Coop-DMAC: A Cooperative Directional MAC Protocol for Wireless Networks

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***Abstract*—Directional antennas in wireless networks can provide substantial performance gain and opportunities. In the case of high-frequency systems, such as emerging 60 GHz networks, they are inherent feature of the system design. In contrast to the traditional omni-directional antennas, directional antennas are capable of reducing the interference level, increasing the communication range, and improving spatial reuse. However, new challenges need to be solved, such as the deafness problem and the asymmetric-in-gain. In this paper, we propose Cooperative-Directional MAC (Coop-DMAC) protocol to address the new challenges. The Coop-DMAC is completely distributed and relies on limited cooperation between networked nodes. In Coop-DMAC, nodes are supposed to exchange local information including the angle of arrival of their neighboring nodes and the duration of data transmission to improve their spatial reuse. In this paper, we analyze and evaluate the performance of Coop-DMAC, and pay particular attention to the performance and network topology. Simulation results validate our theoretical analysis and show that the proposed Coop-DMAC protocol outperforms the standard IEEE 802.11ad MAC protocol in terms of higher goodput in most common network topologies considered in the paper.**

I. INTRODUCTION

In recent years, directional antenna technology has become as a promising technology for local area wireless networks. In general, the use of directional antennas can reduce the overall interference level and introduce another spatial dimension, which has a potential to significantly improve the system performance. More importantly, directional antennas are necessary for emerging millimeter-wave band systems such as 60 GHz networks.

A number of new challenges exists when directional antennas and links[1], [2] are employed. For example, a directional transmission requires the transmitting node and the receiving node to face towards each other before the transmission takes place. Otherwise, the deafness problem may happen, which decrease the network performance. Due to the same reason, estimating or tracking nodes' movement becomes desirable. Moreover, efficiently utilizing the spatial reuse requires nodes to carry out transmissions cooperatively, i.e., nodes should be aware of the decisions and actions of their neighboring nodes. In this paper, we introduce Cooperative-Directional MAC (Coop-DMAC) to handle the aforementioned challenges. In Coop-DMAC, the deafness problem is addressed by letting idle nodes switch directions according to the location and the mobility of their neighboring nodes and the network status. Two cooperative mechanisms are used in Coop-DMAC to improve its spatial reuse. Nodes obtain the network topology by sharing their neighboring Angle of Arrival (AoA) information. Besides, communicating nodes are supposed to announce the duration of their imminent transmission to their neighbors. In this way, nodes can estimate the generated Signal-to-Interference Ratio (SIR). If the caused interference is not harmful to the ongoing transmissions, parallel communications can be carried out and the spatial reuse of the network is improved. In that sense, Coop-DMAC loans an operational principle from interference limited dynamic spectrum access community. We note that the caused interference level is not only related to the transmission power and the distance between networked nodes, but also determined by the locations of nodes and the beamwidth of the directional antennas. Hence, we investigate the relation between the network topology and the performance of directional MAC protocols. The rest of this paper is organized as follows. We review related work in Section II and describe the Coop-DMAC protocol in Section III. The relation between system performance and network topology is investigated in Section IV. The simulation results are shown in Section V. The paper is finally concluded in Section VI.

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II. RELATED WORK

A majority of directional MAC protocols [1], [2], [3], [4], [5], [6] rely on the Directional Virtual Carrier Sensing (DVCS) and Directional Network Allocation Vector (DNAV) [7] schemes to avoid collision. DVCS and DNAV allow a node to sense the channel in a certain direction and block it until the ongoing transmission completes. These schemes are based on the AoA measurements and no extra positioning equipment, such GPS, is required.

The deafness problem emerges when directional antennas are applied [8]. Deafness problem does not exist in omni-directional MAC protocols because onmi-directional nodes inherently hear the transmission in its vicinity. In order to alleviate the deafness problem, the majority of directional MAC protocols assume that their antennas can also work in the omni-directional mode which ensures the reception in all directions. Choudhury et.al propose Basic DMAC [3], which is often considered as the benchmark of directional MAC protocols. Basic DMAC assumes that all directional nodes know the profiles of their neighboring nodes, such as their directions, from an upper layer. In this way, no neighbor discovery or localization scheme are needed in Basic DMAC. Idle nodes are supposed to listen to the channel omni-directionally and assumed to be capable of finding the AoA of the received signal. To achieve the communication between Directional-Directional (DD) neighbors, Basic DMAC uses their common neighbors to forward the Ready To Send (RTS) frame.

Shihab et al. propose DtDMAC [5] that only relies on the directional mode. Furthermore, DtDMAC needs no equipment for synchronization because it works in a complete asynchronous manner. In DtDMAC, communications between DD neighbors is enabled without any intermediate nodes. It continuously rotates its receiver beam sector by sector to achieve omni-directional receiving. The transmitter repeatedly transmits Directional RTS (DRTS) frames according to the number of sectors to ensure the reception of the RTS at the intended receiver. If the location of the intended receiver is known, the transmitter needs to transmit $2M$ DRTS in the direction of its intended receiver, where M denotes the number of sectors. Otherwise, the transmitter needs to transmit up to $2M^2$ DRTS, i.e., $2M$ DRTS in each of M directions, with a random backoff duration in front of each DRTS to guarantee the reception. Obviously, the control overhead severely limits the system performance when M is large.[1] Moreover, neither the transmitter nor the receiver informs its neighbors after the DRTS and Directional CTS (DCTS) exchange which may cause deafness and collisions.

In order to provide high speed and reliable communications for new emerged wireless applications, the IEEE 802.11ad task group has worked on the IEEE 802.11ad standard [9]. It achieves high data rates up to multi-gigabit level in the 60 GHz mm-wave wave band, where a lot of unlicensed spectrums exist worldwide. The directional antenna is used to compensate the pathloss. The traditional 802.11 architecture is no longer suitable for 60 GHz wireless ad hoc networks. A new architecture named Personal Basic Service Set (PBSS) is used in 802.11ad which performs in an ad hoc manner. In a PBSS, one station (STA) is chosen as the PBSS Central Point (PCP) / Access Point (AP) which synchronizes the BPSS and schedules the transmission in Data Transmission Time (DTT). The aforementioned DVCS and DNAV schemes are adopted by 802.11ad standard. However, due to the fact that 60 GHz channel is heavily location depended and the link can be efficiently blocked for example by human bodies, it is risky to use a specific central STA for network synchronization and scheduling in mobile environments.

