MAC Protocols for Ad Hoc Networks with Directional Antennas : Overview and Comparison

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Abstract

In recent years, the employment of directional antennas in ad hoc networks has significantly increased. MAC protocols for ad hoc networks with directional antennas have the potentiality of spatial reuse, large coverage range and network capacity, which mitigates the negative effects associated with omnidirectional antenna systems. However, they suffer from some issues such as hidden terminal problems, deafness, neighbor discovery, flaws with directional carrier sensing, etc. In this paper, we have surveyed the MAC protocols for ad hoc networks with directional antennas, which have been published in the literature, and compared them qualitatively in terms of major characteristics and network performances.

1. Introduction

Typically, an ad hoc network comprises of wireless nodes that are capable of self organization. The links in ad hoc networks are usually temporary and wireless, and the link quality changes dynamically. Recently, the practical use of ad hoc networks has been realized in the fields of emergency services, vehicular communication, traffic monitoring, etc. In the design of MAC protocols for ad hoc networks, most of the research in the past was based on the use of omnidirectional antennas [1,27]. However, the limitations such as limited channel bandwidth, lower throughput, and limited energy supply [14,27] in ad hoc networks cannot be overcome by the use of omnidirectional antennas. Ad hoc networks with directional antennas are gaining popularity since they can achieve higher gain which implies the increase in transmission range. With the increase in transmission range, the number of hops and delay are decreased. This ensures increased network lifetime through lower power consumption. Also, spatial reuse is increased by the reduced interference caused by narrower beam width. This results in higher throughput [1,14,18,23].

The MAC protocols in ad hoc networks with directional antennas are being actively studied even a decade after its introduction, thanks to the various advantages of directional antennas over omnidirectional antennas. However, the use of MAC protocols using directional antennas suffer from some issues such as hidden terminal problems, deafness, neighbor discovery, HoL(Head of Line) blocking problem, flaws with directional carrier sensing, change in beam-forming pattern due to antenna rotation, etc [1,27]. Various MAC protocols using directional antennas have been proposed in order to minimize the effects of these issues [1,9,14,22-24,27]. However, works on survey and comparisons of MAC protocols using directional antennas can be found until the year 2006 [20,25]. Lot of protocols has been proposed after that and we cannot find any analytical study of those protocols. In our paper, we have tried to incorporate some efficient protocols from inceptive period till the recent years. In this paper, we survey 22 of these protocols and compare their major characteristics, focusing on the impact of key issues like hidden terminal problems, deafness, and neighbor discovery. The qualitative analysis of various directional MAC protocols presented in this paper not only provides an insight of existing works but also will avail to generate efficient schemes.

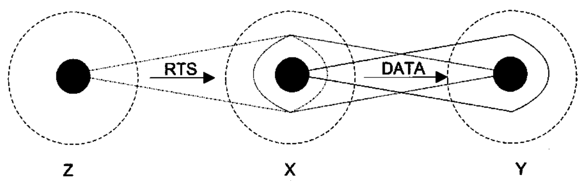
The rest of the paper is organized as follows: In the following section, we present key issues related to MAC protocols using directional antennas in ad hoc networks. The existing MAC protocols are reviewed in Section III and compared in Section IV. Finally, the paper is concluded in Section V.

II. Issues in the Design of MAC Protocols for Ad Hoc Networks with Directional Antennas

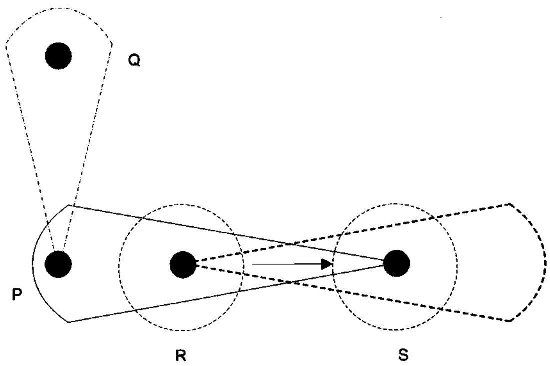
A. New Hidden Terminal Problem

The so-called hidden terminal problem in omnidirectional transmission can be resolved by using the RTS/CTS(Request To Send/Clear To Send) handshaking mechanism prior to the data transmission. The directional transmission of RTS/CTS, in MAC protocols using directional antenna, leads to the formation of the hidden terminal problem once again. This problem can be categorized as follows :

Hidden terminal due to asymmetry in gain : Any two nodes may be out of range if at least one of them is in the omnidirectional mode. But they can come in range if they beam form in each other's direction [22]. This may cause collision as depicted in (Figure 1). Two nodes X and Y are beamformed in each other's direction and communicating directionally. Initially Z is in omnidirectional mode and at a distance from node Y, so it is unaware of the communication between X and Y. If Z has a packet to deliver to Y, it changes to directional mode and sends DRTS to Y. Now, as Y and Z are beamformed towards each other, it is possible that DRTS from Z will interfere at Y. This will cause collision in the ongoing communication between X and Y [1,22].



