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A Survey On MAC Protocols for Wireless Adhoc Networks with Beamforming Antennas

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***Abstract*—The beamforming antenna technology is a promising solution to many challenges facing wireless ad hoc networks. Beamforming antennas have the ability to increase the spatial reuse, improve the transmission reliability, extend the transmission range and/or save the power consumption. If they are effectively used, they can significantly improve the network capacity, lifetime, connectivity and security. However, traditional Medium Access Control (MAC) protocols fail to exploit the potential benefits due to the unique characteristics of wireless ad hoc networks with beamforming antennas. To that end, numerous MAC protocols have been designed over the years to harness the offered potential. In this paper, we survey the literature on MAC protocols proposed for wireless ad hoc networks with beamforming antennas during the last decade. We discuss the main beamforming-related challenges facing the medium access control in ad hoc networks. We present taxonomy of the MAC protocols proposed in the literature based on their mode of operation and the mechanisms used to address the challenges. In addition, we provide a qualitative comparison of the protocols highlighting their features, benefits and requirements. Finally, we provide directions for possible future work.**

***Index Terms*—Medium Access Control, Beamforming Antennas, Directional Antennas, Wireless Ad hoc Networks.**

I. Introduction

TRADITIONALLY, wireless networks are designed to provide single hop connectivity either to cellular base stations or to WLAN access points. However, the possibility of extending the wireless coverage, improving the overall capacity and enabling network auto-configuration with no infrastructure support has sparked the idea of multi-hop wireless networks [1]. The concept of multi-hop wireless networks dates back to the 1970s when the packet radio networks were introduced. However, the development of the multi-hop wireless networking paradigm has surged in the 1990s with the increasing interest in mobile ad-hoc networks and their applications in battlefield and disaster relief environments which later evolved to a broader arena that encompasses wireless mesh networks, wireless sensor networks and vehicular ad-hoc networks just to name a few [2]. The research on multi-hop wireless networks has attracted both academia and the wireless industry resulting in rapid commercialization as well as numerous standardization efforts.

Motivated by the rapid deployment and emerging applications, the research community is interested in developing innovative solutions to address the challenges facing multi-hop wireless networks. Some of the key challenges include interference-limited capacity, power efficiency, quality of service and security. In this context, the "smart beamforming antennas" technology is a promising technology to be utilized with multi-hop wireless networks [3], [4]. Smart beamforming antennas have provided significant improvements in expanding coverage, mitigating interference and increasing capacity when deployed in cellular networks [5], [6] and wireless LANs [7]. However, omni-directional antennas are dominating all forms of multi-hop wireless networks due to the cost and size limitations. On the other hand, the recent advances in the antenna technology along with the shift towards higher operating frequencies have made it feasible to use this technology even in small, mobile and battery-operated devices [8], [9]. Nevertheless, the traditional network protocols fail to interact with an underlying smart beamforming antenna since these protocols were originally designed to run on nodes equipped with omni-directional antennas. The lack of the appropriate control over the antenna beamforming may deteriorate the overall performance even below the level achieved by omni-directional ones [10]. Hence, it is important to investigate innovative protocols, specially at the MAC layer, that are capable of harnessing the potential benefits of using smart beamforming antennas in wireless ad hoc networks.

A. Antenna Basics and Types

In this section, we provide a concise overview on beamforming antennas. We do not intend to cover all their aspects but aim to provide the reader with enough knowledge to understand the MAC research reported in this survey. For additional details please refer to [5], [11]–[13].

The primary function of any radio antenna is to couple electromagnetic energy from one medium to another. Traditionally, simple dipole antennas are used to radiate/receive energy equally to/from all directions. These antennas are known as omni-directional antennas. On the other hand, directional antennas are able to radiate/receive energy to/from one direction more than the others. An important characteristic of an antenna is its gain as it is used to quantify the directionality of the antenna. The gain of an antenna in a certain direction indicates the relative power in that direction compared to the omni-directional antenna. The gain is usually measured in dBi with the gain of an omni-directional antenna equals 0 dBi. Since the transmission and reception characteristics of the antenna are reciprocal, the directional antenna has both transmission and reception gains. The gain values in all directions of space are represented by the antenna radiation pattern. A directional antenna pattern usually consists of a high gain main lobe (beam) and smaller gain side and back lobes. Figure 1 shows

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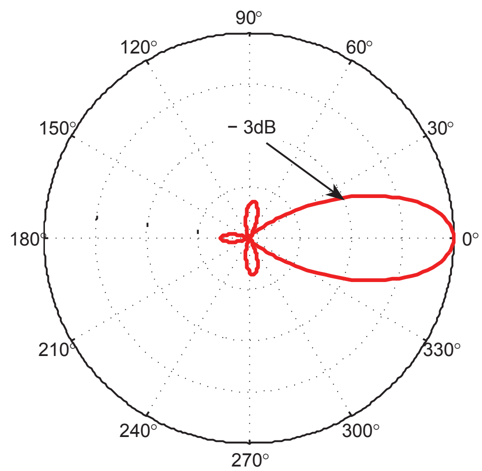


Fig. 1. Antenna radiation pattern with a main lobe pointing at 0^o and side lobes with smaller gains.

an example for an antenna radiation pattern. The peak gain is the maximum gain over all directions and lies along the axis of the main lobe which is also known as the boresight of the antenna. Another characteristic of a directional antenna is its beamwidth which formally refers to the angle subtended by the directions on either side of the boresight which are 3dB less in gain. However, ideal directional antennas are assumed to have an ideal antenna pattern in which the gain is constant in the main lobe and zero outside.

The relation between the antenna characteristics and the transmitted and received power is governed by Friss equation [11]. The received power P_r at a distance r from a transmitter with transmission power P_t is given by:

$$P_r = \frac{P_t G_t G_r}{K r^{\delta}}, \quad (1)$$

where G_t and G_r are the transmitter and receiver gains along the straight line joining the transmitter and receiver, δ is the path loss exponent and K is a constant that is a function of the wavelength. A receiver can interpret the received signal if the received power is greater than or equal to the receiver sensitivity threshold.

Directional antennas are often realized by means of antenna arrays. In order to produce a specific antenna radiation pattern, single antenna elements (e.g. dipoles) are arranged in an antenna array with physical separation in terms of a fraction of the wavelength. The overall radiation pattern of an antenna array is determined by the number of elements, the element spacing, the geometrical configuration of the array and the amplitude and phase of the applied signal to each element.

The “smart antennas” technology combines an antenna array with Digital Signal Processing (DSP) techniques that allow the antenna elements to transmit and receive in an adaptive, spatially sensitive manner. Beamforming antennas lie under the umbrella of “smart antennas” which also includes Multiple Input Multiple Output (MIMO) systems [14]. Unlike MIMO systems that utilize adaptive antenna arrays at both the transmitter and the receiver to overcome the limitations of multi-path environments, a beamforming antenna employs sophisticated antenna array control algorithms to automatically and adaptively control the overall radiation pattern of the antenna[1]. In particular, DSP algorithms are used to estimate the Direction-of-Arrival (DoA) of the signal and use this information to calculate the weights applied to the signal at each antenna element that are responsible for changing the radiation pattern. The amount of control over the beamforming process relies on the sophistication of these algorithms. Beamforming antennas are classified into switched beam systems and steered beam systems.

1) Switched Beam Antenna Systems:

In switched beam systems, the antenna array is combined with a fixed Beam Forming Network (BFN). The BFN consists of a predetermined set of weight vectors, where the configuration of weights in a vector determines the direction in which the antenna radiation pattern is beamformed. Based on the direction-of-arrival estimation, the BFN chooses a weight vector to be applied to the signal received/transmitted by the antenna array. In other words, the antenna adaptively switches to one of the predefined set of beams.

Switched beam antennas can provide most of the benefits of smart antennas at a small fraction of complexity and expense. Spatial reuse, range extension and power saving are possible with this type of smart antennas. However, they do not guarantee maximum gain due to scalloping [5]. Scalloping is the roll-off of the antenna pattern as a function of the angle from the boresight. If the desired direction is not on one of the predetermined boresights, the transceiver will suffer from gain reduction. Moreover, switched beam antennas are not able to fully eliminate the interference outside the main lobe due to the absence of control on the side lobes.

2) Steered Beam Antenna Systems:

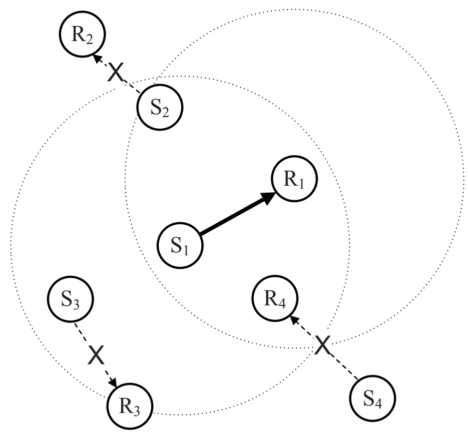
They are also known as Adaptive Antenna Array (AAA) systems. They provide a high degree of flexibility in configuring the radiation patterns. Using a variety of sophisticated signal processing algorithms, the adaptive array antennas can adapt their weights in order to maximize the resulting Signal to Interference and Noise Ratio (SINR). The boresight of the main lobe can be directed towards the target using phase shifters. This type is known as phased antenna arrays. By increasing the complexity of the DSP algorithms, nulls can be additionally placed in the direction of interfering sources to suppress their interference.

Although adaptive antenna array systems can outperform switched beam systems especially in multi-path environments, the associated complexity and cost are limiting factors [14]. The need to continuously locate and track various types of signals complicates the signal processing task and results in a significant increase in the power consumption.

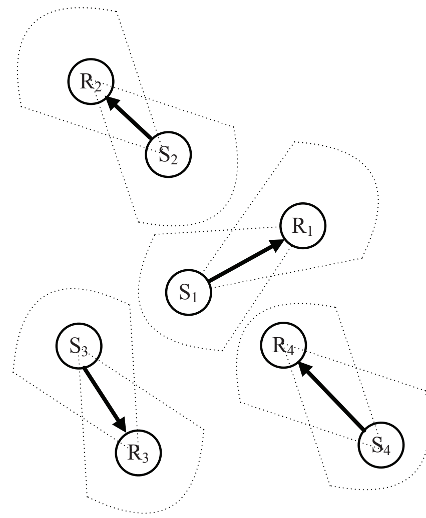
B. Benefits of Beamforming Antennas

In the last decade, the use of beamforming antennas in multi-hop wireless networks has received increasing attention in the research community due to their potential benefits and numerous advantages compared to the traditional omni-directional antennas [15]. Some of these benefits include the following aspects:

[1]Many refer to “ beamforming antennas” as simply “directional antennas”. In this paper, we will use the two terms interchangeably.



(a) Omni-directional antennas.



(b) Directional antennas

Fig. 2. An illustrative example of the spatial reuse benefit of directional antennas.

- Since a directional antenna is able to radiate energy in the direction of the intended receiver, this transmission does not interfere with neighboring nodes residing in other directions. Moreover, the directional reception and the ability of sophisticated beamforming antennas to completely suppress the reception from interfering directions can significantly reduce interference. This increases the spatial reuse of the wireless channel as multiple simultaneous transmissions can take place within the same vicinity which promises a significant improvement in the wireless network capacity. Figure 2 shows how the limited scope of the directional transmissions and receptions can increase the channel utilization significantly. In case of the omni-directional antenna, a single communication S_1-R_1 precludes all other communications that involve the neighbors of either S_1 or R_1, whereas using beamforming antennas all four pair wise communications can occur simultaneously. The increase in network capacity, when beamforming antennas are used, is supported with theoretical analysis [16], [17], simulations [3] and experimental results [18].
- The gain of the beamforming antenna results in focusing more energy in the intended direction which increases the Signal-to-Noise Ratio (SNR) for the same transmit power. This increase in the SNR improves the link reliability and robustness against fading. Moreover, a better link quality could result in a higher transmission rate.
- For the same transmit power as omni-directional antennas, the directional gain of beamforming antennas is translated to communication range extension. This extension may lead to fewer-hops routes and consequently a reduction in the end-to-end delay [19]. In addition, the communication range extension makes it possible to bridge network partitions [20] and may improve the connectivity of the network [21].
- Reductions in the power consumption can trade-off the benefit of range extension. For a specific pair of nodes, beamforming antennas are able to reduce the transmit power while maintaining the same wireless link quality as omni-directional antennas [22], [23]. Thus, energy efficient communication is possible with beamforming antenna which makes this technology an attractive option to be used in battery-operated networks.
- The unique features of beamforming antennas reduce the risks of eavesdropping and jamming, hence, providing more secure wireless communication [24], [25].

In addition to the above-mentioned benefits, beamforming antennas provide more opportunities such as location estimation [26] and efficient broadcasting [27]. However, the numerous benefits of beamforming antennas come on the expense of an increase in cost and complexity relative to the omni-directional antennas. As discussed in Section I-A, there are different types of beamforming antennas that vary in complexity and capabilities. Based on the network requirements, a proper antenna type can be used to balance the performance benefits and the associated cost [3].

