Directional Antenna-based Medium Access Control and Routing for Ad hoc Networks: Challengues and Solutions

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***Abstract*—An area of growing interest has been to apply directional antennas to MANET protocols, which typically assumed a uniform equipment of omnidirectional antennas. In contrast to omnidirectional antennas, directional antennas have the benefits of reduced collision and extension of communication distance in a narrower range of directions. Existing work that applies directional antennas to MANET mostly focuses on MAC protocols. Besides, most of them are modifications of IEEE 802.11 DCF MAC, a popular MAC protocol typically adopted by MANET research. Nevertheless, there are many other MAC protocols, such as TDMA based MAC protocols for MANET, and it is unclear how directional antennas could be applied to them as well. Though some work applies directional antennas to addressing network layer issues, these efforts focus on location assisted route discovery and neighbor discovery of nodes outside of omnidirectional coverage range, many other issues, such as network-wide broadcast, need to be addressed. This paper reviews recent advancements in directional antenna-based medium access control and routing protocols for MANET and points out the challenges and directions for future research.**

***Index Terms*— Directional Antennas, MAC, Routing, MANET**

I. INTRODUCTION

Ad hoc networks consist of mobile nodes, which dynamically and spontaneously create and maintain the network topology via wireless communication. The Carrier Sense Medium Access (CSMA) protocol, when applied to ad hoc networks, suffers from the *hidden terminal* and the *exposed terminal* problems [35]. MACA (Medium Access Collision Avoidance) [19] relieves these problems by utilizing RTS and CTS (Request-To-Send and Clear-To-Send) frames. MACAW [2] further refines MACA with more optional control frames. FAMA (Floor Acquisition Multiple Access) [11] combines non-persistent carrier sensing and the RTS/CTS scheme together. The IEEE 802.11 MAC DCF specification [17] is a variation of the CSMA/CA (CSMA with Collision Avoidance) protocol that supports both the carrier sensing and the virtual sensing (RTS/CTS scheme). DBTMA (Dual Busy Tone Multiple Access) [5], [12] is also an RTS/CTS-based MAC protocol, which splits a single channel and uses a pair of *transmit* and *receive* busy tones.

The MAC protocols stated above all assume the usage of omnidirectional antennas. The directional antenna based MAC protocols, however, are capable of transmitting only in certain narrower azimuth and thus significantly reduce the chance of collision and increase the effective network capacity. Recently, there have been a few directional MAC protocols proposed for ad hoc networks. For instance, [20] applies directional antennas to the IEEE 802.11 MAC DCF specification by sending the RTS, data, and ACK frames directionally and succeeds in achieving better network throughput. However, this work relies on extra location tracking support. To avoid this problem, [24] utilizes the exchange of omnidirectional RTS/CTS frames between communicating nodes in order for them to identify the directions of each other. However, this work does not have the benefit of reserving the channel directionally. A directional version of DBTMA is described in [16] that demonstrates improved performance and comparable effectiveness of spatial reuse with other directional MAC protocols.

The have been hundreds of work on routing with omni-directional for MANET. Among

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them DSR[18], AODV[25], OLSR[8] are some of the most well-known protocols. However, only a little recent work are directional antenna-based. [23] is one of the first work that study ad hoc routing issues with the use of directional antennas. This work provides an effective route discovery optimization for routing protocols by constraining each route request to a certain narrow angle. [3] modified DSR [18] by *sweeping* the RREQ packet sequentially in all directions. This work studies its network performance based on a directional antenna-based MAC protocol similar to DMAC [20]. [27], [29], [34] apply directional antennas across multiple layers including routing.

In the following sections, we will review in detail recent work on MAC and routing protocols for MANET that apply directional antennas to their design. After that, we will conclude with challenges and future directions.

II. DIRECTIONAL ANTENNA-BASED MAC

[20], [24] are two early efforts that apply directional antennas to designing a MAC protocol for ad hoc networks. Similar to [20], [30] applies directional transmission to RTS/CTS/DATA. in IEEE 802.11 DCF (*distributed coordination function*), though RTS may also be transmitted omnidirectionally.

[33] is distinguished from other research in that it supports beamforming at the receiver. This work adds the capability of *directional virtual carrier sensing* (DVCS), including *AOA caching*, *beam locking/unlocking* and *DNAV setting*, into IEEE 802.11 DCF to better utilize directional antennas. AOA caching caches AOA (*Angle-of-Arrival*) information obtained from the prior frame received from the currently intended receiver, and uses it for the next directional transmission. All frames are usually transmitted directionally, except that omnidirectional RTS is transmitted in need of direction finding. Beam locking/unlocking allows a sender and receiver to lock their (steerable) antenna patterns towards each other to maximize signal gain once DATA is transmitted and until ACK is received. DNAV is basically a directional version of NAV that reserves the channel in different directions with different durations. Experimental results show significant improvement on network capacity even with mobility.