(Figure 1) Hidden terminal problem due to asymmetry in gain.



(Figure 2) Hidden terminal problem due to unheard RTS/CTS.

Hidden terminal due to Unheard RTS/CTS : As depicted in (Figure 2), P is communicating with Q directionally. While this communication is going on, nodes R and S beamform towards each other and start communicating directionally. Due to antenna orientation of node P, it is unaware of the communication between R and S. Later, on finishing the communication with Q, P gets the data packet destined to R. Thus, node P's transmission may cause collision on the ongoing communication between R and S [1,22].

B. Deafness

This problem arises when the intended receiver node is unable to receive a packet due to the antenna gain pattern [1,21,23]. Deafness can be of various types [19]. Here, we present some scenarios that lead to deafness.

In case of the protocols where a node sends RTS/CTS only in the direction of the destination, other nodes located in different angular direction, who wish to transmit, will never know that its intended receiver isvbusy. They assume congestion to be the cause of failure and back-off longer before attempting again [19].

Deafness also can occur due to continuous hearing of unwanted data. All the nodes hearing RTS/CTS set the DNAV(Directional Network Allocation Vector). When a node is transmitting DATA, the idle nodes that fall within the antenna beam receive the DATA directionally and become deaf to the other directions. This unnecessary reception of DATA causes poor spatial reuse and degrades throughput [19].

Deafness can also occur if the deafness at receiver cannot be identified. A sender cannot determine whether the beam of the receiver towards itself is blocked or not. The sender sends RTS. If the receiver' s DNAV is already set and the antenna beam is blocked it will not be able to send CTS [19].

C. Neighbor Location and Neighbor Discovery

In order to beam-form the main lobe in the correct direction and achieve maximum gain, it is vital for a transmitter node to have the knowledge of the receiver location. If the beam-formed is in correct direction, the interference caused by other nodes can also be overcome.

It is difficult for beam-forming antennas to determine where to point and when to point the antenna to transmit or receive [26]. Informed discovery and non-informed discovery(blind discovery) are mentioned in [26]. In informed discovery, a node can get the information of its non-neighbor through some sort of methods like AoA(Angle of Arrival) caching, maintaining location table or performing multi-hop routing. This will help in pointing the non-neighbor. Non-informed neighbor discovery is the most challenging issue. Here, a node can be totally unaware of some other nodes. In TR-BF(Transmit and Receive Beam-Forming) mechanism, all nodes are synchronized with each other [26]. When the direction for any two nodes matches, i.e. transmit beam-form of one node aligns with receive beam-form of another node, periodic control messages are transferred. However, the limitation of this algorithm is the need for synchronization on each node.

D. Some Other Issues

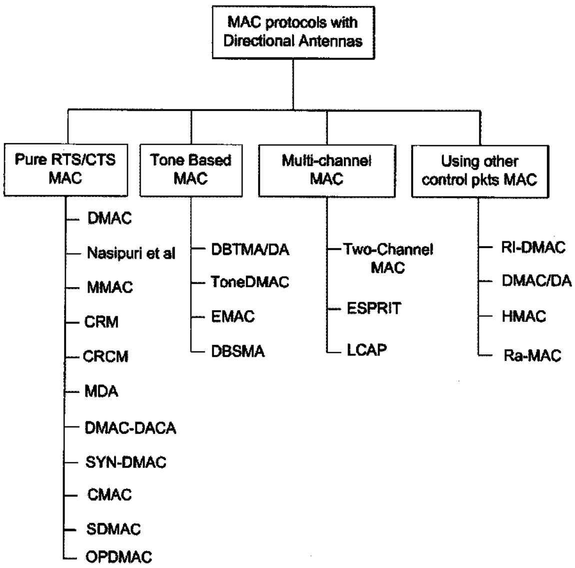
Issues like HoL blocking problem, side lobe pattern, the rotation of antenna array and change in beam-forming pattern are also of major concern. Since the MAC layer uses FIFO queues to manage packets to be sent in the shared medium, it introduces HoL blocking problem [24]. If a packet in top of the queue is blocked because the medium is not free in that direction, then other packets which are in the queue with some other directions are also blocked. The side lobe pattern may change while steering the main beam around the node [20]. Due to this, the interference caused by side lobes cannot be determined. The need of re-determination of neighbors becomes an important issue for mobile nodes. The change in beam-forming pattern of the nodes causes change in whole of the neighborhood pattern and interference [20].