In directional MAC protocols, the directions of neighbors gain in importance because nodes need them to carry out directional communications and avoid collisions. Instead of simply assuming availability, the majority of the directional MAC protocols try to address it. In a number of different proposals, extra devices or mechanisms are used to provide such information, e.g., [4] uses the GPS and [3] relies on an unspecified upper layer mechanism. However, as stated in [7], directions obtained from AoAs ares more reliable than from the extra devices because the AoA represents the real path of the wireless signal.

[1] We note that the number of sectors can be large especially in the case of future mm-wave systems where beam width generated by phased antenna arrays can be very narrow

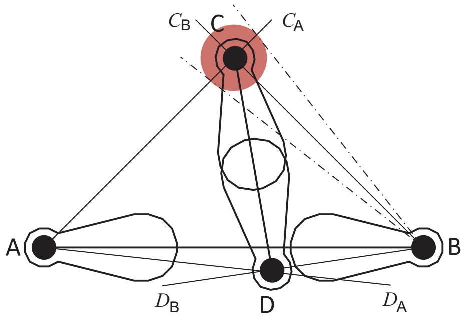

Fig. 1. An example of two pairs of directional nodes are communicating concurrently.

To the best of our knowledge, most of the papers on directional MAC protocols considers only very limited and simplified network topologies. For example, the authors simulate their protocol with a fixed and constant topology. For instance, a linear distribution topology is used in [10], and a grid topology is used for simulation in [11].

III. Coop-DMAC Design

Coop-DMAC adopts a general and widely used directional-only antenna model as shown in Figure 1. Beamwidth is defined as the width of the main lobe of the antenna. The effect of side lobe is also considered. Coop-DMAC is applicable to different kinds of directional antennas, e.g., it is designed for directional-only antennas, but it is also compatible if the antenna is able to receive in omni-drectional mode. The antenna should be in capable of transmitting and receiving towards a fixed direction, and being virtually omnidirectional, i.e. antenna can steer its beam from sector to sector with a constant angular velocity. In order to achieve localization and address the deafness problem, nodes are assumed to be able to cover all directions. Moreover, nodes are assumed to be capable of estimating the AoA of the received signals, i.e., nodes should be able to bind the direction and the transmitting node if the received signal is successfully decoded.

In this section, we describe Coop-DMAC in the following steps. We first introduce the directional carrier sensing schemes of Coop-DMAC. In the second step, we show how the AoA exchange mechanism helps to find the network topology, discover neighbors, and increase the spatial reuse. After that, we outline the detailed operations of Coop-DMAC. At last, we present how Coop-DMAC addresses the mobility problem.

A. Carrier Sensing

In general, applying carrier sensing with directional antenna is more complicated due to its directionality. Collision avoidance and the deafness problem in omni-directional MAC protocols are intuitively solved by its omni-directional carrier sensing. However, simply sensing the direction of the destined node can neither solve the deafness problem nor detecting all potential sources of collision in directional networks. The directional antenna can only be interfered via some special directions due to its directionality. Coop-DMAC adopts two types of carrier sensing schemes. The Dual Directional Carrier Sensing (DDCS) scheme is used for detecting potential collisions not only in the direction of the destined node, but also in the opposite direction. The Idle Listening (IL) - Directional Medium Reservation (DMR) scheme is used to address the deafness problem.

1) DDCS Scheme: Collisions may occur at both the transmitter side and the receiver side due to handshake and ACK mechanism. Therefore, before transmitting, the transmitter should perform carrier sensing not only towards the direction of the destined node, but also towards the opposite direction to avoid collision. As shown in Figure 2 where the dashed circles indicate the transmission ranges of nodes, node A is going to transmit to node B. Obviously, node A has to sense the direction of node B to ensure that no node is transmitting in this direction which may cause a collision at node A when node A is receiving from node B. The area sensed by node A is marked by the sector AGH which angle is equal to the beamwidth of the adopted antenna. Nodes which locate out of AGH cannot generate interference at node A when it is receiving directionally from node B because these nodes are not in the receiving beam of node A. However, simply checking the direction of node B cannot avoid the collision at node B, the destination of this communication. Hence, in order to ensure no node is able to interfere the reception of node B of the imminent communication, node A also needs to sense the opposite direction of node B. As shown in Figure 2, node A is supposed to sense the sector ACD that subtends a central angle of twice the beamwidth.

We first show the necessity of performing this opposite carrier sensing. We divide the area BEF where potential interfering nodes for node B may locate into two areas, ACDEF and BCAD. We assume that node X is inside ACEFD and it is transmitting to node B. If only the direction of node B is sensed, node A will transmit to node B without considering the transmission between node X and node B, which will causes a collision at node B. Therefore, node A also needs to sense the direction of the potential interference source of node B before starting transmitting.

After that, we show the sufficiency of this opposite carrier sensing. First, we assume that node Y locates out of sector BEF. Node A does not need to sense the direction of node Y because: (1) node A may not able to detect the transmission from node Y to node B because node A may be not in the range of node Y's transmitting beam; (2) node B does not

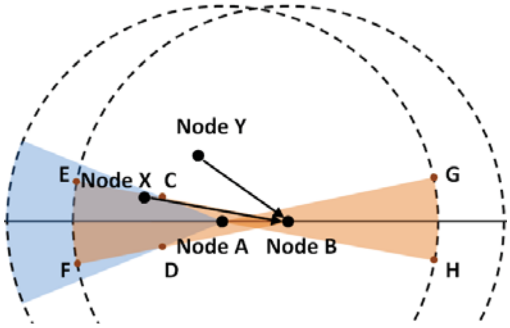

Fig. 2. Sensed area of DDCS scheme.

face towards node A if it is receiving from node Y, i.e., no collision can occur even though node A ignores node Y and starts transmitting to node B while node B is receiving from node Y. In other words, there is no collision to avoid due to the directivity of the antenna. Second, we assume that node Y locates in BCAD. In this case, even through node A is sensing in the direction of node Y, it is not capable of detecting the transmission from node Y to node B. In other words, the collision cannot be avoided even the directional sensing is performed. Therefore, node A does not need to sense the direction which is out of ACD.