[4] presents a similar MAC protocol termed DMAC (originally presented in [20]) that applies DNAV. Using DMAC, MMAC presents *multi-hop RTS MAC* (MMAC), which uses RTS over multiple hops to establish links between distant nodes, and then transmits CTS/DATA/ACK over a single hop. MMAC is a first attempt to exploit the longer transmission range of directional antennas in MAC protocol design.

[6] studies the combinations of applying directional transmission of RTS and CTS to reserve the channel for CSMA/CA based protocols. Its key conclusion is that the decision on blocking the antenna in a certain direction is not based on the mere event of hearing or not hearing a reservation packet, but on the direction information included in the RTS/CTS packet.

[21] presents *circular directional RTS*, a new way of exploiting directional antennas that a sender scans through all directions with directional RTS before CTS is sent back. However, its benefit is not clearly explained. It also presents the use of a *location table*, a similar scheme to AOA caching.

[10] deems power reduction with an inexpensive adaptive antenna array as the key factor in improving the network capacity. This work studies the potential use of adaptive antenna arrays in networks using protocols based on the IEEE 802.11 DCF and extends IEEE 802.11 DCF in three ways. (1) the IEEE 802.11 *Network Allocation Vector* (NAV) is assigned different values depending on the receiver of the RTS frame: if the receiver has a packet destined to the sender or receiver of the impending transmission (corresponding to the RTS frame), the conventional IEEE 802.11 NAV (a delay of CTS + DATA + ACK) is used; otherwise the SHORT_NAV (a delay of CTS) is used. This scheme combines IEEE 802.11 DCF, in which RTS/CTS are prevented from colliding from DATA/ACK, with

MACA [19], in which recipients of RTS frame are encouraged to initiate data transmission, since they only need to care for CTS, but not DATA. (2) The RTS/CTS handshake is termed as *OMNI-Mode* and the DATA/ACK exchange is termed as *ARRAY-Mode*. As in [13], [24], the RTS/CTS handshake is utilized to collect channel information, which is then used to set up adaptive antenna array in the ARRAY-Mode. (3) Several power control variants are presented to reduce the power in the ARRAY-Mode.

In [9], a media access control protocol is proposed for ad hoc network stations with adaptive antenna arrays. The protocol is based on the IEEE 802.11 distributed coordination function (UCF) and uses omnidirectional RTS/CTS exchanges to initiate data packet transmissions. Unlike previous directional antenna MAC protocols, the proposed protocol accommodates the active ing of co-channel interferers that may arise during the course of ongoing transmissions. This is done using a three-way handshake where neighboring stations cooperate during link activations thus allowing the active receiver to dynamically potential future interfering packet transmissions. The protocol uses omnidirectional transmission combined with beamformed reception, and is referred to as selective CSMA with cooperative ing (SCSMA/CN). Packet type identification is used to enable/disable carrier sensing based upon whether or not existing transmissions are protected by antenna beamforming. Simulation results are presented which show that the proposed protocol can achieve higher capacity than previous comparable MAC protocols. The results also include the effects of transmit power control on system performance.

[32] explores the possibility for a unified approach to medium access control in adhoc networks with smart antennas. It first presents a unified representation of the PHY layer capabilities of the different types of smart antennas, and their relevance to MAC layer design. It then defines a unified MAC problem formulation, and derive unified MAC algorithms from the formulation. Finally, using the algorithms developed, it investigates the relative performance trade-offs of the different technologies under varying network conditions.

[16] modifies the original DBTMA by transmitting RTS/CTS frames, data frame, and the dual busy tones directionally. One fundamental requirement of applying directional antennas is "direction locationing," with which a node can select an antenna element in the intended direction. This problem is addressed in [20] by relying on GPS or beaconing messages. However, this solution suffers from inaccuracy due to hardware capability and has the drawback of soft-state schemes, especially in a highly mobile environment. This issue is tackled in [24] via omnidirectional exchange of RTS and CTS frames between neighboring nodes in order for them to learn each others' relative direction by selecting the direction with the strongest gain for a received frame. Our protocol relies on similar antenna support for neighboring nodes to learn their relative directions. The difference is that ours transmits directional CTS instead of omnidirectional CTS frame.

Some MAC protocols are not based on the RTS/CTS handshake. [28] applies smart antennas to contention-based and contention-free polling schemes for wireless LANs. [1] presents a *receiver-oriented multiple access* (ROMA) channel scheduling protocol that applies *multiple-beam antenna array* to networks with time synchronization. [22] differs significantly from others by assuming that nodes are able to perform simultaneous transmissions/receptions, which expands the benefit of directional antennas from capacity improvement towards *space division multiple access* (SDMA).

Besides, [27], [29], [34] apply directional antennas across multiple layers including MAC.