Most of the protocols reviewed in Section III of this paper have not tried to address these issues yet and, thus, these issues are not taken into comparison in this paper.

III. MAC Protocols for Ad Hoc Networks with Directional Antennas

In this section, we review the MAC protocols for ad hoc networks with directional antennas, which have been published so far. We suggest the readers to refer to the original works for more information about any particular protocol. Also, readers can refer to some foundational works presented in [28] which have been mentioned in the following paragraph and have been referenced and reviewed a number of times in the literature.

A number of MAC protocols using directional antennas have been proposed in literature so far. We have categorized these protocols into four groups: Pure RTS/CTS based MAC, Tone Based MAC, Multi-channel MAC, and MAC using other control packets. Pure RTS/CTS based MACs use the mechanism of RTS/CTS in various ways to lower the issues relating to the use of directional antenna. Tone based MACs use an out of band tone in addition to RTS/CTS. Some protocols use multiple channels to communicate with multiple nodes at a time. Another mechanism is to use RTS/CTS with some other control packets to reduce the issues relating to the use of directional antenna. We have also sorted the MAC protocols reviewed in this paper in these four groups as represented in (Figure 3).



(Figure 3) Categorization of the MAC protocols.

A. D-MAC(Directional MAC)

Directional MAC scheme [2] as proposed by Ko et al. introduces the mechanism of directional and omnidirectional transmission of control, DATA and ACK packets depending upon the situation. Two schemes have been proposed in DMAC. According to scheme 1, RTS, DATA and ACK packets are sent directionally whereas CTS packets are sent omnidirectionally. Thus the node overhearing CTS only blocks the antenna over which CTS was heard. Scheme 2 applies both Directional RTS(DRTS) and Omnidirectional RTS(ORTS). ORTS are sent if none of the directional antennas of the node is blocked. Else, the node will send DRTS. The combined use of DRTS and ORTS reduces the chances of collision.

B. MAC Protocol Using Directional Antenna by Nasipuri et al.

The exact location of the neighboring node is not known priori. This is because, at the start of data transfer, the nodes are viable to be in the state of motion in ad hoc networks. Nasipuri et al. proposed a MAC protocol [3] that is able to find the neighbor location. The exchange of RTS/CTS packets are done omnidirectionally. The receiver of RTS identifies and records the antenna that receives the maximum power of RTS packet. The transmitter of RTS also estimates the direction of CTS transmitter and thus the RTS-CTS handshaking is performed and the directional link is established. Then, DATA and ACK are transmitted directionally. The other nodes overhearing the RTS/CTS will defer their transmission to the communicating nodes. Thus, this successfully reduces the interference.

C. Basic DMAC Protocol and Multi-hop RTS MAC Protocol

R. R Choudhury et al. proposed two MAC protocols [1], namely Basic DMAC protocol and Multi-hop RTS MAC protocol. The Basic DMAC protocol attempts to exploit the spatial reuse property of directionality. However, the problems like hidden terminal, anomaly in shape of silenced region and deafness persists in the basic DMAC protocol.

Multi-hop RTS MAC protocol(MMAC) attempts to exploit the benefit of higher transmission range of directional antennas. The MAC layer is able to decide upon the(Directional Omni) DO-neighbor route to(Directional Directional) DD-neighbor by the information from the upper layer. The intended transmitter reserves the channel to its intended receiver by making use of the DO-neighbor route to its DD-neighbor. Thus, reserving the channel helps other nodes to defer their transmission. This protocol also makes use of high priority forwarding RTS packet, on receiving this packet the DNAV tables are not updated. The transmission of multi-hop RTS packets is probable to suffer from failure of transmission; this may lead to latency of packets delivery because of retransmissions.

D. DBTMA/DA(Dual Busy Tone Multiple Access) Protocol

Z. Huang et al. proposed DBTMA/DA protocol [4] as a modification to DBTMA protocol. This protocol enhances the channel capacity by the directional transmission of RTS/CTS frame, data frame and dual busy tones. This protocol uses busy tones BTr(receive busy tone) and BTt(transmit busy tone). A node transmitting or receiving data sends BTr/BTt directionally, which can be heard by all the nodes within the transmission range.

