, where medium contentions and collisions are common.

3. MAC Protocols for MANETs

In this section, we will first describe several basic components of contention-based MAC protocols. Then, we present some solutions to the classical hidden terminal and exposed terminal problem over MANETs. Finally, we discuss some representative MAC protocols according to their design goals.

3.1. Basic Design Components of MAC Protocol over MANETs

As mentioned earlier, collisions can be quickly detected during the course of transmission in wired networks, such as the collision detection technique used in Ethernet. In contrast, a transmitter cannot detect collisions when transmitting in wireless networks; rather, it relies on the receiver's acknowledgment to determine if any collision has taken place in the transmission duration. Clearly, the resulting collision period is quite long and unaffordable if a long data transmission encounters collisions. In this regard, how to effectively reduce collisions becomes a key issue for MAC design in MANETs.

Several mechanisms has been proposed to avoid collisions in medium access, namely carrier sense, handshake, and backoff mechanism. Carrier sense requires that a node transmit only when the channel is determined idle. Multiple handshakes between the transmitter and receiver includes some short frames to avoid long collision period of data packets, and acknowledgements of successful transmissions. The backoff mechanism forces each node to wait a random period before attempting transmission. In the following, we first introduce these mechanisms in the context of the IEEE 802.11 DCF protocol. Then, we discuss some schemes that outperform the 802.11 DCF by improving these mechanisms.

3.1.1. Carrier sense, handshake, and backoff in the IEEE 802.11 DCF protocol

The IEEE 802.11 DCF is a contention-based MAC protocol. To reduce the collision possibility, it uses carrier sense functions and binary exponential backoff (BEB) mechanism. In particular, two carrier sense functions, physical and virtual carrier-sense functions, are used to determine the state of the medium. The former is provided by the physical layer and the latter by the MAC layer, which is also referred to as the network allocation vector (NAV). NAV predicts the duration that the medium will be busy in the future based on a duration information announced in transmitted frames. When either function indicates a busy medium, the medium is considered busy; otherwise, it is considered idle. In the BEB mechanism, each node selects a random backoff timer uniformly distributed in [0,CW], where CW is the current contention window (CW) size. It decreases the backoff timer by one for each idle time slot (may wait for DIFS after a successful transmission, or EIFS after detection of an erroneous frame). Transmission shall commence whenever the backoff timer reaches zero. When there are collisions during the transmission or when the transmission fails, the node doubles the value of CW until it reaches the maximum value CW_{max}. Then, the node starts the backoff process again, and retransmit the packet when the backoff is complete. If the maximum transmission failure limit is reached, the retransmission shall stop, CW shall be reset to the initial value CW_{min}, and the packet shall be discarded.

The DCF protocol provides two access mechanisms. One is two-way handshake, that is, DATA/ACK, and the other is four-way handshake, that is, RTS/CTS/DATA/ACK. When the length of DATA packet is long, short frames request-to-send (RTS) and CTS should be used to avoid possible long collision period of DATA packets. The four-way handshake and NAV setting are shown in Figure 2.

3.1.2. Carrier sensing range

In the carrier sense mechanism, a node determines the channel is busy when the received signal power exceeds a certain threshold, referred to as carrier sense threshold (CST). Otherwise, the channel is determined idle. It can be seen clearly that the value of CST decides the sensing range and affects both the collision possibility and spatial reuse in MANETs. (Notice that the SINR must exceeds the capture threshold for correct decoding.) The larger the sensing range, the smaller the possibility that a new transmission attempt interferes with some ongoing transmis-

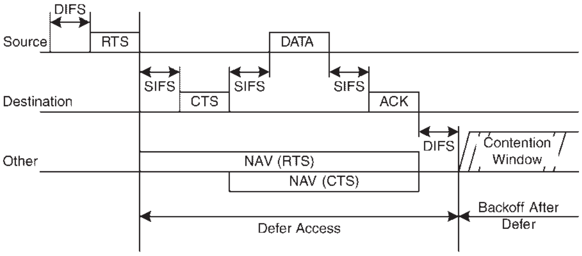

Fig. 2. RTS/CTS/DATA/ACK and network allocation vector (NAV) setting.

sions. On the other hand, a larger sensing range implies that more nodes have to defer their transmissions when one node is transmitting, which leads to poorer spatial reuse. In ns-2, a widely used network simulator that simulates the realistic settings of WaveLAN card of Lucent company, the sensing range is about 550 m, more than twice the transmission range, which is about 250 m. Figure 1 shows both ranges for node *A*, *B*, and *C*.

3.1.3. Backoff mechanisms

Although BEB is widely used in many contention-based MAC protocols for its simplicity and good performance, it suffers from both fairness and efficiency. In BEB, each station resets its CW size to the minimum value after a successful transmission, and doubles its CW after a failed transmission. Therefore, it might be quite likely that a node that has gained the channel and transmitted successfully will gain the channel in the following channel contention. The worst-case scenario is that one node monopolizes the channel while all other nodes are completely denied channel access. On the other hand, BEB is also diagnosed with low efficiency when there are many active nodes [7,14,22] and hence severe contention for the channel. Analysis has shown that after reaching its peak, the aggregate throughput decreases along with the input traffic; also, the aggregate throughput decreases with the number of active stations under saturated status. Thus there are a lot of papers discussing new backoff mechanisms, such as [11–18].

A multiplicative increase and linear decrease (MILD) was proposed in the MACAW protocol [11] to address the large variation of the contention window size and the unfairness problem of BEB. In MILD, the backoff interval is increased by a multiplicative factor (1.5) upon a collision and decreased by 1 step upon a successful transmission, where step is defined as the transmission time of a RTS frame. MILD works well when the traffic load is steadily heavy. However, the 'linear decrease' sometimes is too conservative, and it suffers performance degradation when the traffic load is light or the number of active nodes changes sharply [12]. To overcome these problems, the exponential increase exponential decrease (EIED) backoff algorithm has been studied in References [12,13]. In the EIED algorithm, the contention window size is decreased by a factor r_D upon a successful transmission, and increased by a factor r_I upon a collision. As a result, EIED is not as conservative as the 'linear decrease' of MILD and not as progressive as the 'reset' of BEB.

