A Directional-to-Directional MAC protocol for 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 directional MAC protocols assume interchangeable directional and omni-directional 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 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 DtD MAC, we develop an analytical model that quantifies the saturation throughput in terms of the number of antennae sectors, the packet size and number of contending nodes per channel. The analytical results are validated by simulations. We show that the DtD MAC protocol can provide significant throughput improvement in ad-hoc networks, compared to the omni-directional antennae, if the number of antennae sectors is chosen appropriately.

I. INTRODUCTION

The use of directional antennas in Ad Hoc networks has received growing attention in the past few years. This interest has been driven by the benefits of using directional antennae in ad hoc networks. These benefits include high spatial reuse, longer transmission range, lower interference, etc... More importantly, new technologies that operate at high frequencies (60GHz), such as mmWave, 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 compensated for in part by the high antenna gain of directional antennae.

At the same time, using directional antennae poses new and interesting challenges. Designing efficient wireless MAC protocols to deal with these challenges is key to the success of using directional antennae in ad hoc networks. Some directional MAC protocols were proposed in [2], [3], [4] that were specifically designed to work with directional antennae. Most of these protocols are based on the IEEE 802.11 DCF MAC protocol and use different flavors of the four way handshake to cope with the challenges introduced by the use of directional antennae. In addition to using the RTS/CTS message exchanges, some of these protocols (such as in [5]) make use of a Directional Network Allocation Vector (DNAV) and Angle of Arrival (AoA) caching. This helps nodes discover which direction their neighbors are located in.

One basic assumption that all these MAC protocols make is that nodes can operate in both, directional and omni-directional mode. In addition to increasing the cost of implementation, this assumption may defeat the purpose of using directional antennae altogether. The work in [6] studied the effect of transmitting control packets omni-directionally and concluded that the omni-directional transmission of some control packets will in fact impede the ability of directional antennae to achieve better throughput. Furthermore, this assumption introduces the asymmetry in gain problem.

To overcome the aforementioned problems, we propose equipping nodes with a single directional antenna, whether it be switched beam or steerable. Then we design an efficient wireless MAC protocol called DtD MAC that operates in directional-only mode. As will be shown later in this paper, the performance of such deployment is quite different from the scheme most researches use under the assumption that nodes can operate in both directional and omni-directional mode.

The contributions of this paper are three-fold. First, we propose a wireless directional-to-directional MAC protocol. Second, we develop an analytical model that quantifies the saturation throughput in terms of the number of antennae sectors, the packet size and number of contending nodes per channel. In addition, extensive simulation using the Qualnet network simulator has been conducted, and the results validate our analysis. The remainder of this paper is organized as follows. In section II, we present the related work. The proposed protocol is described in section III. We present the analytical model in section IV. Section V discusses the performance analysis of the proposed protocol. We conclude the in section VI.

II. RELATED WORK

Nasipuri et al. in [2], proposed a MAC protocol that uses a variation of the IEEE 802.11 DCF to better support directional antennae. In this protocol, RTS/CTS packets are sent omni-directionally and then send DATA and ACK packets directionally. Ko et al. in [3], proposed a MAC protocol that sends a directional RTS when at least one of the antenna beams is blocked or an omni-directional RTS otherwise followed by an omni-directional CTS from the receiver. In their scheme, it was assumed that all nodes know the location of their neighbors using technologies such as GPS. Takai et al. in [4], proposed Directional Virtual Carrier Sensing (DVCS), a mechanism that is composed of using DNAV, AoA and beam locking and unlocking. Such a scheme can be used to enhance the performance of directional MAC protocols. Choudhury et al. in [5], presented an insight into problems that are introduced when using directional antenna and proposed a multi-hop RTS
directional MAC. In their protocol, a sending node sends the RTS to the receiver over multi-hops and the CTS, DATA and ACK packets are exchanged directionally.