Although DDCS scheme cannot fully observe the medium to perfectly avoid collisions, it significantly improves the efficiency of directional carrier sensing. Compared to the single directional carrier sensing, the detectable area is increased from AGH to AGH+ACEFD. DDCS increases delay by sensing the opposite directions. However, compared to the frame transmission time, the cost is very limited.

2) IL-DMR Scheme: Coop-DMAC uses the IL scheme to eliminate the deafness problem at idle nodes. It requires an idle node to check all directions of all potential transmitting nodes similar to the virtual omni-directional sensing schemes in [9], [5]. The action of the idle node depends on its knowledge of its neighbors. For instance, if the network is fixed, and the directions of all neighbor nodes are known, the idle node only needs to switch its antenna beams towards its neighbors sequentially. On the contrary, if the directions of neighbors are changing very quickly, and new neighbors may emerge randomly, the idle node needs to circularly sense all directions. In both cases, the idle node senses a certain direction periodically. DMR scheme is applied at the transmitter side. It requires the transmitter to send multiple frames in the direction of its intended receiver to ensure the receiver can receive at least one frame. In Coop-DMAC, IL scheme and DMR scheme are always applied together, so in the rest of the paper we refer it as IL-DMR scheme. In general, idle nodes have two types of actions for changing directions, discontinuously switching between sectors or rotating. Obviously, increasing the switching or rotating speed of idle nodes can reduce the number of repetitions at the transmitter side, which reduces the control overhead. However, the switching or rotating speed cannot be so fast that no complete frames can be received.

We first consider a simple scenario where nodes are immobile and have the full knowledge of the network topology. If no new node is allowed to emerge, an idle node only needs to sense several fixed directions where its neighboring nodes are located. In order to receive at least one complete frame, the residence time of an idle node in a certain direction t_{rx} should be lower bounded by $t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}}$, where t_{fr}, t_{header}, and $t_{\text{inter\_fr}}$ denote the duration of transmitting a frame, the duration of transmitting a frame header, and the inter-frame gap. At the transmitter side, the number of frames n_{tx} need to be sent should be also lower bounded as

$$n_{\text{tx}} \geq \frac{(t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}})(N-1)}{t_{\text{fr}} + t_{\text{gap}}}. \tag{1}$$

Most directional MAC protocols [7], [3] assume that idle nodes are receiving in omni-directional mode. In Coop-DMAC, the omni-directional receiving mode is an extreme case where t_{rx} is 0 and n_{tx} is 1.

Idle nodes have to sense in all directions circularly if the network topology changes rapidly. In order to guarantee a successful reception of at least one frame in a direction, the angular velocity of idle node ω_{rx} should be bounded as

$$\omega_{\text{rx}} < \frac{\theta}{t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}}}, \tag{2}$$

where θ denotes the beamwidth. The longest transmission time takes place when the rotating idle node just leave the direction of the transmitting node before the transmitting node start sending frames continuously. So we have

$$\begin{aligned} t_{\text{longest}} =& \frac{2\pi - \theta}{\omega_{\text{rx}}} + (t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}}), \\ \geq& \frac{2\pi}{\theta}(t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}}). \end{aligned} \tag{3}$$

If the destined node is mobile, the transmitter may need to rotate while it is transmitting to cover all possible directions (cf. SubsectionIII-D). The angular velocity of the transmitting node should be upper bounded according to the longest transmission time in a certain duration. Thus we have

$$\omega_{\text{tx}} < \frac{\theta^2}{2\pi(t_{\text{fr}} + t_{\text{gap}} + t_{\text{header}})}. \tag{4}$$

In this way, Coop-DMAC eliminates the deafness problem at idle nodes.

B. Localization and Spatial Reuse

In general and traditionally, localization is not seen as an essential part of a MAC protocol. However, directional MAC protocols can benefit significantly from localization information, because only knowing directions is not sufficient for supporting efficient spatial reuse.

In order to find the network topology, Coop-DMAC requires nodes to share its cached AoAs of their neighboring nodes by inserting them into frames. As shown in Figure 1, if node A receives a frame from node B which contains AoA information of node C, node A is able to localize it with respect to the direction of node B by applying the law of sines as

$$d_{\text{A-C}} = d_{\text{A-B}} \frac{\sin \angle ABC}{\sin(\angle ABC + \angle BAC)}\ , \tag{5}$$

Nodes should maintain a table which does not only record the AoA of its neighbors, but also the AoA of the neighbors of its neighbors. The distances to its neighboring nodes are normalized to the distance between the node and its first detected neighboring node. With the help of a rangefinder, the node is able to calculate the precise locations of it neighbors.

By using the network topology, a node is able to estimate the antenna gain of their neighboring nodes towards its direction. Thus it can be used to estimate the caused SIR at a neighboring node if it starts transmitting[2]. As shown in Figure 1, we assume that node A wants to transmit to node B while node C is transmitting to node D. We further assume that node A knows the transmission between node C and node D. If node A does not know the network topology, it cannot transmit to node B because it may interfere the transmission between node C and node D. However, if node A knows the location of node C and node D, it knows the directions of these two nodes when they are communicating towards each other.