On the other hand, it is not sufficient to plug-and-play a beamforming antenna to exploit the offered potentials. The beamforming antenna system needs to be appropriately controlled by upper layers of the networking protocol stack [18]. Since the MAC layer lies just above the physical layer, it is the most important layer to be modified in order to realize the full potential of the beamforming antennas.

C. *Medium Access Control (MAC)*

The wireless medium is open and shared by several nodes in the network. If acquiring this resource is left uncontrolled, multiple nodes may try to access it at the same time. The goal of the MAC protocol is to set the rules in order to enable efficient and fair sharing of the common wireless channel [28], [29]. The MAC protocol typically needs to maximize the channel utilization by having as many simultaneous communications as possible.

Medium access control protocols for wireless networks [30] may be classified into two major categories: contention-based and contention-free MAC. In contention-based MAC, nodes compete to access the shared medium through random access. In case of conflict occurrence, a distributed conflict resolution algorithm is use to resolve it. The most commonly considered contention-based MAC mechanism is the Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). On the other hand, contention-free MAC is based on a controlled access in which the channel is allocated to each node according to a predetermined schedule.

The IEEE 802.11 Distributed Coordinated Function (DCF) is one of the CSMA/CA based protocols which has lately received a great attention due to its simplicty. In IEEE 802.11 DCF MAC [31], a node wishing to access the wireless medium should perform physical carrier sensing before initiating transmission. This is the CSMA part of the protocol. However, the performance of CSMA degrades significantly in multi-hop wireless networks due to the hidden terminal problem [29]. When two nodes are outside the carrier sensing range of each other, they are said to be hidden. If both nodes attempt to communicate with a common node, collision occurs at the receiving node. To overcome this problem, collision avoidance is implemented by a handshaking mechanism before data transmission [32]. The data transmission is preceded by transmitting a short Request-To-Send (RTS) packet to the intended receiver which in turn responds with a short Clear-To-Send (CTS) packet if the channel is idle at the receiver site for Short Interframe Spacing (SIFS) period. Both RTS and CTS packets contain the proposed duration of transmission. Nodes located in the vicinity of the communicating nodes, which overhear either of these control packets, must themselves defer transmission for the proposed duration. This is called Virtual Carrier Sensing (VCS) and is implemented through a mechanism called the Network Allocation Vector (NAV). A node updates the value of the NAV with the duration field specified in the RTS or CTS. Thus, the area covered by the transmission range of the sender and receiver is reserved. This procedure reduces the probability of collision dramatically. Figure 3 shows the collision avoidance operation in IEEE 802.11 MAC.

The IEEE 802.11 MAC protocol uses a backoff mechanism to resolve channel contention. Before initiating a transmission, each node performs both virtual and physical carrier sensing. If NAV is not set, and the channel is sensed idle, the node defers for DCF Interframe Spacing (DIFS) period before sending its packet. If the channel is found busy (by physical carrier sensing), the node chooses a random backoff interval from [0, CW], where CW is called the contention window. The CW is initialized to the value of CW_{min}. After every idle slot time, the node decrements the backoff counter by one. When the counter reaches zero, the node can transmit its packet. In case a CTS or ACK packet is not received back, the node assumes a collision has occurred with some other transmission and it invokes the binary exponential backoff algorithm. In this backoff algorithm, the node doubles its CW, chooses a new backoff interval and tries retransmission again once the backoff timer expires. The CW is doubled on each collision until it reaches a maximum threshold, called CW_{max}. Retransmission retries are limited by a threshold after which the packet is discarded. If the medium is sensed busy during the backoff stage, the node freezes its backoff and resumes it once the medium has become idle for DIFS duration. Once a transmission is successfully transmitted, CW is initialized to its minimum value for the next transmission.

The design of IEEE 802.11 implicitly assumes an omni-directional antenna at the physical layer. When smart beamforming antennas are used, IEEE 802.11 MAC does not work properly. Researchers have looked into adapting IEEE 802.11 to the case of beamforming antennas. Choudhury et al. propose a directional version of IEEE 802.11 DCF MAC under the name of "Basic DMAC" [33] which is considered the benchmark for directional medium access control protocols[2]. To exploit the spatial reuse benefits, the Basic DMAC require the active nodes to perform carrier sensing, back-off, and the four-way handshake in a directional mode while the idle nodes reside in an omni-directional mode.

D. Scope and Outline

In this paper, we conduct a survey of thirty eight MAC protocols proposed particularly for wireless ad hoc networks with beamforming antennas during the last decade. Such a survey is required to provide a comprehensive and up-to-date overview of this emerging research field. Although there are a couple of survey papers found in the literature [34]–[36], they are incomplete and outdated. Moreover, their classifications are coarse when compared with the taxonomy presented in this paper. The focus of this survey is on the MAC protocols that allow the nodes to transmit/recieve one packet at a time. The MAC protocols that permit concurrent-packet transmission/reception and MIMO techniques lie outside the scope of this paper and interested readers are refered to [37]–[40].

The rest of this paper is organized as follows. In Section II, we discuss several antenna-specific MAC challenges. We present a taxonomy of directional MAC protocols for wireless ad hoc networks in Section III. Details of the surveyed MAC protocols in each category are presented in Sections IV and V. We compare the protocols in Section VI. Some discussions and future work directions are discussed in section VII. Concluding remarks are presented in Section VIII.

II. MAC Challenges with Beamforming Antennas

Conventional wireless MAC protocols were designed to overcome the challenges of the wireless medium such as hidden terminal problem and exposed terminal problem [30]. The unique characteristics of beamforming antennas pose unprecedented challenges that should be considered in the design of the directional MAC protocols for wireless ad hoc networks. In this section, we discuss the main beamforming-related challenges facing the medium access control.

[2] The term "directional MAC protocols" is commonly used to refer to the MAC protocols designed particulary for wireless networks with beamforming antennas.

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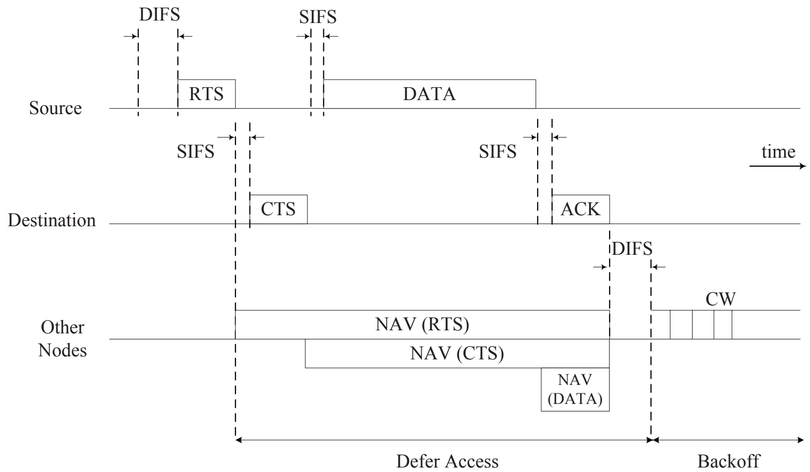

Fig. 3. Channel reservation in IEEE 802.11 MAC.

A. Deafness

While exploiting the spatial reusability using beamforming antennas, deafness is by far the most critical challenge [41], [42]. Deafness [43] was first identified in the context of the Basic Directional MAC (DMAC) protocol [33]. It occurs when a transmitter tries to communicate with a receiver but fails because the receiver is beamformed towards a direction away from the transmitter. Due to the characteristics of directional beamforming, the intended receiver is unable to receive the transmitter's signal and as a result appears deaf to the transmitter.

Considering the example in Figure 4, nodes B and C are engaged in directional communication while node A is in the backoff stage. Node A cannot sense the ongoing communication and is basically unaware of it, thus it attempts to communicate with node B at the end of its backoff . Since node B is beamforming in another direction, it is deaf to node A's transmission and cannot respond. Due to the absence of CTS response, node A typically considers this kind of failure as an indication of collision and reacts accordingly. It invokes the binary exponential backoff algorithm before attempting retransmissions. Multiple retransmissions could happen until node B has finished the dialog with node C and switches back to the omni-directional mode. These unnecessary retransmissions reduce the network capacity. Moreover, the exponential increase in the backoff contention window results in channel underutilization as shown in Figure 4.

The consequences of deafness may be even more severe. Assume that node C has multiple packets to send to node B. Once node C has finished transmitting the first packet, it immediately prepares to transmit the next packet by choosing a backoff interval from the minimum contention window. It is likely that node A is still engaged in the large backoff phase when node C finishes counting down its small backoff value for the second packet. Node C acquires channel access and communicates again with node B. This scenario can continue for a long time, causing node A to drop multiple packets before it gets fortunate enough to grab the channel access from node C. This scenario depicts that deafness may lead to short-term unfairness between flows that share a common receiver. If the MAC protocol requires the node to carrier-sense, backoff and communicate directionally, it may suffer from prolonged period of deafness if it has multiple back-to-back packets to be transmitted. Moreover, a chain of deafness is also possible in which each node attempting to communicate with a deaf node becomes itself deaf to another node. This could also result in a deadlock scenario [43].

B. New Hidden Terminals

The traditional hidden terminal problem in wireless networks occurs when two nodes are outside the carrier sensing range of each other and both of them attempt to communicate with a common node causing collision. The collision avoidance concept was proposed to solve this problem which is implemented by means of RTS/CTS handshaking before data transmission [32]. The RTS/CTS handshaking mechanism informs the neighboring nodes about imminent communication.

In the context of beamforming antennas, the hidden terminal problem occurs when a potential interferer could not receive the RTS/CTS exchange due to its antenna orientation during the handshake and then initiates a transmission that causes collision. There are two new types of directional hidden terminal problems [44]:

1) Hidden Terminal Due to Asymmetry in Gain:

This problem is basically due to the fact that the antenna gain in the omni-directional mode (G_o) is smaller than the gain when the antenna is beamformed (G_d). If an idle node is listening to the medium omni-directionally, it will be unaware of some ongoing transmissions that could be affected with its directional transmission.

To explain this type of hidden terminal problem, we refer to the scenario in Figure 5. Assume that node A and node C are out of each other's range when one is transmitting directionally (with gain G_d) and the other is receiving omni-directionally (with gain G_o). However, they are within each other's range only when both the transmission and reception are done directionally (both with gain G_d). First, node B transmits RTS directionally to node C, and node C responds back with a directional CTS. Node A is idle (still in omni-directional mode) so it is unable to hear the CTS. Data

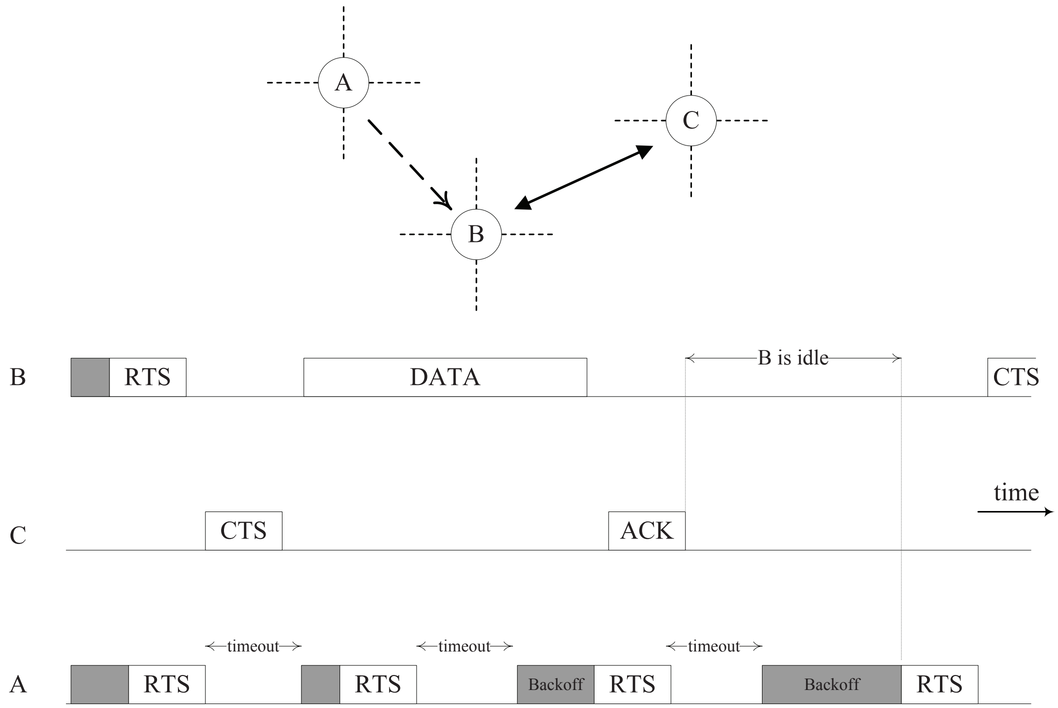

Fig. 4. A scenario illustrating the deafness problem.