Realizing that there is a different optimal contention window size for different number of active nodes, many studies focused on adaptive contention window schemes [14,15]. By collecting observed collision statistics, these schemes estimate the number of currently active nodes and hence calculate a new contention window size to schedule the next transmission. Note that in these schemes, timely and accurate estimate of the number of active stations, which, at the same time, is not easy [19], is a prerequisite to significant performance improvements.

A fast collision resolution (FCR) algorithm was proposed in Reference [17]. The FCR algorithm has the following characteristics: (1) uses much smaller initial (minimum) contention window size as compared to the IEEE 802.11 MAC; (2) uses much larger maximum contention window size as compared to the IEEE 802.11 MAC; (3) increases the contention window size when a node is in both collision state and deferring state (after the node senses the start of a new busy period); (4) reduces the backoff timers exponentially fast when a prefixed number of consecutive idle slots has been detected; (5) assigns the maximum successive packet transmission limit to achieve good fairness performance. It is demonstrated in Reference [17] that this algorithm indeed resolves collisions faster and reduces the idle slots more effectively than the BEB of the IEEE 802.11 MAC protocol.

3.1.4. Sender-initiated and receiver-initiated channel access

Multiple handshakes between a transmitter and a receiver can be largely divided into two categories, sender-initiated (SI) and receiver-initiated (RI). Both the two-way DATA/ACK and four-way RTS/CTS/DATA/ACK handshake of the IEEE 802.11 MAC protocol are sender-initiated. The sender has full knowledge of packets in its queue and it initiates the handshake only when there are pending packets. The exchange of short RTS and CTS frames in a four-way handshake between a transmitter and a receiver serves as a channel reservation that notifies overhearing nodes to defer their access to the shared channel so as to avoid collisions. In receiver-initiated channel access, a receiver polls its neighbor actively to see if they have packets for itself. Multiple access collision avoidance by invitation (MACA-BI) [20] adopts a three-way handshake, that is, CTS/DATA/ACK, to conduct the channel access where the CTS frame severs as the polling packet. The receiver needs to receive relatively long data packets and has better knowledge of the contention around itself. In addition, the three-way handshake has less control overhead than the four-way handshake of the IEEE 802.11 MAC protocol, which explains why MACA-BI outperforms the four-way handshake of the IEEE 802.11 when traffic characteristics are stationary or predictable. However, it does not work well in the dynamic *ad hoc* network environments because the polled nodes may have no packets for the polling station and the transmission time of polling packets, as a result, is wasted.

In an effort to achieve the advantages of both SI and RI channel access, some hybrid channel access methods are explored. A hybrid channel access scheme was proposed in Reference [21]. A node that implements this scheme operates alternately in two modes, SI or RI. The transmission pair will try to enter into RI mode when the sender sends the same RTS packet for more than one half of the times allowed in the IEEE 802.11 MAC protocol and has received no response from the intended receiver. By adaptively sharing the burden of initiating the collision-avoidance handshake between the nodes that experience different levels of contention, better fairness may be achieved with almost no degradation in throughput. In another scheme, the multihop packet scheduling scheme [22], when the receiver is overloaded, a negative CTS (NCTS) is used to notify the transmitter of congestion, and then the transmission pair enters into the RI mode. When congestion is mitigated and backlogged packets have been transmitted, the receiver initiates a three-way handshake and then the transmission pair comes back to the SI mode. In this way, this scheme effectively keeps upstream nodes from overloading downstream ones. As a result, end-to-end throughput is greatly improved by reducing collisions and avoiding dropping packets at the first few hops; end-to-end delay is also greatly decreased by reducing long queuing delay at forwarding nodes.

It is important to note that in both SI and RI handshakes, acknowledgements for successful transmissions are necessary due to the unreliable wireless environment of MANETs. Even if the transmission of DATA packets is collision-free, it may still be corrupted by short-term channel fading. Therefore, MAC protocols should provide a way to allow the transmitter to know whether the transmission is successful or not. In other words, the bidirectional information exchange for each DATA packet transmission, such as a DATA/ACK handshake, is necessary between a transmitter and a receiver.

3.1.5. Batch transmission

Batch transmission is another way to improve the efficiency of MAC protocols. A node does not need to contend for the channel again for one or more succeeding packets/fragments after a successful transmission. This is somewhat equivalent to the case where longer DATA packets are used in the IEEE 802.11 protocol. Since the collision probability may be the same before each transmission attempt, throughput is improved as the successful transmission period is prolonged.

In fact, batch transmission has already been adopted by the IEEE 802.11 protocol in a fragmentation/defragmentation scheme. Given a fixed channel bit error rate, it is clear that longer packets are more vulnerable to transmission errors. Therefore, fragmentation that creates smaller data units than the original large DATA packets can increase transmission reliability by reducing the packet error probability. Note that each fragment needs to be acknowledged by the receiver. Once a node has gained the channel, it continues to send fragments until all fragments have been sent, or an acknowledgement is not received, or the node is restrained from sending any additional fragments due to a maximum transmission time limit. Should the sending of the fragments be interrupted due to one of the above reasons, the node will resume transmission when the next opportunity for transmission comes. Batch transmission has also been used in several other schemes, such as opportunistic auto rate (OAR) [54]. In OAR, each node opportunistically sends multiple back-to-back data packets whenever the channel quality is good and hence achieves significant throughput improvements over time-varying channels.

Despite its throughput enhancement, batch transmission itself does not necessarily reduce the potential collision probability experienced by each transmission attempts when there are many concurrent users. So the efficiency is still affected by the collisions. In addition, it is harmful for urgent messages and real-time data, which have strict end-to-end delay requirements because whichever node occupies the channel, blocks transmissions by other nodes. To alleviate this side effect, schemes like the IEEE 802.11, OAR or FCR, also define a maximum period to limit the total duration of continuous transmissions by one node.

3.2. Solutions to Hidden Terminal and Exposed Terminal Problems

In multihop wireless networks, the hidden terminal problem is a main cause for collisions and the exposed terminal problem limits the spatial reuse as previously discussed in Subsection 2.1.2. Notice that multihop wireless networks span a large area, each node may have multiple hidden terminals. Hence the hidden terminal problem is commonplace, which differs from a single wireless LAN, where each node can sense all others' transmissions and requires only one-hop wireless transmissions.

