Directional MAC Protocol for IEEE 802.11ad based Wireless Local Area Networks

Anique Akhtar and Sinem Coleri Ergen

Abstract—**IEEE 802.11ad defines a new physical and medium access control layer for IEEE 802.11 networks to operate in the unlicensed 60 GHz millimeter wave spectrum for multi-gigabit wireless communications. Higher frequency waves have higher propagation loss but smaller antenna size. Hence, for millimeter wave networks, higher number of antennas can be packed together, enabling beamforming with very large gains. In this paper, we propose a novel Directional MAC protocol for Basic Stations (DMBS) with the goal of fully leveraging spatial reusability, and limit deafness and hidden terminal problems with minimal overhead, and without using any complicated hardware for localization. The distinguishing features of DMBS are threefold. First, DMBS extends the association beamforming training time (A-BFT) of IEEE 802.11ad, during which the stations perform initial beamforming training with the access point (AP), by an intelligent listening mechanism. This mechanism allows the stations to passively learn about the best direction of the neighboring stations, decreasing the associated beamforming training overhead. Second, DMBS determines the best transmission direction by using multi-directional sequential (circular) RTS/CTS (Request To Send/ Clear To Send) (CRTS/CCTS) packets, and tracks the best direction by updating its beamforming table upon reception of every RTS/CTS packet, without requiring any additional hardware for localization. If the location information of the destination is up-to-date, the source station only transmits directional RTS/CTS (DRTS/DCTS) in the known direction. Third, DMBS uses two network allocation vectors (NAVs). The first NAV, denoted by NAV1, is used to reduce deafness by determining the busy nodes upon the reception of every RTS/CTS packet. The second NAV, called NAV2, is used to minimize hidden terminal problem while maximizing spatial reusability by determining whether a transmission can interfere with active communication links. If NAV2 is set, then the node defers its multi-directional communication but still communicates directionally. We provide a novel Markov chain based analytical model to calculate the aggregate network throughput of DMBS. We demonstrate via extensive simulations that DMBS performs better than existing directional communication protocols in terms of throughput for different network sizes, mobilities and number of receivers.**

Index Terms—**millimeter wave, IEEE 802.11ad, directional communication, medium access control, wireless networks, 60GHz**

I. Introduction

Multi-gigabit wireless communications in the unlicensed 60 GHz millimeter wave spectrum enable many new applications in wireless local area networks (WLANs), such as wireless display and high-speed device synchronization. IEEE 802.11ad is an amendment that defines a new physical and medium access control (MAC) layer for WLANs to operate in the millimeter wave spectrum [2], [3], [4], [5]. The distinguishing characteristics of millimeter wave are short wavelength, large bandwidth, high attenuation through most solid materials and high interaction with atmospheric constituents. Progress on antenna array design has demonstrated the feasibility of packing large steerable arrays in small form factors [6], [7], enabling beamforming with very large gains to be implemented in IEEE 802.11ad [8]. Directional communication also increases spatial reuse since there can be multiple communication links at the same time in the same neighborhood without much interference.

The large communication range and high throughput of directional communication come at the cost of more coordination overhead in the communication protocol design, for learning the best beam direction and determining interfering transmissions. Communication between two devices is only possible if the devices have their beams pointing towards each other. Beamforming training is used to help choose the best beam direction pair that gives the highest channel gain. Apart from gathering location information, MAC protocol design also faces other beamforming related problems, including directional hidden terminal [9] and deafness problems [10]. The hidden terminal problem occurs when a potential interferer could not receive an RTS or CTS hence does not defer its communication, and then initiates a transmission that causes a collision with an ongoing communication. Deafness occurs when a transmitter fails to communicate with a receiver because the receiver antenna is pointing in a different direction. Therefore, the receiver fails to receive the RTS, and might appear deaf to the transmitter.

Table I summarizes the previous work on directional MAC protocols. Initial MAC protocols [11], [12], [13] are based on determining the best beam direction for both transmitter and receiver by using omni-directional RTS/CTS (ORTS/OCTS) packets. The disadvantage of using ORTS/OCTS is that these protocols only allow the communication of Omni-Omni (OO) neighbors, which are neighbors that can receive omni-directional transmission when they are in omni mode. This means that these protocols are not utilizing the range provided by directional communication.

Protocols [14], [15], [9], [16] propose the usage of directional RTS/CTS (DRTS/DCTS) packets to increase the communication range to Directional-Omni (DO) neighbors, which are neighbors that can receive the directional transmission of the node when they are in omni mode. The main challenge of

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TABLE I
RELATED WORK ON DIRECTIONAL MAC PROTOCOLS

Ref	RTS	CTS	Range	Beamforming Information	Antenna	Channel(s)	MAC Challenges Addressed	
							Deafness	Hidden Terminals
[11]	Omni	Omni	OO	DoA	Switched	Single	No	No
[12]	Omni	Omni	OO	Exchange Antenna weights	Adaptive array	Multi	No	Yes
[13]	Omni	Omni	OO	Exchange Antenna weights	Adaptive array	Multi	No	Yes
[14]	Dir	Omni	OO	GPS	Switched	Single	No	No
[15]	Dir	Dir	DO	DoA	Adaptive array	Single	No	No
[9]	Dir	Dir	DO	Upper Layer	Adaptive array	Single	No	No
[16]	Dir	Dir	DO	Assumed Available	Switched	Single	Yes	No
[17]	Multi-dir sequential	Dir	DO	DoA	Switched	Single	Yes	Yes
[18]	Multi-dir sequential	Multi-dir sequential	DO	DoA	Switched	Single	Yes	Yes
[19]	Multi-dir sequential	Multi-dir sequential	DO	Upper Layer	Switched	Single	Yes	Yes
[20]	Multi-dir sequential	Multi-dir sequential	DO	Assumed Available	Switched	Single	Yes	Yes
[21]	Multi-dir concurrent	Multi-dir concurrent	OO	Periodic Updates	Adaptive array	Single	No	Yes
[22]	Multi-dir concurrent	Multi-dir concurrent	DO	Assumed Available	Adaptive array	Single	Yes	Yes
[23]	Dir	Dir	DO	Hello Packet	Adaptive array	Single	Yes	Yes
[10]	Dir	Dir	DO	Assumed Available	Switched	Multi	Yes	No
[24]	Dir	Dir	DO	DoA	Switched	Two channel	Yes	No
[25]	Dir	Dir	DO	DoA	Switched	Two channel	Yes	Yes
[26]	Dir	Dir	DO	DoA	Switched	Multi	Yes	Yes
[27]	Dir	Dir	DO	Assumed Available	Switched	Two polarized channels	No	No
[28]	Dir	Dir	DO	DoA	Switched	Two channels	Yes	Yes
[29]	Omni	Omni	OO	GPS	Switched	Multi	Yes	Yes
[30]	Omni	Omni	OO	Assumed Available	Adaptive array	Multi	Yes	Yes

using DRTS/DCTS, however, is determining the best beam direction. These protocols assume either the availability of the location information of the nodes in the network through Global Positioning System (GPS) [14], upper layers [9], [16], or the determination of the Direction of Arrival (DoA) of incoming transmissions by more complicated receivers employing digital beamforming [15]. Moreover, these protocols tend to suffer more from hidden terminal and deafness problems since they do not inform their neighbors of ongoing communication.

Protocols [17], [18], [19], [20] use multi-directional sequential (Circular) RTS/CTS (CRTS/CCTS) control packets in order to minimize hidden terminal and deafness problems while still keeping the transmission range to DO neighbors. The RTS and CTS packets are transmitted in directional mode sequentially from each of the sectors. This informs all the neighboring nodes of the ongoing transmission, thus, minimizes hidden terminal and deafness problems. However, the huge amount of control packet overhead before each data transmission greatly reduces the overall throughput of the system. To tackle this overhead, the transmission of multi-directional concurrent RTS/CTS packets [21], [22], [23] or the use of an additional channel for control packet transmission [10], [24], [25], [26], [27], [28], [29], [30] have also been proposed. In multi-directional concurrent RTS/CTS packets, the communicating nodes send packets directionally from each of their sectors concurrently by the use of adaptive antenna arrays. Although these protocols solve the overhead problem, they may be difficult to implement in IEEE 802.11ad transceivers due to the requirement of sophisticated hardware for concurrent transmission. The use of additional channel for simultaneous control packet transmission and reception also requires complicated hardware design for IEEE 802.11ad receivers. Furthermore, all of these protocols still assume either the availability of the location information [19], [20], [22], [10], [27], [30] or continuous tracking of the location of neighboring nodes by either introducing extra packet overhead, e.g. periodic hello packet transmission [21], [23], or more complex hardware, e.g. DoA detection [17], [18], [24], [25], [26], [28].