Hsu et al. in [7] propose an analytical model to study the throughout performance of directional CSMA/CA MAC protocols. The proposed model assumes directional transmission and omni-directional reception.

Jakllari et al. [8] proposed a MAC protocol that uses directional antennae exclusively, called PMAC. 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.

III. THE DIRECTIONAL-TO-DIRECTIONAL (DtD) MAC PROTOCOL

In this section, we outline the architecture of the proposed MAC protocol. Each subsection describes the functionality and purpose of each component used in the protocol design.

A. Continuous sector scanning by idle nodes

To minimize the effect of deafness, we realized that having the idle nodes switch between beams in a clockwise/anti-clockwise fashion is a must. In essence, such a behavior emulates the presence of an omni-directional antenna at the receiver. Idle nodes spend $2 \times DRTS + SIFS + \chi_{BO}$ time in each sector. $\chi_{BO}$ is added to compensate for the time that a sending node may spend backing off. The detailed derivation of this value is discussed in more detail in Sec. III-E

Any node that hears a transmission on one of its beams, sets the DNAV and continues to scan sequentially through all the other beams. First, following such an approach would alleviate the deafness problem. Second, this mechanism also minimizes the chance of a sender finding the receiver pointing in another direction. Or in other words, this would minimize the number of nodes that do not hear other’s handshake messages. Hence, minimizing the directional hidden terminal problem.

This gain, however, comes at the cost of increasing the number of handshake packets that need to be sent by the sender. This increased cost can be explained as follows: node $S$ in Fig. 1 would like to engage in communication with node $R$. These two nodes are not synchronized. Further, assume that node $R$ was idle and was continuously switching between beams. In the worst case scenario, node $S$ would need to send $2M$ DRTS packets to establish a connection with node $R$, where $M$ is the number of antenna sectors.

B. DRTS and DCTS

Since nodes are not synchronized, nodes may change their direction and attempt to send in a direction that is already busy (another pair of nodes are in communication). To solve this issue we propose that nodes sense the medium for a sufficiently long period of time before sending their RTS message. This sensing period is set to be equal to the transmission time of a DATA packet plus a SIFS period. This way, a sending node will always overhear the ACK or DATA packet of the 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 needs to send at most $2M$ DRTS packets in the direction of the receiver.

This number can be explained by the fact that since the nodes are not synchronized, a receiving node may beamform in the direction of the sender just after a DRTS was sent. Therefore, a sender needs to send 2 DRTS packets to ensure that the receiver is not pointing in its direction. Because the receiver may be in any of its $M$ sectors, the sender is required to send $2M$ DRTS packets to successfully contact the receiver (assuming that the sender knows the direction of the receiver).

If the direction of the receiver is not known, then a sender randomly chooses a direction and transmits $2M$ DRTS in that direction. If no response is received, then the sender goes on to the next sector and so on. If the sender goes through all the sectors in this fashion, and no response is received from the intended receiver, then the packet is dropped and the upper layers are notified. In the worst case, a sender would have to send $2M^2$ packets if $M$ directions. This would cause the sender to send $2M^2$ DRTS packets.

An idle node that receives a DRTS caches the AoA and responds with a DCTS in the direction of the sender, if it is the intended receiver. After sending the DCTS, the receiver locks its antenna in the direction of the sender and waits for the DATA. If the DATA is not received within the $DATATimeout$ time, the receiver unlocks its antenna and continues sector scanning.

C. DATA and ACK

Upon receiving a DATA packet that is intended for it, the receiving node replies with a directional ACK that acknowledges the DATA received. If a sending node does not receive an ACK within a $ACKTimeout$ time, it backs off and sends the DATA packet again for $DATAMaxNum$ times.

