A Wireless Full-duplex and Multi-hop Network with Collision Avoidance using Directional Antennas

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***Abstract*—Wireless full-duplexing enables multi-hop wireless networks to increase network performance, such as the end-to-end throughput. However, the combination of wireless full-duplexing and multi-hop communication produces a secondary transmission collision problem due to the increase of transmission opportunities. This paper proposes directional asynchronous full-duplex medium access control (DAFD-MAC) to avoid interference on primary and secondary nodes. DAFD-MAC suppresses the secondary transmission collision problem by sending a data frame with directional antennas and also a Network Allocation Vector (NAV) frame while receiving the data frame. The simulation results show that the proposed DAFD-MAC outperforms carrier sense multiple access/collision avoidance (CSMA/CA), full-duplex MAC (FD-MAC), and multi-hop full-duplex MAC (MFD-MAC).**

I. INTRODUCTION

Today, wireless communication is indispensable to our daily lives. Because it is so widespread, higher performance of wireless networks is required. Wireless multi-hop communication enables the construction of a wireless network with multiple relay nodes needing small transmission power, even though a single-hop network needs significantly large transmission power [1].

For many years, wireless communications were achieved in a half-duplex manner, in which a sender node was unable to receive data in the same band while sending data. However, the recent progress of hardware and software technologies provides wireless devices, especially digital signal processors, with more processing power. These devices enable wireless full-duplex communication with digital cancellation as well as analog cancellation of the incoming sending signals through receiving antennas [2]–[5]. Since most medium access control (MAC) protocols assume half-duplex communication, the intrinsic difference of the transmission poses a challenge to develop full-duplex (FD) MAC protocols.

Some MAC protocols have been proposed between an access point (AP) and nodes in wireless LANs, i.e., within a single-hop wireless network [4], [5]. However, this paper focuses on FD-MAC for a multi-hop wireless network.

In basic MAC protocols for full-duplex wireless communication, a primary sender node, which acquires the channel first (i.e., initiates the transmission), specifies one node from its neighboring nodes as a secondary transmission node, and then the secondary transmission node starts the transmission according to the primary sender's transmission [5], [6].

As we discuss in detail in Section II, the secondary transmission interferes with the primary transmission, which causes a data collision. We define the data collision as a secondary transmission collision problem. In this paper, to solve the secondary transmission collision problem, we propose directional asynchronous full-duplex MAC (DAFD-MAC), which utilizes directional communication. However, it is known that the use of directional communication induces the deafness problem [7]. Because of the deafness problem, neighboring nodes around the primary and secondary transmissions are not able to detect these transmissions. In DAFD-MAC, a destination node of the secondary transmission transmits a Network Allocation Vector (NAV) frame in the opposite direction of the source node of the secondary transmission. The NAV frame is transmitted by directional antennas with full-duplexing. The notification by the NAV frame decreases the secondary transmission collision. We evaluated DAFD-MAC by computer simulation. The evaluation results show that the proposed DAFD-MAC achieves higher throughput and decreases the collision ratio compared to the conventional methods of carrier sense multiple access/collision avoidance (CSMA/CA), FD-MAC [5], and multi-hop full-duplex MAC (MFD-MAC) [6].

The rest of the paper is organized as follows. In Section II, we set the background of the present study by reviewing recent studies related to multi-hop communication, full-duplex communication, and the secondary transmission collision problem. In Section III, we propose DAFD-MAC to avoid the secondary transmission collision problem. In Section IV, we evaluate our proposed DAFD-MAC by computer simulation. Finally, we conclude our work in Section V.

II. RELATED WORK

A. Wireless Full-duplex and Multi-hop Communication

Full-duplex communication enables transmission and reception on the same frequency channel at the same time [4], [5]. This particular characteristic of simultaneous communication allows effective use of wireless resources in the time domain. A conventional radio can only perform half-duplex communicating because the transmitting signal is too strong to receive a signal from another node. However, the development of self-interference cancellation has made full-duplex communicating possible [2]–[5], [8], [9]. For example, Choi et al. [2], Everett et al. [3], Sahai et al. [4] and Jain et al. [5] succeeded in canceling a received signal by using a field-programmable gate array (FPGA) on a WARP V2 platform [10].