We assume that the system has reasonably accurate capability to estimate the distance between nodes. This could be, of course, provided by some localisation hardware but also radio ranging could be used where one has to make some simplifying assumptions on the radio channel between transceivers. Such ranging techniques have been developed in the context of cellular networks (LTE) and many indoor localisation systems for IEEE 802.11 networks. Although we are agnostic in this paper for the actual method used for derivation of distance metrics, for the sake of completeness we show the situation under simplified assumption that we have Line-of-Sight (LoS) links with short distances enough to follow Friis Transmission Equation. This is, of course, a simplification just to illustrate our approach. In this simplified scenario, node A can estimate the SIR $SIR_{\text{D}_{\text{AB}}}$ at node D if it is transmitting to node B directly as,

$$SIR_{\text{D}_{\text{AB}}} = \frac{G_{\text{CD}} G_{\text{DC}}}{G_{\text{AD}} G_{\text{DA}}} \frac{PL_{\text{CD}}}{PL_{\text{AD}}} = \frac{G_{\text{m}}^2}{G_{\angle\text{CAD}} G_{\angle\text{CDA}}} \frac{PL_{\text{CD}}}{PL_{\text{AD}}}, \tag{6}$$

where G_{m} is the gain in the main lobe, and G_θ is the gain in the direction θ. Moreover we have assumed here, without loss of general applicability of the method, that all nodes have same transmission power. It is worth noting that the transmitter also needs to receive controlling frames such as ACK frame. Furthermore, the SIRs at its destined receiver should also be considered. Therefore, node A, as the transmitter, should consider SIRs at all involved nodes, i.e., node A, node B, node C and node D. If all related SIRs, i.e., $SIR_{\text{A}_{\text{CD}}}$, $SIR_{\text{A}_{\text{DC}}}$, $SIR_{\text{B}_{\text{CD}}}$, $SIR_{\text{B}_{\text{DC}}}$, $SIR_{\text{C}_{\text{AB}}}$, $SIR_{\text{C}_{\text{BA}}}$, $SIR_{\text{D}_{\text{AB}}}$, and $SIR_{\text{D}_{\text{BA}}}$ are lower than the threshold, node A is allowed to carry out a simultaneous transmission towards node B.

[2]We note that the estimated SINR at the neighborhood is not very accurate due to the uncertainties related to the channel and environment, but the estimate nevertheless useful for enhancing MAC operation.

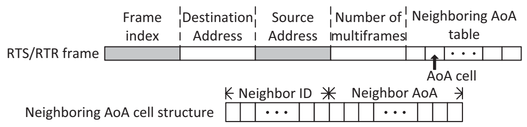

Fig. 3. Frame structure of RTS frame and RTR frame.

C. Protocol Details

In this subsection, we present the details of Coop-DMAC design which combines all aforementioned techniques. A complete Coop-DMAC procedure includes two 2-way handshakes, an RTS/RTR broadcast mechanism, and an aggregated data frame transmission scheme.

1) Multiframe transmission: Due to the large overhead in directional MAC protocols, Coop-DMAC uses an aggregated scheme, namely multiframe transmission. It is similar to the MAC Protocol Data Unit (MPDU) aggregation in IEEE 802.11ad standard [9]. The number of data frames in the multiframe transmission is inserted in control frames, so the receiver and its neighboring nodes know how long the ongoing transmission goes on. Only a single ACK frame is required to feedback the index of the successfully received data frame after the multiframe transmission. Before the multiframe transmission, the directional connection between the transmitter and its intended receiver is built by the Node-Location-Request (NLR) - Location-Report (LR) handshake.

2) NLR-LR handshake: NLR and LR frames are the shortest frames defined in Coop-DMAC which contains three main fields, i.e., frame type, destination address, and source address. NLR frame is sent by a transmitter to lock its intended receiver after carrier sensing. Before sending NLR frames, the transmitter checks its AoA table. If the direction of its intended receiver has been recorded, the transmitter starts transmitting NLR frames towards the recorded direction. Otherwise, it randomly selects a direction and sends NLR frames circularly for one full turn or until getting the reply from its intended receiver. All idle nodes, including non-destined nodes, are supposed to reply a LR frame immediately after receiving an NLR frame. The destined receiver stays in the direction of the transmitter and waits for the upcoming frame. Otherwise, it turns its beam out of the direction of the transmitter and carries on sensing with IL scheme. After receiving NLR frame and LR frame, nodes update the AoA of the source node. Collisions may occur if two nodes are transmitting NLR frames to each other at the same time with the same inter-NLR interval. Coop-DMAC randomly selects the interval between two NLR frames, which asynchronizes the transmission to increase the probability of building successful connection.

3) RTS-RTR broadcast mechanism and DRTS-DCTS handshake: The multiframe transmission prolongs the transmission duration which aggravates the deafness problem. Informing neighboring nodes about the imminent communications can alleviate the corresponding performance degradation by allowing their neighboring nodes to avoid transmitting to them. Therefore, RTS frame is transmitted by the transmitter, and the RTR frame is transmitted by the receiver after NLR and LR handshake and before multiframe transmission. RTS and RTR frames have the same frame structure which contains the AoA of the neighboring nodes as shown in Figure 3. The RTS and RTR transmission also obey the DMR scheme to ensure the reception at idle nodes. In order to avoid unnecessary waiting time caused by the deafness problem, acknowledgement of RTS and RTR frames is not expected. That is, RTS and RTR frames are supposed to send back-to-back with only the minimal inter-frame interval. To efficiently transmit RTS frames and RTR frames, three rules are drawn up. First, do not transmit both RTS frame and RTR frame to a same node. Second, do not transmit to a node which is involved in an ongoing transmission. Third, do not transmit RTS frame and RTR frame so that they collide with each other. Therefore, Coop-DMAC uses the DRTS/DCTS handshake before RTS/RTR broadcast. After receiving the LR frame from its intended receiver, the transmitter inserts the IDs of its available neighboring nodes in a DRTS frame and sends it to its intended receiver. In other words, the list includes all available neighboring nodes, which the transmitter can send RTS frames. After receiving the DRTS frame, the receiver replies with a DCTS frame with the decision of RTS and RTR list according to the three rules. The frame structure of DRTS and DCTS frames are shown in Figure 4. After the DRTS/DCTS handshake, the transmitter and the receiver send their RTS and RTR frames to the directions of their neighboring nodes, respectively. The one who finishes transmitting first turns its beam towards its partner and starts a timer to wait for its partner to finish transmission. After receiving an RTS or RTR frame, a node is able to update the AoA of the source node, estimate the beam direction of the communicating pair, and also estimate the duration of the imminent communication. Moreover, Coop-DMAC allows nodes to adjust the transmission order according to received RTS/RTR frames to alleviate the Head-of-Line (HoL) blocking problem [2], which further improves its spatial reuse.