In this paper, we propose a Directional MAC protocol for basic stations (DMBS) with the goal of maximizing total system throughput via efficiently handling deafness and hidden terminal problems while maximizing the spatial reusability with minimum overhead, without requiring any additional hardware or capability for the IEEE 802.11ad transceivers. In IEEE 802.11ad [2], the beamforming training between the stations and AP takes place during the beacon transmission interval (BTI) and association beamforming training time (A-BFT) phases, whereas the beamforming training between the stations is scheduled during the data transfer interval (DTI) phase. The prior work, specifically focusing on IEEE 802.11ad, work on the relay-assisted transmission [31], grouping based multicast efficiency [32], [33] and priority based access to the time intervals [34]. On the other hand, DMBS combines the general structure of the beacon interval of the IEEE 802.11ad protocol with an efficient MAC protocol to minimize the beamforming and control packet overhead while maintaining up-to-date location information and high spatial reusability without any additional hardware. The main novelties of DMBS are listed as follows:

- DMBS combines the usage of DRTS/DCTS and CRTS/CCTS to track the location of the neighboring nodes while transmitting these control packets. Prior work mostly focused on the usage of CRTS/CCTS transmission to handle directional hidden node and deafness problems, based on the assumption of the availability of the location information [17], [18], [19], [20]. In DMBS, CRTS/CCTS are only used when the location information of the destination is not available or outdated, whereas DRTS/DCTS are used when the location information is already available. This assures that we keep the control packet overhead minimal by employing circular communication only when it is needed. Using directional communication in the transmission of RTS/CTS packets assures that the nodes can reach DO neighbors.
- In DMBS, each node keeps a beamforming (BF) table to store the beamforming information of all the neighboring nodes. This BF table is updated during the A-BFT phase and upon reception of every RTS/CTS control packet. First, we incorporate an Intelligent Listening during A-BFT (ILA) mechanism, in which the stations gather beamforming information and update their BF table by listening to the channel while the stations perform beamforming training with the AP during the A-BFT. ILA mechanism was first proposed in [1] and is only one feature of the proposed DMBS protocol. Second, every node updates its BF table upon reception of every RTS/CTS packet by checking the sector ID used to send those RTS/CTS packets. In previously proposed MACs, nodes only process the RTS/CTS packets that are destined to themselves.
- DMBS employs two NAVs: NAV1 and NAV2. NAV1 is used to keep a list of all the busy nodes in order to resolve the deafness problem. The transmitter does not communicate with an already busy node. On the other hand, NAV2 is used to determine the interfering links in order to limit hidden terminal problem while exploiting spatial reusability. If a node has its NAV2 set, then it only defers its circular communication but still communicates directionally.
- DMBS does not require any additional hardware for tracking the location of neighboring nodes nor any complex receiver for determining the direction of incoming packets. DMBS exploits the transmission of CRTS/CCTS control packets to determine the location of nodes, and the reception of every RTS/CTS packet in tracking their location.

There has been a lot of analytical models for omni-directional CSMA/CA protocols, but very few efforts have been made to analytically model directional MAC protocols. In [35], an analytical model is proposed to study the performance of directional CSMA/CA MAC protocols, in which packets are transmitted directionally and received omnidirectionally. [36] models the deafness problem in directional CSMA/CA protocol. [37] analyses the performance of a directional co-operative MAC protocol that uses relay nodes to improve the successful delivery ratio of packets over the network, but while ignoring spatial re-use, which might deteriorate due to multi-hop links. [38] proposes a randomized exclusive region (REX) based scheduling scheme to increase spatial reuse by studying the region around a transmitter that would cause interference. An analytical model is given to investigate the network performance. [39] provides an analytical model for networks that use both directional as well as omni-directional antennas. Apart from RTS/CTS packets, the protocol also utilizes Neighbor Information Packet (NIP) sent by the over hearer idle nodes to minimize the hidden node problem. However, none of these models consider CRTS/CCTS packets based on the assumption of the availability of the location information.

Apart from proposing the novel DMBS protocol, we provide a novel Markov chain based analytical model to calculate the corresponding aggregate network throughput. This model is the first directional CSMA/CA based analytical model that supports the transmission of both DRTS and CRTS packets. We also provide an event-based network simulator for the implementation of the DMBS protocol in MATLAB, called MMWAVEMAC, which is available at [40].

The rest of the paper is organized as follows. Section II describes the network topology, frame structure and beamforming training in the IEEE 802.11ad protocol. Section III describes DMBS protocol. Section IV provides the numerical analysis of the DMBS protocol. Section V gives the performance evaluation of DMBS compared to previously proposed protocols. Section VI gives concluding remarks and future work.

II. IEEE 802.11AD PROTOCOL

In IEEE 802.11ad, a personal basic service set (PBSS) consists of one PBSS control point (PCP) or AP, and N ($1 \leq N \leq 254$) non-PCP/non-AP directional multi-gigabit (DMG) stations (STAs) [2]. Although PBSS is centrally controlled by PCP/AP, peer-to-peer communication among non-PCP/non-AP STAs is also supported. The time is divided into beacon intervals (BI), which are further divided into access periods as follows:

- Beacon Transmission Interval (BTI): An access period during which the AP performs an initiator sector level sweep (SLS) by sending out DMG beacon frames for BF training. The DMG beacon frames indicate the beginning of each BI and inform surrounding STAs the relevant access management information. The presence of the BTI is optional. A non-AP STA shall not transmit during the BTI of the PBSS of which it is a member.
- Association BF Training (A-BFT): An access period during which beamforming training is performed with the AP that transmitted a DMG beacon frame during the preceding BTI. The presence of the A-BFT is optional and signaled in DMG beacon frames.
- Announcement Transmission Interval (ATI): A request-response based management access period between

PCP/AP and non-PCP/non-AP STAs. STAs can send request frames to request allocation in the following DTI to exchange frames between STAs. The presence of the ATI is optional and signaled in DMG beacon frames.

- Data Transfer Interval (DTI): An access period during which frame exchanges are performed between STAs. There is a single DTI per beacon interval. The DTI comprises contention-based access periods (CBAPs) and scheduled service periods (SPs). CBAPs employ 802.11 CSMA/CA for channel access by STAs, while SPs are reserved using service period request (SPR) command after the PCP/AP polls an STA during the ATI period. It is possible to use any combination in the number and order of SPs and CBAPs in the DTI.

The PCP/AP provides the basic timing and scheduling of the access periods within a beacon interval, manages membership of the network, and generates the scheduling information and communicates it with the non-PCP/non-AP STAs.

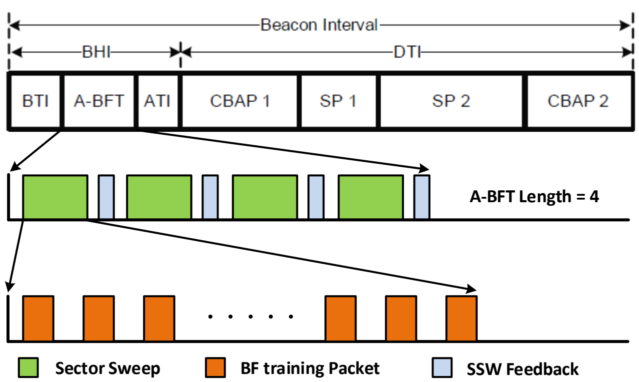

Fig. 1. A-BFT phase in 802.11ad.

A. BF Training

BF training is a bidirectional process in which the transmitting and receiving STAs determine the appropriate antenna settings for the best transmission direction. In IEEE 802.11ad, the STA-AP beamforming takes place during the BTI and A-BFT access periods, whereas the STA-STA beamforming takes place during the DTI access period before the STA-STA transmission. The BF training of STAs may comprise of a Sector Level Sweep (SLS) and a beam refinement protocol (BRP) phase. In the SLS phase, the initiator of the beamforming sends a training frame from each of its sectors sequentially and the responding STA can receive in a quasi-omni mode to determine the best transmitting sector for the initiator STA. Similarly, the responder sends out a training frame from each of its sectors and the initiating STA can receive in a quasi-omni mode to determine the best transmitting sector for the responder STA. Sector sweep feedback information is then exchanged between the two devices. After this, both nodes know each other's best sector IDs. In the BRP phase, the STA trains its antenna arrays and improves its antenna array configuration to fine-tune their beams to achieve the best data rate.

The BF training of the PCP/AP with the non-PCP/non-AP STAs starts during the BTI when the PCP/AP initiates the beamforming with the sector sweep while all the non-PCP/non-AP STAs listen in quasi-omni direction. A-BFT phase is slotted as shown in Fig. 1. All the STAs that received the initiator sector sweep (SSW) randomly choose a time slot in the A-BFT. During this A-BFT time slot, the STA performs responder sector sweep, also informing the PCP/AP of its best sector, and receives feedback from the PCP/AP, called SSW-Feedback, confirming the successful SLS phase of beamforming. Only one STA can receive a SSW-Feedback from the PCP/AP per A-BFT slot. The STA that fails to receive a SSW-Feedback, backoffs and retries later. A STA that has successfully been associated with the PCP/AP upon successful reception of the SSW-Feedback stops contending for the A-BFT, which gives other STAs in the network a better chance to associate with the PCP/AP. The BRP phase of the beamforming may be performed during the scheduled DTI access period.

B. RTS/CTS Transmission

IEEE 802.11 implements a handshake before transmission to avoid collisions [41]. Data transmission is preceded by a short Request-to-Send (RTS) packet to the intended receiver, which in return responds with a short Clear-to-Send (CTS) packet if the channel is idle at the receiver side. Both RTS and CTS packets contain the proposed duration of transmission so all the nodes that overhear these control packets must defer their transmission for the proposed duration. This is implemented by each node updating their Network Allocation Vector (NAV) with the duration field specified in RTS or CTS. If a NAV is a positive number, there is a countdown until it reaches zero. If NAV is equal to zero, the station can transmit.

The transmission of RTS and CTS packets adopt carrier sense multiple access with collision avoidance (CSMA/CA). A station listens to the medium before the transmission. If the channel is idle for a period of time equal to a distributed interframe space (DIFS), the station transmits. Otherwise, the station persists to monitor the channel until it is measured idle for a DIFS. The station then generates a random backoff interval before transmitting to minimize the probability of collision with other transmitting stations. The backoff time is uniformly chosen in the range $[0, CW-1)$. CW is called contention window size, and depends on the number of failed transmissions for the packet. At the first transmission attempt, CW is set equal to a value CW_{min} called minimum contention window size. After each unsuccessful transmission, CW is doubled, up to a maximum value CW_{max}. The backoff time counter is decremented as long as the channel is sensed idle, frozen when the channel is sensed busy, and reactivated when the channel is sensed idle again for more than a DIFS.