[4], [5] also proposed a wireless full-duplexing MAC protocol referred to as FD-MAC. FD-MAC assumes only single-hop communication between an AP and a client node. We define single-hop full-duplexing as bidirectional full-duplexing. Figure 1(a) illustrates bidirectional full-duplexing. In this figure, one full-duplex transmission at most is happening between the AP and node A.

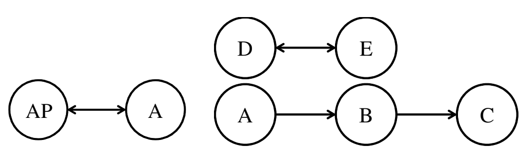
FD-MAC has two candidates for timing adjustment: synchronous [4] and asynchronous [5]. The synchronous method requires clock synchronization. In this paper, we focus on asynchronous timing adjustment because clock synchronization for all nodes in a multi-hop network is a daunting task.

When applying wireless full-duplexing to a wireless multi-hop network, the MAC protocol, which is different from FD-MAC, requires a mechanism to select a full-duplex communicating pair in a multi-hop network. The wireless full-duplex and multi-hop network is able to have not only bidirectional full-duplexing but also relay full-duplexing. Figure 1(b) shows the relay full-duplexing. This full-duplex situation is possible for simultaneous transmissions between node D and E, as an example of bidirectional full-duplexing. Another possible full-duplex situation is when node B receives a frame from node A while transmitting a frame to node C, as an example of relay full-duplexing.

B. Secondary Transmission Collision Problem

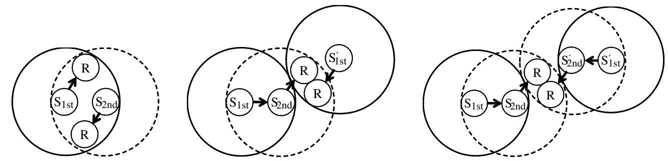
The application of wireless full-duplexing to wireless multi-hop communication is not simple because of the secondary transmission collision problem. Figure 2 shows three cases of the secondary transmission collision problem. The first case, shown in Figure 2(a), occurs when receiver nodes exist in an overlapping area between a primary transmission and a secondary transmission belonging to the same full-duplexing process. The second case, shown in Figure 2(b), occurs when receiver nodes exist in an overlapping area between a secondary transmission and a primary transmission, both of which belong to another full-duplexing process. Figure 2(c) shows the third case, which occurs when nodes exist in an overlapping area between a secondary transmission and another secondary transmission, both of which belong to another full-duplexing process.

Generally speaking, we use Request To Send/Clear To Send (RTS/CTS) frames to avoid collision in a multi-hop communication [11]. However, RTS/CTS frames are not sufficient to avoid the secondary collision in wireless full-duplex and multi-hop communication. This is assuming that both the primary transmission node and the secondary transmission node send RTS/CTS frames to defer the transmission by the neighbor nodes. The transmission of RTS/CTS sometimes sets the NAV to neighbor nodes that will not cause a collision. For example,



(a) Bidirectional full-duplexing (b) Relay full-duplexing

Fig. 1. Bidirectional full-duplexing and relay full-duplexing



(a) First case (b) Second case (c) Third case

Fig. 2. Three cases of the secondary transmission collision problem

when the destination node of a secondary transmission receives a CTS frame transmitted by the primary transmission node, the destination node of the secondary transmission cannot transmit a CTS frame.

