A Distributed Directional-to-Directional MAC Protocol for Asynchronous Ad Hoc Networks

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***Abstract*— The use of directional antennae in ad hoc networks has received growing attention in recent years. However, most existing directional MAC protocols assume interchangeable directional and omnidirectional modes of operation. Such operation reduces the spatial gain and introduces the asymmetry-in-gain problem. In this paper, we propose a directional-to-directional (DtD) MAC protocol for ad-hoc networks that operates in the directional mode exclusively. The protocol is fully distributed, does not require any synchronization, eliminates the asymmetry-in-gain problem, and alleviates the deafness problem. To study the performance of the proposed DtD MAC, we develop an analytical model that estimates the saturation throughput as a function of the number of antenna sectors, packet size and number of contending nodes. The analytical results are validated by extensive simulations with the QualNet simulator. We show that the DtD MAC protocol is practical to take the advantage of directional antennae to improve network throughput and achieve better fairness in ad-hoc networks.**

I. Introduction

The use of directional antennae in ad hoc networks has received growing attention recently. The benefits of using directional antennae in ad hoc networks include high spatial reuse, longer transmission range, lower interference, etc. More importantly, emerging technologies that operate at higher frequencies, such as millimeter-wave (mmWave) at 60 GHz, need to use directional antennae to perform well [1]. This is because, at such high frequencies, the signal suffers from high path loss due to oxygen absorption and atmospheric attenuation, which can be partially compensated for by the high antenna gain of directional antennae.

Although using directional antennae for point-to-point communications has shown great performance gain, there are great challenges to use directional antennae in distributed networks due to the deafness problem: it is very difficult for two nodes with directional-only antennae to initiate a transmission if their antennae are not pointing to each other.

Most of the existing directional MAC protocols proposed for ad hoc networks deal with the deafness problem by making the common assumption that nodes can operate in both directional and omnidirectional modes. Besides the increasing cost of supporting the dual-mode operation, this assumption may defeat the purpose of using directional antennae altogether [2]. According to the study in [2], using omnidirectional transmission for control packets will in fact impede the ability of directional antennae to achieve better throughput. Furthermore, dual-mode operation introduces the asymmetry-in-gain problem. The-asymmetry-in-gain problem occurs when a node's omnidirectional radial range does not reach the destination node, however, its directional range does [3]. This problem brings new deafness problems and magnifies the hidden terminal problem, especially when control packets are sent omni-directionally or idle nodes sense the wireless medium omni-directionally.

Therefore, there is a pressing need to develop a MAC protocol for ad hoc networks with directional-only antennae. Ideally, this MAC protocol should be simple and scalable. It should allow all users to communicate, and to join and leave the system without the support of centralized controllers. However, to the best of our knowledge, there is no existing MAC protocol that can work for this purpose due to the many challenges imposed by directional-only antennae.

As the first step, we design a novel Directional-to-Directional (DtD) MAC protocol to meet the challenges. The main contributions of this paper are three-fold. First, we propose a novel DtD MAC protocol for ad hoc networks with directional-only antennae. The DtD MAC protocol is fully distributed, asynchronous, and does not rely on the use of omnidirectional antennae. Second, we develop an analytical model that estimates the saturation throughput as a function of the number of antenna sectors, packet size, and number of contending nodes in an ad hoc network. In addition, extensive simulation using the QualNet network simulator has been conducted, and the results demonstrate the feasibility of the proposed protocol and validate our analysis.

The remainder of this paper is organized as follows. Sec. II highlights the related work. The proposed protocol is described in Sec. III, and the its performance is studied in Sec. IV. The concluding remarks are presented in Sec. V.

II. Related work

Nasipuri *et al.* proposed a MAC protocol that uses a variation of the IEEE 802.11 DCF to support nodes with directional antennae [4]. In this protocol, ready-to-send (RTS) and clear-to-send (CTS) packets are sent omni-directionally, and then DATA and ACK packets are sent directionally. Ko *et al.* proposed a MAC protocol that sends a directional RTS when at least one of the antenna beams is blocked, or an omnidirectional RTS otherwise, followed by an omnidirectional CTS from the receiver [5]. It was assumed that all nodes know the location of their neighbors using technologies such as GPS. Takai *et al.* in [6] proposed Directional Virtual Carrier Sensing (DVCS), a mechanism that is composed of using Directional Network Allocation Vector (DNAV), Angle of Arrival (AoA) and beam locking and unlocking. DVCS can be used to enhance the performance of directional MAC protocols. Hsu *et al.* in [7] proposed an analytical model to study the throughout performance of directional CSMA/CA MAC protocols. The proposed model assumed directional transmission and omnidirectional reception.