Out-of-band busy tone signal is widely used in many schemes to overcome the hidden terminal problem, or the exposed terminal problem, or both [24,27,42,44]. In the scheme busy tone multiple access(BTMA) [24], a base station broadcasts a busy tone signal to keep the hidden terminals from accessing the channel when it senses a transmission. The scheme relies on a centralized network infrastructure which is not available in *ad hoc* networks. The dual busy tone multiple access (DBTMA) scheme [25,27] employs a transmit busy tone at a transmitter to prevent the exposed terminals from becoming new receivers, and a receive busy tone at the receiver to prevent the hidden terminals from becoming new transmitters. The exposed terminals are able to initiate data packet transmissions, and the hidden terminals can reply to RTS requests and initiate data packet reception.

The busy tone technique provides a simple solution to the hidden terminal and exposed terminal problems, but it requires additional channels and transceivers. The busy tone channel must be close to the DATA channel and hence can have similar channel gain to that of the DATA channel, and there must also be enough spectral separation between these channels to avoid inter-channel interference. However, the bandwidth requirement of busy tone signal is small and the decoding is much simpler than that over the DATA channel. A node only needs to check the existence of the busy tone signal at certain frequency by the sensed power level. Thus it might be viable in MANETs and deserves more experimental studies.

Floor acquisition multiple access with non-persistent carrier sensing (FAMA-NCS) [23] provides another solution to the hidden terminal problem. It uses long dominating CTS packets to act as a receiver busy tone to prevent any competing transmitters in the receiver's range from transmitting. To guarantee no collision with an ongoing data transmission, this scheme requires each node that hears the interference to keep silence for a period of one maximum data packet. Clearly, this is not efficient, especially when the RTS/CTS negotiation process fails or DATA packets are relatively short.

Beside busy tone related schemes, there are many studies that employ multiple channels to alleviate these two problems for DATA packet transmissions, which will be discussed in detail in the following subsection.

3.3. Employing Multiple Channels to Improve Efficiency

Notice that in schemes that only one channel, all kinds of packets, such as RTS/CTS/DATA/ACK in the IEEE 802.11 protocols, are transmitted in the same channel. There thus exist collisions between any two kinds of these packets. To avoid the collisions, the bidirectional exchanges of these packets significantly limit the spatial reuse due to the coupling of hidden and exposed terminal problems as discussed in Subsection 2.1.2.

One common approach to reduce collisions between different kinds of packets is to exploit the advantage of multiple channels, and transmit different kinds of packets over different separate channels [26–35,38,40,46].

3.3.1. Schemes with a common control channel

Many schemes use a separate channel for transmitting control packets, such as RTS and CTS, and one or more channels for transmitting data and acknowledgements, that is, DATA and ACK. In the Dynamic Channel Assignment (DCA) scheme [29], the overall bandwidth is divided into one control channel and n data channels. Each data channel is equivalent and has the same bandwidth. The purpose of the control channel is to resolve the contention on data channels and assign data channels to mobile hosts. Each mobile host is equipped with two half-duplex transceivers. One is for control channel, and another is dynamically switched to one of the data channels to transmit data packets and acknowledgements. A five-way handshake is used. RTS and CTS are used for negotiation of a data channel for data transmissions, and CTS and RES (reservation) packets notify the neighbors of the sender and receiver of the reserved data channel, respectively. All RTS, CTS, and RES packets are transmitted over the control channel. DCA follows an ‘on-demand’ style to assign channels to mobile hosts, and does not requires clock synchronization. The collisions between data packets are alleviated due to the use of multiple data channels. Two similar protocols, which also dynamically negotiate a data channel for data transmission, were proposed in References [30,31]. These two protocols only use one half-duplex transceiver, but require more complex negotiations and bookkeeping.

The DBTMA scheme [27] splits the single common channel into two sub-channels: a data channel and a control channel. Data packets are transmitted on the data channel. Control packets (RTS/CTS) are transmitted on the control channel. As discussed in Subsection 3.2, two busy tones are used: the transmit busy tone, which indicates that a node is transmitting on the data channel, and the receive busy tone, which indicates that a node is receiving on the data channel. It gives a solution to both hidden and exposed terminal problems. However, in the DBTMA scheme, no acknowledgment is sent to acknowledge a transmitted DATA packet, which is clearly deficient for unreliable wireless links. Furthermore, potential collisions between acknowledgments and other packets could greatly degrade the performance.

MAC with dual transmission channels (DUCHA) [32] introduces a NACK period in which the receiver busy tone is lengthened if the received data packet is corrupted due to channel fading. The sender, which senses the NACK tone, will conclude that the data transmission has failed. The NACK period is also exploited to alleviate the MAC contentions between the upstream nodes and the downstream nodes of a multihop path by allowing the receiver to begin to contend for the channel after a successful reception while keeping the neighboring nodes silent during the NACK period.

MAC with a separate control channel (MAC-SCC) [34] still regards the two channels as one control channel and one data channel, and the data channel is assigned more bandwidth than the control channel. Note, however, control packets RTS and CTS can be transmitted not only over control channel but also over data channel in order to reduce transmission time, as long as the transmitter senses both channels are idle. MAC-SCC also uses two NAVs for the data channel and the control channel, respectively. The two NAVs make it possible for the control channel to schedule not only the current data transmission but also the next data transmission, thereby reducing the backoff time.

3.3.2. Schemes without a common control channel

Unlike those schemes that use a common control channel, this kind of schemes does not rely on it. Instead, they are flexible in arranging different channels for RTS/CTS/DATA/ACK to reduce collisions. Both interleaved CSMA (ICSMA) [35] and Jamming-based MAC (JMAC) [36] are such schemes, which divide the entire bandwidth into two channels and employ one half-duplex transceiver for each channel. ICSMA [35] uses two channels of equal bandwidth. A node is permitted to originate transmission in either channel. The transmitter sends RTS and DATA on one channel, and the receiver responds by sending CTS and ACK on the other channel. This scheme supports simultaneous transmissions between two nodes. That is to say, when one node is sending RTS or DATA, or receiving CTS or ACK from the other node, the latter one is also sending the same kind of packets at a different channel to the former one.