C. Modulation and Coding Schemes

The IEEE 802.11ad uses different modulation and coding schemes (MCSs) to provide support for multiple data rates [5],

[42], [43]. IEEE 802.11ad defines four different PHY layers: Control PHY, SC PHY, OFDM PHY and low-power SC PHY (LPSC PHY). Control PHY uses MCS0 (27.5 Mbit/s); SC PHY uses MCS1 to MCS12 (385 to 4620 Mbit/s); OFDM PHY uses MCS13 to MCS24 (693 to 6756 Mbit/s); and LPSC PHY uses MCS25 to MCS31 (626 to 2503 Mbit/s).

Each MCSi has a corresponding SINR requirement γ^i such that link l can transmit with MCSi if the SINR achieved at the corresponding link, given by $\gamma_l = \frac{p_l g_l}{N_0 + \sum_{k \neq l} p_k g_{kl}}$, is greater than or equal to γ^i, where p_l is the transmit power of link l, g_l is the channel gain in link l, g_{kl} is the channel gain from the transmitter of link k to the receiver of link l, and N_0 is the background noise power.

MCS0 is used in the transmission of control packets including CRTS, CCTS, DRTS, and DCTS to increase the range of communication, whereas the data packets are transmitted by using higher rates adjusted according to the received signal strength.

III. Directional MAC protocol for Basic STAs (DMBS)

DMBS protocol aims to maximize total system throughput by combining the general structure of the beacon interval of the IEEE 802.11ad protocol with an efficient MAC protocol to minimize the beamforming and control packet overhead while maintaining up-to-date location information and high spatial reusability without any additional hardware or capability requirement for the IEEE 802.11ad transceivers. The main features of DMBS are as follows:

- DMBS provides an efficient mechanism to both passively and actively learn and track the location of the neighboring nodes without requiring any additional localization hardware nor any complex receiver for determining the direction of incoming packets. First, the nodes employ Intelligent Listening during A-BFT (ILA), in which they passively gather beamforming information by listening to the channel while the stations perform beamforming training with the AP. Second, the nodes passively listen to every RTS/CTS packet and update the beamforming information accordingly. Third, the nodes actively learn about the best transmission direction through CRTS/CCTS packets in the case the location of the receiver is not up-to-date.
- DMBS allows the communication of the DO neighbors by transmitting either DRTS/DCTS packets in the best direction or CRTS/CCTS packets in all the directions in directional mode.
- DMBS employs adaptive transmission of DRTS/DCTS and CRTS/CCTS to limits hidden terminal problem. RTS/CTS packets are transmitted to eliminate the simultaneous transmission of the DO neighbors within the mainlobe of the transmitter/receiver in the direction of the transmitter/receiver. The additional NAV usage enables the nodes reduce interference in the network in the case of a neighboring transmission that they can interfere with, by deferring the circular communication while still allowing directional communication. This reduces the protocol overhead considerably while maximizing spatial reusability, resulting in higher overall throughput.
- DMBS keeps a list of busy neighboring nodes at each node to eliminate the deafness problem. The nodes do not try to initiate communication with a busy receiver. Moreover, idle nodes listen in omni-direction mode and update their BF table on the reception of each control packet to prevent persistent deafness.

Algorithm 1 STA actions during A-BFT upon reception of initiator SSW from the PCP/AP.

```
Choose a random time slot in A-BFT.
if chosen time slot then
    Perform responder SSW
else
    Listen to the responder SSW packets of the DO neighboring STAs
    Retrieve the best sector ID of the neighboring STAs
    Store best sector ID in BF information table
end if
```

In DMBS, each node maintains BF information table to keep two beamforming information entries corresponding to each neighboring node: 1) its own sector ID used to communicate with the neighboring node, 2) sector ID the neighboring node uses to communicate with this node. Each transmitted packet includes the sector ID it was sent from. Furthermore, the transmitted packet also includes the best sector ID of the destination node, if that information is available in the BF table.

A. *Intelligent Listening during A-BFT (ILA)*

In ILA, the STAs passively gather information by listening to the channel when neighboring STAs perform beamforming training with the PCP/AP during A-BFT, and then use that information to decrease the overhead of beamforming with those STAs before the data transmission in DTI phase. As explained in detail in Section II-A, all the STAs that receive the initiator SSW from the PCP/AP randomly choose a time slot in the A-BFT, and perform responder SSW during that time slot. The idle STAs during a time slot, on the other hand, listen in quasi-omni direction, so receives all the packets corresponding to the responder SSW from their DO neighbors. Processing responder SSW packets allows each STA know the best sector ID of all the DO neighboring STAs, i.e. the best direction the DO neighboring STAs should communicate, at the end of the A-BFT access period. This gathered information is then included in the BF information table to eliminate the overhead of beamforming between STAs before the data packet transmission during the DTI period. The actions of STAs during A-BFT upon reception of initiator SSW from the PCP/AP are summarized in Algorithm 1.

Let us consider the scenario shown in Fig. 2. The PCP/AP performs the initiator SSW during the BTI. Each STA then randomly chooses a timeslot in A-BFT to perform the responder SSW. During STA A's SSW, all other STAs, including the PCP/AP, listen in quasi-omni direction. Therefore, STA

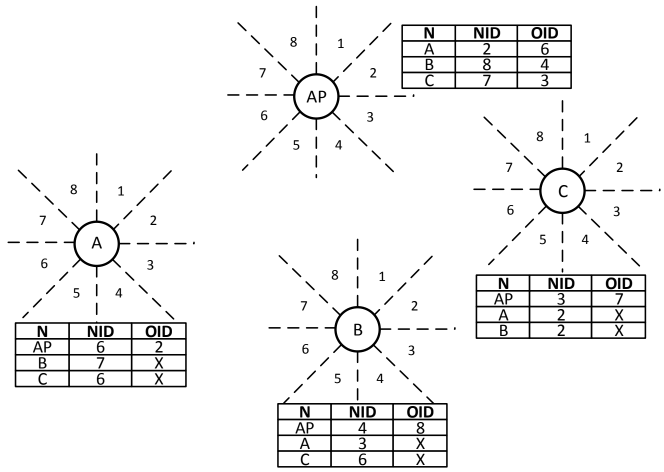

Fig. 2. Illustration of the ILA mechanism. (N = Neighboring Node; NID = Neighbor's best sector ID; OID = Own best sector ID)

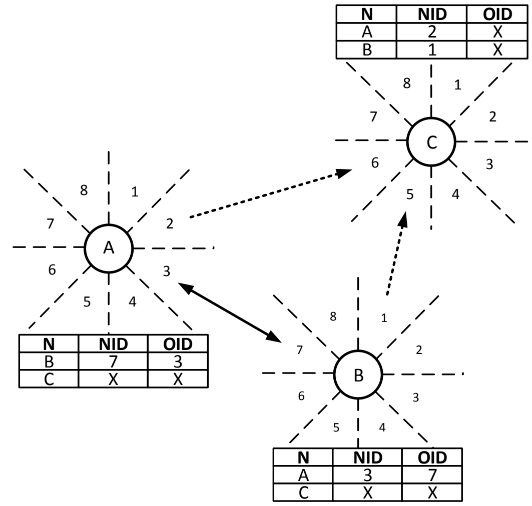

Fig. 3. Illustration of the BF information table update upon reception of CRTS/CCTS transmission. (N = Neighboring Node; NID = Neighbor's best sector ID; OID = Own best sector ID)

B learns that the best sector ID of STA A to communicate to STA B is 3, whereas STA C determines the best sector ID of STA A to communicate to STA C as 2. Following the responder SSW of STA A, in the same timeslot, PCP/AP sends the SSW feedback to STA A. Similarly, STAs B and C perform the responder SSW in different timeslots, during which the neighboring STAs determine their best sector ID to communicate to these neighbors. The resulting BF information tables are shown in the figure.

B. Updating BF Information Table

The BF table is partially filled by the ILA mechanism during the A-BFT. Each node that receives the responder SSW during A-BFT updates their BF table. Furthermore, on the reception of every RTS/CTS packets the BF table is updated.

The users listen in omni-directional mode whenever they are idle or in backoff mode. If a node receives a packet and the BF table for the sender is empty, it updates the BF table with the best sector ID of the neighbor (NID). If the BF table already has the corresponding node's best sector ID, then that value is updated. If the new sector ID is different from the previous one, the node also deletes its own best sector ID (OID) for the corresponding node. The reason for deleting the entry is that if the best sector ID of the neighboring STA (NID) is outdated, due to mobility and/or new obstacles in between, most probably, the best sector ID of the STA (OID) is also outdated.

An example for the update of an empty BF information table with CRTS/CCTS packet reception is illustrated in Fig. 3. STAs A and B communicate with each other by using CRTS-CCTS-DATA-ACK transmission. Following the reception of CRTS/CCTS packets, the nodes learn about the best sector IDs to communicate with each other. Meanwhile, the neighboring STA C also determine the best sector ID of STAs A and B to communicate to STA C and fill the corresponding entries in the BF table accordingly.

C. NAV mechanism

NAV is used to defer the communication of the nodes interfering with an ongoing transmission for the duration specified in RTS/CTS packets. In omni-directional transmission, all the nodes around the transmitter and receiver are considered as interfering nodes. In the directional communication, however, only the nodes within the mainlobe of the transmitter and receiver need to defer their communications in the direction of that transmitter and receiver, respectively. The reason for this is if a node within the mainlobe of a receiver sends packets in the direction of that receiver, the gain of the antennas of both nodes will be mainlobe gain, whereas in all other cases at least one of the antennas will contribute with the sidelobe gain. Since the mainlobe gain is much larger that sidelobe gain in millimeter wave communications, the contribution from all other nodes will be negligible in most cases. Moreover, keeping the number of nodes that defer their communication to a minimal increases spatial reusability, resulting in higher throughput.