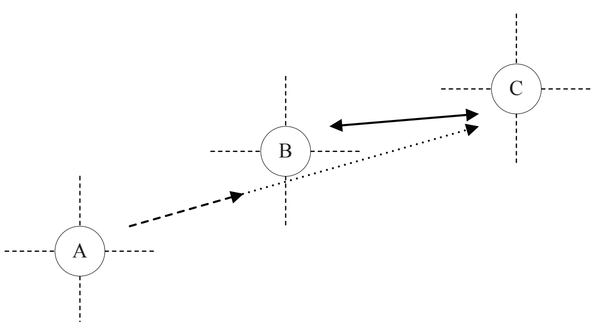

Fig. 5. A scenario to illustrate the hidden terminal problem due to the asymmetry in gain.

transmission begins from node B to node C with both nodes pointing their transmission and reception beams towards each other. While this communication is in progress, node A has a packet to send to node B. Node A beamforms towards node B (which is the same direction of node C) and performs the carrier sensing. Since the channel is sensed idle, node A sends a directional RTS to node B. However, since node C is receiving data directionally using a beam pointed toward node B (and node A), the RTS from node A interferes with node B's data transmission at the receiver C causing collision.

2) Hidden Terminal Due to Unheard RTS/CTS:

This type of hidden terminal problem occurs as a result of the loss in the channel state information during beamforming. When a node is involved in a directional communication, it would appear deaf to all other directions and important control packets may be lost during that time. In contrast to the deafness problem in which the packet cannot be received by its intended receiver, this type of new hidden terminals occurs when a ”neighboring node” fails to receive the channel reservation packets (RTS/CTS) exchanged by a transmitter-receiver pair. Hence, it becomes unaware of the imminent communication between that particular transmitter-receiver pair and accordingly could later initiate a transmission that causes collision. An illustrating example is shown in Figure 6. Suppose that node A is engaged in a directional communication with node D. While this communication is in progress, node B sends RTS to node C which in turns replies with CTS. Since node A is beamformed towards node D, it cannot hear CTS from node C. While the communication between node B and node C is in progress, node A finishes the communication with node D and now decides to transmit to node C. Since the DNAV at node A is not set in the direction of node C (due to the unheard CTS), node A transmits RTS to node C causing collision at node C.

C. Head-of-Line Blocking

The Head-of-Line (HoL) blocking problem with directional MAC protocols was first identified in [45]. It occurs as a result of the typically used First-In-First-Out (FIFO) queueing policy. This policy works fine in the presence of omni-directional antennas since all outstanding packets use the same medium. If the medium is busy, no packets can be transmitted. However, in case of beamforming antennas, the medium is spatially divided and it may be available in some directions but not others. If the packet at the top of the queue is destined to a busy node/direction, it will block all the subsequent packets even though some of them can be transmitted as illustrated in Figure 7. Using the FIFO queueing policy, although node

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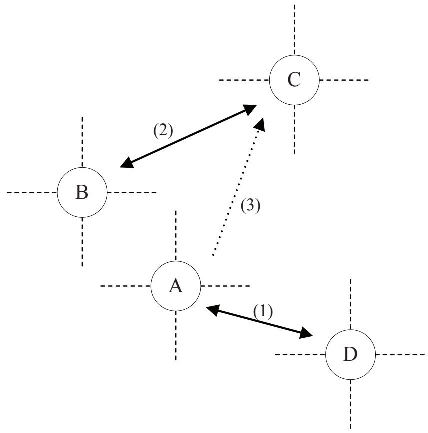

Fig. 6. A scenario to illustrate the hidden terminal problem due to unheard CTS.

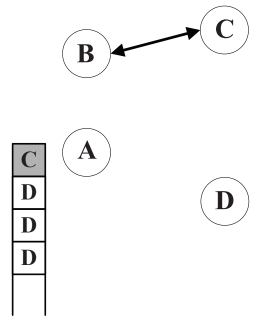

Fig. 7. A scenario to illustrate the head-of-line blocking problem

A has packets that can be transmitted to node D, they are blocked by the packet destined to the busy node C. The HoL blocking problem is aggravated when the top packet goes into a round of failed retransmissions including their associated backoff periods as discussed in [46].

D. Communication Range Under-utilization

In contrast to the previous problems that mainly offset the benefit of spatial reuse introduced by beamforming antennas, the operation of the directional MAC protocol may limit the full exploitation of the communication range extension offered by beamforming antennas. If the protocol requires the omni-directional transmission of control packets or the idle node to reside in an omni-directional mode, the communication range is limited. It is possible for nodes to communicate over the extended range if both the transmitter and the receiver could agree to beamform towards each other at the same time which is a challenging issue in the presence of asynchronized medium access. Following the terminology introduced in [33], the node has three types of neighbors: (1) The Omni-Omni (OO) neighbors: Those are neighbors that can only receive the omni-directional transmissions of the node when they are listening in an omni-directional mode. (2) The Directional-Omni (DO) neighbors: Those are neighbors that can also receive the directional transmissions of the node when they are listening in an omni-directional mode. (3) The Directional-Directional (DD) neighbors: Those are neighbors that can receive the directional transmissions of the node only if they are already beamformed in the direction of the node. The challenge facing the MAC protocols is how to allow communication to occur between DD-neighbors.

E. MAC-layer Capture

Since a packet can be received from any direction, it is common that the antenna of an idle node resides in an omni-directional mode in order to be able to listen in all directions. When a signal is detected, the antenna will beamform towards the direction of maximum received power, receive the packet, decode it and pass it up to the MAC layer. If the packet is not destined to this node, the packet will simply be dropped. The time the node wastes in receiving packets, not intended to it, might refrain the node from transmitting/recieving useful packets to/from other directions thus resulting in channel underutilization. This problem is identified in [47] under the name of ”MAC-layer capture” as a limiting factor in the potential increase in the spatial reuse when beamforming antennas are employed. It is worthy to note that the MAC-layer capture problem is not restricted to the use of beamforming antennas. However, in the case of omni-directional antennas, there is little motivation to avoid being captured by ongoing frames because captured nodes are not expected to initiate any concurrent transmissions until the medium is idle. On the contrary, beamforming antennas spatially divide the shared medium and a transmission in one direction does not affect other directions.

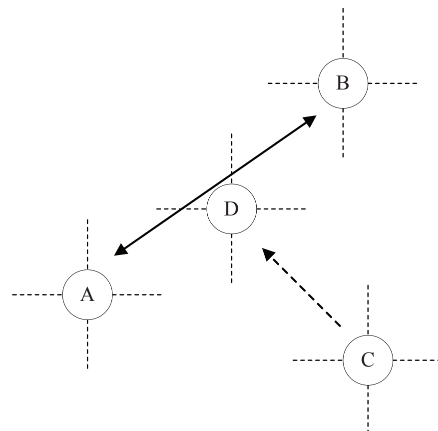

Fig. 8. A scenario to illustrate the MAC-layer capture problem

In the context of beamforming antennas, the MAC-layer capture problem basically occurs when the node does not perform any intelligent control of the underlying antennas when it is idle. Considering the example in Figure 8, suppose that node A has a packet to transmit to node B and node C has a packet to transmit to node D. Using beamforming antennas, the two dialogues could occur concurrently. However, if node A starts its transmission first towards node B, the idle node D will get engaged in receiving node A's transmission thus its concurrent communication with node C is not possible. The MAC-layer capture problem does not only reduce the spatial reuse but also leads to the negative consequences of deafness as pointed out in [48] and [49].

III. MAC Protocols Classification

The problem of designing an efficient MAC protocol for wireless ad hoc networks with beamforming antennas has been of a great interest during the last decade. In this section, we present a taxonomy of the proposed directional MAC protocols as shown in Fig 9. The MAC protocols can be broadly classified into random access protocols and synchronized access protocols. Random access protocols allow the stations to access the shared medium randomly through contention with each other. Synchronized access protocols allow the stations to access the medium based on a predetermined schedule which can be achieved through local and/or global synchronization.

A substantial number of directional MAC protocols presented in the literature belongs to the former category. Most random access protocols rely on the concept of Carrier Sensing Multiple Access (CSMA) in which physical carrier sensing is performed before initiating transmission. Random access protocols can be further classified into sub-categories according to the tool(s) used to handle MAC main challenges such as deafness and hidden terminals. The first sub-category of directional MAC protocols rely solely on control packets in particular RTS/CTS packets traditionally used for collision avoidance. The second sub-category employs busy tones that are usually transmitted on a dedicated control channel. The protocols that rely on the control packets can be further classified based on how the initial control packet (i.e RTS packet) is transmitted. (1) Omni-directional RTS: The RTS packet is transmitted in all directions with the antenna operating in an omni-directional mode. (2) Uni-directional RTS: The RTS packet is transmitted directionally towards the direction of the intended destination only. (3) Multi-directional RTS: The RTS packet is transmitted towards some or all available directions. The multi-directional transmission could be either sequential or concurrent. If the antenna pattern is formed of a single beam, the multi-directional transmission could be achieved by transmitting copies of the packet sequentially over different directions (one direction at a time). When the beamforming antenna is capable of forming multi-beam antenna pattern, the packet could be transmitted to multiple directions concurrently at the same time. Figure 10 shows the coverage range of the different transmission modes.

Throughout the literature, we found some directional MAC protocols that belong to the category of synchronized access protocols. The basic idea is to coordinate conflict-free transmissions to occur simultaneously which requires some sort of synchronization between the nodes. Time is usually divided into frames and each frame consists of sub-frames which are simply a group of time slots. In one sub-frame, channel contention is usually used to perform a schedule for contention-free data transmission in the rest of the frame. Since achieving global synchronization is considered difficult in multi-hop wireless networks, recent protocols have chosen to rely on local coordination between neighboring nodes.

Aside from the above taxonomy, MAC protocols for wireless ad hoc networking with beamforming antennas can be classified in different ways. One classification could be according to the antenna capabilities whether switched-beam antennas, steered beam antennas or adaptive antennas with null capabilities. Another classification could be based on supported communication range which is limited by the antenna modes at each side of the wireless link. A third classification is whether the MAC protocol use a single channel or multiple channels. Directional MAC protocols can also be classified based on the power awareness of the protocol or its IEEE 802.11 compatibility. It is worthy to note that the above classes are not independent of each other and hence one directional MAC protocol may belong to more than one class. In this work, our classification is based on the taxonomy shown in Fig 9 which provides the fine granularity needed to understand the benefits and tradeoffs associated with the surveyed protocols. In the next two sections, we will review the operation of thirty eight directional MAC protocols that best represent the progress in this field.

IV. Review of Random Access Protocols

Due to the lack of a pre-determined access schedule, stations compete to access the shared medium through random access. In case of conflict occurrence, a distributed conflict resolution algorithm is used to resolve it. Most random access protocols rely on the concept of CSMA. A station wishing to access the wireless medium performs carrier sensing before initiating transmission. If the medium is idle, the station is allowed to transmit. If the medium is sensed busy, the station defers transmission for a random period of time. In traditional wireless networks with omni-directional antennas, collision avoidance mechanisms have been widely used to improve the performance of CSMA-based protocols. Collision avoidance is performed using control packets (e.g. RTS/CTS packets) and/or busy tones. In the context of beamforming antennas, similar mechanisms are employed to address the major MAC challenges with beamforming antennas such as directional hidden terminals and deafness.

A. *RTS/CTS-based protocols*

In this section, we overview the directional MAC protocols that rely on the control packets in their operation. These protocols are inspired by the operation of the IEEE 802.11 DCF [31] due to its simple design and its wide spread usage. As discussed in Section I-C, the IEEE 802.11 DCF MAC is based on the concept of CSMA/CA. Small RTS/CTS control packets are exchanged prior to data transmission as part of the collision avoidance process.

Since the design of IEEE 802.11 MAC implicitly assumes an omni-directional antenna at the physical layer, researchers have looked into modifying its operation in order to exploit the potential benefits of beamforming antennas. A common design choice adopted by directional MAC protocols designers is the directional transmission of both the data and acknowledgment packets. However, there are several variations for how RTS/CTS packets are transmitted in order to deal with the challenges associated with beamforming antennas.