In JMAC [36], the medium is divided into two channels: *S* channel and *R* channel. RTS and DATA are transmitted on the *S* channel, and CTS and ACK are transmitted on the *R* channel. A transmitter also transmits jamming signals on the *S* channel while waiting or receiving a CTS/ACK frame on the *R* channel. For a receiver, while it is waiting or receiving a DATA frame on *S* channel, it jams the *R* channel to prevent neighboring nodes from transmitting RTS frames on the *S* channel. Jamming signal is the one that, with sufficient energy, can cause the medium to become busy. Since it will stop if the RTS/CTS exchange fails, it resolves the erroneous reservation problem in the IEEE 802.11 protocol. In addition, it also effectively blocks hidden terminals from transmitting, which may interfere with ongoing transmissions.

3.3.3. Schemes with synchronization

The schemes discussed above are all contention-based, and do not need synchronization information for MAC. However, accurate synchronization may benefit MAC design as shown in References [37–39], although it is difficult for a large scale MANET [40,41]. In the hybrid activation multiple access (HAMA) scheme [37], a neighbor protocol was proposed to update the two-hop neighborhood information over a common channel on the best-effort basis. Using this neighborhood information, each node determines whether to transmit in the current time slot using a spreading code that is dynamically assigned. In this way, it provides collision-free data transmissions. In the scheme multichannel MAC (MMAC) [38] each node is equipped with a single half-duplex transceiver and can use one of N channels that are of the same bandwidth. Time is divided into fixed intervals using beacons, and there is a small window at the start of each interval to indicate traffic and negotiate channels for use during the interval. The scheme binary-countdown/RTS/OTS/agree-to-send(ATS)/disagree-to-send(DTS)/ensure-to-send(ETS)/neaten-to-send(NTS) (BROADEN) [39] partitions the wireless channel into one control channel and one data channel. Time synchronization is used to conduct a binary countdown mechanism so that there is only one successful competitor when multiple active nodes exist.

3.4. MAC Protocols With Transmission Power Control (TPC)

While the CSMA/CA mechanism is simple, it can be overly conservative [43,45–47,49], leading to low-spatial reuse, low-energy efficiency as well as high co-channel interference. This is because that, in the CSMA/CA, all nodes transmit control and data packets at a fixed (and maximal) power level; and any node that senses signal with power level higher than a certain threshold or hears the RTS or the CTS defers its transmission until the ongoing transmission is complete. For illustration, consider the situation in Figure 3, where node A uses its maximum transmission power (TP) to send packets to node B. If omnidirectional antennas are used, the region reserved for the communication between node pair A and B is the union of the regions circled by the RTS transmission range, the CTS transmission range, and the physical carrier sensing range. According to CSMA/CA, since nodes D and E fall into the reserved region and thus have to refrain from transmission (either data or control packet) to avoid interfering with the ongoing transmission between A and B. However, it is easy to show that the three data transmissions $A \rightarrow B$, $D \rightarrow C$, and $F \rightarrow E$ can be concurrent if the nodes are able to synchronize locally and select appropriate transmission powers. Furthermore, all the necessary transmission power will be less than the maximum transmission power defined in CSMA/CA, which means much energy can be saved.

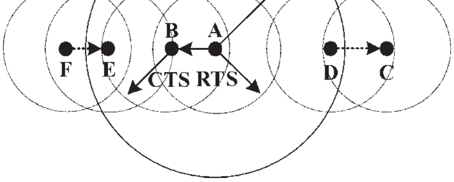

Fig. 3. Inefficiency of classic CSMA/CA.

Due to the benefits of increasing spatial reuse and energy conservation, power control MAC protocols have been extensively researched. The basic idea of distributed power control MAC proposed in the literatures is as follows. Nodes exchange their RTS and CTS packets at the maximum allowable power($P_{\max}$) in order to reduce the collision probability of data and ACK, but send their data and ACK packets at the minimum power ($P_{\min}$) necessary for reliable communication.

In Reference [44], RTS and CTS packets are sent at the highest (fixed) power level ($P_{\max}$), and the DATA and ACK is sent at a lower power level. This basic power control scheme is designed to improve energy efficiency. However, as shown in Reference [46], it may also degrade network throughput. The reason is that reducing power for data transmission also reduces carrier-sensing range so that ACK (as well as DATA) are more likely to be collided. In Reference [46], the authors enhanced this approach by periodically increasing the TP of the data packet to $P_{\max}$, allowing for enough time to protect the reception of the ACK at the source. While this class of power control schemes achieves good reduction in energy consumption, it contributes little to improving the throughput in comparison with the 802.11 MAC protocol. The main reason is that, as in the 802.11 approach, RTS and CTS messages are used to silence neighboring nodes, preventing concurrent transmissions from taking place over the reserved floor.

To increase spatial reuse, References [43] and [45] introduce the *interference—limited* media access control schemes. Concurrent data transmissions are allowed as long as the multiple access interference does not corrupt the ongoing neighboring transmissions. This is completely different from the idea of 'carrier-sensing' based media access control schemes, in which any node in the carrier sensing range of an ongoing transmission node pair should defer its intended transmission. In Reference [43], the authors proposed a new MAC protocol that combines the mechanisms of power control, RTS/CTS dialogue, and busy tones. The main idea is to use the exchange RTS and CTS packets (based on the signal strength of

RTS/CTS) between two intended communicators to determine relative channel gain. This information is then utilized to derive the minimum power level necessary for the transmission of data packets. The power level used for RTS and data transmission should be less than the maximum allowable power level above which it may cause interference to the ongoing neighboring communication. The maximum allowable transmission power level (used to transmit RTS) is determined based on how strong the receiving busy tones (BT_r) are around the intended sender. CTS and receiving busy tone (BT_r) are transmitted by receivers at the maximal power level. In addition, a sender sends transmission busy tone (BT_t) during data transmission at the same power level as that of data. Any node that hears BT_t should not agree to intended reception. In the power-controlled multiple access (PCMA) protocol [45], similar to Reference [43], PCMA generalizes the transmit-or-defer 'on/off' collision avoidance model of CSMA/CA to a more flexible 'variable bounded power' collision suppression model. The main distinction of [45] in comparison to [43] is the use of *interference margin*, whereby a greater number of simultaneous transmissions are allowed, thus increasing spatial reuse. The interference margin is advertised by the receiver over a separate busy tone channel.