IEEE 802.11ad supports STAs with multiple NAV timers, one for each sector [2]. However, the previous papers implementing Directional NAV (DNAV) for each sector assume the availability of the incoming direction for the RTS and CTS packets with additional or more complex hardware through either GPS or DoA [15], [23], [9]. Since DMBS does not assume the pre-knowledge of the sector that it overhears the RTS/CTS packets from, we employ two NAVs, NAV1 and NAV2, to minimize deafness and hidden terminal problems.

Algorithm 2 summarizes the NAV update process upon reception of RTS/CTS control packets:

- NAV1 keeps a list of all the busy nodes and the time duration they are busy for. NAV1 is updated after the reception of every RTS/CTS packet. The nodes defer their communication with the destination nodes in the NAV1

Algorithm 2 NAV Update upon reception of RTS/CTS control packets.

Update NAV1 with source and duration of packet;
if DRTS or DCTS control packet received **then**
    Update NAV2 with duration of packet;
else if both CCTS and CRTS control packets received **then**
    Find relative position;
    if node can interfere with communication **then**
        Update NAV2 with duration of packet;
    end if
end if

Algorithm 3 Transmitter's behavior in sending data packet.

if NAV1 for the destination is non zero **then**
    Defer communication.
else
    if tries $< n_{max}$ and BF info available **then**
        Send DRTS.
    else if NAV2 is not set **then**
        Send CRTS
    else
        Defer communication.
    end if
end if

Algorithm 4 Receiver decision mechanism upon reception of RTS packet.

if RTS received has BF info and RTS sent from expected sector **then**
    Send DCTS;
else if receiver's NAV2 is not set **then**
    Send CCTS;
end if

list for the corresponding duration field, thus eliminating any potential deafness problem.

- NAV2 is set if a node can cause interference to an ongoing communication. NAV2 forces the node to defer its circular communication but can still communicate in directional mode:
  - If DRTS or DCTS control packet is received, NAV2 is updated to include duration.
  - If a node receives both CRTS and CCTS packets, it will determine whether it can interfere with the ongoing communication. From the CRTS packet, a node first determines the best sector ID of the transmitter to reach that node. From the CCTS packet, a node determines which sector ID the transmitter needs to use to transmit to the receiver. Comparing these two sector IDs, a node can find its relative position with respect to the transmitter's direction of communication. The node will set its NAV2 if it is exactly in the direction of communication or is in vertically opposite direction.
  - If a node receives only one of CCTS and CRTS without receiving a DRTS or DCTS, it will not set its NAV2 value because it is not a potential interferer.

If NAV2 is set it means that the node knows it can cause interference to the ongoing transmission but does not know in which sector ID it would cause interference. In that case, the node will definitely cause interference if it sends a CRTS or CCTS packet. Therefore, it has to limit its circular (CRTS/CCTS) transmissions. On the other hand, the probability it causes interference if it communicates using DRTS/DCTS is only $1/S$, where S is the total number of sectors. Hence, it doesn't limit its DRTS/DCTS transmissions, which increases spatial reusability in the network.

D. Transmitter

A transmitter uses both NAV1 and NAV2 to minimizes hidden terminal and deafness problems effectively while maximizing spatial reusability, as given in Algorithm 3. When a transmitter has a packet to send, it first checks its NAV1 to make sure the destination node is not busy. If the destination node is busy, the transmitter defers its communication. If the destination node is not busy, the transmitter has the beamforming information of the destination node and the number of failed transmission attempts since the last successful transmission is less than n_{max}, it sends DRTS packet in the best sector direction. Otherwise, the transmitter needs to send a CRTS packet. If the transmitter's NAV2 is clear, the transmitter sends a CRTS packet otherwise it defers its communication.

A transmitter may not receive a response back for three reasons: the destination node is busy and hence deaf, the destination node has moved or the destination node has NAV2 set and is not allowed to respond with CCTS. If the transmitter fails to get a CTS response back from the receiver after n_{max} consecutive DRTS, it is assumed that the beamforming information is outdated and the subsequent RTS is sent by using CRTS (Only if NAV2 is not set).

Algorithm 3 explains the behavior of a transmitter when it has a packet to send. Variable 'tries' keeps the number of failed transmission attempts since the last successful transmission. Exponential backoff is executed if the RTS response is not received or the communication is deferred.

E. Receiver

A receiver adapts a mechanism that assures a DCTS is sent only if the received RTS packet contains up-to-date best sector ID information and the sector ID information for the source of the RTS packet exists in the BF information table, otherwise a CCTS is sent, as given in Algorithm 4. Upon reception of an RTS packet, the receiver extracts the beamforming information from the RTS packet. The receiver determines which sector the transmitter used to send the RTS, which is the best sector ID of the transmitter. The receiver compares this sector ID retrieved from the received RTS packet with the sector ID in its BF information table corresponding to this transmitter to check whether it was sent from the expected sector. Only if these two sector IDs are the same, does the receiver send a DCTS. This comparison enables the receiver to have up-to-date BF information table.

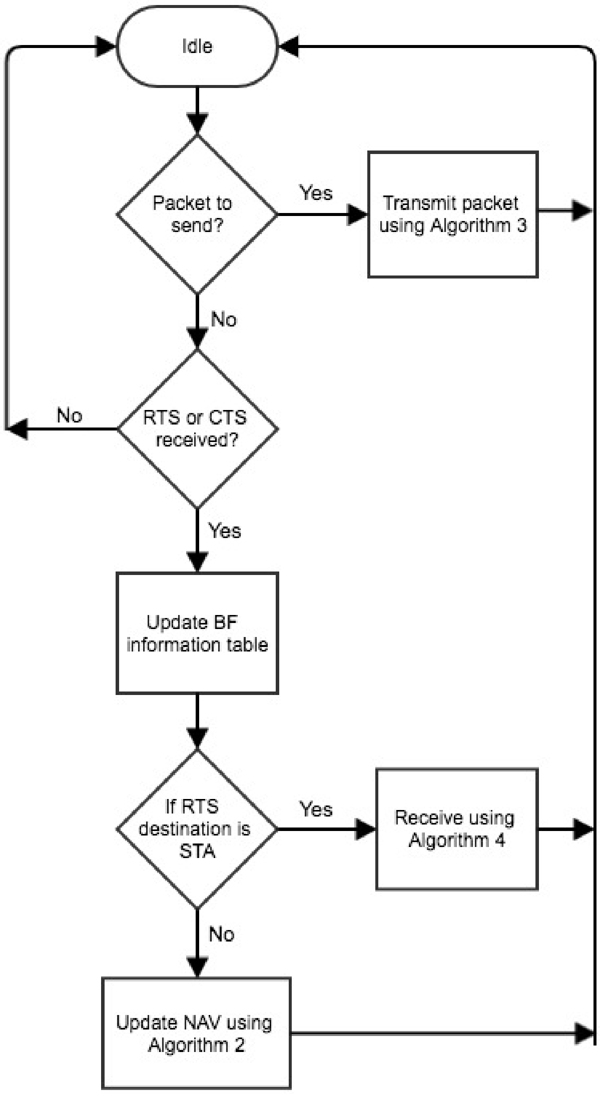

Fig. 4. DMBS Flow Chart

The receiver sends a CCTS in all other cases given as follows: (1) The RTS does not include beamforming information about the best sector ID of the receiver or (2) the received RTS was not sent from the expected sector (Only if NAV2 is not set). The RTS would not include beamforming information if the transmitter does not know the best sector ID of the receiver. This would happen if the transmitter has never received a control packet from this receiver before or the sector ID information became outdated. The received RTS would not be sent from the expected sector if the transmitter or receiver moved so the transmitter no longer uses the same sector it used last time to communicate with the receiver. Algorithm 4 explains the behaviour of a receiver upon the reception of an RTS packet.

The flowchart of the DMBS protocol combining all of these algorithms is provided in Fig. 4.

IV. Performance Analysis

In this section, we analyse the aggregate throughput capacity of directional CSMA/CA system. We provide a mathematical analytical model for directional MAC protocols. With slight changes, this model can be used to model most directional MAC protocols. We hope that this model can help evaluate existing directional MAC protocols as well as help develop future MAC protocols. This analytical model also serves as a validation for our simulation results.

We assume the existence of a finite number of nodes operating in saturation condition, i.e., the transmission queue of each station is always nonempty. We assume that the collisions can only happen in the transmission of RTS and the probability of further collisions is minimal and can be ignored. The radios are half duplex, meaning a node cannot transmit and receive at the same time. A node does not have the capability to receive multiple signals at the same time. For the analytical model, we assume that the wireless channel is not error-free, but the errors can happen in the data packets alone.

We model the nodal state diagrams of the nodes in the network by using discrete-time Markov chains. The transition probabilities of all the nodes are assumed to be the same, facing the same channel conditions, similar to Bianchi's model given in [44]. The original model was proposed for omni-directional WLANs. The model allows the calculation of the probability of a node being in transmission state or in non-transmission state. We extend this model for directional WLANs based on the further classification of the *transmission* and *non-transmission* states for the transmission of different types of RTS and CTS messages, and the reception and overhearing of packets. We do not assume that each STA can hear every other STA in the network like in the Bianchi's model. Instead, we assume that STAs can only sense the STAs that are transmitting in their direction. We also address the backoff freezing problem of the Bianchi's model.