For directional-antenna only networks, Jakllari *et al.* proposed a MAC protocol called PMAC [8]. PMAC polls its one hop neighbors to obtain their location information and schedules transmissions/receptions. At the scheduled time, nodes (the sender and receiver) point their antennae towards each other and carry their communication exclusively using directional antennae. Although PMAC eliminates the asymmetry-in-gain problem, it requires network synchronization. Furthermore, the optimal frame duration is a system parameter that may be difficult to obtain in dynamic network conditions. In addition, the neighbor discovery time is proportional to the number of antennae sectors used (i.e., at least one frame duration for every direction). Finally, having nodes poll all of their one-hop neighbors may not be efficient if the traffic is bursty. Therefore, it is desirable to develop a directional MAC protocol for ad hoc networks, which can operate in a distributed, asynchronous manner. This motivates us to develop our own DtD MAC protocol.

III. Directional-to-Directional MAC protocol

In this section, we outline the main components of the proposed Directional-to-Directional (DtD) MAC protocol.

A. Continuous sector scanning by idle nodes

To minimize the effect of deafness caused by directional antenna, nodes who want to initiate a transmission should send multiple directional RTS (DRTS) messages in each direction. Idle nodes should switch their sensing directions clockwise (or anti-clockwise) continuously . Without synchronization, an idle node should spend $DRTS + SIFS + \chi_{BO}$ time in each sector to capture the DRTS intended to itself, where $SIFS$ is the Short Inter-Frame Spacing (SIFS) and χ_{BO} is the sender sensing time and the maximum backoff time between two $DRTS$, respectively. The derivation of this value will be discussed in Sec. III-C. Overhearing a transmission on one of its beams, a node will set its DNAV accordingly and continue to scan sequentially through all the other directions.

The above continuous scanning mechanism can avoid persistent hearing of DATA not targeted for the receiver. Second, it also reduces the chance a receiver pointing to another direction and missing the sender's DRTS request. In addition, it increases the number of neighbors that set their DNAVs properly to mitigate the directional hidden terminal problem.

B. DRTS/DCTS/DATA/ACK

In ad hoc networks, MAC protocols exchange RTS/CTS messages to solve the hidden terminal problem. With directional antenna, if nodes are not synchronized, a sender may change its direction and attempt to send in a direction that is already in use (another pair of nodes that are communicating). To solve this problem, a sender should sense the medium for a sufficiently long period of time before sending its DRTS message. This sensing period is set to be equal to the transmission time of a DATA packet and a SIFS period. This way, a sender will always overhear the ACK or DATA packet of the on-going transmission taking place in a certain direction and refrain from transmitting to avoid collisions.

In addition, to guarantee that the sender captures the receiver, it sends multiple DRTS messages in each direction. In our protocol, if the direction of the receiver is not known, a sender randomly chooses a new direction and transmits up to $2M$ DRTS in that direction. In the worst case, a sender would have to send $2M$ packets in M directions for each retry. This would cause the sender to send $2M^2$ DRTS packets.

When the receiver gets the DRTS successfully, it caches the AoA, responds with a Directional CTS (DCTS) in the direction of the sender, locks its antenna in the direction of the sender and waits for the DATA. Upon receiving a DATA packet that is intended for it, the receiver replies with an ACK. If a sending node does not receive an ACK within an $ACK_{TIMEOUT}$ time, it backs off and re-sends the DATA packet again for $DATA_{MaxNum}$ times. If the DATA is not received within the $DATA_{TIMEOUT}$ time, the receiver unlocks its antenna and continues sector scanning.