To avoid using busy tone to locally broadcast the interference margin, the power-controlled dual channel (PCDC) protocol [47] advertises it by RTS and CTS, which are transmitted on a separate control channel. In addition, to further increase the spatial reuse and provide better protection of ACK packets than the schemes by [43,45], the authors in Reference [47] propose the use of a second control channel for sending ACK messages.

Although the simulations of the TPC schemes in References [43,45,47] indicate impressive throughput performance, as Reference [49] pointed out, there are four major design issues with these schemes that make their practicality questionable:

- In References [43,45,47], the channel gain is assumed to be the same for both the control (or busytone) and data channels. In fact, it might not be true.
- It is assumed that nodes are able to transmit on one channel and, simultaneously, receive on the other. To do so, a mobile node must be equipped with two transceivers. The complexity and cost of the additional hardware may not justify the increase in throughput.
- Interoperability with existing standards and hardware is, if not impossible, difficult. Currently, most wireless devices implement the IEEE 802.11b standard. The class of two-channel protocols is not backward compatible with the IEEE 802.11 standard, which makes it difficult to deploy such schemes in real networks.
- Finally, the optimal allocation of the total spectrum between the data and control channels is load dependent. For the allocation to be optimal under various traffic loads, it has to be adjusted adaptively. However, it is not feasible in practice.

The power-controlled MAC (POWMAC) protocol proposed in Reference [49] addresses all the above issues and provides a comprehensive, throughput-oriented MAC solution for MANETs using a single-transceiver and a single channel. Instead of alternating between the transmission of control (RTS/CTS) and data packets, as done in the 802.11 scheme, POWMAC uses an access window (AW) to allow for a series of RTS/CTS exchanges to take place before multiple, concurrent data packet transmissions can commence. The length of the AW is dynamically adjusted (based on local traffic load information) to allow for concurrent interference-limited transmissions to take place in the same vicinity of a receiving node. Collision avoidance information is inserted into the CTS packet and is used to bound the transmission powers of potential interferers, rather than to silence such nodes. Simulation results demonstrate the achievable, significant throughput and energy gains.

Before we end this subsection, it is important to note that the choice of interference margin in interference-limited media access power control schemes is a difficult issue. As both over-provisioning and under-provisioning of interference margin leads to performance loss, one may expect that it is better to dynamically adjust the interference margin based on local traffic load and topology.

3.5. Rate Adaptive MAC Protocols

As wireless channel is time varying and location dependent due to path loss, shadowing, small-scale fading as well as interference, rate adaptation is a powerful way to overcome channel variations. As a matter of fact, unlike the original IEEE 802.11 protocol that only supports a single base rate, the IEEE 802.11a and 802.11b PHY/MAC standards have incorporated physical-layer multirate capability. The feasible data rate set of the IEEE 802.11a is 6, 9, 12, 18, . . . , 54 Mbps whereas that of the IEEE 802.11b is 1, 2, 5.5, and 11 Mbps. By adapting modulation and error-coding schemes to channel conditions, both high throughput and energy efficiency are expected to improve.

The first commercial MAC that utilizes rate adaptation was the auto rate fallback (ARF) protocol [53]. With ARF, senders attempt to use higher transmission rates after consecutive transmission successes, which indicate high channel quality, and revert to lower rates after failures. Under most channel conditions, ARF provides a performance gain over pure single rate IEEE 802.11. However, ARF cannot well adapt to fast multipath fading.

In Reference [54], a protocol termed receiver-based auto rate (RBAR) was proposed. In RBAR, receivers measure the channel quality using physical-layer analysis of the request-to-send (RTS) message, and then set the transmission rate for each packet according to the highest achievable value determined by the channel conditions. As Figure 4 shows, the sender *Src* chooses a data rate based on some heuristic and then stores the rate and the size of the data packet into the RTS. Node *A*, overhearing the RTS, calculates the duration of the requested reservation D_{RTS} using the rate and packet size carried in the RTS. *A* then updates its NAV to reflect the reservation. While receiving the RTS, the receiver *D*st generates an estimate of the conditions for the impending data packet transmission based on the SINR of RTS. *D*st then selects the appropriate rate based on that estimate, and transmits it and the packet size in the CTS back to the sender. Node *B*, overhearing the CTS, calculates the duration of the reservation D_{CTS} and updates its NAV to reflect the reservation. Finally, *Src* responds to the receipt of the CTS by transmitting the data packet at the rate chosen by *D*st. In the case that the rates chosen by the sender and receiver are different, then the reservation D_{RTS} calculated by *A* will no longer be valid. Thus, D_{RTS} only serves as a tentative reservation. Final reservations are confirmed by the presence or absence of a special subheader, called the reservation subheader (RSH), in the MAC header of the data packet. The fields in the reservation subheader consist of only those fields needed to update the NAV, and essentially amount to the same fields present in a RTS.

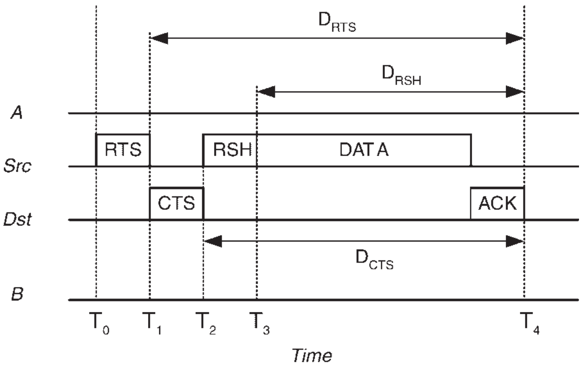

Fig. 4. Timeline of RBAR protocol.

As channel condition is evaluated just before data packet transmission, the estimation of the channel condition is quite accurate, so that RBAR yields significant throughput gains as compared to ARF (as well as compared to the single-rate IEEE 802.11).