Fig. 5 shows the per node Markov chain, where $W_i = 2^i W$, W denotes the minimum contention window size, m is the maximum backoff stage value, and p is the packet error probability that includes the conditional collision probability as well as the packet errors due to the channel. Let $b_{i,k}$ be the steady state probability of state (i, k), in which $i \in [0, m]$, $k \in [0, W_i - 1]$. These states can further be divided into *transmission states* ($i \in [0, m],\ k = 0$) and *non-transmission states* ($i \in [0, m],\ k \in [1, W_i - 1]$). The probability that a station transmits in a randomly chosen slot time, denoted by τ, is then the sum of the steady state probabilities of all the *transmission states* and given by [44]

$$\tau(p) = \sum_{i=0}^{m} b_{i,0} = \frac{2(1-2p)}{(1-2p)(W+1) + pW(1-(2p)^m)} \quad (1)$$

Each of the *transmission state* forms its own Markov chain, as shown in Fig. 5. A station performs a CRTS and DRTS in *CRTS* and *DRTS* states, respectively. A station goes to *Success state* if the RTS is received by the destination station. A station continues with the rest of the communication (CTS, DATA, and ACK) in the *Success state*. If the RTS is not received

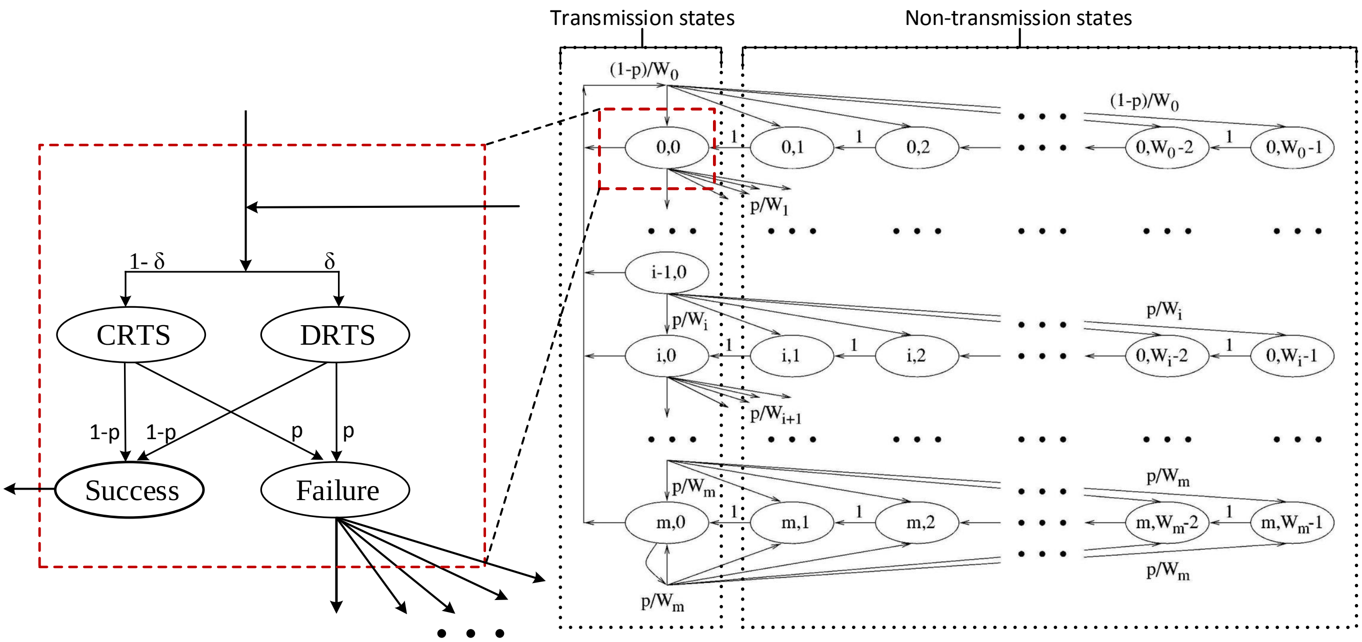

Fig. 5. Markov chain for the backoff mechanism divided into transmission and non-transmission states, with one transmission state further explained.

successfully, the station goes into *Failure state*, waits there for *DIFS* time before backing off. δ is the probability of the transmission of DRTS. We define b_c, b_d, b_s and b_f as the steady state probability that a station in a *transmission state* resides in *CRTS, DRTS, Success* and *Failure* state, respectively. Since the transmission state itself forms a repetitive stationary Markov chain, we can solve it to obtain $b_c = \frac{1-\delta}{2}$, $b_d = \frac{\delta}{2}$, $b_s = \frac{1-p}{2}$, and $b_f = \frac{p}{2}$. Let β denote the beamwidth of each station's antenna such that $\frac{2\pi}{\beta}$ is the number of sectors. T_c, T_d, T_s, and T_f are defined as the time duration the station spends in *CRTS, DRTS, Success* and *Failure* state, respectively, and given by

$$T_c = \frac{2\pi}{\beta}.T_{RTS} + (\frac{2\pi}{\beta} - 1).T_{SBIFS} \tag{2}$$

$$T_d = T_{RTS} \tag{3}$$

$$\begin{aligned} T_s = T_{SIFS} + T_{CTS} + T_{SIFS} + T_{TXOP} + T_{SIFS} \\ + T_{RTS} + T_{DIFS}; \end{aligned} \tag{4}$$

$$T_f = T_{DIFS} \tag{5}$$

where T_{RTS}, T_{SBIFS}, T_{SIFS}, T_{CTS}, T_{TXOP}, and T_{DIFS} are the time duration of the RTS transmission, SBIFS, SIFS, CTS transmission, payload transmission and DIFS, respectively, taken from 802.11ad standard [2]. During CRTS transmission, the node transmits an RTS packet sequentially in each direction. T_{SBIFS} is the time duration between two sequential RTS packets, required to change the antenna direction. T_{SIFS} is the time duration between packet transmissions and receptions. T_{TXOP} is the amount of time required to transmit a data packet. T_{DIFS} is the time duration during which a node senses the medium before transitioning into the next state.

We define π_c and π_d as the steady state probability that a station in a *transmission state* resides in the *CRTS* and *DRTS* state at any given time, respectively. π_c and π_d are therefore calculated by including the time duration of each state as follows:

$$\pi_c = \frac{b_c T_c}{b_c T_c + b_d T_d + b_s T_s + b_f T_f} \tag{6}$$

$$\pi_d = \frac{b_d T_d}{b_c T_c + b_d T_d + b_s T_s + b_f T_f} \tag{7}$$

When a node is in a *non-transmission state* it would either be in *receive, overhearing DRTS, overhearing CRTS,* or *idle* state with probability P_r, P_{od}, P_{oc}, and P_i, respectively. Based on the assumption of collisions only occurring in RTS packets, we are ignoring all the other possible states as the probability of those states are minimal. A node is in *receive* state when it successfully receives an RTS packet that is intended for itself. A node can sense the channel busy and go in *overhearing DRTS* and *overhearing CRTS* state when it receives a DRTS and CRTS not intended for itself, respectively. The backoff counter freezes in the *overhearing DRTS* and *overhearing CRTS* state hence accounting for the backoff freezing. Otherwise, the node is in *idle* state that lasts for a slot length, denoted by σ. Let π_i represent the steady state probability that the node in a *non-transmission state* resides at any time in the *idle* state. Let T_r, T_{od}, T_{oc}, and T_i denote the time a node spends in *receive, overhearing DRTS, overhearing CRTS,* and *idle* state, respectively.

$$\pi_i = \frac{P_i T_i}{P_i T_i + P_{od} T_{od} + P_{oc} T_{oc} + P_r T_r} \tag{8}$$

Let x be a node in the network and N be the total number of nodes in the network. A node x is in *overhearing DRTS* state if only one other node transmits DRTS in x's direction and no other node transmits in x's direction:

$$P_{od} = (N-1).p_2.p_1 \tag{9}$$

where p_2 is the probability a node transmits in $x's$ direction and p_1 is the probability that no other node transmits RTS in $x's$ direction in the following T_{RTS} time. $(N-1)$ is included because there can be a combination of $(N-1)$ such node scenarios that can overhear the DRTS packet.

$$p_2 = \tau\delta\frac{\beta}{2\pi} \tag{10}$$

where $\tau\delta$ is the probability of the transmission of DRTS and $\frac{\beta}{2\pi}$ is the probability that the transmission is in the direction of x.

$$p_1 = (1 - \tau(\pi_c + \pi_d)\frac{\beta}{2\pi})^{((N-2).T_{RTS})} \tag{11}$$

where $\tau(\pi_c + \pi_d)$ is the probability that a node is in *DRTS* or *CRTS* state at any given time and $\frac{\beta}{2\pi}$ is the probability that the transmission is in the direction of x. T_{RTS} is there to take into account the following RTS period of time. Since there is one transmitter and one receiver, the remaining $(N-2)$ nodes need not to transmit in the direction of the ongoing communication.

Similarly, a node x is in *overhearing CRTS* state when only one other node transmits CRTS in the direction of x and no other node transmits in x's direction:

$$P_{oc} = (N-1).p_3.p_1 \tag{12}$$

where p_3 is the probability a node transmits CRTS in the direction of x and given by

$$p_3 = \tau(1-\delta)\frac{\beta}{2\pi} \tag{13}$$

where $\tau(1-\delta)$ is the probability that a node transmits DRTS and $\frac{\beta}{2\pi}$ is the probability it is in $x's$ direction.