E. ToneDMAC

R.R Choudhury et al. proposed ToneDMAC [5] to address the problem of deafness caused by the use of directional communication. In this protocol, the two nodes of a sender-receiver pair perform directional communication starting with the exchange of DRTS and DCTS. Other neighboring nodes, attempting to communicate with these nodes, faces failure. Assuming congestion to be the cause of failure, the neighboring nodes increase the back-off timer after each failure. The two nodes upon completing the communication send omnidirectional out-of-band tone which informs the neighbors that the cause of failure was not congestion but deafness of the communicating nodes. The neighboring nodes cancel their remaining back-off and opt for smaller random value and attempts retransmission again.

F. CRM(Circular Directional RTS MAC)

Korakis et al proposed CRM [6] which is capable of full exploitation of directional antennas. In this protocol, RTS is transmitted directionally, consecutively over all antenna beams. This mechanism benefits because no prior knowledge of receiver location is required. This protocol makes the use of location table which maintains information about node itself, its neighbor, the beam index on which the node heard the packet, and the beam index on which the neighbor sent the packet. This record helps in keeping track of the neighbor.

This protocol, however, doesn' t have directional CTS communication which lowers the spatial reuse and, thus, cannot fully exploit directional antennas.

G. EMAC(Efficient MAC)

Ueda et al. proposed EMAC [7] which is a receiver-oriented and rotational sector based directional MAC. It maintains the neighborhood direction information in AST(Angle Signal Table). Through AST, any node n will have the directional information about node m, which will help in resolving medium access issues during transmissions and receptions.

In this protocol, the node listens in omnidirectional sensing mode when it is idle. Upon sensing some signal, the node rotates its directional antenna sequentially to cover entire 360 degrees. Through this process, the direction of the maximum signal strength is determined. The control packets are transmitted with a preceding tone. This enables the receiver to track the best possible direction to receive the signal and, thus, the reception of control packets is done in that direction. The transmission and reception of DATA and ACK are done directionally.

H. CRCM(Circular RTS and CTS MAC)

Jakllari et al presented a modified CRM protocol called CRCM [8]. The objective of this protocol is to solve the issues of hidden terminal, deafness and neighbor's discovery. The basic operation of this protocol is similar to CRM ; however, this protocol introduces the use of directional transmission of CTS packets. The receiver of DRTS sends DCTS to the transmitter. In addition, the receiver also sends DCTS to other neighbors that are in the coverage range of receiver. These neighboring nodes were unable to hear the DRTS and, thus, could interfere with the ongoing transmission. However, the transmission of multiple packets for single data packet has chances of degrading the MAC performance.

I. MDA(MAC protocol for Directional Antennas)

Gossain et al. presented a novel scheme to solve the issues of deafness and hidden terminals. The antenna model in MDA operates on both omni and directional modes. The reception of signals is done in omnidirectional mode with gain Go whereas the transmission takes place in directional mode with gain Gd. The directional transmission depends upon the direction through which the received signal is the strongest.

MDA [9] maintains a DNT(Directional Neighbor Table) which is established during route discovery phase. Though CRM and CRCM considerably lower the region of deafness, they cannot overcome this issue completely. MDA performs DoD(Diametrically opposite Directional) transmission of RTS and CTS on those sectors where neighbors are found. MDA uses EDNAV(Enhanced DNAV) scheme. EDNAV comprises of DNAV and DT(Deafness Table). Both DNAV and DT are involved for information while sending a packet, whereas one of them is updated upon receiving a packet. The use of EDNAV helps in clearly indentifying the scenario of deafness and collision.

J. Two-Channel MAC

Y. Pan et al proposed a two-channel MAC protocol [10] ich uses directional antenna that can operate in omni and directional modes depending upon the situation. When a node is transmitting data frames, it is done in directional mode. Omni mode is used for receiving signals and frames other than data frames.

This protocol also makes use of two channels, namely control channel for RTS/CTS and ACK frames and data channel for DATA frames.

K. DBSMA(Directional Busy Signal Multiple Access)

Kulkarni et al. proposed DBSMA [11] protocol which is able to meet most of the requirements of MAC protocols using directional antennas. The transmission and reception of all control and data frames are done directionally. In idle state, a node rotates the hearing direction of its antenna so that it can listen in all directions. There is no use of any other control packet except RTS and CTS, thus reducing overhead. A busy tone is transmitted after successful reception of RTS and until the DATA and ACK transmission is completed. IS(Invitation Signal), a narrow-band signal similar to busy tone, is used to determine the direction for the reception of RTS.

In directional communication, one direction might be highly congested whereas another direction might be less congested. In such cases, using same back-off for all the direction will not be an efficient approach. DBSMA also proposes to use independent back-off for each direction.