4) Channel occupation estimation: A complete transmission procedure is shown in Figure 5. Similar to the channel occupation estimation scheme in cognitive MAC protocols [12], [13], the number of DATA frames in the multiframe transmission is inserted in RTS frames and RTR frames. Moreover, the index of RTS and RTR frames are assigned in a reverse order. Therefore, all informed neighboring nodes are able to precisely estimate the duration of the ongoing transmission. For instance, an idle node receives an RTS frame or a RTR frame as marked by the black arrow in Figure 5. By knowing the index of the received RTR/RTS frame, and the number of the data frames in multiframe transmission, the

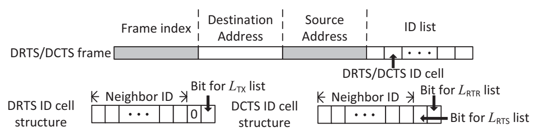

Fig. 4. Frame structure of DRTS frame and DCTS frame.

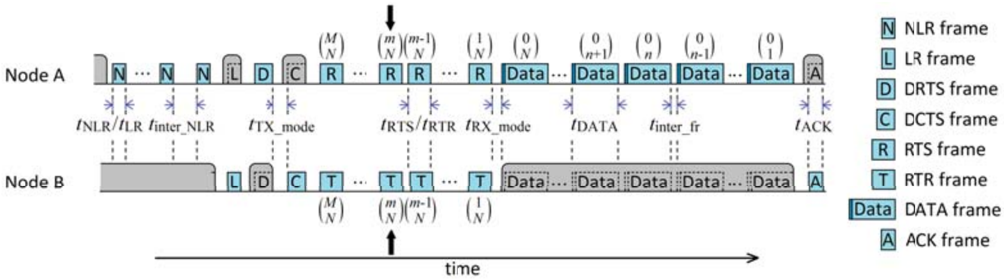

Fig. 5. A complete transmission cycle of Coop-DMAC in time domain.

remaining time for the ongoing transmission can be calculated.

D. Mobility

As mentioned in [14], if the speed of a neighboring node is constant, the distance determines the stability of its direction. Coop-DMAC assesses the reliability of the direction of a node by estimating its relative speed and its relative location. For example, node B wants to transmit to node C in Figure 1. We assume that node B knows the maximal relative speed V_{BC} of node C by observing its movement for a long enough time. We further assume that the relative location of node C is available at B by using the shared AoA information. After the last communication which determined the last precise location C_0, node C may move towards an arbitrary direction. We use the red circle with radius $r_{\mathrm{BC}} = V_{\mathrm{BC}}t$ to represent all possible locations of node C after time t.

As shown in Figure 1, the possible direction of node C after time t is within the two dashed lines. The uncertainty of the direction is defined as the maximal possible change of direction C_{B} which is equal to $\arcsin \frac{V_{\mathrm{BC}}t}{d_{\mathrm{B-C}}}$ in this instance. If the uncertainty of direction is larger than the beamwidth, the transmitter needs to sweep all possible directions according to (4) to ensure the reception.

IV. Network Topology and Performance

In recent years, stochastic geometry models have been used for investigating the performance of large scale wireless networks [15]. However, the typical scenario of using directional antennas is quite different from the omni-directional ones. First, the interference generated by directional antennas are not identical in all directions. Therefore, compared to the distribution of locations, the specific network topology plays a more important role in network performance. Second, many promising directional antenna techniques, such as 802.11ad standard, are operating in the millimeter wave band whose high pathloss severely limits the network scale. Third, in order to have successful transmission, directional nodes are more likely to know the direction of its neighbors. In this way, directional nodes have the potential to avoid interference by selecting directions intelligently. Therefore, we investigate the relation between network topologies and the performance in this study. To simplify the proof, we assume that the beamwidth of all nodes are identical, and only line of sight links are considered in this study. Therefore, a N node network can own at most $\binom{N}{2}$ undirected links. It is worth noting that the network topology in this study includes both the locations of all networked nodes and their beamwidth.

Besides the destined transmissions, interference is also generated via links. However, the level of interference is not the same for different links. Under a given network topology, some links may be interfered with other transmissions that are carried out in other links. For instance, in Figure 1, link DA may be interfered with the transmission via link BA. In order to represent the interference level of links, we have the following definition.

Definition 1: Non-interferable link is the link which cannot be interfered with any other transmission in the network.

The number of non-interferable links represents the potential of a network to carry out parallel transmissions. Thus we define the non-interferable factor to represent the potential of the spatial reuse of a network.

Definition 2: Non-interferable factor of a network is defined as the ratio of the number of non-interferable links to the number of all links. Non-interferable network is the network where all links are non-interferable links. The Non-interferable factor of a non-interferable network is 1.

The larger non-interferable factor means that more simultaneous transmissions can be carried out. Generally, the highest performance takes place when all links are non-interferable links. In order to find the highest performance with respect to the network topology, we first consider node N_1 whose beamwidth approaches to θ. As shown in Figure 6, we define the direction of its first neighboring node N_2 as ray l_2 whose initial point is N_1. Therefore, the transmission from N_1 to N_2 can interfere the area between ray l_1 and ray l_3, where the angle between l_1 to l_2 and the angle between l_2 to l_3 approach

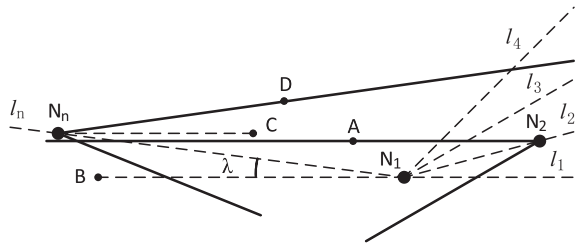

Fig. 6. Proof of Theorem1.