A node x is in *receive* state when only one node transmits toward x and no other node transmits in x's direction with the corresponding probability given by

$$P_r = \tau\, p_1 \tag{14}$$

Now, P_i can be calculated as

$$P_i = 1 - (P_r + P_{od} + P_{oc}) \tag{15}$$

Finally, the packet error probability p is given by

$$p\ = 1 - p_1.p_4.(1 - p_p) \tag{16}$$

where p_p is the probability of packet error due to wireless channel and p_4 is the probability that the receiving node is in the idle state. $p_1.p_4.(1-p_p)$ is the probability of a successful transmission and p is the packet error probability. p_4 is given by

$$p_4 = (1-\tau)\pi_i \tag{17}$$

The time durations the node spends in the non-transmission states are given by

$$T_e = \sigma \tag{18}$$

$$T_{oc} = T_{RTS} \tag{19}$$

$$\begin{aligned} T_r = \delta\, T_{RTS} + (1-\delta)E[CRTS] + T_{SIFS} + T_{CTS} \\ + T_{SIFS} + T_{TXOP} + T_{SIFS} + T_{ACK} + T_{DIFS} \end{aligned} \tag{20}$$

$$\begin{aligned} T_{od} = T_{RTS} + T_{SIFS} + T_{CTS} + T_{SIFS} + T_{TXOP} \\ + T_{SIFS} + T_{ACK} + T_{DIFS} \end{aligned} \tag{21}$$

where σ is the basic timing unit, slot time taken from 802.11ad standard [2]. A node that successfully receives a DRTS backs off for the duration of the communication. $E[CRTS]$ is the expected time spent receiving the CRTS packet and waiting for the transmitter to finish transmitting the CRTS. This value depends on the sector CRTS packet is received. Assuming every node is equally likely to receive the CRTS packet in any sector,

$$E[CRTS] = \frac{\beta}{2\pi}\sum_{n=1}^{\frac{2\pi}{\beta}}(n(T_{RTS} + T_{SBIFS}) - T_{SBIFS}) \tag{22}$$

Based on the derivation of the previous parameters, the saturated network throughput can be calculated by

$$TH = N.\frac{\tau(1-p)E[packet\ payload\ size]}{\tau E[T_t] + (1-\tau)E[T_{nt}]} \tag{23}$$

where

$$E[T_t] = (1-\delta)T_{crts} + (\delta)T_{drts} + pT_f + (1-p)T_s \tag{24}$$

and

$$E[T_{nt}] = P_{od}T_{od} + P_{oc}T_{oc} + P_rT_r + P_eT_e \tag{25}$$

where $E[T_t]$ and $E[T_{nt}]$ are the expected time in transmission state and non-transmission state, respectively.

Fig. 6 shows the comparison of the analysis results with the actual simulation of the DMBS protocol. The parameters used for both analysis and simulation are shown in Table III with the δ parameter set to 0.5 and p_p in the range 0.01 to 0.5. The difference in throughput mainly results from the difference in the scenarios of numerical analysis and simulation. In the simulation, a node is either a transmitter or a receiver. However, in the numerical analysis, the node is both a transmitter and receiver. Therefore, the throughput is plotted as a function of the number of transmitters for fair comparison. Moreover, in the simulations, δ varies over time and space, whereas, in the analysis, we have chosen an average value. Also, the theoretical model only assumes collisions in the RTS packet, whereas there may be collisions in all packets in the simulations. Furthermore, the analysis is not able to completely model the fine features of the DMBS protocol, i.e., BF table update, ILA, NAV mechanisms, intelligent transmitter and receiver behaviors. Nonetheless, the numerical analysis still gives performance very close to the simulation. As the p_p increases, more and more packets are lost due to wireless channel errors and the overall throughput decreases. The degradation is much severe in the simulation because simulation uses an exponential backoff which is not the case in the analytical model.

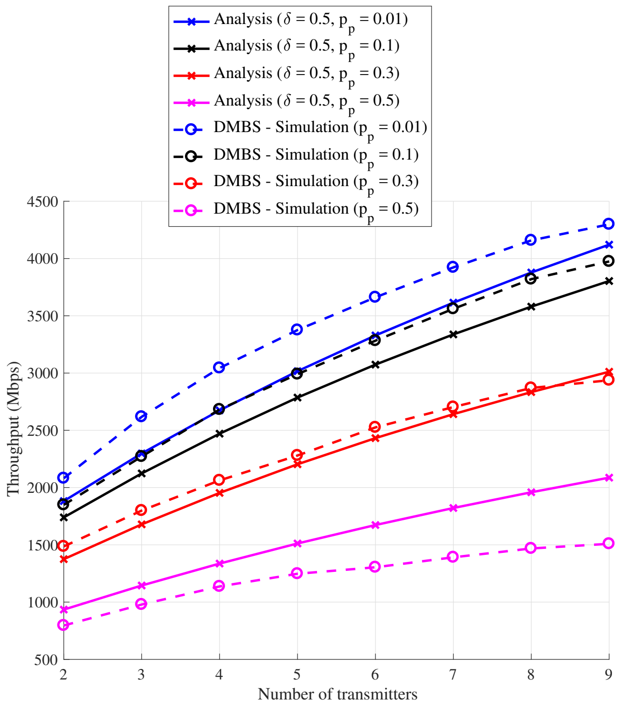

Fig. 6. System throughput calculated through numerical analysis ($\delta = 0.5$) compared with simulation results of DMBS under single destination and static network scenario.

V. Performance Evaluation

In this section, we evaluate the aggregate throughput performance of the proposed DMBS protocol by analyzing the performance improvement by each feature of DMBS and comparing its performance to that of the existing protocols for different network sizes, mobilities and number of receivers.

A. Simulation Environment

The simulations are performed in an event-based simulator created in MATLAB, called MMWAVEMAC [40]. We have made this simulator publicly available for others to use for their directional network simulations.

Simulation results are obtained based on 1000 independent random network topologies, where the nodes are uniformly distributed within a square area of side length 25 m. The simulations are performed for two different scenarios, single destination and multiple destination scenarios. In the single destination scenario, the transmitter nodes randomly choose a destination node at the beginning and send packets to the same destination during the simulation. In the multiple destination scenario, the transmitter nodes randomly choose a new destination node for each packet. In both scenarios, more than one transmitter may choose the same node as the destination of the packets. The mobility of the nodes is implemented by using random waypoint mobility model [45]. We assume that all communication is contention based without any scheduled service period. We are simulating a single AP environment where all the STAs are synchronized through the transmission of the beacon frames by the AP. This synchronization allows the nodes to know the starting time of the contention based access period (CBAP). During this CBAP, the STAs contend for the channel to transmit their packets.

TABLE II
MCS and SINR Threshold

MCS mode	MCS1	MCS2	MCS3
Modulation	QPSK	QPSK	16QAM
Code rate	1/2	2/3	2/3
Data rate	0.952 Gbps	1.904 Gbps	3.807 Gbps
SINR threshold	5.5 dB	13 dB	18 dB

The MCSs and corresponding SINR thresholds used in the simulations are given in Table II. The received power is calculated by using

$$P_R(d) = kP_T G_T G_R d^{-\alpha}, \tag{26}$$

where P_R, P_T, G_T, G_R, and d are receive power, transmit power, transmit antenna gain, receive antenna gain, and distance between transmitter and receiver, respectively; $k = (\frac{\lambda}{4\pi})^2$, in which λ is the wavelength; and α is the path loss exponent dependent on the propagation environment and usually takes the value between 2 to 4 [46]. Two dimensional cone plus circle model is used assuming all STAs are on the same plane [47], [48], [49]. The antenna gains of the mainlobe and sidelobe in the model are calculated by $G_m = \eta 2\pi/\beta$ and $G_s = (1-\eta)2\pi/(2\pi-\beta)$, respectively, where η is the antenna radiation efficiency [49]. The simulation parameters are given in Table III.

B. Simulated MAC Protocol Details

To evaluate the throughput performance of the proposed DMBS protocol, we have simulated DMBS, different variations of DMBS excluding a set of the features of DMBS and existing protocols. The simulated protocols are given as follows:

DMBS (Directional MAC protocol for Basic STAs): This is our protocol.

DMBS-W/O-I (DMBS Without ILA): This protocol is the same as DMBS, except the exclusion of the ILA mechanism.

DMBS-W/O-IB (DMBS Without ILA and BF table update): This protocol has the same features as DMBS-W/O-I, except that we are not updating the BF information table upon the reception of each packet. BF table is only updated when a node receives a packet addressed to the node itself.

DMBS-W/O-IBN (DMBS Without ILA, BF table update and NAV2): This protocol is the same as DMBS-W/O-IB, except the NAV2 mechanism. If the transmitter does not have the best sector ID to reach destination node available in the BF information table or does not receive a CTS packet corresponding to a DRTS packet for n_{max} times, it transmits CRTS packet, regardless of the value of NAV2. Similarly, if the received RTS does not contain the best sector ID

TABLE III
SIMULATION PARAMETERS

Antenna Radiation Efficiency (η)	0.9
Antenna Beamwidth (β)	$\frac{\pi}{6}$
Transmission Power	10 dBm
Background Noise	-80 dBm
SINR threshold	5.5 dB
CWmin	16
CWmax	1024
Slot time (σ)	5 μs
SIFS (T_{SIFS})	3 μs
SBIFS (T_{SBIFS})	1 μs
DIFS (T_{DIFS})	13 μs
RTS/CTS time (T_{RTS}/T_{CTS})	7 μs
DTI time	5000 μs
Packet Size	256 Kb
Path Loss Exponent (α)	2
n_{max}	3

information or the RTS is not sent from the expected sector, the receiver sends the CCTS, regardless of the value of NAV2.

CDHM-W/O-D (Circular and Directional control packets Hybrid MAC Without Deferring on control packets): This protocol is similar to DMBS-W/O-IBN, except that the receiver does not check whether the RTS is sent from the expected sector. If a transmitter knows the best sector ID to reach the destination, it sends DRTS packet. If a transmitter does not know the best sector ID or is not successful in sending DRTS packet for n_{max} times, it sends CRTS packet. Similarly, if a receiver knows the best sector ID to reach a transmitter, it responds with a DCTS packet without checking whether the DRTS is from the expected sector.

CDHM (Circular and Directional control packets Hybrid MAC): This protocol implements the combined usage of DRTS/DCTS and CRTS/CCTS packets, similar to CDHM-W/O-D except that the nodes defer their communication on the reception of control packets. Protocols similar to CDHM include [15] and [50]. If the transmitter does not get a response to the DRTS packet for a certain number of times, an omni-directional RTS is sent in [15] whereas the RTS packets are transmitted over adjacent beams in [50].