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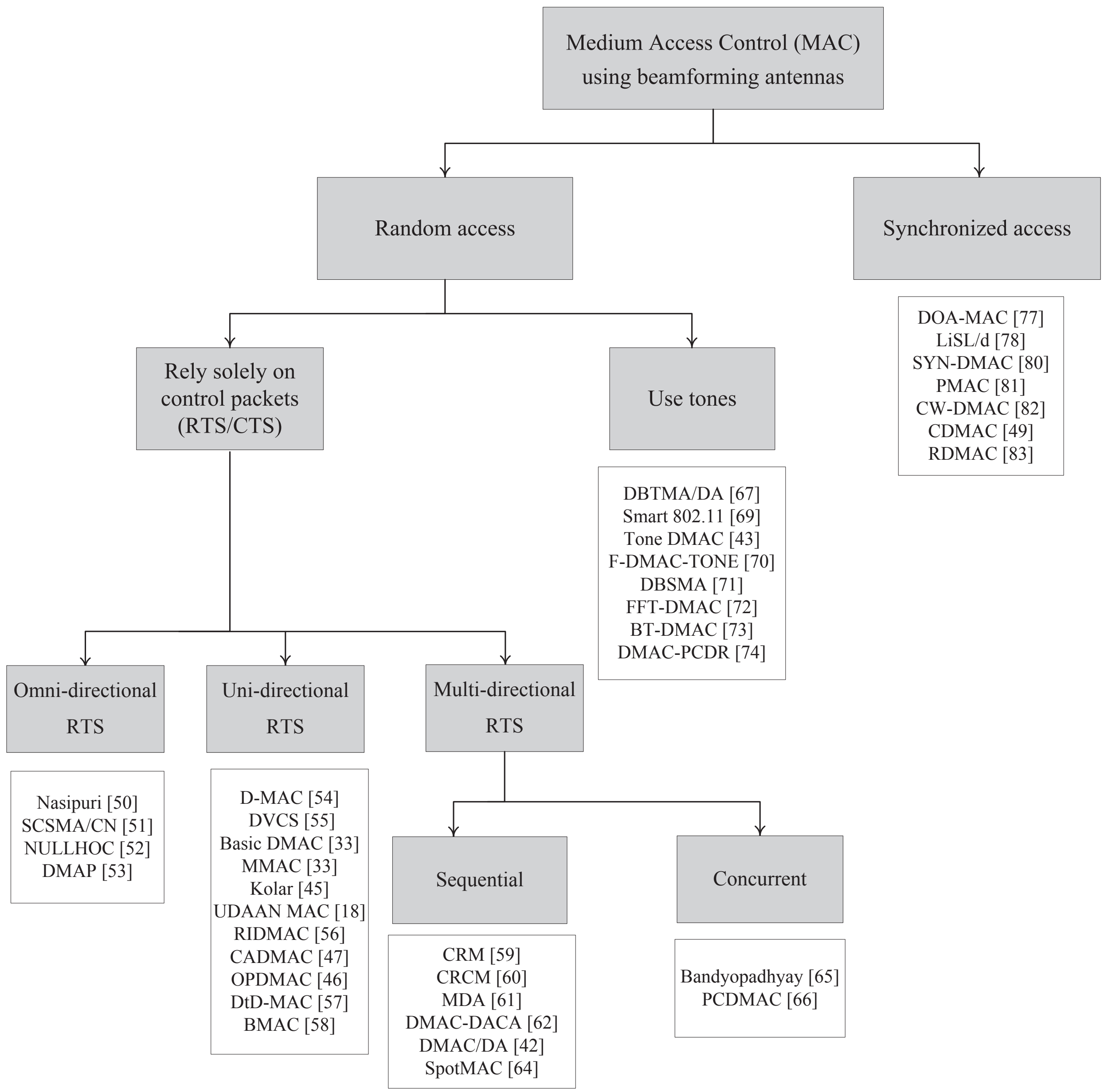

Fig. 9. A taxonomy of MAC protocols for wireless ad hoc networks with beamforming antennas.

1) Protocols that use omni-directional RTS:

Nasipuri et al. in [50] are among the first to investigate appropriate MAC protocols for multi-hop ad hoc networks with multiple antennas. They assume a very simple antenna model in which each node is equipped with multiple directional antennas forming non-overlapping beams that can collectively cover the entire plane. In this protocol, the authors propose that the data and its acknowledgement should be exchanged directionally in order to reduce the interference, thereby increasing the network throughput. Since the neighbors' location information may not be available at each node, especially with frequent node movements, they propose to send both RTS and CTS omni-directionally (ORTS/OCTS). Idle nodes listen to the surrounding medium in an omni-directional mode. When a node receives RTS for itself, it marks the beam from which it received the packet and responds with the omni-directional CTS. Upon receiving the CTS in response, the sender node also knows the direction of the intended receiver by noting the antenna beam that received the RTS packet with the maximum power. Each neighboring node that receive either the RTS or CTS, begin an off-the-air period for the duration specified in the RTS/CTS packet similar to IEEE 802.11 NAV. Although the reported results show an increase in the total throughput, the proposed protocol has some limitations. Since the channel reservation is done in an omni-directional mode, the communication range is limited by the omni-directional gain. Also, the spatial reuse is severely affected by the need to transmit the RTS/CTS omni-directionally.

Fahmy and Todd propose in [51] the Selective CSMA with Cooperative Nulling (SCSMA/CN) protocol for ad hoc network stations with adaptive antenna arrays. They propose to transmit all the packets omni-directionally and exploit the

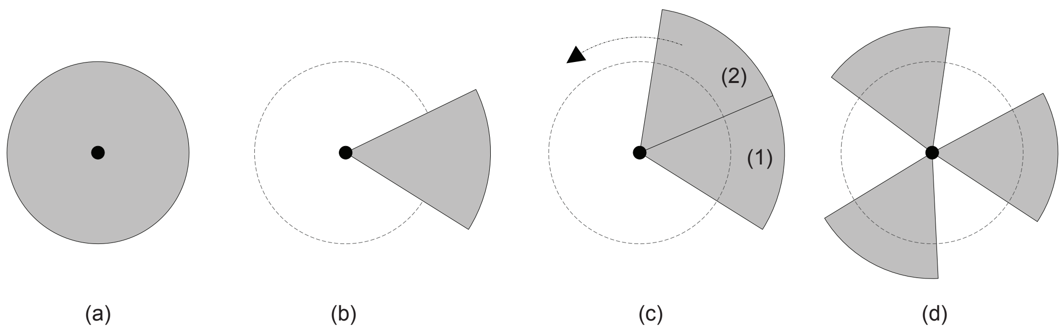

Fig. 10. The coverage range of different tranmission modes. (a) Omni-directional. (b) Uni-directional. (c) Multi-directional Sequential. (d) Multi-directional concurrent.

nulling capabilities of the receiving antenna to dynamically null potential future interfering packet transmissions. After the exchange of RTS/CTS packets, the source node along with all of the nodes that received the CTS packet simultaneously transmit a short Cooperative Nulling (CN) packet so that the beamforming weights at the destination node are calculated. The beamforming antenna attempts to maximize the desired signal and null those interfering transmissions. Following this, the destination node and all of the neighbors of the source node send CN packets in the same fashion so beamforming can be performed at the source node. Using this method, the reception of DATA and ACK packets is protected. SCSMA/CN employs selective CSMA in the sense that carrier sensing is used only if the ongoing packets are unprotected RTS/CTS packets. The presented results show capacity improvements over IEEE 802.11 and protocols with steered-beam antennas (no nulling capabilities). However, the performance of the protocol is limited to the available degrees of freedom of the antenna array.

In [52], Mundarath et al. also consider ad hoc networks with adaptive antenna arrays. They propose NULLHOC MAC protocol that can work in multi-path environments. In the NULLHOC protocol, the total bandwidth is divided into two orthogonal channels: a Data Channel (DC) and a Control Channel (CC). The access rights to the DC are obtained through three control packets transmitted omni-directionally on the CC. The source sends RTS packet that contains the antenna weights the node will use for receiving the ACK. If the destination is able to involve in this communication, it responds with CTS packet that contains the receiving and transmitting antenna weights. Then, the source reserves the access right to the DC by sending a Data-Send (DS) control packet that contains the antenna weights that the node will use while transmitting the DATA packet. Nodes that overhear either RTS, CTS, and/or DS record the details of the corresponding communication. When the nodes finish their communication, they have to wait for a fixed duration before they are allowed to initiate a new communication. This is done because these nodes may not be aware of new ongoing communications that started while they were communicating. The simulation results show that NULLHOC protocol provides up to a factor of two increase in throughput relative to IEEE 802.11. However, the throughput gains tend to saturate as the number of antennas increase due to increased control overhead.

In order to alleviate some of the problems facing medium access in the presence of beamforming antennas, Arora et.al propose a Directional MAC with Power control (DMAP) in [53]. They assume switched beam directional antenna with constant gain in the main lobe. They use separate control and data channels to solve hidden terminal problem due to unheard RTS/CTS messages at the expense of additional sophisticated hardware. Idle nodes listen omni-directionally to the data and control channels. When a node has a packet to send, it first sends the RTS omni-directionally with a common fixed power. Upon reception, the intended receiver estimates the Angle-of-Arrival (AoA), calculates a power control factor and encapsulates it in the Directional CTS (DCTS) sent to the source node. The source node uses the power control factor to calculate the sufficient transmit power needed to transmit the data packet. The power of the DCTS is scaled by a power-scaling factor that ensures that every potential interferer listening omni-directionally can hear the DCTS. Transmission of DCTS from minor lobes of the receiver at scaled power would also prevent potential interferers located in other directions. The authors claim this may resolve deafness as well. The simulation results show that DMAP improves the network throughput and reduces the energy consumption at the same time.

2) Protocols that use uni-directional RTS:

In [54], Ko et al. are the first to propose modifications for IEEE 802.11 DCF for ad hoc networks with directional antennas. They assume packets can be transmitted directionally or omni-directionally but packet reception can be done omni-directionally only. They propose the D-MAC protocol in which RTS is sent directionally (DRTS) towards the intended receiver to avoid unnecessary waiting time if one of the other directions is blocked. The basic assumption here is that each node knows the location information of each of its neighbors by means of Global Positing System (GPS) and each node transmits based on the direction derived from the physical location information. To avoid collisions at the receiver, omni-directional CTS is sent followed by directional DATA and ACK exchange. The simulation results show performance improvement due to the increase in the number of concurrent transmissions in the network. The results reported with this simple D-MAC have motivated a lot of research in the area.

Takai et al. propose in [55] the concept of Directional

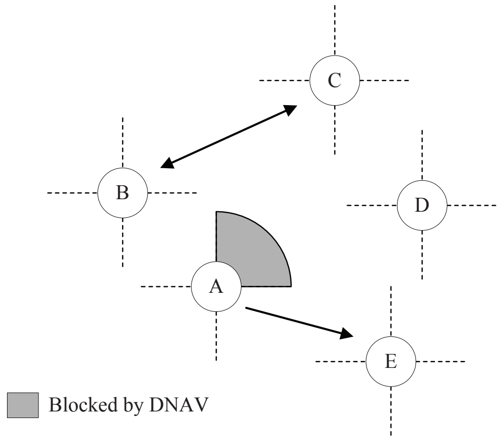

Fig. 11. A scenario to illustrate the DNAV mechanism.

Virtual Carrier Sensing (DVCS) for contention based MAC protocols to make effective use of directional antennas, while also providing interoperability with omni-directional antennas. Three primary capabilities are added to the original IEEE 802.11 for directional communication with DVCS. First, each node caches estimated AOAs from neighboring nodes when it hears any signal. Using the AOA cache, a source node can transmit DRTS without the need of additional hardware. Second, when a node receives an RTS from a neighbor, it adapts its beam pattern to maximize the received power and locks the pattern for the rest of the communication. Also, the source node locks its beam pattern after CTS reception. Beam locking prevents the nodes from being distracted by signals from other directions. The third and main capability to support DVCS is the use of directional NAV (DNAV). Each node maintains a DNAV table which can consist of multiple DNAVs each has its own direction, width and expiration time. If a node receives a packet from a certain direction, it needs to defer transmissions only in that direction in which other communication is in progress. DVCS determines that the channel is available for a specific direction when no DNAV covers that direction. Figure 11 illustrates the DNAV mechanism. Node A sets its DNAV for the beam towards node C to avoid interfering with the ongoing communication between node B and node C. Based on the concept of DVCS, node A is not allowed to transmit to node D but can freely communicate with node E. The simulation results show that directional communication with DVCS can increase the network capacity three to four times.

Choudhury et al. generalize the ideas in [54] and propose a directional version of IEEE 802.11 DCF MAC under the name of "Basic DMAC" in [33]. Basic DMAC is considered the benchmark for directional medium access control protocols. The authors assume that an upper layer is aware of the neighbors of a node and is capable of supplying the transceiver profiles required to communicate with each of these neighbors. The MAC layer receives these transceiver profiles along with the packet to be transmitted. In Basic DMAC, RTS/CTS/DATA/ACK are all transmitted directionally. An idle node listens to the channel omni-directionally but when it receives a signal, its antenna system is capable of determining the Direction-of-Arrival (DoA) of this incoming signal. The receiving node locks onto that signal and receives it. The physical carrier sensing and the backoff phase are performed while the antenna is in a directional mode. Moreover, Basic DMAC performs DVCS using DNAV tables similar to [55]. In the context of Basic DMAC, most of the MAC challenges with beamforming antennas have been identified. The authors evaluate the the tradeoffs associated with Basic DMAC. The results show that directional communication has the potential to improve the performance in terms of aggregate throughput and end-to-end delay. However, the performance mainly depends on the topology and flow pattern in the network. Random topologies with unaligned flows perform much better than aligned topologies since the spatial reuse can be exploited.