Typically, channel coherence time exceeds multiple packet transmission time for both mobile and non-mobile users. It is wise to let a user transmit more packets when in good channel condition and transmit less packets when in bad channel condition. In RBAR, only one packet is allowed to transmit each time, which is not efficient especially when channel is good. To better exploit durations of high-quality channels conditions, [55] introduces the OAR protocol to opportunistically send multiple back-to-back data packets whenever the channel quality is good. By exploiting good channel condition and reducing overhead for competing channel, OAR achieves significant throughput gains as compared to RBAR. Moreover, over longer time scales, OAR ensures that all nodes are granted channel access with the same time-shares as achieved by the single-rate IEEE 802.11. From the point view of throughput, proportional fairness [58] is achieved by OAR.

In the above schemes, only time diversity is considered. These schemes mitigate channel variations rather than utilize channel variations. In wireless LANs or mobile *ad hoc* networks, it is usual that a node needs to communicate with several neighbors. Since channel quality are normally time-varying and independent across different neighbors, this provides the node with a opportunity to choose one of its neighbors with good channel quality to transmit data before those with bad channel quality, if the first-in-first-out (FIFO) service discipline is not strictly enforced. In other words, multiuser diversity may be exploited. However, it is not simple to utilize the multiuser diversity due to signaling problem. To exploit the multiuser diversity in a distributed fashion, [59] presents the opportunistic packet scheduling and auto rate (OSAR) protocol. The basic idea of OSAR is to extend the functionality of the collision avoidance process (RTS/CTS) to probe channel conditions of several candidate receivers simultaneously. In the beginning, the intended sender multicasts RTS message to a selected group of candidate receivers. Each candidate receiver evaluates the instantaneous link quality based on the RTS. The candidate receiver with channel quality better than a certain level is allowed to access the medium. Considering more than one candidate receiver may have good channels and are ready to receive data, a coordinating rule is applied to avoid collision. The RTS includes a list of the media access priority of each candidate receiver. According to the priority list, the qualified candidate receiver with the highest priority is ensured to access the channel first. After that, rate adaptation and packet bursting technique are employed to utilize high-quality channel. Since the signaling required for utilizing multiuser diversity reuses the signaling for collision avoidance, which is an important component for CSMA/CA MAC, overhead is very small. ns-2 simulation results show that the proposed protocol can achieve significant performance gain without sacrificing fairness.

3.6. MAC Protocols Using Smart Antennas

In recent years, one research direction that has been firmly trusted is the exploitation of smart antennas. Smart antennas, which include switched beam antennas, steered-beam antennas, adaptive array antennas, and multiple-input-multiple-output (MIMO) antennas, are capable of directional transmission and reception, interference suppression, and achieving diversity gain. Smart antenna technology offers a variety of potential benefits for wireless communication systems. In particular, it can improve spatial reuse, transmission range and hence network capacity. Especially, the MIMO technology, which relies on the use of adaptive digital beamforming at both ends of the communication link, provides extremely high spectral efficiencies [67,68].

Since the design of contention-based MAC protocol by using fully adaptive arrays and MIMO systems is still in its infancy because of complexity, the following discussion mainly focuses on the challenges and solutions of MAC protocol design with switched beam antennas and steered-beam antennas, which have been extensive studied. We believe these schemes are also helpful in the design of MAC protocol with fully adaptive arrays and MIMO systems.

One of the first papers using directional antennas based on 802.11 MAC is [61] by Ko *et al*. The authors assume transmission could be omnidirectional or directional while reception is omnidirectional only. CTS frames are always transmitted omnidirectionally, while RTS control frames are transmitted directionally or omnidirectionally. Using directional RTS has potential to increase spatial reuse while using omnidirectional RTS can reduce the collision of CTS and/or ACK. So there is tradeoff between spatial reuse and collision. But in general, using directional antennas could lead to high spatial reuse since DATA and ACK are transmitted directionally, thus reducing interference region. One strong assumption in Reference [61] is that each node knows exact locations of other nodes by means of additional hardware such as GPS, and each node transmits signals based on the direction derived from such physical location information.

Considering the locating and tracking problem in mobile *ad hoc* networks, Nasipuri *et al*. [62] proposed another MAC protocol that does not require additional hardware to identify the directions to specific nodes. Both RTS and CTS frames are transmitted omnidirectionally in this study. By comparing the received power from each (sectorized) antenna upon receiving RTS and CTS, the receiver and transmitter can determine the direction of each other. Though both directional transmission and directional reception are considered in Reference [62], any neighboring node hearing RTS and CTS should defer its transmission (in any direction) until the data packet transmission completes. This definitely does not fully utilize the benefit from directional antennas.

To exploit spatial reuse with both directional transmission and directional reception, Takai *et al*. [64], proposed a new carrier sense mechanism called DVCS. RTS is firstly transmitted directionally according to the cached angle of arrivals (AOA) information. If directional RTS fails for four times, the transmitter will transmit omnidirectional RTS up to three times before notifying the higher layer of a link failure. The node updates the cached AOA each time it receives a newer signal from the same neighbor, and invalidates the cache if it fails to get CTS response back from the neighbor after four directional transmissions of the RTS frame. The reception of RTS is omnidirectional. Transmission and reception of CTS are directional and omnidirectional, respectively, and transmission and reception of DATA and ACK are both directional. The distinguishing feature of the DVCS protocol is as follows. Other than totally silencing all the neighbors that hear RTS and CTS as Reference [62], neighboring nodes only need to keep silence in certain directions with the help of DVCS. In other words, neighboring nodes are allowed to transmit as long as it does not interfere with the ongoing transmission. In this way, spatial reuse may be greatly increased. Another nice feature of the DVCS protocol is that it can allow nodes with directional antennas to be interoperable with nodes with omnidirectional antennas. In addition, the DVCS protocol is relatively generic in the sense that it does not depend on whether switched beam antennas or steered-beam antennas are configured.

To increase spatial reuse and transmission range, Choudhury *et al*. [65] proposed a basic DMAC protocol and multihop RTS MAC protocol. The basic DMAC protocol is similar to the DVCS protocol [62]. The basic idea of multihop RTS protocol is that a node uses multihop RTSs to establish links between distant nodes, and then transmits CTS and DATA over a single hop. Since an idle node operates in the omnidirectional mode to receive signal, RTS (even transmitted in directional mode) may not reach the intended receiver even though the receiver is in the transmission range when both directional transmission and directional reception are applied. Note that it is assumed that an upper layer at a node is aware of its neighbors, and is capable of supplying the transceiver profiles required to communicate to each of these neighbors.