BDMAC (Basic DMAC): This protocol represents a simple implementation of IEEE 802.11ad, in which RTS/CTS/DATA/ACK packets are all transmitted directionally [9]. The nodes determine the best sector to reach their destination nodes by performing beamforming training in advance during a time period scheduled by the PCP/AP before the DTI.

CRCM (Circular RTS and CTS MAC): This protocol is a modified implementation of CRCM protocol [18], in which the RTS and CTS packets are sent circularly prior to any data transmission, and the neighboring nodes receiving these control packets defer their communication only in the direction of reception determined by using DoA techniques. Since we don't assume the availability of complex hardware required for determining DoA, in the modified CRCM, all the nodes defer their communication upon reception of RTS/CTS packets.

CRCM-W/O-D (CRCM Without Deferring on control packets): This protocol is similar to CRCM, except that nodes no longer defer their communication if they receive RTS/CTS control packets. This leads to a higher amount of collisions but higher spatial reusability in the network.

C. Comparison with Existing Protocols

Fig. 7 shows the comparison of the network throughput performance of DMBS to that of the existing protocols for different number of nodes under single destination and static network scenario. DMBS and BDMAC perform better than all the other protocols for different network sizes. BDMAC performs better than other protocols since the nodes do not need to perform beamforming training frequently in a static network. The nodes use DRTS/DCTS packets once they perform beamforming training. Since only the nodes within the main lobe of the transmission defer their transmissions, the spatial reusability is high. CRCM and CRCM-W/O-D have almost the same performance and both perform poorly compared with other protocols. This is because they employ CRTS/CCTS packets before every data transmission. This both increases the control packet overhead and decreases spatial reusability, decreasing the overall throughput significantly. CDHM and CDHM-W/O-D perform much better than CRCM and CRCM-W/O-D, since they combine the usage of CRTS/CCTS and DRTS/DCTS packets. We observe that not deferring the transmissions upon reception of control packets improves the overall network throughput. This demonstrates that the effect of increasing the spatial reusability dominates that of increasing the number of collisions by not deferring the transmission of neighboring nodes. The main reason for this dominance is the low probability of the collision of simultaneous transmissions in directional communication. DMBS performs better than CDHM-W/O-D since the protocol employs not only an intelligent mechanism to jointly use CRTS/CCTS and DRTS/DCTS packets but also an intelligent listening during A-BFT, intelligent processing upon reception of every RTS/CTS packet to passively perform the beamforming training, and intelligent usage of NAV1 and NAV2 to limits hidden terminal and deafness problems while increasing spatial reusability.

Fig. 8 shows the comparison of the network throughput performance of DMBS with that of the existing protocols for different number of nodes under multiple destination and static network scenario. DMBS again performs better than all the

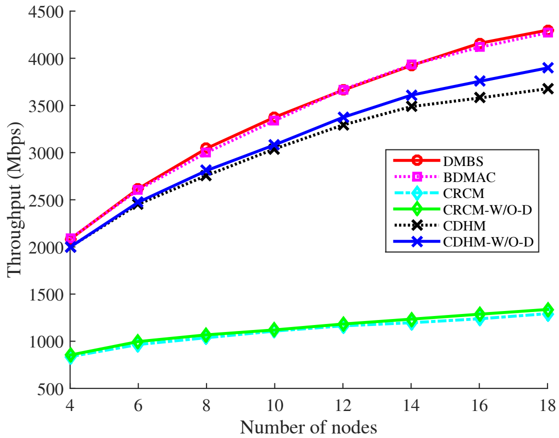

Fig. 7. Comparison of the network throughput performance of DMBS to that of the existing protocols for different number of nodes under single destination and static network scenario.

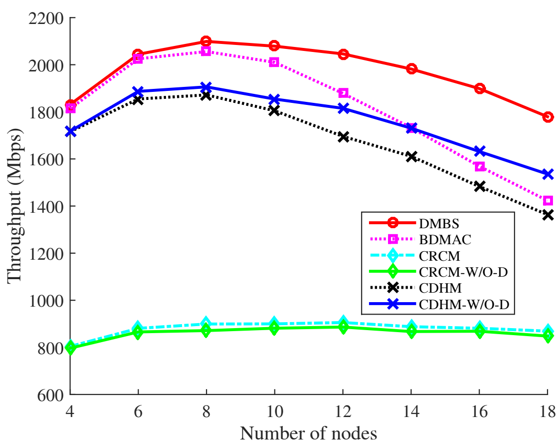

Fig. 8. Comparison of the network throughput performance of DMBS to that of the existing protocols for different number of nodes under multiple destination and static network scenario.

existing protocols for different network sizes. The network throughput of all the protocols have decreased compared to the single destination scenario due to the increase in the overhead of beamforming training with multiple destinations. The decrease in throughput is greater for larger network sizes, mainly due to the increase in the number of possible destination nodes. Every time the transmitter selects a new destination, it needs to perform beamforming training again, hence increasing the overhead. BDMAC experiences the most decrease in network throughput mainly because of the overhead caused by the scheduled beamforming training that needs to be repeated every time a transmitter selects a new destination to transmit to. Similarly, CDHM and CDHM-W/O-D experience a decrease in throughput since they need to use CRTS/CCTS packets each time a new destination node is selected. On the other hand, CRCM and CRCM-W/O-D experience the least throughput decrease, since these protocols use CRTS/CCTS before every transmission even if the destination node is the same. Despite the usage of joint CRTS/CCTS and

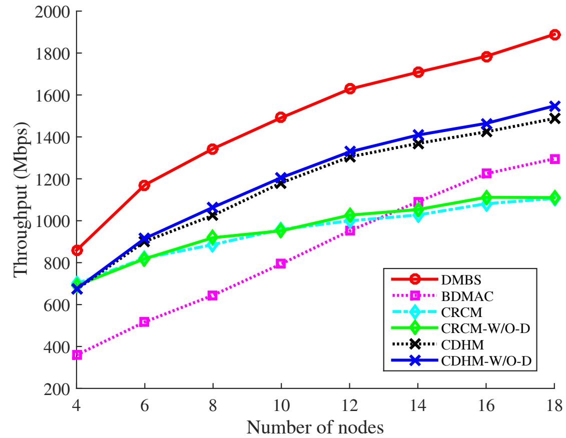

Fig. 9. Comparison of the network throughput performance of DMBS to that of the existing protocols for different number of nodes under single destination and mobile network scenario.

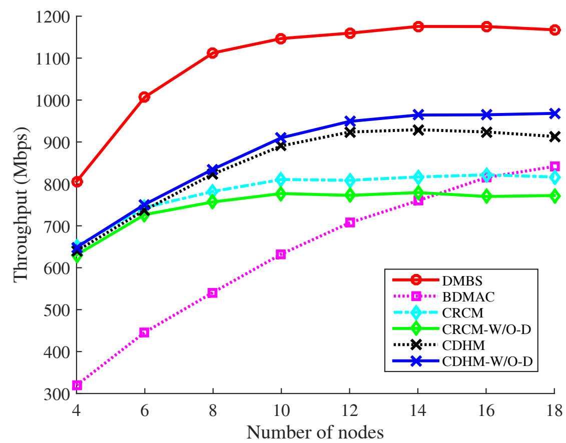

Fig. 10. Comparison of the network throughput performance of DMBS to that of the existing protocols for different number of nodes under multiple destination and mobile network scenario.

DRTS/DCTS packets, the throughput of DMBS decreases the least, mainly due to the intelligent listening during A-BFT and intelligent processing upon reception of every RTS/CTS packet to passively perform the beamforming training and tracking, eliminating the transmission of CRTS/CCTS packets every time a new destination node is selected. An alternative protocol where the nodes perform beamforming training and store the best transmission direction for all possible destination nodes beforehand would outperform all these protocols in this case, however, with little adaptivity and large packet overhead in mobile networks.

Figs. 9 and 10 show the comparison of these protocols in a mobile network for single destination and multiple destination scenarios, respectively. BDMAC experiences the most decrease in network throughput compared to the static network scenario since the beamforming information becomes stale leading to high packet loss in a mobile network. CRCM and CRCM-W/O-D experience the least decrease in throughput since they perform beamforming training by using CRTS/CCTS packets before every transmission. The decrease

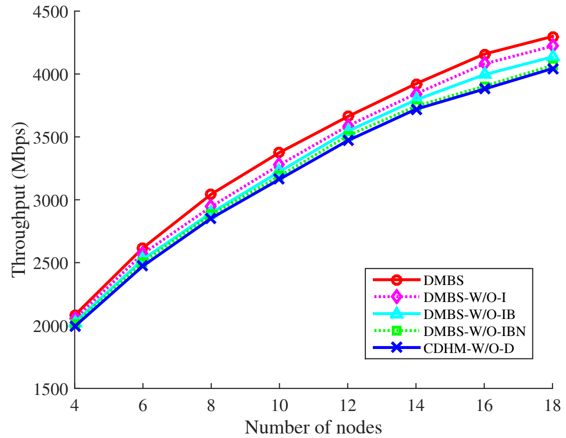

Fig. 11. Throughput performance of different variations of DMBS protocol for different number of nodes under single destination and static network scenario.