L. DMAC-DACA(Directional MAC with Deafness Avoidance and Collision Avoidance)

Li et al. proposed DMAC-DACA. This protocol uses a switched beam antenna system and is able to beam-form in any antenna beam for transmission and reception [12]. This protocol performs omnidirectional back-off, and senses the channel busy if there is any signal in its intended direction of transmission. This protocol also performs the sweeping of RTS/CTS in all directions so that all DO(Directional Omni) neighbors are informed of the transmission/reception.

Various techniques are used to avoid deafness issues occurring differently. It makes use of DNT(Deaf Neighbor Table) and DV(Deafness Vector) to address the deafness issue when either the transmitter or the receiver is deaf. Each node maintains a DNT which includes the information of deaf neighbors and the time after which the deaf neighbor will be available. DV value is retrieved from DNT. DV informs about the unavailability of the destination until certain time. Thus, the transmission will be deferred until that time. The location information retrieved from GPS is used to solve issue of deafness due to deaf zone. The location information is added to the basic RTS/CTS and the sweeping RTS/CTS.

M. SYN-MAC(Synchronized MAC)

Wang et al. proposed SYN-MAC [13] to address the issues of using MAC protocols using directional antennas in ad hoc networks. The timing structure of SYN-MAC consists of three phases: random access phase(Phase I), DATA phase(Phase II) and ACK phase(PHASE III) [13]. Channel contention and route discovery are performed at Phase I. During this phase, multiple transmitter-receiver node pairs may be selected. The first selected node pair should avoid collision with the later ones. Parallel collision-free data transmission takes place at Phase II. In this phase, each node pair can choose different data rate and transmission power depending upon the channel condition. Parallel contention-free ACK transmission takes place at Phase III. One ACK is enough for all the correctly received packets sent in phase II.

N. RI-DMAC(Receiver Initiated DMAC)

RI-DMAC [14] proposed by Takata et al. mainly focuses on solving the deafness issue with directional antennas. This protocol has both sender-initiated and receiver-initiated operations. Sender-initiated operation is default whereas receiver-initiated operation is triggered only the transmitter knows the next packet in transmitter' s queue is intended to itself. This protocol makes the use of polling table to poll the potential deafness node using RTR(Ready to Receive) frame after each complete dialog. After receiving RTR, the potential deaf node infers that the intended receiver is idle. The least recently transmitted node is selected from the polling table of deaf node to improve fairness.

O. DMAC/DA(Directional MAC/Deafness Avoidance)

DMAC/DA protocol [15] is proposed by Takata et al. to solve the issue of deafness. It introduces the WTS(Wait To Send) frames. This protocol maintains a neighbor table with the potential transmitters. When two nodes are to communicate, the sender verifies, by physical carrier sensing, the number of beams in which potential transmitters exists. It also checks its DNAV table and neighbor table to find out the potential transmitters and their DNAV setting. The number of potential transmitters is included in RTS and send to the intended receiver directionally. The receiver also finds out number of intended transmitters and includes this value in CTS. After RTS/CTS handshake, both the sender and receiver transfer WTS frames to the intended transmitters. Upon receiving the WTS frames, the intended transmitters defer their own transmission and recognize the nodes as busy.

P. ESPRIT(Signal Parameter Estimation via the Rotational Invariance Technique)

K. Liu et al. proposed the ESPRIT [16] protocol which uses two channels and operates on two omni and directional modes. All packets are transmitted in omni mode in channel one and in directional mode in channel two. The protocol makes use of two NAV tables, (Omnidirectional Network Allocation Vector) ONAV and DNAV. ONAV gives the information about the blocking of channel one and DNAV informs the period during which channel two cannot be used. The whole process of communication is simplified into four steps : (i)RTS transmission, (ii)RTS reception and CTS transmission, (iii)CTS reception and DATA transmission, and (iv)DATA reception and ACK transmission.

Q. CMAC(Cooperative MAC)

Munari et al. proposed CMAC which attempts to exploit the benefits of using directional antenna and to improve the overall network performance [17]. Each node maintains a table called CR(Communication Register) which contains the record of all the ongoing communications. The CTS in CMAC has the ids of source and destination. RTS, CTS and ACK frames have the data needed for CR. On receiving any of these frames, CR is updated if necessary. RTS/CTS frames in CMAC are sent in circular fashion as in CRM. The combined use of circular handshaking and multiple receptions helps in reducing the impact of deafness. Cooperation among nodes is achieved by informing the nodes, who intend to switch to idle mode, about the communication that has started concurrently.