There are two major problems with the basic DMAC protocol and the DVCS protocol [65], both caused by directional transmission and/or directional reception. One is the hidden terminal problem and the other is the deafness problem. The deafness problem may result in unproductive control packet transmissions and even false indication of link breakage when RTS-retransmit limit has been reached. To alleviate these two problems, Korakis *et al*. [66] proposed a new MAC protocol based on circular directional RTS (circular directional CTS is also mentioned but not investigated in detail). The directional RTS is transmitted in one direction each time, and keeps going in a circular way until it scans all the area around the transmitter. The RTS contains the duration of the intended four way handshake and beam pair information (which is available if the transmitter knows the direction of receiver before sending RTS) so that the neighbors are aware of the intended handshake and can defer their transmissions in the direction of transmitter or receiver if this harms the ongoing transmission. In this way, both hidden terminal problem and deafness problem can be greatly alleviated. One disadvantage of circular directional RTS is that it increases the time for RTS-CTS handshake significantly. In addition, this scheme still cannot well address the hidden problem due to asymmetry in gain [65].

It is also worth mentioning some other efforts along this line. In Reference [63], Ramanathan presented a broad-based examination of the potential gain by using beamforming antennas. One of the interesting findings is that link power control is essential in exploiting the benefits of beamforming antennas to their fullest. In Reference [69], Ramanathan *et al*. provided a method to employ power control. MAC protocols with adaptive array antennas were studied in References [71] and [70]. A graph theory-based approach to designing MAC protocol for various types of smart antennas (including MIMO systems) can be found in Reference [72] by Sundaresan and Sivakumar.

3.7. Fairness Enhanced MAC

Fairness can be largely divided into per-node fairness and per-flow fairness. As per-node fairness can be improved by adopting fairer backoff mechanisms as discussed in Subsection 3.1.3, in this subsection, we focus on per-flow fairness.

In MANETs, there are several unique characteristics that make it very difficult to achieve, or even consistently define, the notion of fairness. First, the contention for the wireless channel is location-dependent. Transmission of a packet involves contention over the joint neighborhoods of the sender and the receiver. And the level of contention for the wireless channel in a geographical region is dependent on the number of contending nodes and traffic status in the region. Second, there is a tradeoff between channel utilization and fairness. Spatial reuse of the channel bandwidth can be achieved by scheduling simultaneous transmissions whose regions are not in conflict. However, achieving fairness requires allocating the channel to a flow with a large contention for a certain time-share, which correspondingly reduces the channel reuse. Third, since there is no centralized control, no station is guaranteed to have accurate knowledge of the contention even in its own neighborhood due to the dynamic traffic and topology of MANETs. As a result, it is very difficult to design mechanisms to achieve fairness.

Many papers, such as References [73–76], began to use the flow contention graph to study the flow fairness in MANETs. Figure 5 shows an original topology and its flow contention graph. There are six flows, each lying between a pair of neighboring nodes.

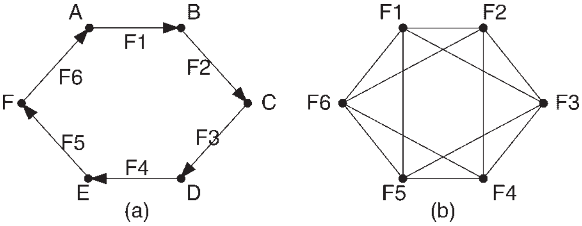

Fig. 5. An original topology (a) and its flow contention graph (b).

Clearly, at any time there are at most two flows that can transmit simultaneously without colliding with each other, such as $F1$ and $F4$. Translating this restraint into flow contention graph, we can see that there is no link between the two corresponding vertexes. Fairness is achieved by scheduling the same channel resource to the flows, which have the same level of contentions in the contention graph, if possible.

The tradeoff between fairness and channel utilization can be defined as an optimization problem:

$$\text{MAX} \sum_{i=1}^{N} w_i f_i(x_i) \tag{2}$$

where N is the number of flows, x_i is the rate for flow i, $f_i(x_i)$ is a strictly concave utility function, and $w_i(> 0)$ is to provide weighted fairness or service differentiation. Note the solution x_i of this problem must correspond to a feasible scheduling to achieve it. The utility function $f(x)$ can be defined in terms of flow rate x as:

$$f_\alpha(x) = \begin{cases} \log x, & \text{if } \alpha = 1 \\ (1-\alpha)^{-1} x^{1-\alpha}, & \text{otherwise} \end{cases} \tag{3}$$

It is shown that the flow rate allocation will approach the system's optimal fairness as $\alpha \to 0$, the proportional fairness as $\alpha \to 1$, and the max-min fairness as $\alpha \to \infty$.

Since the optimal solution of the above problem depends on global topology, and is difficult to achieve in MANETs, several sub-optimal and distributed solutions were proposed. In References [73,74], the schemes require information to be exchanged between neighbors to construct a local flow contention graph, and accordingly coordinate the channel access. The scheme in Reference [73] schedules a delay in the backoff procedure of MAC layer according to the flow degree. In Reference [74] the minimal contention window size of backoff timer is dynamically adjusted based on the obtained share of bandwidth. In contrast, proportional fair contention resolution (PFCR) [75] and fair MAC (FMAC) [76] do not need any knowledge of the topology of the network. PFCR introduces a *NO_CONTEND* state and begins contending for the channel with a probability of x_i when a flow has a packet to transmit and the channel is idle. And it observes the experienced contention and accordingly adjusts x_i. The basic idea of FMAC is trying to let each flow transmit exactly one packet in a time interval t whose length changes with the load of the network or the contention context. The number of transmissions in the time interval t serves as the feedback signal to adjust the contention window or the time interval. All these schemes achieve better fairness than the IEEE 802.11 with more or less sacrifice of aggregate throughput in certain topologies. However, they are all limited to one-hop flows. This is because, although multihop flows are not unusual in MANETs, defining and achieving fairness for multihop flows turns out to be a very complicated issue. One of the reasons is that fairness with respect to end-to-end flow rate is tightly coupled with higher layer protocols, such as routing and congestion control.