In order to exploit the benefit of highest communication range with beamforming antennas, communication should be possible between nodes that are neighbors only when both the transmitter and the receiver are in directional mode known as DD-neighbors. To support the full range extension, Choudhury et al. propose the MMAC protocol in [33]. The MMAC protocol aims to transmit the data packet over the longest possible hops. Since the idle nodes reside in omni-directional mode, they propose to propagate the RTS over multiple hops to inform the DD-neighbors to beamform towards the transmitter. In MMAC, the MAC layer receives a packet from an upper layer containing the DO-neighbor route to the next DD-neighbor. A special RTS packet contains the DO-neighbor route is transmitted to the next neighbor on that route. Nodes along that route forward the RTS according to the encapsulated route. The special RTS gets highest priority and is forwarded with a preceding backoff. Once the RTS is received by the DD-neighbor, CTS, DATA and ACK are transmitted over the single long hop. The simulation results show that MMAC outperforms Basic DMAC in terms of aggregate throughput. The limitations of this protocol include the long delay of RTS propagation and the risk of losing RTS over multiple hops. Also, the intermediate multi-hop paths for RTS propagation may not always be available.

Kolar et al. in [45] identify the HoL blocking problem associated with directional MAC protocols with beamforming antennas and FIFO queuing. The authors propose a new greedy queuing policy that can be implemented within the DMAC protocol. Based on the DNAV table, the authors propose using the least wait time to pick a packet for transmission. The simulation results show that the new queueing policy outperforms the existing one in terms of overall throughput and end-to-end delay. However, the proposed scheme does not consider the effect of deafness, which may cause the DNAV entries to be invalid.

In [18], Ramanathan et al. propose and implement a complete system for ad hoc networks with directional antennas called UDAAN. The UDAAN-MAC protocol has two features that differentiate it from previous approaches which are a new backoff mechanism and the integration of power control. The authors propose a new backoff algorithm (called forced idle) in which the duration and the window adjustment mechanism depend on the type of event causing the backoff, for example whether the event is busy channel, missing CTS, or missing ACK. If the channel is sensed busy, the contention window remains constant. If CTS is found missing, the value of the contention window is increased linearly. In case of the absence of an ACK, the increase of contention window is exponential. Upon receiving an ACK the value of the contention window decreases exponentially. On the other hand, the UDAAN-MAC protocol is a power-controlled MAC. The RTS is sent at the power indicated in the radio profile sent with direction by the forwarding layer. The RTS contains the transmitted power and the source node's current receiver threshold. Using this information the receiver can adjust the transmit power for the CTS packets. The DATA and ACK are power adjusted in a similar manner. The UDAAN-MAC protocol performs power-controlled DVCS. The DNAV table contains the duration, the direction and the allowed power. The last field indicates the power above which interference will occur in this direction. This direction may still be used to transmit if it is deemed that the intended transmission is sufficiently low power so as to not bother the busy nodes.

In [56], Takata et al. address the deafness problem by a Receiver-Initiated Directional MAC (RIDMAC) protocol. By default, the RIDMAC protocol is a sender-initiated DMAC in which all packets are transmitted directionally. If a transmitter noticed that there is another packet addressed to the same receiver in the head of its queue, it appends the size of the next packet to the header of the current data frame. Each node maintains a polling table and uses the information in the header of the data frame to update its table. After exchanging the DATA/ACK frames, the transmitter and the receiver check their own polling table whether potential deafness nodes exist or not. If more than one node is registered in the polling table, the least recently transmitting node is polled using a directional Ready-To-Receive (RTR) packet. Once RTR is received, the polled node, that was possibly suffering from deafness, transmits the data frame.

Choudhury and Vaidya propose a Capture-Aware Directional MAC (CADMAC) to address the MAC-layer capture problem in [47]. The CADMAC protocol aims to prevent a node susceptible to capture from operating in the omni-directional mode while idle. If the capture directions are known, the node forms a multi-beam pattern with main-lobes in directions other than the capture directions. CADMAC assumes time is divided into cycles with each cycle subdivided into ON and OFF durations. During the ON duration, the MAC layer records every received packet and the beam used to receive it. If a beam proves to be the receiver of only capture traffic, then the beam is black-listed. At the end of the ON duration, CADMAC decides to turn off all black-listed beams for the next OFF duration. In CADMAC, RTS/CTS/DATA/ACK are all transmitted directionally but the DVCS is modified to be capture-aware. When a node overhears an RTS or a CTS packet on a particular beam, CADMAC recommends the physical layer to turn off that beam for the proposed duration. The simulation results show improvements in throughput and end-to-end delay when compared to capture-unaware directional MAC protocols.

Bazan and Jaseemuddin propose an Opportunistic Directional Medium Access Control (OPDMAC) protocol in [46]. The OPDMAC protocol aims to grasp the transmission opportunities offered by beamforming antennas by eliminating the use of the over-conservative binary exponential backoff algorithm commonly used by most directional MAC protocols. In OPDMAC, the node is not forced to undergo idle backoff after a transmission failure but can rather take the opportunity of transmitting other outstanding packets in other directions. This novel mechanism minimizes the idle waiting time, increases the channel utilization, reduces the impact of the deafness and prevents the head-of-line blocking. After each successful transmission, the node is forced to remain idle for a random period of time called the Listening Period (LP) even if it has packets outstanding for transmission. During LP, the node listens in an omni-directional mode. The listening phase is needed to reduce the transmission failures due to deafness and to allow each node to update its channel state information. The simulation results show that OPDMAC outperforms other protocols in terms of throughput, delay and fairness.

In [57], Shihab et al. propose the Directional-to-Directional MAC (DtD-MAC) protocol that requires the beamforming antennas to operate in directional mode only. Instead of the omni-directional idle listening, DTD-MAC performs directional idle listening through continuous directional scanning to sense all directions. Using DtD-MAC, communication is possible with DD-neighbors and the hidden terminal problem due to asymmetry in gain is alleviated. However, the problem of deafness is aggravated and the probability of collision is increased. To address these issues, the sender transmits multiple DRTS packets towards the receiver (up to $2M$ DRTS where M is the number of beams) in order to capture the continuously scanning idle receiver. Moreover, DtD-MAC requires the carrier sensing to be greater than the DATA period to avoid collisions. The reported results show that the large control overhead and excessive delay limit the performance of the protocol when the number of beams increases.

Fakih et al. propose the BMAC protocol for ad hoc networks with adaptive antenna arrays in [58]. BMAC performs joint channel gathering and medium sharing. The channel acquisition is performed proactively through a periodic training sequence. When receiving this training sequence, the channel to the corresponding node is estimated and the channel coefficients and the node identifier are saved in a channel table. When there is data ready to be sent, the source node sends a Beamformed RTS (BRTS) to maximize the power at the destinations and make nulls towards the potentially interfering neighbors. When receiving the BRTS, the destination node calculates the exceeded power for further transmitted power correction and then it sends an Omni-directional CTS (OCTS) packet containing this correction factor. The results show that BMAC offers higher throughput than the conventional DMAC in multi-path fading environment.

3) Protocols that use multi-directional sequential RTS:

Korakis et al. propose the Circular RTS MAC (CRM) protocol in [59] which is the first protocol to employ the multi-directional sequential transmission of the RTS packet. The rationale is to inform all the neighbors about the upcoming communication using directional transmissions only and hence the protocol is able to achieve communication range extension as well. In CRM, the directional RTS is transmitted consecutively in a circular way until it scans all the area around the transmitter. The transmitter does not need to know

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the direction of the receiver. The duration field of the RTS packet is decreased by the RTS transmission period, every time an RTS packet is transmitted in the cycle. The receiver replies with a directional CTS after the conclusion of the circular RTS. Although CRM addresses some of the challenges facing medium access with beamforming antennas, the control overhead of the protocol is significantly large.

In [60], Jakllari et al. propose the Circular RTS and CTS MAC (CRCM) protocol that requires circular RTS and circular CTS packets prior to data transmission. Similar to CRM [59], the sender transmits circular directional RTS packet to all directions and the receiver sends a directional CTS towards the sender. Different from CRM, CRCM requires the receiver to circularly transmit CTS to inform un-aware neighbors about the imminent communication. Unaware neighboring nodes are those nodes that are in the coverage range of the receiver but not in that of the transmitter. The CRCM protocol protects the ACK reception from collision and hence handles the hidden terminal problem due to the asymmetry in gain at the expense of additional delay and large control overhead.

Gossain et al. in [61] propose a MAC protocol for Directional Antennas (MDA) that also employs the circular directional RTS/CTS transmissions. A key difference from the previous protocols is that both the sender and the receiver transmit the circular RTS and CTS packets simultaneously after they successfully exchange a single directional RTS/CTS. This somehow decreases the delay and ensures the circular control packets are only transmitted after the original RTS is successfully received. To avoid coverage overlap of the circular RTS/CTS, MDA employs a Diametrically Opposite Directional (DOD) procedure. It is obvoius that the MDA protocol needs a prior determination of the neighbors' location. This is performed using a directional neighbor table that is established during the route discovery process and maintained by overhearing packets at the MAC layer. In MDA, the overhead associated with the DOD RTS and CTS packets is optimized by sending these packets only through those directions where neighbors are found. Another new feature in MDA is the use of an Enhanced DNAV (EDNAV) mechanism that differentiate between collision avoidance and deafness avoidance. The EDNAV consists of two components: A DNAV table which is modified when the node receives the first directional RTS/CTS packets and a Deafness Table (DT) that is modified when a node receives a DOD RTS/CTS. The simulation results show that MDA performs better than IEEE 802.11, Basic DMAC and CRM protocols.

Li and Safwat propose a DMAC protocol with Deafness Avoidance and Collision Avoidance (DMAC-DACA) in [62]. In this protocol, the basic directional RTS/CTS exchange is followed by sweeping RTS/CTS counterclockwise to inform all the neighbors about the upcoming communication. Deafness is avoided using a deafness neighbor table that use the sweeping RTS/CTS to record the deafness duration of neighboring nodes. The authors also address another type of deafness that occurs due to the MAC-layer capture problem discussed is Section II-E. The location information, retrieved by GPS, is added to the RTS/CTS frames. Using this information, the node that receives RTS/CTS can update the record in its deafness neighbor table if any of the neighbors is in the coverage area of the upcoming transmission. The idea of allowing the reservation messages to carry information about the direction of transmission was first proposed in [63] to balance the tradeoff between spatial reuse and collision avoidance. The DMAC-DACA protocol performs collision avoidance through the DNAV mechanism. A node updates its DNAV if the transmitter or the receiver node is a DD-neighbor of this node.

In [42], Takata et al. propose a Directional MAC with Deafness Avoidance (DMAC/DA) to address the tradeoff between deafness avoidance using additional control frames and the excessive overhead associated with them. In DMAC/DA, Wait-To-Send (WTS) frames are transmitted by the transmitter and the receiver after the successful exchange of directional RTS and CTS similar to MDA [61]. However, WTS frames are transmitted only to the directions where potential transmitters are located in order to reduce the control overhead. The potential transmitter is selected either based on the history of previous communications or by means of explicit next packet notification if possible. The simulation results show that DMAC/DA outperforms circular directional MAC protocols, especially when the numbers of flows and beams are large.

In [64], Chin proposes the SpotMAC protocol that is based on the use of pencil (narrow) beams. Pencil beams provide high spatial reuse and constrain the hidden terminal problem to a linear topology. SpotMAC uses an additional inverted RTS/CTS exchange to overcome the hidden terminal problem. A node that wants to transmit to a downstream neighbor must first ask its upstream neighbor for permission using an RTS-req packet. The upstream neighbor blocks transmission in that direction and responds with a CTS-ACK packet. The sender node will then undergo DRTS/DCTS/DDATA/DACK dialog with its downstream neighbor. Finally, the node will send an ACK-ACK packet to unblock the upstream neighbor. The above mechanism is very conservative since the upstream neighbor may be deaf to the RTS-req packet and hence the communication towards the downstream neighbor is unnecessarily blocked. The author proposes to optimize SpotMAC by enabling the inverted RTS/CTS exchange only if there is persistence interference form upstream neighbor. The use of pencil beams increases the probability of deafness significantly. Whenever a failure is encountered, SpotMAC allows the sender to contend for the channel quickly by backoffing for a random period of time derived from a constant contention window. This reduces the effect of deafness. If the number of failures exceeds a threshold, the contention window is increased exponentially. The results show that pencil beams can achieve very high spatial reuse in non-deafness scenarios.

4) Protocols that use multi-directional concurrent RTS:

Among the early attempts to exploit the capabilities of beamforming antennas in adhoc networks, Bandyopadhyay et al. in [65] propose an adaptive MAC protocol for wireless ad hoc networks using a kind of adaptive antenna arrays known as ESPAR. The ESPAR antenna is capable of forming multiple directional beams as well as multiple nulls. Each node periodically collects its neighborhood information and forms an Angle-SINR Table (AST). The AST specifies the strength of radio connection from each node to its neighbors at different particular directions. Using these information, a Neighborhood-Link-State Table (NLST) at each node is formed to determine the best possible direction of communication with any of its neighbor. According to the proposed MAC protocol, idle nodes remain in a selective multi-directional listening with their nulls steered towards active communicating nodes. Also, RTS and CTS packets are sent selectively multi-directional to avoid interfering with known ongoing communications. Moreover, communicating nodes should steer nulls towards directions that are selectively ignored in the RTS/CTS transmission since nodes in those directions are not aware of this communication and may interfere with it.