R. HMAC(Hybrid MAC)

Jain et al. presented HMAC [21] which makes use of information obtained from the physical and network layers for its operation. The antenna model used in HMAC is switched-beam smart antenna. The angle of arrival of the incoming signal is calculated accurately. It makes use of SCH(Schedule update with intelligent feedback) frame which is transmitted to the node that falls away from the communication range of sender while transmitting RTS/CTS. Separate queue is used for each beam and, thus, helps in avoiding HoL blocking problem.

HMAC uses the same packet format for control messages as that in the IEEE 802.11 standards and IFS(Inter-Frame Space). So, it is said to be compatible with IEEE 802.11. HMAC introduces algorithms for mitigating deafness and contention resolution. Jump back-off and role priority switching mechanisms helps in enhancing throughput.

S. LCAP(Load-based Concurrent Access Protocol)

LCAP [22] proposed by Arora et al. exploits the use of directional antennas further by power control mechanism. LCAP introduces a novel idea of concurrent transmission in the same neighborhood. If the SINR at receiver is higher than some threshold value SINRth, then the transmission can take place even if the direction is already reserved.

It uses two different channels for data and control packets. However, these channels are not used simultaneously. When data channel is being used for transmission, control channel is never in the transmit mode. The control channels are also used for route-discovery messages. Various channel access problems are minimized by the use of dual channels. This protocol also minimizes the interference that may occur due to the use of directional antennas.

T. Ra-MAC(Range-adaptive MAC protocol)

Ra-MAC [23] proposed by Chen et al. makes use of smart antennas and adjusts the transmission ranges according to the distance between the communicating node pairs.

Unlike the previous MAC protocols with a single directional transmission range, Ra-MAC introduces three-fold directional transmission ranges. The concept of LD(Low-Distance), MD(Medium-Distance) and HD(High-Distance) patterns of adaptive transmission ranges is introduced in the protocol. The dual access mode as described in Ra-MAC performs LD-communication when receiver is 1-hop neighbor of the transmitter. When the receiver is between 1-hop and 2-hop distance from the transmitter, HD-RTS is sent to perform MD-communication. HD-communication is not used in transmission. This protocol makes use of additional control packet SOD(Start Of Dialog) which attempts to minimize the hidden terminal problem and deafness. R-DNAV(Range-based DNAV) used in this protocol is an extension of DNAV with distance information.

〈Table 1〉 Comparison based on the transmission and reception modes of various packets
(O : Omnidirectional, D : Directional, N/A : Not Applicable, "–" : Information not available).

Protocol	Physical carrier sensing	RTS		CTS		DATA		ACK		Additional packets /Tones
		TX	RX	TX	RX	TX	RX	TX	RX	
DMAC Scheme 1	D	D	O	O	O	D	O	D	O	-
DMAC scheme 2	D	O/D	O	O	O	D	O	D	O	-
Nasipuri et al.	O	O	O	O	O	D	D	-	-	-
MMAC	D	D	O	D	D	D	D	D	D	-
DBTMA/DA	-	D	O	D	O	D	D	-	-	Dual busy tones
Tone DMAC	D/O	D	O	D	O	D	O	D	O	(OoB) Tone
CRM	O	Rot. D	O	D	O	D	D	D	D	-
EMAC	O	O	Cir. D	O	Cir. D	D	D	D	D	Preceding tone
CRCM	-	Rot. D	O	D	O	D	D	D	D	DCTS for unaware nodes
MDA	-	D	O	D	O	D	D	D	D	DoD RTS /DoD CTS
Two Channel MAC	-	O	O	O	O	D	O	-	-	RFA
DBSMA	D	D	D	D	D	D	D	D	D	Busy Tone
DMAC-DACA	-	Sweep. D	O	Sweep. D	O	D	-	D	-	N/A
SYN-MAC	-	D	O	D	O	D	D	D	D	CRTS
RI-DMAC	O	D	D	D	D	D	D	D	D	RTR
DMAC/DA	O	D	O	D	D	D	D	D	D	WTS
ESPRIT Channel 1/2	-/-	O/-	O/-	O/D	O/-	-/D	-/D	-/D	-/D	-
CMAC	-	Rot. D	O	Rot. D	O	D	D	D	D	N/A
HMAC	D	D	O	D	O	D	D	D	D	SCH
LCAP		O	O	D	D	D	D	D	D	N/A
Ra-MAC	-	O	O (LD or HD)	D	D	D	D	D	D	SOD
SDMAC	-	O	D	D	D	D	D	D	D	Type I/II - DRTS/DCTS
OPDMAC	D	D	O	D	O	D	O	D	O	N/A

U. SDMAC(Selectively Directional MAC protocol for wireless mobile ad hoc networks)

Li et al. proposed SDMAC which addresses the issues of deafness and new hidden terminal problem by making use of two types of DRTS and DCTS [24]. Type I of DRTS/DCTS initiates the communication between the sender and receiver. These control packets contain additional fields "Outgoing Beam" which gives the beam number used in current communication and "Beam Status" which gives the traffic status in all beam directions. Type II of DRTS/DCTS is used to inform the neighbors of sender and the receiver about the data transmission. Each node maintains a deafness table and records its deaf neighbors and their duration of deafness.