Directional antennas can also be used to reduce interference by directing a beam form toward a desired direction [7], [12]–[15]. The use of directional antennas enables a receiver node to avoid interference coming from unwanted directions [7]. These antennas also reduce the overlapping area between a primary transmission and a secondary transmission. Directional MAC (DMAC) is one of the representative MAC protocols that enable transmission while avoiding interference by using directional antennas [7], [16]. However, DMAC has a deafness problem due to the directional antennas [7]. This problem occurs when a transmission node fails to communicate with its intended receiver, because the receiver's directional antenna is pointed in a different direction [7], [17].

[6] proposed MFD-MAC, which applies wireless full-duplexing to a wireless multi-hop network. MFD-MAC has a mechanism in which a primary transmission node specifies a secondary transmission node that likely has a frame to transmit. However, MFD-MAC does not consider the secondary transmission collision problem.

[18] proposed a synchronous MAC protocol with full-duplexing and directional antennas. However, the MAC protocol must be synchronized across whole networks before the nodes can start transmission. Achieving clock synchronization for all nodes in a multi-hop network is a daunting task. Additionally, [18] does not consider the secondary transmission collision problem.

III. DAFD-MAC

From the discussion in Section II, we design the DAFD-MAC protocol. The primary goal of our MAC protocol design is suppression of the secondary transmission collision problem and improvement of the end-to-end throughput.

A. Concept of DAFD-MAC

DAFD-MAC has two characteristics. The first characteristic is interference avoidance between a primary transmission and a secondary transmission by using directional antennas. Figure 3 shows an example of wireless full-duplexing with directional antennas. We define $\mathrm{S}_{\mathrm{1st}}$ as a primary transmission node, $\mathrm{S}_{\mathrm{2nd}}$ as a secondary transmission node, $\mathrm{D}_{\mathrm{2nd}}$ as a destination node of the secondary transmission, and $\mathrm{N}_{\mathrm{S}_{\mathrm{1st}}}$, $\mathrm{N}_{\mathrm{S}_{\mathrm{2nd}}}$, and $\mathrm{N}_{\mathrm{D}_{\mathrm{2nd}}}$ as neighboring nodes of $\mathrm{S}_{\mathrm{1st}}$, $\mathrm{S}_{\mathrm{2nd}}$, and $\mathrm{D}_{\mathrm{2nd}}$, respectively. The solid lines show primary and secondary transmissions, and the dashed lines show transmission flows.

In Figure 3, relay full-duplexing happens among the primary transmission node $\mathrm{S}_{\mathrm{1st}}$, the secondary transmission node

S_{2nd}, and the destination node of the secondary transmission D_{2nd}. Node S_{2nd} receives a data frame from node S_{1st} while transmitting a frame to node D_{2nd}.

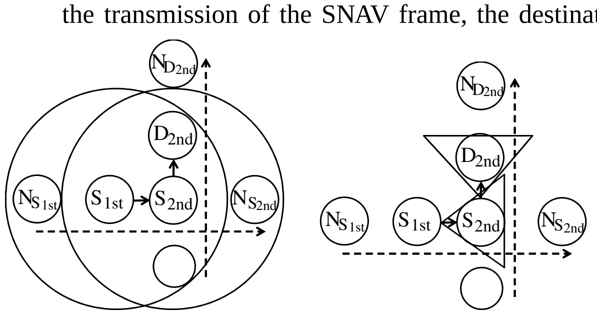
Figure 3(a) shows an example of the secondary transmission collision problem due to the use of omni-directional antennas. Nodes S_{1st} and S_{2nd} use omni-directional antennas to transmit data frames, and the transmissions are a primary transmission and a secondary transmission, respectively. The receiver node D_{2nd} experiences interference from the primary and secondary transmissions and cannot receive any frames.

Figure 3(b) shows an example of avoidance of the secondary transmission collision problem by using directional antennas. Nodes S_{1st} and S_{2nd} use the directional antennas to send data frames. Therefore, it is possible for receiver node D_{2nd} to receive the secondary transmission, because node D_{2nd} does not experience interference from the primary transmission.