In [66], Capone et al. propose a Power-Controlled Directional MAC (PCDMAC) protocol for wireless mesh networks with adaptive antennas. A novel feature in PCDMAC is the transmission of the RTS and CTS packets concurrently in multiple directions with a tunable power per direction that is adjusted to avoid interference with ongoing transmissions. This is done to inform the maximum number of neighbors of the new transmission. PCDMAC employs a DNAV that has an additional entry specifying the minimum power gain to reach an active node. After the successful exchange of RTS/CTS packets, the DATA and ACK packets are transmitted directionally with the minimum required power to reduce the interference and increase the spatial reuse. The simulation results show that both the throughput and fairness are improved using the PCDMAC protocol.

B. *Tone-based protocols*

In this section, we review the directional MAC protocols that use tones as part of their operation. A tone is a pure unmodulated sinusoidal wave transmitted at a particular frequency. Tones do not contain any information and hence do not need decoding but only need to be detected. In traditional ad hoc networks, tones (known as busy tones) are typically transmitted by busy nodes on separate dedicated channels (narrow bands) to inform all the nodes in their neighborhood about the ongoing transmission and hence protect them from collisions. The disadvantages of using tones are the bandwidth offset and the additional required hardware. In the context of wireless ad hoc networks with beamforming antennas, tone-based MAC protocols use tones together with RTS/CTS control packets to perform collision and/or deafness avoidance.

In [67], Huang et al. extends the idea of the Dual Busy Tone Multiple Access (DBTMA) [68] for the case of Directional Antennas (DBTMA/DA). In the proposed protocol, the channel is split into a data channel for data frames and a control channel for control frames with the two busy tones, transmit busy tone (BTt) and receive busy tone (BTr), are assigned two separate single frequencies in the control channel. When a node has data to send and it cannot sense BTr, the node transmits an omni-directional RTS since the receiver direction is not known. When the RTS is received and the receiver does not sense BTt, it responds with a directional CTS and turns on the directional BTr. Upon receiving the CTS, the source nodes transmits the data frame directionally and turn on the directional BTt until the data transmission is completed. The simulation results show that the network performance is improved by applying directional antennas to DBTMA and the performance is also better than that of the IEEE 802.11.

Singh and Singh propose Smart 802.11 protocol for ad hoc networks with adaptive antenna systems in [69]. When a node has a packet to send, it beamforms towards the intended receiver and transmits a short sender-tone to initiate communication. All idle nodes that receive the sender-tone beamform towards the sender and enter a random defer phase before transmitting the receiver-tone. When the sender receives the receiver-tone, it transmits its packet and waits for the receipt of an ACK. If there is no ACK, it enters backoff as in IEEE 802.11. Since the proposed protocol does not take care of hidden terminals, the authors rely on dynamically forming nulls towards interferes as well as the use of forward error correcting codes.

Choudhury and Vaidya propose ToneDMAC in [43] which specifically addresses the problem of deafness. In ToneDMAC, the backoff phase is performed in an omni-directional mode to alleviate the possibility of deadlocks and prolonged periods of deafness. ToneDMAC uses a tone-based notification mechanism that allows the neighbors of a node to distinguish congestion from deafness and react appropriately. After the data communication is over, both the sender and the receiver transmit out-of-band tones omni-directionally to inform their neighbors about the end of their deafness period. The neighboring node, that detects a tone, can identify the originator using the frequency and the duration of that tone. If the tone-receiving node is in a backoff phase waiting to communicate with a tone-originating node, it preempts its long backoff phase, initializes its contention window, and backs off with the minimum contention window. This reduces the unnecessary waiting time induced by using exponential backoff following transmission failures caused by deafness. The simulation results show that ToneDMAC is effective in mitigating the adverse effects of deafness.

In [70], RamMohan et al. address the problem of hidden terminals due to unheard RTS/CTS. They propose Fragmentation-based Directional MAC with TONE (F-DMAC-TONE) protocol that does not assume separate data and control channels. F-DMAC-TONE uses a combination of three features to solve the problem. When a node returns from directional to omni-directional mode, it undergoes a pause period before attempting transmission in another direction. This pause period increases the probability that the node learns of the true status of the channel. Ideally, the pause period must be long enough for an ongoing communication to finish. However, such a long pause period will lead to wasted resources if there was no ongoing transmission resulting in increased delay and degraded performance. To address this issue, a second feature in F-DMAC-TONE is the fragmentation of packets into smaller chunks transmitted individually but acknowledged collectively. The third feature is the use of a short TONE signal in between fragments to inform other nodes capable of causing collisions with the ongoing transmission. The simulation results show a significant decrease in the number of collisions due to the unheard RTS/CTS problem. However, a marginal improvement in the throughput and delay performance is achieved. This is mainly because the hidden terminal problem is not that critical when compared to the deafness problem.

Kulkarni and Rosenberg in [71] propose the Directional

Busy Signal Multiple Access (DBSMA) protocol that relies on the use of busy tones. In DBSMA, all the transmissions, receptions, and idle listening are performed directionally to achieve better connectivity. When a node is in an idle state, its directional antenna sweeps continuously to cover the whole region. When a node wants to transmit, the node transmits an out-of-band invitation signal which is long enough to capture an idle sweeping receiver. The invitation signal is followed by an RTS packet. The invitation signal locks sweeping antennas in one direction to receive the RTS and the intended receiver responds with a CTS packet. While in the reception mode, the receiver continuously transmits a busy signal to alleviate any possibility of collision from the hidden terminals. In DBSMA, if the sender senses a busy signal or busy channel in one direction, it may choose to communicate with another node in another direction. Moreover, DBSMA uses a separate backoff counter for each direction in order to adapt independently to the traffic conditions in different directions. The results show a performance improvement when compared to the CRM protocol [59]. However, the deafness problem is not addressed even though it is more severe with the directional idle listening proposed in DBSMA.

In [72], Li et al. propose the Flip-Flop Tone directional MAC (FFT-DMAC) protocol that utilize two pairs of tones to solve the deafness and hidden terminal problems. The first pair of tones are transmitted omni-directionally to announce the start and end of a communication, therefore, overcoming the deafness problem. The second pair of tones are sent directionally by the receiver towards the sender to solve the hidden terminal problem and to acknowledge the receipt of both RTS and DATA packets. In FFT-DMAC, each node maintains a ”deafness nodes” list and ”ongoing transmission nodes” list that are updated with the reception of tones. The simulation results show that FFT-DMAC outperforms Tone-DMAC in the number of successful packets received per second.

Dai et al. propose the Busy Tone Directional MAC (BT-DMAC) protocol for wireless ad hoc networks using directional antennas in [73]. BT-DMAC combines the use of two busy tones with the DNAV table [55] to solve the deafness and hidden terminal problems. When the transmission is in progress, the transmitter and the receiver turn on the transmitting busy tone BTt and the receiving busy tone BTr, respectively. Each tone is transmitted omni-directionally and is pulse-modulated with the node ID and the beam used for communicating. Any node hearing the busy tones learns the node IDs and the beam numbers from the tones and deduces whether the potential sending will interfere with the current transmission. The mechanism adopted by BT-DMAC increases the probability of successful data transmission.

In [74], Takatsuka et al. propose a Directional MAC protocol with Power Control and Directional Receiving (DMAC-PCDR) that mitigates the interference caused by directional hidden terminals and minor side lobes. The DMAC-PCDR protocol is based on the ideas proposed in [75] and [76] but is implemented with less control overhead. DMAC-PCDR employs directional idle receiving through the continuous rotation of the antenna beam while the node is idle. Directional receiving eliminates the hidden terminal problem due to asymmetry in gain and the interference caused by the reception through the side lobes. In order to enable an idle receiver to receive the signal, each control packet (RTS or CTS) is transmitted with a preceding tone that is long enough for an idle node to hear it. The node which receives the preceding tone stops the rotation and receives the packet. On the other hand, DMAC-PCDR improves spatial reuse of the wireless channel and extends the communication range through transmission power control. It has three access modes and each mode is selected depending on the information available about the receiver’s location.

V. Review of Synchronized Access Protocols

Most of the challenges facing the medium access are related to the location-dependent carrier sensing adopted by random access protocols. An alternative approach to address these issues to better exploit the benefits of beamforming antennas is the use of synchronized access protocols. Based on the availability of synchronization among competing nodes, conflict-free data transmissions occur according to a pre-determined time schedule. To build feasible schedules, nodes exchange control packets in a contention-based phase prior to the data transmission phase. Other mechanisms could also be done before data transmission including neighbor discovery and accurate beamforming. Synchronization could be performed network-wide or local based on the protocol requirements.

In [77], Singh and Singh propose the DOA-MAC protocol for nodes equipped with adaptive antenna array in ad hoc network. DOA-MAC is based on the slotted ALOHA with each slot broken into three minislots. In the first minislot, all transmitters transmit a simple tone towards their intended receivers. The receivers then run a DOA algorithm to identify the direction of the transmitters. Each receiver forms its directed beam towards the direction that has the maximum power and forms nulls in all the other identified directions. The second minislot is the packet transmission minislot. After receiving the packet, the receiver rejects the packet if it is not the intended destination. Otherwise, the receiver responds with an ACK in the last minislot. The simulation results show that DOA-MAC achieves higher throughput than the Basic DMAC [33].

Zhang proposes a TDMA-based directional MAC protocol called LiSL/d in [78] and evaluates its performance in [79]. The LiSL/d protocol performs link scheduling through pure directional transmission and reception. Time is divided into frames and each frame is divided into three sub-frames. The first sub-frame is devoted for neighbor discovery which is performed through scanning and three-way handshakes. During the neighbor discovery process, the two nodes detect each other and agree on a future time slot at which the two nodes would reassure the connection and see if they can make any reservations. Reassurance and reservation are made at the second sub-frame when the two nodes point towards each other with their beams and exchange another three-way handshakes. The third sub-frame is for data transmission. The simulation results show that the LiSL/d significantly outperforms DVCS [55] and IEEE 802.11 when jamming is present.

Wang et al. in [80] propose a directional MAC protocol termed SYN-DMAC for ad hoc networks with synchronization. The timing structure of SYN-DMAC consists of three time phases in each cycle which are: Random access, DATA and ACK phases. The random access phase serves as channel contention for data transmission. Multiple RTS/CTS packets are exchanged and multiple data transmissions can be scheduled. The later scheduled data transmissions should not collide with previous scheduled transmissions. Upon receiving the directional RTS, the receiver replies with directional CTS if it can engage in the communication session, or with directional negative-CTS if it has been already committed to another session or the beam towards the sender is blocked. Upon receiving the CTS, the intended sender sends a directional CRTS (confirmed RTS) to confirm the reservation. In the DATA phase, parallel contention-free data transmission is achieved and in the ACK phase parallel contention-free ACK packets are sent.

In [81], Jakllari et al. propose a synchronous Polling-based MAC (PMAC) protocol for mobile ad hoc netwoks with directional antennas. In this protocol, the time is divided into contiguous frames and each frame is divided into three segments: search, polling and data transfer. In the search segment, each node searches for new neighbors by transmitting or receiving pilot tones directionally. If two nodes discover each other, they exchange a list of the available slots in their corresponding polling segments. Once a pair of nodes agree upon a polling slot, they communicate in the same slot periodically, frame after frame, until they lose connectivity. The polling slot allows the nodes to schedule data transfers in the third segment of the frame and also allows them to keep track of the direction of each other that may change due to mobility. The communication in the polling slot is preceded by the exchange of control packets to avoid collisions. In the data transfer segment, multiple data transfers take place according to the schedules formed in the polling segment. In PMAC, RTS and CTS messages are used prior to the data transfer in order to detect possible rare collisions. The results show that PMAC achieves high channel utilization even in mobile scenarios.

In [82], Subramanian and Das propose the Contention Window Directional MAC (CW-DMAC) protocol to address the deafness and hidden terminal problems using single channel and single radio interface. The idea is to separate the transmission of control and data packets in time without the need of network-wide synchronization. Through contention, several RTS/CTS packets are exchanged omni-directionally within a control window duration. The size of the control window is defined by the sender of the first RTS/CTS packet. In CW-DMAC, the omni-directional RTS/CTS packets are overloaded with the beam index in which the actual DATA/ACK transmission will happen directionally. This information will help any other node in the same neighborhood to exchange RTS/CTS within the same control window if they do not interfere with the previously reserved transmissions. When a node receives an RTS but cannot send the CTS due to beam blockage, it instead sends a Negative CTS (NCTS) to inform the sender that the data transmission cannot happen without interfering with the already reserved transmissions. Upon receiving the NCTS, the sender sends a TC (Transmission Cancel) packet omni-directionally to inform neighbors that the current transmission has been canceled. At the end of the control window, the directional DATA packets are transmitted simultaneously followed by concurrent transmission of ACK packets. The simulation results show that CW-DMAC improves the network throughput when compared to Basic DMAC.