C. Backoff

In omnidirectional MAC protocols, if no CTS is replied by the receiver, a sender should backoff (BO) a random period before retry, and the average BO time is exponentially increased after each failed transmission. This is because the unsuccessful RTS transmissions are most likely due to collisions, and increasing the BO time can reduce the collision probability. However, when using directional antennae, the deafness problem is introduced, and most of the DRTSs are not replied due to deafness, since a directional receiving node may only sense one direction at any given time. Therefore, the Binary Exponential Backoff (BEB) algorithm used in the IEEE 802.11 MAC protocol may not be efficient in the DtD MAC protocol. Since a sender is required to send up to $2M$ DRTS packets in each direction, it may be required to increase its BO window up to $2M$ times during this stage. To ensure that a sending node can capture its intended receiver with at most $2M$ DRTS attempts and to alleviate the effect of deafness, we propose a random BO scheme: for the $(2i-1)$-th DRTS ($i = 1, 2, ..., M$), the contention window size W_{2i-1} is randomly chosen from $[0, W_{\max})$, and for the $2i$-th DRTS, W_{2i} is randomly chosen from $[W_{\max} - DRTS - SIFS - W_{2i-1}, W_{\max})$. This BO scheme is designed to ensure that an idle receiver can capture a DRTS no matter which direction it begins to sense, as explained below.

First, without synchronization, an idle node should spend at least $(DRTS + SIFS + BO_{max})$ in each direction to ensure that if there are DRTSs coming from that direction, the idle node can capture at least one of them. Second, in the worst case, the idle node will spend $(M-1)(DRTS +$

$SIFS + BO_{max}$) time in other directions before it senses the sender's direction, so the sender should ensure that the duration between the beginning of the first DRTS to the beginning of the $2M$th DRTS should be longer than $(M - 1)(DRTS + SIFS + BO_{max})$:

$$(2M-1)(DRTS+SIFS)+\sum_{i=2}^{2M} BO_i \geq (M-1)(DRTS+SIFS+BO_{max}). \quad (1)$$

where BO_i is the BO time before the i-th DRTS.

To ensure (1), a sufficient condition is

$$BO_{2i-1} + BO_{2i} \geq BO_{max} - DRTS - SIFS, \quad (2)$$

for $i = 1, 2, \cdots, M$.

If $BO_{2i-1} \in [0, BO_{max})$, then choose BO_{2i} from $[BO_{max} - DRTS - SIFS - BO_i, BO_{\max})$ will ensure (2). Therefore, our BO scheme can ensure an idle receiver to capture at least one DRTS from the sender. The key parameter in the BO scheme is W_{max}, which should be appropriately chosen to balance the tradeoff between collisions and channel time being wasted during BO.

D. Control flow of the DtD MAC protocol

Figure 1 outlines the normal operation of the protocol. As being observed, a sender only attempts to send after it senses the medium in the direction of transmission idle for $DATA + SIFS$ time and when the DNAV entry in the direction of the receiver is not set. If the direction of the receiver is not known, then the sender sends the DRTS in a randomly chosen direction. In both cases, a maximum of $2M$ DRTS packets are sent in any direction. After sending the DRTS, it waits in the direction for the DCTS to return. If the DCTS is not received, then the sender should backoff and send the DRTS again. If the DCTS is received, then the node continues to send the DATA and wait for the ACK.

E. Design features of the DtD MAC protocol

The main design features and advantages of the proposed DtD MAC protocol are summarized below.

- *Eliminate asymmetry-in-gain problem:* The asymmetry-in-gain problem is caused by the use of both directional and omnidirectional antennae within the same network, where the directional antennae have a higher gain than omnidirectional antennae. Since the DtD MAC only relies on directional antennae, we eliminate this problem for directional antennae with low side lobe gains.
- *Fully distributed:* The DtD MAC protocol does not require any centralized controller and can operate in a fully distributed manner. This is an advantage unmatched in existing protocols using directional antennae exclusively.
- *Eliminate the need for synchronization:* Sending multiple DRTS packets in each direction allows the network to operate without synchronization. This is another advantage, since synchronization is difficult in ad hoc networks.
- *Alleviate the deafness and collision:* Since a sender is required to send multiple DRTS packets in each direction, it minimizes the deafness problem. Since each sender is required to sense the medium for $DATA + SIFS$ time in a new direction before transmitting, DtD MAC can reduce the chance of collisions due to deafness.