D. Directional Network Allocation Vector (DNAV) and Angle of Arrival (AoA) caching

NAVs are used in the IEEE 802.11 MAC protocol. Each node maintains a NAV that is updated from the duration field of the overheared RTS/CTS packets. For directional antennae, the use of a similar mechanism was proposed in [4]. This mechanism keeps a NAV value for each beam of the antenna, called directional NAV (DNAV).
At the same time, sending nodes need to estimate the
direction of the intended receiving node. To achieve this, each
node estimates and caches the AoA of signals it overhears.
The AoA information is updated every time a node receives
a signal from one of its neighbors. Before sensing the medium, a
sending node checks its AoA cache to determine the direction
that the receiver is in. If the DNAV for that specific direction
is not blocked (i.e. the medium is free), then it senses the
medium for a sufficiently long time in the the direction of
transmission and sends DATA directionally in the direction of
the receiver.

If the AoA is unavailable for the intended neighbor, the
DRTS packets are sent on one of the sectors randomly and
continues to be sent on the one of sectors until the transmission
has been attempted on each of the sectors at least once.

E. Backoff

In omni-directional MAC protocols, if RTS or DATA pack-
et are not received and CTSed or ACKed by the receiver, a
sending node is required to backoff (BO). This is because
most of the unsuccessful RTS/DATA transmission are due
to collisions, and hence, congestion. However, when using
directional antennae the situation is quite different. This is
because the deafness problem is introduced and most of the
DRTSs are not replied to. Also, the hidden terminal problem
is magnified, which means that in fact most of the DRTS packets
are lost due to deafness and not congestion in the network.

Due to the fact that most unresponded to DRTSs are caused
by deafness, the BEB algorithm used in the IEEE 802.11
MAC protocol proved to be undesirable in DtD MAC [9].
Since sending nodes are required to send up to $2M$ DRTS
packets for 1 DATA packet transmission, it may be required
to increase its BO window $2M$ times during this handshake
stage. At the same time, using a non Additive Increase
Multiplicative Decrease (AIMD) type BO algorithm may lead
to congestion collapse under congested network conditions.
This leads us to conclude that a AIMD type BO algorithm with
a relatively small difference between $W_{\min}$ and $W_{\max}$
is desirable. Therefore, we propose the use of a BEB type
BO algorithm and derive a limit on the upper bound of the BO
window ($W_{\max}$) that depends on $M$ (the number of antenna
sectors) to guarantee that a sending node will be able to capture
its intended receiver (with high probability).

To ensure that an idle receiver can capture a DRTS for a
sending node, we need to satisfy the following

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

The LHS of (1) represents the average time it takes to transmit
$2M$ DRTSs and the RHS represents the average time duration
the receiver takes to scan all sectors, which can be reordered as

$$M \times RTS \geq M \times BO_{max} - \sum_{i=1}^{2M-1} BO_i, \quad (2)$$

where $0 \leq BO_i \leq \sum_{i=1}^{2M-1} W_{min} \times 2^{i-1}$. Then we can
calculate the average value of $BO_i$ to be as

$$E[BO_i] = \frac{1}{2} \sum_{i=1}^{2M-1} W_{min} \times 2^{i-1}. \quad (3)$$

Then (2) can be rewritten as

$$E[ \sum_{i=1}^{2M-1} W_{min} \times 2^{i-1} ] \geq M \times (BO_{max} - RTS), \quad (4)$$

Where the LHS of Eqn.(2) can be represented as $W_{min}, 2W_{min}, 4W_{min}, \ldots, 2^k W_{min}, 2^k W_{min}, \ldots, 2^k W_{min}$.