Two improvements of Queue-SDMAC(Q-SDMAC) and Q-SDMAC with cache are also introduced in [24]. Q-SDMAC schedules packets in a queue and, thus, helps to overcome HoL blocking problem. Q-SDMAC with cache just caches the neighbor node ID and the incoming direction of packets from the node.

V. OPDMAC(Opportunistic Directional MAC)

OPDMAC [18] proposed by Bazan et al. aims at maximizing the spatial reuse without multiple RTS/CTS transmissions, decreasing the overhead significantly. OPDMAC is a very new protocol proposed in the literature. It modifies the back-off mechanism to fit the directional transmission. The random back-off in one direction should be independent of the packet transmission in any other directions.

In OPDMAC, the sender scans the packets in the queue sequentially and selects the first unblocked packet. The sender senses carriers directionally towards the intended

〈Table 2〉 Comparison with respect to various system parameters
(G^o : Gain in omnidirectional mode, G^d : Gain in directional mode, "–" : Information not deducible)

Protocol	Antenna model	Gain	Spatial reuse	Range extension	DNAV	SINR/SNR	Overhead
DMAC	Switched beam	$G^o=G^d$	Low	Low	No	Low	Low
Nasipuri et al.	Switched beam	$G^o=G^d$	Very Low	Very Low	No	Low	Low
MMAC	Steered beam	$G^o<G^d$	High	High	Yes	High	Medium
DBTMA/DA	Switched beam	$G^o<G^d$	Medium	Medium	No	Medium	Low
Tone DMAC	Switched beam	$G^o<G^d$	Medium	Medium	No	Medium	Medium
CRM	Switched beam	$G^o<G^d$	Medium	Medium	Yes	High	High
EMAC	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Medium	Medium
CRCM	Switched beam	$G^o<G^d$	Medium	Medium	Yes	High	Very High
MDA	Switched beam	$G^o<G^d$	Medium	Medium	EDNAV	Very High	Medium
Two Channel MAC	Switched beam	$G^o<G^d$	Very Low	Very Low	No	-	Low
DBSMA	Switched beam	$G^o<G^d$	High	High	Yes	High	Very Low
DMAC-DACA	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Low	Low
SYN-MAC	Switched beam	$G^o<G^d$	Medium	Medium	No	High	Low
RI-DMAC	Switched beam	$G^o<G^d$	High	High	Yes	Very High	Low
DMAC/DA	Switched beam	$G^o<G^d$	High	High	Yes	Very High	Low
ESPRIT	Switched beam	$G^o<G^d$	Medium	Medium	Yes	Medium	Medium
CMAC	Switched beam	$G^o<G^d$	Medium	Medium	No	High	Medium
HMAC	Switched beam	$G^o<G^d$	Medium	Medium	HNAV	High	Medium
LCAP	Switched beam	$G^o<G^d$	Very High	High	Yes	High	Low
Ra-MAC	Switched beam	$G^o<G^d$	High	Very high	RDNAV	High	Very Low
SDMAC	Switched beam	$G^o<G^d$	High	High	Yes	High	Medium
OPDMAC	Switched beam	$G^o<G^d$	Very High	Medium	Yes	High	Very Low

receiver. If the medium is idle for DIFS(Distributed IFS) period, RTS is transmitted; otherwise, the transmission is deferred over this direction. Then, it rescans the queue to find next unblocked packet to transmit. The receiver receiving the RTS sends CTS after SIFS(Short IFS) period. Upon failure to receive CTS, the sender rechecks its queue and sends unblocked packets in some other direction. The time of packet transmission in other direction acts as back-off time in one direction.

IV. Comparison of Protocols

We have made a comparative analysis of the MAC protocols using directional antennas in ad hoc networks. The analysis is summarized in the form of three tables.

In 〈Table 1〉, we have analyzed the protocols in terms of the mode of physical carrier sensing and the mode of communication during the transmission and reception of control, DATA and ACK frames [20]. This table also gives information about the use of additional packets.

In 〈Table 2〉, we have compared the MAC protocols in parameters like antenna model, gain, spatial reuse, range extension, use of DNAV, and SINR/SNR. Higher spatial reuse can be obtained when there is higher directional communication, which in turn increases the range extension [25]. Higher directional communication also helps in avoiding interference, thus increasing SINR.