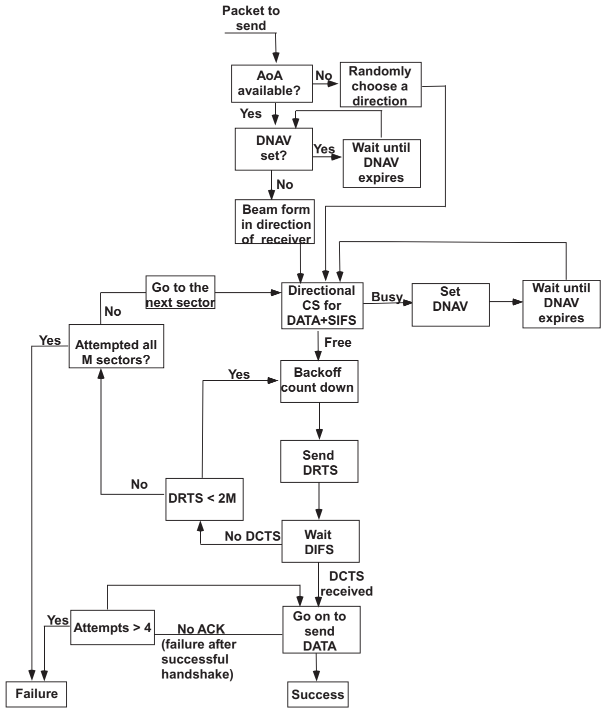


Fig. 1. Control flow of the DtD MAC protocol.

IV. Performance Evaluation

In this section, we first analyze the saturation throughput of networks using the DtD MAC and then we present our simulation results to validate our analysis.

A. Network throughput analysis

In this section, we derive the system's MAC-layer saturation throughput, assuming that all nodes in the network are continuously loaded for transmission.

Consider a system that consists of N nodes, each of them is equipped with an M-sector directional antenna. Nodes are randomly and uniformly distributed in the area. Using directional antennae, all nodes can directly communicate with each other, and each source node randomly picks a destination. Each node can be in one of the six states. Each node's state transition process is represented by a discrete time Markov chain, as shown in Fig. 2. The *success* state is the state at which a node resides after completing a successful data transmission. The *receive* state is the state at which a node successfully receives a packet. The *failure* state is the state at which a node fails to transmit a packet. The *defer* state is the state at which a node enters when it has a packet to send, but it is forced to defer transmission due to its DNAV. The *overhear* state denotes the state where a node overhears other nodes. Otherwise, a node is considered to be in the *idle* state.

Let τ denote the packet transmission probability and p denote the conditional failure probability. Similar to the approach

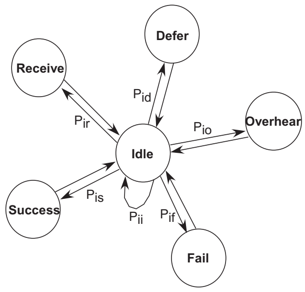


Fig. 2. Markov chain state diagram for each node.

in [9], τ can be derived as

$$\tau(p) = \frac{2(1+p)(1-p^{2M})(W_{max}-1)}{(1-p^2)+(\frac{5+6C-W_{max}}{4})p^2(W_{max}-1)+(1-p^{2M})(p^3-p^{2M+1})}. \quad (3)$$

Next, we need to calculate p, the conditional failure probability. Let the steady state probabilities of the node state Markov chain be denoted as π_i, π_s, π_r, π_f, π_d, and π_o, and the average time periods that a node stays in the corresponding states be T_i, T_s, T_r, T_f, T_d, and T_o, respectively. We define the continuous-time state process $X = \{X_t, t \geq 0\}$ with the node state variable at time t, X_t, which denotes the state into which the system transitioned at the last transition time occurring before time t. Let π' represent the steady state probability that the continuous time semi-Markov process X resides in the idle state at any time. Then, π' can be calculated in terms of its embedded discrete time state process as [10]

$$\pi' = \frac{\pi_i T_i}{\pi_i T_i + \pi_s T_s + \pi_r T_r + \pi_f T_f + \pi_d T_d + \pi_o T_o}. \quad (4)$$