$\frac{\theta}{2}$. To avoid unnecessary interval between two allocations, we allocate N_3 in the ray l_3. If we repeat the allocation for the whole circle, up to $\lfloor\frac{4\pi}{\theta}\rfloor$ neighboring nodes are able to be allocated around N_1. However, considering the area of interference in Figure 2, no node is allowed to be allocated in the opposite direction of a pre-allocated node. Therefore, at least half of the nodes should be removed to avoid interference. In order to simplify, we assume that all nodes are allocated one by one in the upper half plane.

We consider node N_n, the $n-1$th neighboring node of node N_1 which is allocated in the corresponding rays l_n as $(n-1)\frac{\theta}{2} < \pi < n\frac{\theta}{2}$. We assume that all links including N_1N_2, N_1N_n and N_2N_n are non-interferable. Obviously, node N_n should be placed above the ray N_2A, which is one side of the beam of node N_2 when it is facing towards node N_1. We extend ray l_1 to an auxiliary point B and draw an auxiliary line N_nC which is parallel to it. Let $\angle BN_1N_n$ be λ, thus $\angle CN_nN_1$ is equal to λ.

As we assumed before, λ is less than $\frac{\theta}{2}$. We add an auxiliary point D which lies on the upper side of node N_n's beam. As shown in the figure, $\angle DN_nC$ is equal to $\frac{\theta}{2}-\lambda$ which is greater than 0. Consider that node N_n is located above line N_2A, so node N_2 must be in the range of node N_n's beam, i.e., link N_2N_n is not interferable, a contradiction. Therefore, λ must be greater than or equal to $\frac{\theta}{2}$. That is, if we want to allocate $n-1$ nodes around node N_1, the beamwidth of all nodes should be less than $\frac{2\pi}{n}$. Therefore we have derived the following theorem.

Theorem 1: The necessary condition of existing a n nodes non-interferable network where all nodes are capable of hearing each other is that the beamwidth $\theta \in [0, \frac{2\pi}{n})$.

In general, a larger beamwidth covers more directions, which may reduce the rotating/switching overhead if nodes need to communicate with different nodes. Therefore, for a n nodes network, increasing the beamwidth while keeping the network being non-interferable can optimize the performance. Repeating the analysis of node 1 to all nodes and considering the symmetry, we have,

Corollary 1: For a wireless network consisting of n directional nodes whose beamwidth approaches to $\frac{2\pi}{n}$ and all nodes are capable of hearing each other, the non-interferable network exists only when all n nodes are allocated at the vertices of a regular n-sided polygon, respectively.

It is worth noting that the non-interferable factor only represents the level of potential spatial reuse of a network topology. The final performance of a directional MAC protocol depends on the protocol design. Therefore, it can be used as a criterion to test the level of the spatial reuse of directional MAC protocols. Moreover, network optimization and planning can also be done based on the network topology.

V. Simulation Results

In this section, we present the MATLAB simulation results to investigate the performance of Coop-DMAC. Antennas are modelled as shown in Figure 1 with 25dBi gain. We assume that the propagation delay is zero. The cumulative goodput is chosen as the performance metric. Only the saturated network condition is considered in our simulation and each node is supposed to maintain a transmission queue which contains all neighboring nodes. Nodes always try to transmit to the first destination node in their transmission queue. The transmitting node moves the current receiving node to the tail of its transmission queue after a successful transmission. Some key configurations of the simulation are listed in Table I. In order to compare Coop-DMAC with 802.11ad standard, most of the PHY parameters, e.g., the modulation and coding scheme (MCS) of 802.11ad standard are adopted. The data rate of control PHY is set to 27.5Mbps, and all data frames are transmitted with MCS4 whose data rate is 1155Mbps. Omni-directional mode is used by idle nodes in the first simulation. In other simulations, only directional-only antennas are used so that the idle nodes are supposed to continuously rotate according to (2). All simulations are repeated enough times to ensure that the results are statistically reliable.

TABLE I
SIMULATION PARAMETERS

MAC header	84bits
RTS/RTR payload	$\lfloor(N^*-2)/2\rfloor \times$ 14bits
DRTS/DCTS payload	$\lfloor(N^*-2)/2\rfloor \times$ 6bits
ACK payload	$M^{**} \times$ 6bits
DATA payload	2000Bytes
t_{SIFS}	2μs
t_{DIFS}	4μs
- Initial CW size	10μs
maximal retry number	6

* Number of neighboring nodes
** Data frames in multiframe transmission.

A. Baseline Comparison

In this simulation, we compare the cumulative goodput of Coop-DMAC and the Contention Based Access Period (CBAP) of 802.11ad. Omni-directional mode is used when a node is idle for both protocols. We assume that all nodes are maintaining a transmitting queue, including all neighboring

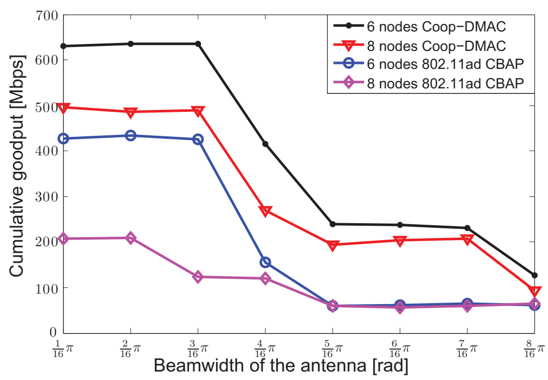

Fig. 7. Cumulative goodput with respect to the beamwidth of Coop-DMAC and 802.11ad CBAP. The number of multiframes of Coop-DMAC and the length of A-MPDU of 802.11ad are all fixed to 5.