In 〈Table 3〉, we have summarized the impact of the different issues on the surveyed MAC protocols using directional antennas. Greater directional transmission or the spanning of RTS/CTS helps in increasing the neighbors' information and decreasing the effects of hidden terminals and deafness.

The above-mentioned MDA, DMAC-DACA, SYN-DMAC, CMAC, SDMAC and OPDMAC protocols are based on pure RTS/CTS mechanism as shown in (Figure 3). These

〈Table 3〉 Impact of different issues on MAC protocol design.

Protocol	Impact of Issues		Neighbor Disc./Info.
DMAC	High	High	Low
Nasipuri et al.	High	High	Low
MMAC	Medium	Medium	Medium
DBTMA/DA	low	Medium	Low
Tone DMAC	Medium	Low	Low
CRM	Low	Medium	Medium
EMAC	Low	Medium	High
CRCM	Low	Low	High
MDA	Low	Low	High
Two Channel MAC	Low	Medium	Medium
DBSMA	Very Low	Low	High
DMAC-DACA	Medium	Low	Medium
SYN-MAC	Low	Low	Medium
RI-DMAC	Medium	Very Low	High
DMAC/DA	Medium	Very low	High
ESPRIT	Medium	Medium	High
CMAC	Low	Very Low	Low
HMAC	Medium	Medium	Medium
LCAP	Low	Low	High
Ra-MAC	Low	Low	High
SDMAC	Very Low	Low	Very High
OPDMAC	Low	Low	Medium

protocols employ multiple directional transmissions of control packets, resulting in the increased coverage range. The problems of deafness and hidden terminals are greatly reduced, and both neighbor discovery probability and SINR is increased. These protocols do not use additional control packets which do not add up extra overhead. Of them, OPDMAC is a newly proposed protocol which does not use multiple directional RTS/CRS and reduces overhead and HoL blocking problem.

EMAC and DBSMA are two tone based MAC protocols that outperforms other MAC protocols in this group. The higher directional transmissions in these protocols increase the coverage range, SINR and neighbor discovery whereas the problems of hidden terminals and deafness are reduced.

LCAP uses two channels for control and data packets. The use of multiple channels facilitates concurrent transmissions. This increases the spatial reuse and SINR.

HMAC and Ra-MAC are two protocols that, in spite of using additional control packets, achieve greater spatial reuse and successfully lower the negative effects associated with the use of directional antennas. A novel approach of dynamic directional range selection, depending upon the distance between transmitter and receiver, is presented in Ra-MAC. It provides an energy efficient MAC scheme.

V. Conclusions

In this paper, we have made an attempt to make a qualitative comparison of various MAC protocols using directional antennas in ad hoc networks. The study of various MAC protocols from the beginning of employing directional antennas to recent years has been reviewed and compared with each other. Most of these protocols use the combination of omnidirectional and directional antennas for transmission and reception of packets. The capacity of exploiting benefits of directional communication by making spatial reuse, interference reduction and range extension is vital for prominent MAC protocols.

From our observation we can see that MDA achieves very high SINR but compromises with overhead and range extension. Similarly the impact of deafness in CMAC is very low, but it compromises with low neighbor discovery. Among the 22 protocols that we have studied, DBSMA is able to achieve high SINR and range extension while keeping the overhead low. The impact of hidden terminal and deafness are also lower with high neighbor discovery. SDMAC also has lower impact of hidden terminal and deafness, with very high neighbor discovery. But it compromises with overhead in order to achieve higher spatial reuse, range extension and SINR. After analyzing all the results, we conclude that DBSMA and SDMAC perform better than other protocols.

We have observed that there always remains the room for trade-off between spatial reuse and collision, which in turn introduces retransmission and packet drop. Concurrent operation of multiple links(i.e. spatial reuse) causes the number of control packets to increase, which in turn increases overhead.

The use of multiple channels helps in concurrent transmissions in a node at the same time. We presume this can greatly increase the efficiency of the network and reduce the negative effects related with the use of directional antenna.

These observations suggest that the design of generic MAC protocol that satisfies everything is not possible. MAC protocols should be efficient in regard to the application area. However, the purposed protocols rarely define an area of application. So, they all seem to be generic ones.

Various techniques can be formulated in order to make efficient MAC protocol for the application of given criteria. For example, we can observe that various MAC protocols use circular, rotational or sweep control packets. If the topology is linear, these type of control packets, instead of increasing the efficiency, increases overhead. If the topology is dense and indoor, high degree of spatial isolation can enable concurrent transmission even on closely located nodes.

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