The second characteristic of DAFD-MAC is the 5-way handshake. The 5-way handshake prevents the deafness problem [17] by sending NAV frames to neighboring nodes of a primary and a secondary transmission. One example of neighboring nodes is $N_{S_{1st}}$, $N_{S_{2nd}}$, and $N_{D_{2nd}}$ in Figure 3. The 5-way handshake uses five special frames: Request To Send (RTS), Request and Clear To Send (RCTS), Set Network Allocation Vector (SNAV), Directional Set NAV (DSNAV), and ACK frames, all of which have different roles. We describe the details of the 5-way handshake in Section III-B.

The operation of DAFD-MAC is as follows:

1) A node, which has a frame to transmit, uses CSMA/CA to resolve the contention against neighboring nodes. The node, which wins the contention, transmits an RTS frame. We refer to this node as a primary transmission node.
2) The destination node of the RTS frame obtain permission for secondary transmission and transmits an RCTS frame. We refer to the node as a secondary transmission node. The RCTS frame includes two destination addresses: the primary transmission node and the secondary transmission node.
3) The primary transmission node, which receives the RCTS frame, transmits the SNAV frame. The destination node of a secondary transmission waits until the end of the transmission of the SNAV frame. After the transmission of the SNAV frame, the destination node transmits a DSNAV frame. It should be noted that the start timing of a primary transmission, a secondary transmission, and the DSNAV transmission is the same.
4) At the end of the transmission of the SNAV frame, the primary and secondary transmissions begin. The primary and secondary transmission nodes avoid interference by directing a beam forms toward the destination. The destination node of the secondary transmission starts the transmission of the DSNAV frame. We use directional antennas with a beam angle of $\frac{4\pi}{3}$ rad for the transmission of the DSNAV frame. The directional antennas are focused in the opposite direction of the secondary transmission node to avoid interference with the secondary transmission. Details of the beam angle are described in Section III-C. All nodes use location information for the directional communication. DAFD-MAC assumes that all nodes know the location information of their surrounding nodes by using existing techniques such as angle of arrival (AOA) localization and global positioning system data (GPS) [13], [19].
5) To prevent collisions, a pair of communication nodes exchange ACK frames with each other at the same time by using directional antennas.



(a) Secondary transmission collision problem

(b) Proposed method

Fig. 3. Collision avoidance with directional antennas: (a) collision problem, (b) avoidance using directional antennas

B. 5-way Handshake

The 5-way handshake consists of five control frames: RTS, RCTS, SNAV, DSNAV, and ACK.

The RTS frame is transmitted by a primary transmission node and includes the destination address and the end time of the primary transmission. The destination address also represents the source address of a secondary transmission. The end time is used for calculating the NAV duration. The neighboring nodes, which received the RTS frame, set up the NAV, and defer their transmission. The primary transmission node, which transmitted the RTS frame, waits until receiving the RCTS frame, which is the response of the RTS frame. The primary transmission node does not start a primary transmission if the primary transmission node does not receive the RCTS frame during the assigned time period.

The RCTS frame, which is transmitted by the secondary transmission node, includes the two destination addresses of the primary and secondary transmissions and the end time of the full-duplexing communication. The secondary transmission node compares the end times of the primary transmission and the secondary transmission and selects the later time as the end time of the full-duplexing. The RCTS frame has three roles. The first role is the response to the RTS frame transmitted by the primary transmission node. The second role is notification to the node selected as the destination of the secondary transmission. The third role is deferment of the transmission of neighboring nodes around the secondary transmission node.

The SNAV frame is transmitted by the primary transmission node and includes the end time of the full-duplexing. The end time of the full-duplexing uses the same end time in the RCTS frame. The SNAV frame defers the transmission of the neighboring nodes around the primary transmission node. To

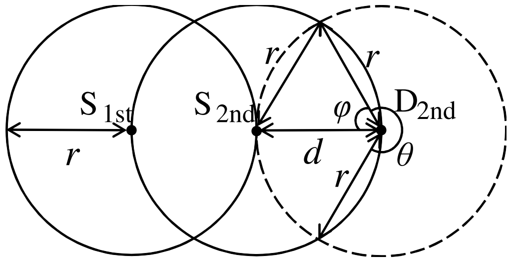


Fig. 4. Beam angle when transmitting the DSNAV frame

defer the transmission of the neighboring nodes, the primary transmission node needs to be notified of the end time of the full-duplexing.