Consider a node T whose next packet is to be forwarded to a neighboring node R. The probability of failure of T's packet at an arbitrary time t_0 is given by

$$\begin{aligned} p &= 1 - \Pr\{\text{success} \mid \text{a transmission attempted}\} \\ &= 1 - p_1 p_2 p_3, \end{aligned} \quad (5)$$

where

$$\begin{aligned} p_1 &= \Pr\{\text{receiver node is idle at } \mathrm{t}_0\} = \pi', \\ p_2 &= \Pr\{\text{signal is strong enough at receiver}\}, \\ p_3 &= \Pr\{\text{no stations in the sender's beam} \\ &\quad \text{initiate a transmission in} \\ &\quad \text{the receivers direction in the} \\ &\quad 2\mathrm{DRTS} + 2 \text{ slot times}\} \\ &= (1 - \pi'\tau(\frac{1}{M})^2)^{(N-2)(2DRTS+2)}. \end{aligned}$$

For simplicity, in our analysis we assume $p_2 = 1$. Next, we need to derive the transition and steady state probabilities. Using (3), (4) and (5), we obtain the transition probabilities:

$$P_{is} = P_{ir} = \tau(1-p), \quad (6)$$

$$\begin{aligned} P_{ii} &= (1-\tau)\Pr\{\text{no stations start to transmit} \\ &\quad \text{DRTS or DCTS in its direction}\} \\ &= (1-\tau)(1-\pi'\tau(\frac{1}{M})-\pi' P_{ir}(\frac{1}{M}))^{N-1}, \end{aligned} \quad (7)$$

$$P_{if} = \tau p, \quad (8)$$

$$P_{si} = P_{ri} = P_{fi} = P_{di} = P_{oi} = 1. \quad (9)$$

The calculation of P_{id} and P_{io} is more involved. Since the ratio of the number of packets per packet type is as follows: RTS:CTS:DATA:ACK is M:(1-p):(1-p):(1-p), we can define

$$\begin{aligned} P_{id} &= \Pr\{\text{sender successfully receives} \\ &\quad \text{incoming packet that is not intended} \\ &\quad \text{for it}\}\Pr\{\text{incoming packet is} \\ &\quad \text{DRTS/DCTS}\}\Pr\{\text{it is oriented to} \\ &\quad \text{the direction of next packet}\} \\ &\approx (1 - P_{ii} - P_{is} - P_{ir} - P_{if}) \times p_3 \\ &\quad \times \frac{M + (1-p)}{M + (1-p) + (1-p) + (1-p)} \times \frac{1}{M}, \end{aligned}$$

and P_{io} can then be easily obtained as

$$P_{io} = 1 - P_{ii} - P_{is} - P_{ir} - P_{if} - P_{id}. \quad (10)$$

Due to space limitations, we omit the detailed derivations of the the steady state probabilities and the time intervals that a station stays in each of the individual states. Interested readers are encouraged to refer to [11]. Then, the saturation throughput (in bps) of a network with N active nodes is calculated as

$$\begin{aligned} TH &= \sum_{x=1}^{N} (\text{Throughput of node } x) \\ &= \frac{N\pi_s E[P]}{\pi_i T_i + \pi_s E[T_s] + \pi_r T_r + \pi_f E[T_f] + \pi_d T_d + \pi_o T_o}, \end{aligned}$$

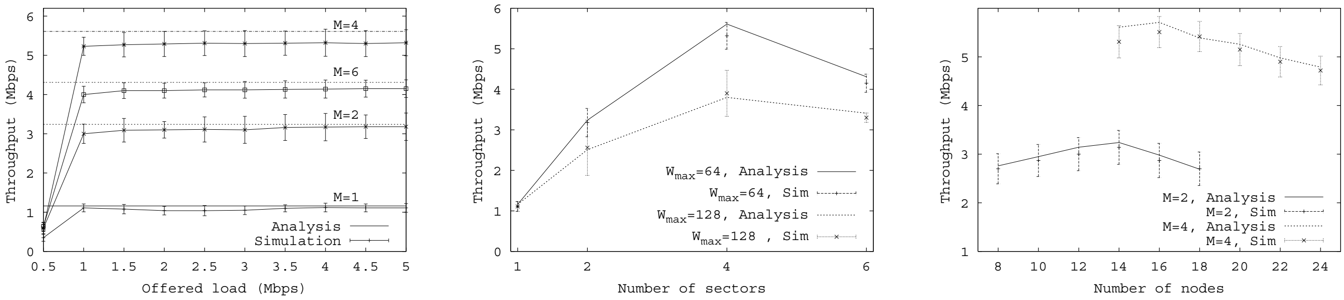
where $E[P]$ is the average payload size of a data packet.