Evaluating the LHS of Eqn.(4) gives

$$LHS = \frac{W_{min}}{2} (1 + 2 + 4 + \ldots + 2^k) + \left[ \frac{W_{min}}{2} \right] \times (2M - 1 - k - 1) = \frac{W_{min}}{2} \times (2^{k+1} - 1) + 2^{k-1} W_{min} \times (2M - k) = 2^k W_{min} - \frac{W_{min}}{2} + 2^{k-1} W_{min} (2M - k)$$

$$RHS = M (2^k W_{min} - RTS)$$

Then solving $LHS - RHS \geq 0$

$$LHS - RHS = 2^k W_{min} (2M - k) - \frac{W_{min}}{2} - (M - 1)2^k W_{min} + M \times RTS = 2^k W_{min} (2 - k) + M \times RTS - \frac{W_{min}}{2} \geq 0$$

which can be rewritten as

$$M \times RTS \geq [2^{k-1} (k - 2) + \frac{1}{2}] \times W_{min}, \quad (5)$$

and depending on $M$, we choose the corresponding $k$ value to
satisfy the equality in (5). Consequently, the upper bound on
the BO window, $W_{max}$ is then given as $W_{max} = 2^k \times W_{min}$

F. Control flow of the DtD MAC protocol

Fig. 2 outlines the flow process of the normal operation
mode of the protocol. As can be observed, a sender only
attempts to send after it senses the medium in the direction of
transmission for sufficiently long 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 packet in a
randomly chosen direction. In both cases, a maximum of $2M$
DRTS packets are sent in any direction. This is because we
would like to guarantee access to the receiver if the receiver
is not engaged in another communication. After sending the
DRTS, a node waits in the direction it sent the DRTS for the
DCTS to return. If the DCTS is not received, then we backoff
and send DRTS again. If the DCTS is received, then the node
continues to send the DATA and finally receiving the ACK.
Four main advantages of DtDMAC are:

- **Eliminate asymmetry in gain:** Asymmetry in gain is caused by the use of directional and omni-directional antennae within the same network. This problem is caused by the fact that directional antennae have a higher gain than omni-directional antennae. Since we only use directional antennae in our protocol, we eliminate this problem. This advantage increases directional range, which in turn, can benefit routing in terms of computing shorter paths [8].

- **Fully distributed:** DtDMAC does not require any centralized controller and can operate in a fully distributed manner. This is an major advantage that is unmatched in any other protocol that uses directional antennae exclusively. This advantage increases the feasibility of implementation and deployment of directional antennae at both sender and receiver in next generation ad hoc networks.

- **Eliminate the need for synchronization:** Sending 2M DRTS packets in each direction allows the network to operate without synchronization, while at the same time, guaranteeing access to a node (if it is idle). This is a major practical advantage, since synchronization is difficult and costly in heterogenous ad hoc networks.

- **Alleviate the effects of deafness and collision:** Since each sender is required to sense the medium for DATA+SIFS time in the direction of its next head-of-line packet prior to sending, DtDMAC can greatly reduce the chance of collisions. The fact that a sender is required to send 2M DRTS packets in each direction, alleviates the effect of deafness. This advantage improves the overall throughputs performance of DtDMAC.

These advantages highlight the fact that DtDMAC is practical and is ready to be deployed in ad hoc networks.

**IV. ANALYSIS**

In this section, we present the analytical model used to measure the saturation throughput of DtD MAC. Before delving into the saturation throughput derivations, we introduce the antennae model used in the next section. Then we present the saturation throughput calculations.

**A. Antenna Model**

A switched beam antennae at each node that comprises of $M$ fixed beam patterns, where $M = \frac{2\pi}{\theta}$ is used. In our studies we vary $\theta$ from $30^\circ$ to $180^\circ$. We assume that a node can either transmit or receive directionally at any given instance of time. In all cases, all the nodes in the network use antennae with identical fixed beamwidths.