The DSNAV frame is transmitted by the node specified by the destination address of the RCTS frame and includes the end time of the full-duplexing. The end time is the same end time in the RCTS frame. The DSNAV frame defers the transmission of neighboring nodes around the destination node of the secondary transmission. To avoid interference with the secondary transmission, the destination node of the secondary transmission transmits the DSNAV frame toward the opposite direction of the source node of the secondary transmission.

The ACK frame is transmitted by the destination nodes of the primary and the secondary transmissions. The ACK frame is for notification of the end of the full-duplexing.

C. Beam Angle of Transmitting the DSNAV Frame

As mentioned in Section III-A, DSNAV is transmitted with $\frac{4\pi}{3}$ rad as the beam angle of the directional antennas. If we use $\frac{4\pi}{3}$ rad for the beam angle, the transmission of the nodes that exist in the communication range of the secondary transmission can be deferred, except for the communication range of the secondary transmission node.

Figure 4 shows the beam angle while transmitting the DSNAV frame. We define beam angle θ as

$$\theta = 2\pi - 2\phi \tag{1}$$

where ϕ is the angle of the isosceles triangle in Figure 4. We assume

$$0 \leq d \leq r \tag{2}$$

where the communication range of the secondary transmission node is r, and the distance between the secondary transmission node $\mathrm{S_{2nd}}$ and the destination of the secondary transmission $\mathrm{D_{2nd}}$ is d. In addition, ϕ is derived as

$$\phi = \frac{\pi}{2} - arcsin\left(\frac{d}{2r}\right) \tag{3}$$

where the length of the base is d and the length of two sides is r in the isosceles triangle in Figure 4. From equations (2) and (3), we obtain

$$\frac{\pi}{3} \leq \phi \leq \frac{\pi}{2}.$$

When $d = r,$ we obtain

$$\phi = \frac{\pi}{3} \tag{4}$$

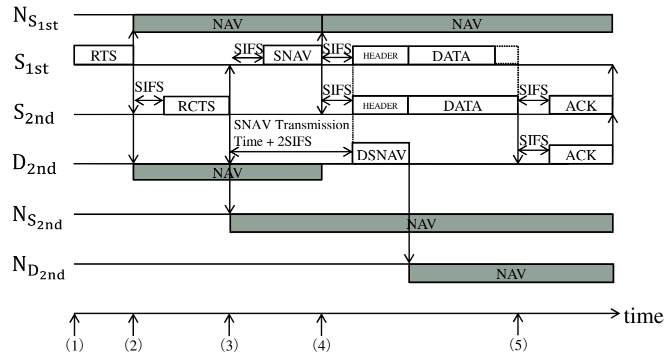


Fig. 5. DAFD-MAC time chart

as the minimum angle of ϕ. We substitute equation (4) for equation (1) and obtain

$$\theta = \frac{4\pi}{3}$$

as the maximum beam angle.

D. Operation Example of DAFD-MAC

Figure 5 shows an example of DAFD-MAC operation. $\mathrm{S_{1st}}$ is a primary transmission node, $\mathrm{S_{2nd}}$ is a secondary transmission node, $\mathrm{D_{2nd}}$ is a destination of a secondary transmission, and the nodes that possibly can communicate with $\mathrm{S_{1st}}$, $\mathrm{S_{2nd}}$ and $\mathrm{D_{2nd}}$ are $\mathrm{N_{S_{1st}}}$, $\mathrm{N_{S_{2nd}}}$ and $\mathrm{N_{D_{2nd}}}$, respectively. The operation is presented in the following.