Wang et al. in [49] propose the Coordinated DMAC (CDMAC) protocol that also requires local synchronization only. The timing structure of CDMAC consists of a contention-period in which control packets are exchanged followed by two contention-free periods for parallel DATA and ACK transmissions. Different from CW-DMAC, CDMAC use three control packets (RTS/CTS/confirmed-RTS) for channel reservation, all transmitted omni-directionally. CDMAC does not require the neighbor directions to be known a priori. The beam indices to be used to transmit DATA/ACK packets are included in the CTS and confirmed-RTS packets. The master node-pair, those who first win the channel contention, specify the duration of the contention and contention-free periods. With the contention-period, multiple data transmissions can be scheduled as long as the new reservations take into consideration the previous ones. In addition to the beam blocking, the CDMAC protocol considers interference caused by side lobes. In CDMAC, the frame formats of both RTS/CTS resemble the IEEE 802.11 frames with DMAC extension to ensure compatibility. The simulation results show that CDMAC outperforms IEEE 802.11 and the Basic DMAC protocol.

In [83], Chang et al. propose Reservation Directional MAC (RDMAC) for multi-hop wireless networks with directional antennas. The RDMAC protocol operates in sessions with each session comprising a reservation period and a transmission period. In the reservation period, the first node to transmit the RTS defines the start and end time of the transmission period. Each node-pair exchanges four control packets. First, omni-directional RTS/CTS packets are exchanged so the node-pair can discover the beams to be used for directional transmission. The neighboring nodes that receive the ORTS/OCTS packets, estimate the direction of arrival and point their antennas towards the sender/receiver to receive the remaining control packets. The reserving nodes transmit directional RTS/CTS packets so the neighbor nodes can update their DNAV taking into consideration any possible interference caused by minor lobes. Similar to [82] and [49], the reserving nodes must avoid initiating a transmission if this transmission conflicts with an already scheduled transmission. However, in RDMAC, if the destination of the head-of-line frame is busy in this session, the transmitter will search for a frame destined to the next non-busy receiver in the queue and hence avoiding the head-of-line blocking problem. The simulation results show that RDMAC outperforms CRM [59] in terms of throughput and delay.

VI. Comparisons

In the previous sections, we classified the existing MAC approaches for wireless adhoc networks with beamforming antennas and briefly discussed the protocols most representative of each class. In this section, we provide a comparative summary of the reviewed MAC protocols. Table I and Table II summarize the main features of the MAC protocols. The features of each protocol include the transmission of the basic protocol packets, the antenna mode during idle listening, the transmission of tones (if applicable), the backoff mechanism, the number of channels required, whether power control is employed or not, the type of the antenna and its capabilities, the supported communication range, how the MAC protocol acquires beamforming information and finally the main beamforming-related MAC challenges addressed by each protocol.

We can observe that almost all the proposed MAC protocols exchange DATA and ACK packets directionally to exploit the benefits of beamforming antennas. However, there are many variations in the transmission of RTS/CTS packets. The omni-directional transmission of RTS/CTS is beneficial to inform all neighbors about imminent communication and hence, reduce the instances of deafness and hidden terminal problem significantly. However, this conservative reservation scheme is not commonly used since it comes on the expense of the spatial reuse and communication range extension. To enable more simultaneous transmissions and extended range communications, several MAC protocols have used directional RTS/CTS handshakes assuming the beamforming information is known a priori which is indeed a challenging task. Moreover, this aggressive reservation scheme lends itself to deafness and directional hidden terminal problems. To address the fundamental tradeoff between omni-directional RTS/CTS and uni-directional RTS/CTS, some MAC protocols rely on the multi-directional RTS/CTS for channel reservation. With switched beam antennas, the control packets are transmitted circularly, one direction after the other, to allow for collision and/or deafness avoidance. The main drawback of this scheme is its large control overhead that can sometimes offset the benefits [44]. Few MAC protocols transmit the RTS/CTS packets concurrently to multiple directions using sophisticated adaptive antenna array systems that can form multi-beam radiation patterns.

Some directional MAC protocols use tones instead of the circular RTS/CTS packets to address the MAC challenges. Tones are commonly transmitted on a dedicated control channel which offsets the bandwidth. Tones are usually transmitted directionally to protect ongoing communication from collisions but transmitted omni-directionally to announce the start and/or the end of a communication to handle the deafness problem. In the MAC protocols that employs directional idle listening, tones are used prior to packet transmission in order to capture the rotating antenna beam of the idle receiving node. The drawback of tone-based protocols is the additional required hardware that increases cost and complexity.

Another approach to handle the MAC challenges is to perform synchronized access rather than random access. By separating the transfer of control and data packets in time, the location-dependent carrier sensing problem are alleviated. Time is divided into frames with the data transfer sub-frame is preceded with a contention-based reservation sub-frame(s). Early synchronized directional MAC protocols assume the availability of network-wide synchronization which is challenging to achieve in multi-hop wireless networks. Few recent synchronized MAC schemes are based on local synchronization. The first winning node-pair in the contention-based period decide the size of control and data sub-frames. Although this approach alleviates the complexity of global synchronization, setting the size of the control and data sub-frame is a critical tradeoff between under-utilization and poor spatial reuse. Moreover, communication between certain neighboring node-pair may not be properly scheduled if each of them lies in a different synchronized zone.

Although the binary exponential backoff (BEB) mechanism was originally designed for networks with omni-directional antennas, we can observe from Table I that most directional MAC protocols have not altered the backoff mechanism. In [84], it was shown that the BEB is not suitable to be used in the presence of beamforming antennas since it limits the possible spatial reuse and aggravates the deafness problem. Some protocols proposed more aggressive backoff mechanism such as constant contention window, separate backoff for each beam and event-based contention window size. With the underlying beamforming antennas in mind, an opportunistic backoff mechanism is proposed in [46] which does not require the node to undergo idle backoff following a transmission failure but rather can exploit this time period to send another packet in another direction.

Integrating power control with beamforming antennas promises significant additional gains [10]. However, the majority of existing directional MAC protocols employ fixed power as shown in the last column of Table I. By the use of link power control, further enhancements could be achieved in terms of network capacity and power consumptions. The DATA transmission power is adjusted based on the information collected using the RTS/CTS packets. In [18], power control is also incorporated in the DNAV. The transmission power of the control packet could also be tuned to inform more neighbors about the imminent communication as proposed in [53], [66].

Throughout the literature, different beamforming antenna types have been used in wireless adhoc networks. Switched-beam antennas are the most used since they are the simplest type and hence facilitating the development of directional MAC protocols. However, some MAC protocols are proposed based on the use of steered beam antennas. In general, protocols that employ uni-directional transmissions only can be easily used with both switched beam and steered beam systems. As shown in table II, few MAC protocols are developed to exploit the nulling capabilities of beamforming antennas. Additional control packets and/or training sequences are exchanged so the nulls can be appropriately formed.

The existing MAC protocols for wireless adhoc networks with beamforming antennas differs in terms of the supported communication range for a specific transmission power. As discussed in section II-D, each node may have three types of neighbors: OO, DO and DD neighbors. However, the features of the MAC protocol decide the possible type of neighbors. A MAC protocol can only allow communication with OO-neighbors if the first packet (usually RTS) is transmitted omni-directionally. In such case, spatial reuse is limited but the gain could be achieved in terms of power savings. If the sending node knows the beamforming information needed to send the RTS packet directionally, the communication range is extended. However, if the MAC requires the idle node to reside in an omni-directional mode, only DO-neighbors can be considered. We can observe from Table II that the DO-communication range is common among the surveyed MAC

TABLE I
DIRECTIONAL MAC PROTOCOL FEATURES COMPARISON PART 1/2

Protocol	Packet transmission			Idle Listening	Tones transmission	Backoff		Channel(s)	Power control
	RTS	CTS	DATA/ACK			Antenna	Mechanism		
Nasipuri [50]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	No
SCSMA/CN [51]	Omni	Omni	Omni	Omni	-	Omni	BEB	Single	No
Nullhoc [52]	Omni	Omni	Dir	Omni	-	Omni	Constant CW	Multi	No
DMAP [53]	Omni	Dir	Dir	Omni	-	Omni	BEB	Multi	Yes
D-MAC [54]	Dir	Omni	Dir	Omni	-	omni	BEB	Single	No
DVCS [55]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
Basic DMAC [33]	Dir	Dir	Dir	Omni	-	Dir	BEB	Single	No
MMAC [33]	Dir (along DO route)	Dir	Dir	Omni	-	Omni	BEB	Single	No
Kolar [45]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
UDAAN D-MAC [18]	Dir	Dir	Dir	Omni	-	Omni	Event-based CW	Single	Yes
RIDMAC [56]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
CADMAC [47]	Dir	Dir	Dir	Multi-dir	-	Multi-dir	BEB	Single	No
OPDMAC[46]	Dir	Dir	Dir	Omni	-	Dir	Opportunistic	Single	No
DtD-MAC [57]	Dir	Dir	Dir	Dir	-	Dir	2 constant CW (Alternate)	Single	No
BMAC[58]	Dir	Omni	Dir	Omni	-	Omni	BEB	Single	Yes
CRM [59]	Multi-dir sequential	Dir	Dir	Omni	-	Omni	BEB	Single	No
CRCM [60]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
MDA [61]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
DMAC-DACA [62]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
DMAC/DA [42]	Multi-dir sequential	Multi-dir sequential	Dir	Omni	-	Omni	BEB	Single	No
SpotMAC [64]	Multi-dir sequential	Dir	Dir/Multi-dir sequential	Omni	-	Omni	BEB	Single	No
Bandyopadhyay [65]	Multi-dir concurrent	Multi-dir concurrent	Dir	Multi-dir	-	-	-	Single	No
PCDMAC[66]	Multi-dir concurrent	Multi-dir concurrent	Dir	Omni	-	Omni	BEB	Single	Yes
DBTMA/DA [67]	Omni	Dir	Dir	Omni	dir/dir	Omni	MILD	Multi	No
Smart 802.11b[69]	-	-	Dir	Omni	dir/dir	Omni	BEB	Single	No
Tone DMAC [43]	Dir	Dir	Dir	Omni	omni	Omni	prempted BEB	Multi	No
F-DMAC-TONE [70]	Dir	Dir	Dir	Omni	dir	Omni	BEB	Single	No
DBSMA [71]	Dir	Dir	Dir	Dir	dir/dir	Dir	BEB for each beam	Multi	No
FFT-DMAC[72]	Dir	-	Dir	Omni	omni/dir	Omni	BEB	Multi	Yes
BT-DMAC [73]	Dir	Dir	Dir	Omni	omni/omni	-	-	Multi	No
DMAC-PCDR [74]	Dir	Dir	Dir	Dir	dir	-	-	Single	Yes
DOA-MAC[77]	-	-	Dir	-	dir	-	-	Single	No
LiSL/d [78]	-	-	Dir	-	-	-	-	Single	Yes
SYN-DMAC [80]	Dir	Dir	Dir	Omni	-	Omni	BEB	Single	No
PMAC [81]	Dir	Dir	Dir	Dir	dir	-	-	Single	No
CW-DMAC [82]	Omni	Omni	Dir	Omni	-	-	-	Single	No
CDMAC [49]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	Yes
RDMAC [83]	Omni	Omni	Dir	Omni	-	Omni	BEB	Single	No

protocols. To exploit the full range extension benefit (DD-range), the MAC protocol should be able to allow the sender and receiver to point towards each other directionally before communication starts. This could be achieved using synchronization or by performing idle listening with a rotational beam.

The early proposals for directional MAC have aimed to exploit the benefits of beamforming antennas through the direct adaptation of existing protocols such as IEEE 802.11, Aloha and BTMA. Later on, several unprecedented beamforming-related challenges have been identified and the directional MAC designers have focused on proposing mechanisms to solve these new problems. From Table II, it is obvious that deafness and directional hidden terminal problems are the most addressed problems. Different mechanisms have been proposed to cope with these problems on the expense of benefits offset and/or additional complexity. In Table III, we compare the advantages and disadvantages of the different directional MAC design choices proposed in the literature.