III. DIRECTIONAL ANTENNA-BASED ROUTING

[23] is one of the first work that study ad hoc routing issues with the use of directional antennas. This work provides an effective route discovery optimization for routing

protocols by constraining each route request to a certain narrow angle. Two schemes are presented. In one scheme, a sender starts a new route discovery by transmitting the query packet in the same direction it used previously. Every node receiving a packet or its forwarded duplicates for the first time forwards the packet in the same direction. In the other scheme, a source node caches the directions used by each node on the last successfully discovered route, and uses this information to estimate the direction towards the destination.

[3] modified DSR [18] by *sweeping* the RREQ packet sequentially in all directions. This work studies its network performance based on a directional antenna-based MAC protocol similar to DMAC [20].

[27], [29], [34] apply directional antennas across multiple layers including routing. They will be described in detail in the next section.

[31] proposes to map probability-based omnidirectional and directional broadcast to *site percolation* and *bond percolation*, respectively, and validate the propositions via proofs and simulations. Based on the mappings, it shows that in order to achieve comparable broadcast coverage as omnidirectional broadcast, directional broadcast incurs lower overhead, in terms of the ratio of the number of received duplicate packets to the number of nodes that receive broadcast packets, than omnidirectional broadcast. It further applies these ideas to designing a collection of directional broadcast schemes, together termed *DIABLO* (DIrectional Antenna Based Broadcast with Low Overhead), for MANET. The goal is to reduce the number of received duplicate packets, while achieving comparable broadcast coverage. A comparative simulation study of DIABLO in comparison with omnidirectional broadcast schemes has been conducted. The study shows that the overhead associated with directional broadcast is reduced significantly by 50% to 70% from omnidirectional broadcast, while the broadcast coverage and the delay of directional broadcast are very similar to those of omnidirectional broadcast.

IV. DIRECTIONAL ANTENNA-BASED CROSS-LAYER WORK

[27] studies the impact of applying directional antennas to CSMA/CA with RTS/CTS MAC protocol. This work aims to analyze some extreme cases, which provide noticeable improvement even as a lower bound, rather than providing a general solution. The work also presents solutions for directional neighbor discovery.

[29] adopts an approach similar to [24]: RTS and CTS are transmitted omnidirectionally and location tracking is done by recognizing the direction with the maximum gain. Similar to [4], [33], the concept of DNAV is used to maintain a *neighborhood active node list* (NANL) for every neighbor of a sender-receiver pair to keep track of the ongoing communication. NANL is propagated throughout the network such that every node builds an *active node list* (ANL) containing the activities of the network. Furthermore, a link-state routing protocol is adopted to distribute link-state information to every node. Based on this information, a source tries to find a path that is most disjoint from ongoing communications to the destination by consulting ANL.

[34] presents *adaptive range control* (ARC), a communication range control mechanism that applies directional antennas across multiple layers. In the physical layer, ARC uses directional reception and notifies MAC about the AOA and reception power. In the MAC layer, DVCS [33] is used and links are classified based on the reception power into *regular* links and *extended* links. The behavior of regular links are maintained while extended links are specially treated such that they could also support communication while being robust. In the routing layer, AODV [26], especially its structure and the way it handles RREQ packet, is modified to support extended links.

[7] presents UDAAN, an interacting suite of modular MAC and routing mechanisms for adaptive control of steerable and switched-beam antennas for ad hoc networks. UDAAN consists of a few new mechanisms: a directional power controlled MAC, neighbor dis-

covery with beamforming, link characterization for directional antennas, proactive routing and forwarding, all working cohesively.

[14], [15] proposes a directional antennas based topology control approach, termed *Topology Control with Directional Power Intensity*, or TCDPIfor short. When topology control is carried out omnidirectionally (for instance, when the radiated power is reduced to one half of the original power), the power intensity shrinks omnidirectionally by one half in all directions. For TCDPI, the same amount of reduced radiated power could be used to form special antenna patterns such that the original power intensity (or range) remains the same in a certain set of angles (directions), but cleared in other angles The goals of TCDPI are to not only reduce power while maintaining network connectivity, but also preserve hop distance and per-hop SNR. Furthermore, we show that TCDPI exhibits a phase transition phenomenon in terms of network connectivity with respect to a critical total beamwidth.

V. CHALLENGES AND FUTURE WORK

As we can observe in the review on directional antenna-based protocols, little research exists on directional antenna-based routing, which contrasts sharply with the huge volume of work on omnidirectional antenna-based routing. Actually, many ideas from omnidirectional antenna-based routing, such as source routing with disjoint paths and location-based routing, are very interesting directions within the context of directional antennas. Most directional antenna-based protocols take advantage of the feature of narrow beam of directional antennas to expand the network capacity and/or reduce the collision rate. However, only a few of these protocols take advantage of the other feature of directional antennas: higher power intensity. This feature leads to longer communication range and thus larger hop distance or shorter routes. It is interesting to see how to leverage on this feature of both of them to further improve the network performance.

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