B. Evaluation methodology and scenarios

To verify the analytical model, we implemented the DtD MAC protocol in QualNet v4.0 [12]. On top of the 802.11b PHY layer model, we implement the directional transmission and receiving procedures. The values of the parameters used in the simulations are listed in Table I, unless explicitly stated otherwise. The network topology is randomly generated by QualNet. 14 nodes are uniformly distributed in a 200×200 m^2 area, and they are grouped as seven source-destination pairs. Each pair is loaded with a Constant Bit Rate (CBR) flow. The simulation runs for 100 seconds and the results are the average of 5 runs that use different random seeds. The 95% confidence intervals of simulation results are also plotted.

C. Network throughput simulations

Figure 3 (a) compares the throughput obtained from simulations. For $M = 1$, the original 802.11 DCF MAC is used, and for $M > 1$, the proposed DtD MAC protocol is used. The relatively small value of $W_{\max} = 64$ chosen here is because: a) the number of nodes competing in the same direction using directional antennae is lower than that using omnidirectional antenna, and b) a large number of DRTS messages are missed due to deafness not collision. The general principle is that $W_{\max}$ could be smaller if M is larger. We observe that, as the offered load increases, the network approaches its maximum saturation throughput. We also observe that the directional antennae (M = 2, 4 and 6) cases achieve higher throughput



(a) Throughput vs. offered load. (b) Throughput vs. the # of sectors. (c) Throughput vs. the number of nodes.

Fig. 3. Throughput performance of DtD MAC.

TABLE I
SIMULATION PARAMETERS

Parameter	Value
N	14
Tx range	200 m
Tx power	15 dbm
Data rate	2 Mbps
Base rate	1 Mbps
$W_{\max}$	64
Packet size	512 Bytes
SIFS	10 μS
Slot time σ	20 μS
MAC header	28 Bytes
PHY header	192 bits
DRTS	160 bits + PHY header
DCTS and ACK	112 bits + PHY header

than the omnidirectional antenna ($M = 1$) case, and $M = 4$ achieves the highest throughput in this scenario.

In Figure 3 (b), we plot the network throughput for increasing number of sectors, and $W_{\max}$ is chosen to be 64 and 128, respectively. From the figure, we observe that for a smaller $W_{\max}$, the throughput is higher overall. Furthermore, we can see that when the number of sectors is 2 or 4, the network throughput is higher than the case when the number of sectors is 6. This is mainly due to the increased overhead of the control messages in the DtD protocol. This leads us to conclude that there is an optimal number of antenna sectors and $W_{\max}$ for a specific network density.

Figure 3 (c) shows that the saturation throughput for a certain number of sectors is maximized for a specific number of nodes. Interestingly, we observe that for a higher number of antennae sectors, the number of nodes that the throughput is maximized at is higher (i.e., 14 vs. 16 nodes for 2 or 4 sectors, respectively). This suggests that a higher number of antenna sectors is desirable for more dense networks.

The analytical model slightly overestimates the throughput. This is mainly due to some approximations used in the analytical model (i.e., Eqn. 10). In all cases, the simulation results and the analytical results match well with each other, which validates our analysis.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we have proposed the DtD MAC protocol that supports directional-to-directional transmissions. To the best of our knowledge, this is the first distributed, asynchronous MAC protocol for ad hoc networks using directional antennae exclusively. The performance of the protocol has been studied through an analytical model and verified by simulations. We have showed that the throughput using the proposed DtD MAC can be maximized when the number of sectors is chosen appropriately with respect to the network density. In the future, we plan to investigate the performance of the DtD MAC protocol in the unsaturated case. In addition, we believe that the DtD MAC protocol will achieve even better performance for high data rate technologies such as mmWave, since they rely on directional antenna to combat high path losses.

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