To take into consideration the physical gains of using directional antennae, we adjust the receiver’s power based on the propagation model $P_R = P_T \times G_T \times G_R \times G_C$ where $P_T,G_T,G_R$ and $G_C$ denote the transmission power, transmitter antenna gain, receiver antenna gain, and channel gains respectively. At the transmitter, we adjust the achievable data rate according to the number of antenna sectors $M$ as $Datarate_M = k_M \times Datarate_O$ where $Datarate_O$ is the transmission data rate for omni-directional antenna and $k_M$ is given as [9]

$$k_M \approx \frac{2\log_2 M + \log_2(SNR_O)}{\log_2(SNR_O)}$$  \hspace{1cm} (6)

**B. Network throughput capacity**

In this section, we derive the throughput capacity of the DtDMAC protocol. This analysis expresses the system’s MAC-layer ‘Saturation throughput’. This measure is an indication of the throughput that can be achieved, assuming that all nodes in the network are continuously loaded for transmission.

Consider a system that consists of $N$ stations. Each station is equipped with an antenna that has $M$ sectors. All stations are assumed to be uniformly distributed. In addition, each source node randomly picks a destination for its packets. Each node can be in one of 6 states. Each node’s state process is represented as a discrete time Markov chain process as shown in Fig. 3. When in the idle state, a node is considered to be either backing off or when the channel is observed to be idle. The success state is the state at which a node resides after completing a successful packet transmission. The receive state is the state at which a node successfully receives a packet. The fail state is the state at which a node failed to transmit a packet. The defer state is the state at which a node enters when it has a packet to send, but is forced to defer transmission due to an entry in its DNAV. The over hear state denotes the state where a node overhears other nodes but decides not to defer.

Let $\tau$ denote the packet transmission probability and $p$ denote the conditional failure probability. $W$ denotes the
length of the minimum contention window and \( m \) denotes the maximum backoff value. Then \( \tau \) is defined as [10]

\[
\tau(p) = \frac{2}{1 + W + pW \sum_{i=0}^{2M-1} (2p)^i}.
\]

Next we need to calculate \( p \), the conditional failure probability. Letting the steady state probabilities of the nodal state Markov chain be denoted as \( \pi_s, \pi_i, \pi_f, \pi_d, \) and \( \pi_o \) and the average time periods that a node stays in the corresponding states be \( T_s, T_i, T_f, T_d, \) and \( T_o \) respectively. We define the continuous-time state process \( X = \{X_t, t \geq 0\} \) by defining the node state variable at time \( t \), \( X_t \) to denote the state into which the system transitioned at the last transition time occurring before time \( t \). We set \( \pi' \) to represent the steady state probability that the continuous time semi-Markov state process \( X \) resides in the idle state at any time. Then, \( \pi' \) can be readily calculated in terms of its embedded discrete time state process as [11]

\[
\pi' = \frac{\pi_i T_i}{\pi_s T_s + \pi_i T_i + \pi_f T_f + \pi_d T_d + \pi_o T_o}.
\]

Now consider a node, \( S \) whose next packet is to be forwarded to a neighboring node \( R \), then the probability of failure of \( S \)'s packet at an arbitrary time \( t_0 \) is given by

\[
p = 1 - Pr\{success \mid a \text{ transmission attempted}\} = 1 - p_1 p_2 p_3,
\]

where

\[
p_1 = Pr\{receiver \ node \ is \ idle \ at \ t_0\} = \pi'.
\]

We do not consider the prob. of the receiver pointing in the direction of the sender when calculating \( p_1 \) because it is assumed that the sender will always capture the receiver by sending \( 2M \) DRTS packets. And \( p_2 \) is then given by

\[
p_2 = Pr\{sender's \ signal \ is \ strong \ enough \ at \ receiver\}.
\]

For simplicity, in our analysis we assume that \( p_2 = 1 \). \( p_3 \), the prob. of a successful handshake exchange between the sender and the intended receiver is given as:

\[
p_3 = Pr\{no \ stations \ in \ the \ sender's \ beam \ initiate \ a \ transmission \ in \ the \ receiver's \ direction \ in \ the \ 2t_{rts} + 2 \text{ slot times}\}
\]

\[
= (1 - Pr\{a \ station \ located \ in \ sender's \ beam \} Pr\{it \ transmits\})
\]

\[
Pr\{it's \ transmission \ is \ in \ direction \ of \ the \ receiver\}(N-2)(2t_{rts}+2)
\]

\[
= (1 - \pi' \pi_s(\frac{1}{M})^{N-2}(2t_{rts}+2).
\]