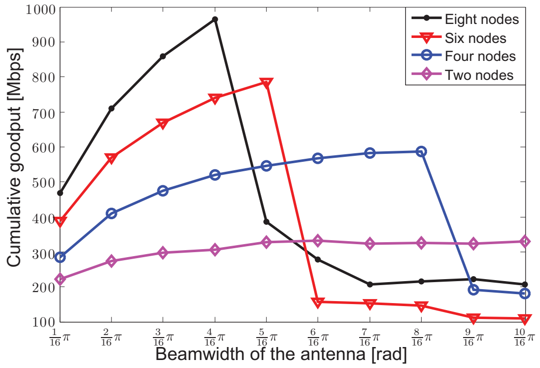

Fig. 8. Cumulative goodput with respect to the beamwidth of the directional antennas. Nodes are allocated at the vertices of the corresponding n-sides regular polygons whose circumscribed circles have the same radius 4m. Nodes are transmitting in pairs. The number of multiframes is fixed to 20.

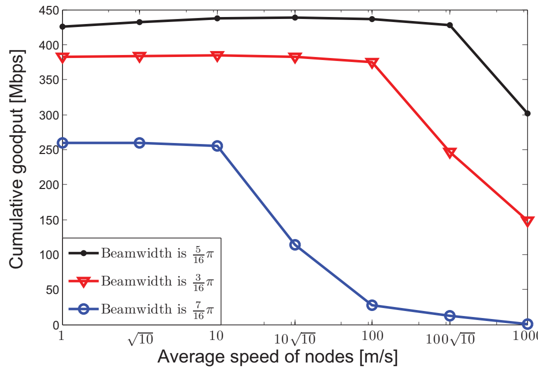

Fig. 10. Cumulative goodput with respect to the speeds of nodes. Four transceivers are moving in uniform circular motion of radius 1m. The center of their orbits are at the vertices of a square with side 8m. The number of multiframes is fixed to 20.

nodes, i.e., a node is able to transmit to any of its neighbors. In order to compare the two protocols fairly, we use the same configurations such as the DIFS duration, length of addresses in the frame header, and the backoff parameters in both protocols. Nodes are allocated in a grid of two rows with edge length 4m. It is shown in Figure 7 that Coop-DMAC outperforms 802.11ad CBAP in terms of goodput. This enhancement owes to the fact that Coop-DMAC allows more simultaneous transmissions than 802.11ad by analyzing the network topology and estimating the channel busy duration. It is also shown that the cumulative goodput of both protocols decrease as the beamwidth increases. It is due to the fact that large beamwidth causes more interference which reduces the non-interferable factor of the network.

B. Beamwidth and number of nodes

In this simulation, n immobile nodes are allocated at the vertices of the corresponding n-sides regular polygons whose circumscribed circle has radius 4m. According to Theorem 1, the network switches from non-interferable network to interferable network at some key points according to the number of nodes, e.g., the fall between the fourth point and fifth point of the eight nodes case. Two major conclusions can be drawn from this simulation. First, the goodput of Coop-DMAC in a non-interferable network increases as the beamwidth increases. It is due to the fact that the large beamwidth reduces the time for sensing the medium in IL-DMR scheme, thus further lowers down the number of RTS and RTR frames sent per neighbor. However, the network turns into interferable when the beamwidth is greater than or equal to $\frac{2\pi}{n}$. It occurs when beamwidth is greater than $\frac{1}{4}\pi$, $\frac{5}{16}\pi$, and $\frac{1}{2}\pi$ in eight nodes case, six nodes case, and four nodes case, respectively.

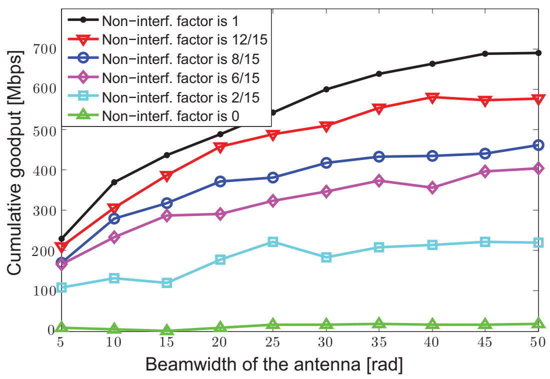

Fig. 9. Cumulative goodput with respect to the non-interferable factors. Six transceivers are allocated according to the non-interferable factors. The number of multiframes is fixed to 5.

C. Topologies

In this simulation, we evaluate the performance of Coop-DMAC with different topologies. We first allocate six immobile nodes at the vertices of a hexagon which has side 4m. We adjust the locations of nodes according to the desired non-interferable factor. For instance, the scenario in which the non-interferable factor is 0 takes place when all nodes are allocated in a common line. Figure 9 shows that the cumulative goodput of the network decreases as the non-interferable factor decreases. It is worth noting that the performance is not perfectly linear to the non-interferable factor. It also relies on the detailed design of the evaluated directional MAC protocol. The relation of network topology and performance is also investigated in the following simulations while the mobility of nodes is jointly considered.

D. Mobility

Coop-DMAC is also designed to provide reliable data communication among mobile nodes. In the following two simulations, we shortly evaluate the performance of Coop-DMAC with different node speeds and network topologies which are caused by node movement.

1) Circular movement: In this simulation, the performance of Coop-DMAC with different nodes speeds are investigated. As shown in Figure 10, nodes speeds are varied from 1m/s, which is less than the average pedestrian walking speed, to 1000m/s, which is around triple the sound speed in air. In order to keep the network topology constant, four mobile nodes are assumed to move circularly around the four vertices

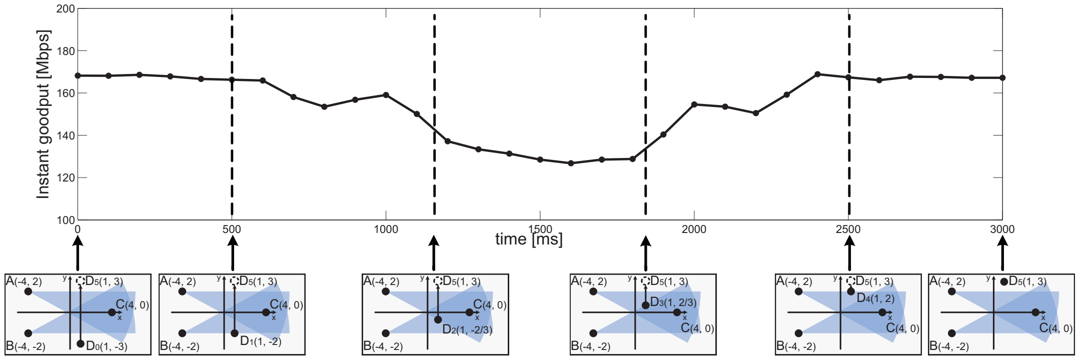

Fig. 11. Instant goodput with respect to the executed time. Node A, node B, and node C are fixed at points (−4m, 2m), (−4m, −2m), and (4m, 0m), respectively. Node D is initially located at point D_0, (1m, −3m). The beamwidths of all nodes are set to $\arctan\frac{8}{15}$. Node D is supposed to move along the x-axis at speed 2m/s. The number of multiframes is fixed to 5.