3.8. Quality of Service in MANETs

While supporting real-time applications with appropriate QoS in MANETs is desirable, it seems to be a formidable task considering network topology and traffic load dynamically change in MANETs, making connection state maintenance and bandwidth reservation extremely difficult. In response, current research mainly focuses on providing service differentiation rather than strict QoS by using distributed control at the MAC layer.

Service differentiation at the MAC layer can be achieved by assigning different channel access opportunities to different types of traffic. Different backoff contention window and DIFS are widely used as differentiation techniques for such purposes. For example, in the enhanced distributed coordination function (EDCF) of IEEE 802.11e draft [77], traffic is divided into eight categories or priority levels. Before transmitting, each node needs to wait for the channel to be idle for a period of time associated with its corresponding traffic category called arbitration interframe space (AIFS). Typically, a shorter AIFS and a smaller backoff contention window are associated with a traffic category with higher priority, by which

EDCF establishes a probabilistic priority mechanism to allocate bandwidth based on traffic categories. In Reference [78], similar differentiation mechanisms are also adopted to associate each packet with a different priority, which is determined based on packet arrival time and packet delay bound. In this way, delay-sensitive traffic is better supported.

Besides prioritized channel access, admission control for the real-time traffic is another powerful tool to support better QoS. It can effectively keep the congestion of the channel at a low level and reduce long queuing delay. A distributed admission control algorithm [79] was proposed for a multicell topology where each cell has a base station. Both data and real-time traffic are considered. This scheme relies on two algorithms, that is, virtual source (VS) and virtual MAC (VMAC), to measure the channel state. In both VS and VMAC algorithms, a virtual packet was put in the MAC layer or the queue. Virtual packets are scheduled to transmit on the radio channel the same way as a real packet, which means channel testing and random backoff are performed when necessary. A virtual packet, however, is not really transmitted when the VMAC decides it wins the channel. When the estimated delay by both VS and VMAC exceeds 10 ms, new real-time sessions are denied service. In contrast, no admission control is applied to data traffic. Note that in addition to call admission control, real-time traffic is assigned smaller backoff contention window than data traffic.

In Reference [80], a scheme referred to as call admission and rate control (CARC) was proposed to provide statistical QoS guarantee in wireless LANs. [81–85] CARC conducts admission control over real-time traffic and rate control over best effort traffic. The rate control algorithm determines the amount of best effort traffic that the MAC layer can deliver in such a way that its contention with real-time traffic is kept at a small level and full utilization of the channel is achieved at the same time. In Reference [86], a stateless wireless *ad hoc* networks (SWAN) model was proposed for MANETs. SWAN uses local rate control for best-effort traffic, and sender-based admission control for real-time UDP traffic to deliver service differentiation.

4. Conclusion and Future Research

In this paper, we have surveyed recent advances in medium access control in mobile *ad hoc* networks. We first pinpointed some challenges and design issues that an efficient MAC protocol needs to take into account. Then, we selectively focused on several research areas that we think are important to MAC design, which include basic mechanisms for contention-based MAC protocols, solutions to the hidden terminal and exposed terminal problems, multichannel transmission, transmission power control, rate adaptation, use of smart antennas, fairness, and QoS provisioning. As can be clearly seen, significant progress has been made in these areas, with numerous schemes and technologies having been developed. More importantly, we have gained deeper understanding of fundamental problems and achievable solutions, which lays a foundation for future progress. At the same time, it is recognized that due to the inherent complexity of mobile *ad hoc* networks, the continuous emergence of new physical layer technologies, and the ever-increasing user demands for newer and better services, many critical issues remain unresolved. Listed below are several of them that need to be further researched.

- *Interference-limited channel access*
  Since carrier sensing, on which the 802.11 MAC protocol is based, has been demonstrated to be inefficient, the collision avoidance may shift from *carrier sensing approach* to *interference-limited approach*. In the latter approach, multiple neighboring node pairs are allowed to communicate concurrently as long as the target SINR of each node pair is satisfied. Accordingly, the hidden terminal and exposed terminal need to be redefined. In addition to increasing spatial reuse, this approach can exploit the benefits of smart antennas, power control, and new modulation and error coding schemes to their fullest potential. Moreover, it is believed to be more general, fundamental, and independent of emerging physical layer techniques.
- *Fairness for Multihop Flows*
  Although fairness in wired networks has been thoroughly studied, it is quite different in MANETs due to the very nature of wireless communication. Although fairness on one-hop flows has been currently studied, that on multihop flows is an open area despite the fact that multihop flows are common in MANETs. Part of the reason for this is that consistently defining and achieving fairness for multihop flows are very challenging. Compared to short flows, longer flows traverse more mobile nodes and consume more channel resource to finish the end-to-end packet transmission, because for each flow, the one-hop transmission at each node

needs to contend for the channel with all its two-hop neighbors. Also, longer flows are more likely to encounter route failures and subsequently re-routing, since network topology is dynamically changing due to mobility. Consider a very simple scenario where only a one-hop flow or a multihop flow in a MANET. The end-to-end throughput of the multihop flow is much less than that of the one-hop flow for the reasons mentioned in the above.

- *Cross-layer Design*
  Many research findings call for the cross layer design for wireless networks. TCP performance [87] in terms of throughput and fairness over *ad hoc* networks is very sensitive to packet loss which may be due to collision, wireless channel error, link breakage as well as congestion. Improvement of link reliability, reducing hidden/exposed terminal problem and deafness problem, and hop-by-hop link-layer congestion control [88,89] are all helpful in improving end-to-end TCP performance. When power control and direction antennas are considered, the control of transmission range and direction of the routing control packets largely affects final routing decision. Another interesting case is the exploitation of channel variations by joint work on opportunistic routing and MAC layer anycasting [90–93]. Overall, we believe that cross layer design seems a must to provide end-to-end QoS at both packet and flow level.

Acknowledgment

This work was supported in part by the U.S. Office of Naval Research under Young Investigator Award N000140210464 and under grant N000140210554.

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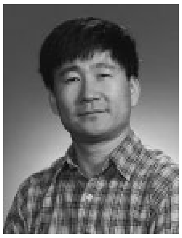

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