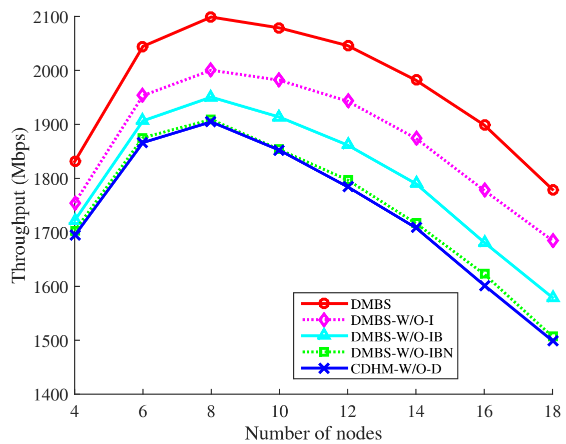

Fig. 12. Throughput performance of different variations of DMBS protocol for different number of nodes under multiple destination and static network scenario.

in the throughput of DMBS is much smaller than that of CDHM and CDHM-W/O-D mainly because of intelligent joint usage of CRTS/CCTS and DRTS/DCTS packets, an intelligent listening during A-BFT, intelligent processing upon reception of every RTS/CTS packet to passively perform the beamforming training and tracking, and intelligent usage of NAV1 and NAV2 to limits hidden terminal and deafness problems while increasing spatial reusability. The performance of these protocols under varying mobility in the network is explored further in Section V-E.

D. Performance of DMBS Features

We evaluate the effect of the features of the DMBS protocol on the improvement in the throughput by comparing its performance to that of the different variations of the DMBS obtained by excluding a set of its features. Figs. 11 and 12 show the network throughput performance of different variations of the DMBS protocol for different number of nodes in a stationary network under single and multiple destination scenarios, respectively. The amount of the improvement achieved by the

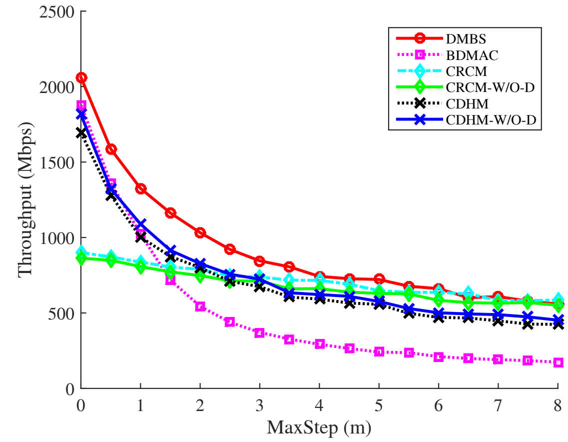

Fig. 13. Network throughput of DMBS and existing protocols for different levels of mobility in a 12-node network with multiple destinations.

ILA mechanism, update of the BF information table upon the reception of each control packet and NAV mechanism are almost the same, and slightly larger than the improvement achieved by checking whether the RTS is received from the expected sector. The improvement in throughput by the ILA mechanism mainly comes from decreasing the beamforming training overhead. Similarly, updating the table upon the reception of every control packet passively performs beamforming training, again decreasing the control packet overhead before data transmission. On the other hand, NAV mechanism increases spatial reusability and reduces hidden terminal problem with low extra packet overhead. The hidden terminal problem occurs when a potential interferer cannot receive an RTS or CTS packet, hence, does not defer its communication, and then initiates a transmission that causes a collision with an ongoing communication. The use of CRTS and CCTS limits the hidden terminal problem since the neighboring nodes of both the source and destination receive these packets and defer their communication. However, CRTS and CCTS increase control packet overhead and decrease spatial reusability, since only the nodes that lie in the direction of the communication may cause interference in the case they transmit in the direction of ongoing communication. Therefore, in DMBS, NAV mechanism allow only the nodes that can cause interference to defer their circular communication while still allowing them to communicate with other nodes using directional communication. The performance of the features of the DMBS under varying mobility in the network is explored in the Section V-E.

E. Performance Under Varying Mobility

Fig. 13 shows the network throughput of DMBS and existing protocols for different levels of mobility in a 12-node network with multiple destinations. As the mobility in the network increases, the network throughput of DMBS, BDMAC, CDHM and CDHM-W/O-D protocols decreases, whereas that of CRCM and CRCM-W/O-D protocols stays almost constant. BDMAC experiences the most decrease in throughput as the mobility increases, since the staleness of

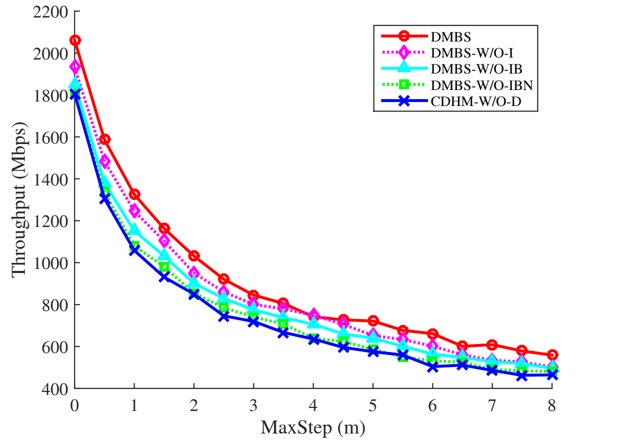

Fig. 14. Network throughput of different variations of DMBS protocol for different levels of mobility in a 12-node network with multiple destinations.

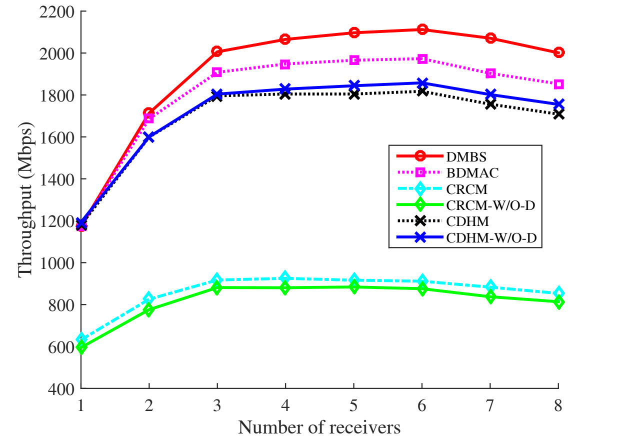

Fig. 15. Network throughput of DMBS and existing protocols for different number of receivers under multiple destination scenario in a network containing 6 transmitters.

the beamforming information results in the loss of DRTS and DCTS packets requiring a separate beamforming training before the DTI. The throughput decrease in DMBS, CDHM and CDHM-W/O-D protocols are less than that of BDMAC because they employ adaptive usage of beamforming training before the transmission of data packets. On the other hand, CRCM and CRCM-W/O-D protocols employ the transmission of CRTS/CCTS packets before every data communication, without exploiting the availability of location information at low mobility case. Therefore, their performance is independent of the mobility of the nodes. DMBS performs better than the existing protocols at all mobility levels. The throughput performance of DMBS gets closer to that of CRCM and CRCM-W/O-D at high mobility levels, since CRTS/CCTS packets need to be transmitted before every data packet transmission to learn the direction of transmission towards the new location of the destination nodes.

Fig. 14 shows the network throughput performance of different variations of the DMBS protocol for different levels of mobility in a 12-node network with multiple destinations. We observe that each feature of the DMBS protocol results in a slight increase in the throughput of the system independent of the mobility level.

F. Performance Under Varying Number of Receivers

Fig. 15 shows the network throughput for different number of receivers under multiple destination scenario in a network containing 6 transmitters. The purpose of changing the number of receivers is to analyze the trade-off between the effect of deafness problem and the overhead of beamforming training on the network throughput. For lower number of receivers, the number of transmitters communicating with the same receiver is high, resulting in the deafness problem. As the number of receivers increases, there are more destinations for the transmitters to beamform with. This alleviates the deafness problem but increases the beamforming overhead in the network. As the number of receivers increases, the throughput of all the protocols increases due to decrease in deafness despite the increase in the overhead of beamforming training. On the other hand, for large number of receivers beyond 6, the throughput slightly decreases with increasing number of receivers. The main reason for this throughput decrease is that the effect of the deafness on the throughput is greatly reduced by having less than 1 node transmitting to the same receiver on average. Thus, we observe the dominating effect of the increasing beamforming training overhead.

VI. Conclusion and Future Work

We propose a novel Directional MAC for Basic STA (DMBS) protocol based on the adoption of an intelligent listening mechanism to passively learn about the best direction of neighboring stations, the joint usage of CRTS/CCTS and DRTS/DCTS packets to learn the location of the neighboring nodes actively as needed, and adaptive utilization of different NAV mechanisms to address deafness and hidden terminal problems with minimal overhead. The protocol has been demonstrated to maximize the network throughput without using any additional or complex hardware. Our proposed analytical model gives results very close to our simulation results. Simulations demonstrate that DMBS performs better than all existing protocols for varying network sizes, mobilities and number of receivers. The contributions of the ILA, updating of BF table on the reception of each control packet and adaptive NAV features of DMBS to the overall throughput are almost the same for different network sizes under various scenarios. The DMBS protocol performs much better than existing protocols at low node mobility, and very close to that of the previously proposed protocol that only employs CRTS/CCTS control packets at high mobility.

In the future, we are planning to investigate the performance of DMBS in terms of alternative performance metrics, including delay and energy consumption. The main reasons for the increase in the delay in contention based directional MAC protocols are beamforming overhead and deafness. Deafness not only increases the average delay but also causes unfair distribution of the delay among the nodes in the network. The usage of CRTS and CCTS packets increases beamforming overhead while causing lower deafness in the network. Also, the effect of the different features of the protocol on the network energy consumption needs to be further studied. ILA provides higher throughput by allowing the nodes to passively collect beamforming information at the expense of higher energy consumption because all nodes are forced to listen during the A-BFT phase. Moreover, the usage of more DRTS and DCTS packets rather than CRTS and CCTS packets decreases the energy consumption during the contention based periods. If these alternative metrics are more important than throughput in the design of the directional MAC protocol, some modifications may also be proposed for DMBS protocol.

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