of a square with side 8m, respectively. The radius of their orbit is 1m. As expected, the larger beamwidth has better resistance against the node's movement. It is due to the factor that larger beamwidth covers more directions which allows larger uncertain directions. Besides, the larger beamwidth can effectively shorten the disconnected time.

2) Straight movement: In order to jointly evaluate the impacts of the node mobility and the network topology, we fixed three nodes and let the fourth node move at a constant velocity. All nodes are assumed to have the full neighboring information at the beginning. The instant goodput from 0ms to 3000ms is shown in Figure 11, where node D moves from D_0 to D_5. As shown in the mini-figure, the non-interferable factor is 1, $\frac{1}{2}$, $\frac{1}{6}$, $\frac{1}{2}$, and 1 in the intervals [0ms 500ms), [500ms 1166ms), [1166ms 1834ms), [1834ms 2500ms), and [2500ms 3000ms], respectively. Considering the delay which arises from the backoff operation, the instant goodput reflects the node's movement.

VI. Conclusions

In this work, we presented Coop-DMAC, a completely distributed asynchronous directional MAC protocol, and analyze the relation between the network topology and the performance of a directional-only MAC protocol. Coop-DMAC uses two directional carrier sensing schemes to avoid collisions and alleviate the deafness problem. Two cooperative mechanisms are used to share the AoA information and the transmitting duration, which significantly improves spatial reuse and addresses mobility problem. By analyzing the interference level of links with consideration of the beamwidth, we found the relation between the network topology and the performance of directional MAC protocols. The simulation results validate our theoretical analysis. Moreover, the results show that Coop-DMAC can achieve higher goodput than the current 802.11ad protocol.

References

[1] H.-N. Dai, K.-W. Ng, M.-L. Li, and M.-Y. Wu. An overview of using directional antennas in wireless networks. *International Journal of Communication Systems*, 26(4):413–448, 2013.

[2] O. Bazan, and M. Jaseemuddin. A survey on MAC protocols for wireless adhoc networks with beamforming antennas. *IEEE Communications Surveys & Tutorials*, 14(2):216–239, 2012.

[3] R. R. Choudhury, X. Yang, R. Ramanathan, and N. H. Vaidya. Using directional antennas for medium access control in ad hoc networks. In *Proceedings of the 8th annual international conference on Mobile computing and networking*, pages 59–70, 2002.

[4] Y. Takatsuka, M. Takata, M. Bandai, and T. Watanabe. A MAC protocol for directional hidden terminal and minor lobe problems. In *Proceedings of the IEEE Wireless Telcom. Symposium*, pages 210–219, 2008.

[5] E. Shihab, L. Cai, and J.-P. Pan. A distributed asynchronous directional-to-directional MAC protocol for wireless ad hoc networks. *IEEE Trans. on Vehicular Technology*, 58(9):5124–5134, 2009.

[6] Q. Chen, J.Q. Tang, D.T.C. Wong, X.M. Peng and Y.G. Zhang. Directional Cooperative MAC Protocol Design and Performance Analysis for IEEE 802.11 ad WLANs. *IEEE Transactions on Vehicular Technology*, 62(6):2667–2677, 2013.

[7] M. Takai, J, et al. Directional virtual carrier sensing for directional antennas in mobile ad hoc networks. In *Proc. of the 3rd ACM Int. Symp. on Mobile ad hoc networking & computing*, pages 183–193, 2002.

[8] R.R. Choudhury, and NF. Vaidya. Deafness: A MAC problem in ad hoc networks when using directional antennas. In *Proc. of the 12th IEEE International Conference on Network Protocols*, pages 283–292, 2004.

[9] IEEE 802.11 Working Group. IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems–Local and Metropolitan Area Networks–Specific Requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band. *IEEE Std*, pages 1–628, 2012.

[10] H.-N. Dai, K.-W. Ng, and M.-Y. Wu. On busy-tone based MAC protocol for wireless networks with directional antennas. *Wireless personal communications*, 73(3):611–636, 2013.

[11] M. Takata, K. Nagashima, and T. Watanabe. A dual access mode MAC protocol for ad hoc networks using smart antennas. In *Proceedings of the IEEE Int. Conf. on Communications*, volume 7, pages 4182–4186, 2004.

[12] J. Ansari, X. Zhang and P. Mähönen. A Decentralized MAC Protocol for Opportunistic Spectrum Access in Cognitive Wireless Networks. *Elsevier J. of Computer Comm.*, 36(13):1399 – 1410, 2013.

[13] P. Wang, J. Ansari, M. Petrova, and P. Mähönen. Demo: CogMAC+-a decentralized multichannel MAC protocol for cognitive wireless networks. In *Proceedings of the 2014 ACM workshop on Software radio implementation forum*, Chicago, USA, 2014.

[14] T. Zhao, J. Luo, W. Yan, and X.-M. Li. DART: A Directional Antenna Based RouTing Protocol for Ad-Hoc Networks with High Mobility. In *Proceedings of the 8th IEEE International Conference on Wireless Communications, Networking and Mobile Computing*, pages 1–4, 2012.

[15] H. ElSawy, E. Hossain and M. Haenggi. Stochastic Geometry for Modeling, Analysis, and Design of Multi-tier and Cognitive Cellular Wireless Networks: A Survey. *IEEE Comm. Surveys & Tutorials*, pages 996–1019, July 2013.