TABLE II
DIRECTIONAL MAC PROTOCOL FEATURES COMPARISON PART 2/2

Protocol	Antenna used			Neighbors		MAC challenges addressed			
	Type	Beam(s)	Nulling	Range	Beamfoming Information	Deafness	Hidden Terminals	HoL	MAC-layer Capture
Nasipuri [50]	Switched	Single	No	OO	DoA	No	No	No	No
SCSMA/CN [51]	Adaptive array	Single	No	OO	-	No	No	No	No
Nullhoc [52]	Adaptive array	Single	Yes	OO	Exchange antenna weights	No	Yes	No	No
DMAP [53]	Switched	Single	No	OO	AoA	Yes	Yes	No	No
D-MAC [54]	Switched	Single	No	OO	GPS	No	No	No	No
DVCS [55]	Adaptive array	Single	No	DO	AoA cache	No	No	No	No
Basic DMAC [33]	Adaptive array	Single	No	DO	Upper layer	No	No	No	No
MMAC [33]	Adaptive array	Single	No	DD	Upper layer	No	No	No	No
Kolar [45]	Switched	Single	No	DO	AoA cache	No	No	Yes	No
UDAAN D-MAC [18]	Switched	Single	No	DO	periodic heartbeats	No	No	No	No
RIDMAC [56]	Switched	Single	No	DO	Assumed available	Yes	No	No	No
CADMAC [47]	Switched	Multiple	No	OO	Assumed available	No	No	No	Yes
OPDMAC[46]	Switched	Single	No	DO	Upper layer	Yes	Yes	Yes	No
DtD-MAC [57]	Switched	Single	No	DD	AoA cache	Yes	Yes	No	No
BMAC[58]	Adaptive array	Single	Yes	OO	Periodic Training Sequence	Yes	Yes	No	No
CRM [59]	Switched	Single	No	DO	DoA	Yes	Yes	No	No
CRCM [60]	Switched	Single	No	DO	DoA	Yes	Yes	No	No
MDA [61]	Switched	Single	No	DO	Upper layer	Yes	Yes	No	No
DMAC-DACA [62]	Switched	Single	No	DO	GPS	Yes	Yes	No	No
DMAC/DA [42]	Switched	Single	No	DO	Assumed available	Yes	Yes	No	No
SpotMAC [64]	Adaptive array	Single	Yes	DO	AoA cache	Yes	Yes	No	No
Bandyopadhyay [65]	Adaptive array	Multiple	Yes	OO	Periodic updates	No	Yes	No	Yes
PCDMAC[66]	Adaptive array	Multiple	No	DO	Assumed available	Yes	Yes	No	No
DBTMA/DA [67]	Switched	Single	No	OO	DoA	No	Yes	No	No
Smart 802.11b[69]	Adaptive array	Single	Yes	DO	Assumed available	No	No	No	No
Tone DMAC [43]	Switched	Single	No	DO	Assumed available	Yes	No	No	No
F-DMAC-TONE [70]	Switched	Single	No	DO	AoA cache	No	Yes	No	No
DBSMA [71]	Switched	Single	No	DD	Periodic updates	No	Yes	Yes	No
FFT-DMAC[72]	Adaptive array	Single	No	DO	Assumed available	Yes	Yes	No	No
BT-DMAC [73]	Switched	Single	No	DO	AoA cache	Yes	Yes	No	No
DMAC-PCDR [74]	Adaptive array	Single	No	DD	GPS	No	Yes	No	No
DOA-MAC[77]	Adaptive array	Single	Yes	DO	Assumed available	No	No	No	No
LiSL/d [78]	Adaptive array	Single	No	DD	Scanning phase	No	No	No	No
SYN-DMAC [80]	Switched	Single	No	DO	Assumed available	Yes	Yes	Yes	No
PMAC [81]	Adaptive array	Single	No	DD	Search phase	Yes	Yes	No	No
CW-DMAC [82]	Switched	Single	No	OO	Assumed available	Yes	Yes	No	No
CDMAC [49]	Switched	Single	No	OO	AoA cache	Yes	Yes	No	No
RDMAC [83]	Switched	Single	No	OO	DoA	Yes	Yes	Yes	No

VII. DISCUSSIONS AND FUTURE WORK

A. Discussions

In the previous sections, we surveyed numerous directional MAC protocols for wireless adhoc networks and discussed their design choices, operation, benefits and tradeoffs. In this section, we discuss few issues that are closely related to medium access with beamforming antennas.

TABLE III
COMPARISON BETWEEN DIFFERENT MAC DESIGN CHOICES FOR BEAMFORMING ANTENNAS

Category	Design Choice	Advantages	Disadvantages
RTS transmission	Omni-directional RTS	– Informs neighbors in all directions about imminent communication – Reduces instances of deafness and directional hidden terminal problems	– Low Spatial reuse – Short Communication Range
	Uni-directional RTS	– Increases Spatial reuse – Extends communication range or decreases transmission power	– Increases instances of deafness and directional hidden terminal problems – Beamforming information is needed a priori
	Multi-directional Sequential RTS	– Eliminates the asymmetry of gain problem – Reduces instances of deafness significantly	– Large control overhead – Large delay
	Multi-directional concurrent RTS	– Reduces instances of deafness and directional hidden terminal problems without jeopardizing the spatial reuse	– Requires complex antenna systems
Tones	Using Tones	– Solves hidden terminal problem – Can be used to address deafness	– Requires complex hardware – Usually needs dedicated control channel
Synchronized Access	Global Synchronization	– Solves most challenges due to conflict-free scheduling	– Complex and not practical in wireless ad hoc networks
	Local Synchronization	– Simple to form conflict-free schedules	– Short Communication Range – Imperfect if nodes lie in different synchronized zones
Idle Listening	Omni-directional	– No deafness when the receiver is idle	– Cannot achieve full communication range extension – Susceptible to MAC- layer capture
	Directional	– Full communication range extension	– Increases instances of deafness
Backoff mechanism	BEB	– Very popular (IEEE 802.11 standard)	– Increases impact of deafness and HoL blocking
	Constant CW	– Reduces impact of deafness and HoL blocking	– Increases collision and may result in deadlocks
	Opportunistic	– Minimizes impact of deafness and HoL blocking	– Works well with multiple flows at each node
Antenna type	Switched beam	– Simplicity	– Less flexible and no guarantee on maximum gain – Does not work well in multipath environment
	Adaptive array	– Provides maximum gain and nulling capability	– High Complexity and higher power consumption

1) *Directional Neighbor Discovery:*

Although the neighbor discovery process does not lie within the domain of the MAC layer, it has a great impact on its operation. In the presence of beamforming antennas, neighbor discovery is not limited to identifying the nodes within the communication range but the beamforming information is also essential. The beamforming information is usually decided based on either the relative position of the nodes [54] or the Angle-of-Arrival (AoA) estimation [55]. The location-based beamforming requires additional hardware such as GPS and implicitly assumes that a Line-of-Sight (LOS) exists between the nodes. Since this assumption may not be true in multi-path environments, the AoA criterion is usually preferred. The neighbor discovery mechanism can be synchronous [78], [81], [85], [86] or asynchronous [87], [88]. In synchronous neighbor discovery algorithms, a node chooses to transmit or receive at the beginning of each time slot. On the other hand, with asynchronous mechanisms, a node alternates between transmitting and receiving each for a random time interval. According to the broadcasted information, the neighbor discovery algorithms can be classified into two groups: direct-discovery algorithms in which a nodes discovers its neighbor only when it successfully hears a transmission from that neighbor and gossip-based discovery algorithms in which nodes gossip about each others' location information [87].

2) *Staleness of Beamforming Information:*

Unless the beamforming information is collected on a per-packet basis as in [58], [59], [89], such information is obtained in advance and recorded in look-up tables. Due to the mobility of the nodes, staleness of beamforming information could occur when the gap between the cached and the actual beamforming information is larger than the beamwidth [90]. If a receiver moves out from the coverage zone of a transmitter's beam to a zone covered by another beam, packet transmissions addressed to this receiver fail. In such case, it is important to deal with these transmission failures at the MAC layer before being reported to the network layer. In [55], if a transmitter fails to get the CTS response back from the receiver after four consecutive directional transmissions of the RTS frame, it is assumed that the corresponding AOA information is out-of-date and subsequent RTS frames are sent omni-directionally. In [91], if a packet transmission fails for three consecutive times, it is retransmitted over adjacent beams as well. The authors in [91] propose the aforementioned location tracking phase to be performed at the MAC layer in order to avoid unnecessary initiation of a costly route recovery phase. This cross-layer interaction between MAC and routing layers enhances the performance of wireless adhoc networks with beamforming antennas.

3) IEEE 802.11 Compatibility:

Due to the vast spread of IEEE 802.11 wireless cards, the incremental deployment of beamforming antenna-based wireless devices is inevitable. Hence, it is crucial for the directional MAC protocol to be backward compatible with the IEEE 802.11 standard. Unfortunately, most of the MAC protocols proposed for adhoc networks with beamforming antennas lack this important feature. The incompatible directional MAC protocols include those that require synchronization between nodes, rely on out-of-band tones, use different RTS/CTS packet formats or transmit multi-direction sequential RTS/CTS packets which result in antenna-dependent inter-frame spacing.

B. Future Work

Despite the rich literature in the area of medium access control in multi-hop wireless networks with beamforming antennas, several important issues still need to be addressed.

1) QoS-aware Directional MAC:

To cope with the pressing need of running content-rich multimedia applications and real-time services, Quality of Service (QoS) support has become a vital component in today's wireless networks. Although utilizing beamforming antennas in multi-hop wireless networks has proven to provide a significant increase in the network performance, mainly in terms of throughput and delay, little attention has been devoted to explore its effectiveness in providing QoS guarantees especially at the MAC layer [92]. Most existing QoS-aware directional MAC protocols are limited to single-hop wireless networks [93], [94].

Both intra-node and inter-node scheduling should be considered in the design of QoS-aware directional MAC protocols for wireless ad hoc networks. Class-based queueing, which is known to be an effective approach for QoS-aware intra-node scheduling, could significantly benefit from the channel spatial separation provided by beamforming antennas [95]. However, inter-node scheduling and channel reservation become a more challenging task that need to be carefully addressed.

2) Analytical Modeling:

The majority of the performance evaluations for MAC protocols in multi-hop wireless networks with beamforming antennas were done via discrete event simulations. The main drawback of this evaluation tool is the huge simulation time than limits the scalability of the considered scenarios. Although there are several analytical models for the IEEE 802.11 DCF MAC with the implicit assumption of using omni-directional antennas, very few attempts were made towards the analytical modeling of directional MAC protocols [96]–[99]. These attempts have relied heavily on the use of Markov chains with simplistic assumptions regarding the antenna radiation pattern, the physical parameters of the channel and/or the traffic characteristics. Moreover, some antenna-specific MAC challenges, such as deafness, are usually ignored in most of the existing models. Further research need to be conducted to develop more accurate and generic analytical models for MAC protocols in multi-hop wireless networks with beamforming antennas.

3) MAC with Heterogenous Antennas:

Most of the proposed MAC protocols for multi-hop wireless networks with beamforming antennas assume that all the nodes in the network have homogenous antennas. The considered antenna homogeneity includes the antenna type, number of beams, radiation pattern and sometimes a beamforming reference direction. However, there may exist real-life scenarios in which nodes within the same network are equipped with heterogenous antennas [100]. Based on the experience gained from the existing directional MAC protocols surveyed in this paper, heterogeneity-aware directional MAC protocols could be designed.

4) Fairness:

An important characteristic of a MAC protocol is to provide fair channel access among competing nodes [101]. However, the existing trend focuses more on the design of MAC protocols that optimize other performance metrics such as throughput and delay. With the goal of enhancing the spatial reuse, these MAC protocols usually result in unfair medium access [102]. Achieving fairness in wireless ad hoc networks with beamforming antennas is a challenging task that needs further research work.

VIII. Conclusion

In this article, we presented a comprehensive survey of MAC protocols in wireless ad hoc networks with beamforming antennas. The directional MAC protocols were designed to exploit the benefits of beamforming antennas and overcome the beamforming-related challenges. We enlisted and discussed the main challenges facing MAC protocols in wireless ad hoc networks with beamforming antennas. We developed taxonomy of the existing MAC approaches and using that we discussed different basic design choices along with their associated tradeoffs. A common design choice is to exchange DATA and ACK packets directionally; however, there are many variations in the transmission of RTS/CTS packets. The omni-directional transmission of RTS/CTS reduces the instances of deafness and hidden terminal problem at the expense of reduced spatial reuse and shorter communication range. On the other hand, uni-directional RTS/CTS handshakes achieve higher spatial reuse and longer communications range but aggravate the critical problem of deafness. To address this trade-off, the control packets (e.g. RTS and CTS) are sometimes transmitted circularly in all directions one at a time to avoid collision and/or deafness. The main drawback of this scheme is its large control overhead that can offset the benefits. Some directional MAC protocols use tones to mitigate deafness and/or directional hidden terminal problems. Tones are commonly transmitted on a dedicated control channel which requires extra bandwidth. Moreover, tone-based protocols require additional hardware that increases cost and complexity. A different MAC design choice is for the channel access to rely on synchronized access rather than random access. By separating the transfer of control and data packets in time, the location-dependent carrier sensing problems are alleviated. However, achieving synchronization in multi-hop wireless networks offers a new set of timing related challenges. Despite the rich literature in this emerging field of MAC protocol design for beamforming antennas, we investigated several opportunities for possible future work including the need for QoS-aware directional MAC protocols, accurate analytical modeling and MAC protocols for wireless ad hoc networks with heterogeneous antennas.

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