Next we derive the transition probabilities using (7), (8) and (9)

\[
P_{ts} = P_{sr} = \pi = (1-p).
\]

\[
P_{ri} = (1-\pi)Pr\{no \ stations \ start \ to \ transmit \ RTS \ or \ CTS \ in \ its \ direction\}
\]

\[
= (1-\pi)(1 - \pi' \pi_s(\frac{1}{M}) - \pi' \pi_r(\frac{1}{M}))^{N-1}.
\]

\[
P_{pf} = \pi p.
\]

\[
P_{si} = P_{fi} = P_{dt} = P_{os} = 1.
\]

The calculation of \( P_{id} \) and \( P_{io} \) is more involved. To simplify the calculation we make use of the fact that the ratio of the number of packets per packet type is as follows: \( \text{RTS:CTS:DATA:ACK} \) is \( M:(1-p):(1-p):(1-p) \). Then we can write \( P_{id} \) as follows

\[
P_{id} \approx (1 - P_{ts} - P_{ir} - P_{if} - P_{rt}) \times p_3
\]

\[
\times \frac{M + (1-p)}{M + (1-p) + (1-p) + (1-p)} \times \frac{1}{M},
\]

and \( P_{io} \) can then be easily obtained as

\[
P_{io} = 1 - P_{ts} - P_{ir} - P_{if} - P_{rt} - P_{id}.
\]

By solving the balance equations for the steady state probabilities, we obtain

\[
\pi_i = \frac{1}{2 - P_{ts}}
\]

\[
\pi_s = P_{ts} \pi_i = \pi_r
\]

\[
\pi_f = P_{if} \pi_i
\]

\[
\pi_d = P_{id} \pi_i
\]

\[
\pi_o = P_{io} \pi_i
\]

And the corresponding time intervals that a station stays in individual states are given as

\[
T_i = \alpha
\]

\[
E[T_s] \approx M \times \text{RTS} + M \times \text{SIFS} + \text{CTS}
\]

\[
+ \text{SIFS} + H + \text{DATA} + \text{SIFS} + \text{ACK}
\]

\[
+ \text{DATA} + \text{DIFS} + E[BO_s]
\]
with $E[BO_s]$ accounts for the average BO spent in a successful transmission. It is given as

\[
E[BO_s] = \sum_{i=0}^{2M-1} E[BO(i) | (i+1) RTS Tx] \times Pr(i+1) RTS Tx
\]

and assuming that the receiver captures the $i$th DRTS with probability $\frac{1}{2M}$ (uniform distribution), $E[BO_s]$ is given by

\[
E[BO_s] = \frac{1}{2} \sum_{i=0}^{k} + \sum_{j=0}^{i-1} 2^j \times W_{min} \times \frac{1}{2M}
+ \sum_{i=k+2}^{2M-1} \frac{1}{2} W_{max} \times (M-1-k) \times \frac{1}{2M}
\]

The length of the overhear duration is given as

\[
T_r = RTS + SIFS + CTS + SIFS + H + DATA + SIFS + ACK + DIFS
\]

Then the throughput (in bps) can be calculated as

\[
TH = \sum_{x=1}^{N} (TH of node x)
= \pi_s T_s + \pi_i ET_s + \pi_r T_r + \pi_f ET_f + \pi_d T_d + \pi_o T_o.
\]

\[
E[P]
\]

where $E[P]$ is the average payload size of a data packet in bits.
of sectors is chosen appropriately with respect to the number of nodes in the network.

In the future, we plan to study the feasibility of DtD MAC for high data rate technologies such as mmWave. In addition, we would like to study ways to improve the performance of DtD MAC through ‘smart’ sector scanning.

REFERENCES