1) RTS frame transmission
The primary transmission node $\mathrm{S_{1st}}$ transmits an RTS frame to defer the transmission of its neighbor nodes with omni-directional antennas. The nodes receiving an RTS frame, such as $\mathrm{N_{S_{1st}}}$ and $\mathrm{D_{2nd}}$, set up the NAV. As shown in Figure 5, the end of the NAV duration corresponds to the end time of the SNAV frame transmission.
2) RCTS frame transmission
The secondary transmission node $\mathrm{S_{2nd}}$, which is specified by the RTS frame, obtains permission for a secondary transmission. Node $\mathrm{S_{2nd}}$ receives the RTS frame and waits for the Short Interframe Space (SIFS) time, and then it starts the RCTS frame transmission with the omni-directional antennas. The neighbor node $\mathrm{N_{S_{2nd}}}$, which received the RCTS frame, is set to the NAV duration. As shown in Figure 5, the end time of the secondary transmission is later than the end time of the primary transmission. Node $\mathrm{N_{S_{2nd}}}$ sets up the NAV duration, which is calculated with the end time of the secondary transmission.
3) SNAV frame transmission
Node $\mathrm{S_{1st}}$, which received the RCTS frame, transmits the SNAV frame with omni-directional antennas after waiting for the SIFS time. The neighboring node $\mathrm{N_{S_{1st}}}$, which received the SNAV frame, sets up the NAV duration, which is calculated with the end time of the secondary transmission.
4) Primary transmission, secondary transmission, and DSNAV frame transmission
Nodes $\mathrm{S_{1st}}$, $\mathrm{S_{2nd}}$, and $\mathrm{D_{2nd}}$ start transmissions at the same time. Node $\mathrm{S_{1st}}$, which transmitted the

SNAV frame, waits for the SIFS time, and starts the primary transmission to Node $\mathrm{S}_{2\mathrm{nd}}$ with the directional antennas. Node $\mathrm{S}_{2\mathrm{nd}}$, which received the SNAV frame, waits for the SIFS time and starts the secondary transmission to node $\mathrm{D}_{2\mathrm{nd}}$ with the directional antennas. Node $\mathrm{D}_{2\mathrm{nd}}$, which received the RCTS frame, waits for the duration of transmitting the SNAV frame + 2SIFS time. After the wait, node $\mathrm{D}_{2\mathrm{nd}}$ starts the transmission of the DSNAV frame to the neighboring nodes $\mathrm{N}_{\mathrm{D}_{2\mathrm{nd}}}$ with the directional antennas of beam angle $\frac{4\pi}{3}$ rad.

5) ACK frame transmission
After the secondary transmission, node $\mathrm{S}_{2\mathrm{nd}}$ and node $\mathrm{D}_{2\mathrm{nd}}$ wait for the SIFS time. After passing the SIFS time, the pair of communication nodes exchange ACK frames with each other.

IV. EVALUATION

A. Simulation Environment

We conduct a computer simulation to evaluate DAFD-MAC. We compare the end-to-end throughput and collision ratio with the following four MAC protocols:

1) CSMA/CA (4-way handshake)
In CSMA/CA, nodes exchange RTS/CTS frames before a data transmission to prevent collisions. Due to the benefit of exchanging RTS/CTS frames, the collision ratio is the lowest compared to the others. Therefore, CSMA/CA is the baseline for performance without full-duplex communication.
2) FD-MAC
FD-MAC [5] uses full-duplex communication. However, FD-MAC is restricted to bidirectional full-duplexing, that is, primary and secondary transmission nodes having frames whose destination is each other. We use FD-MAC as the baseline for comparing relay full-duplexing to bidirectional full-duplexing.
3) MFD-MAC
MFD-MAC [6] has a mechanism in which a primary node specifies a secondary transmission node that likely has a frame to transmit. The mechanism is aimed toward the maximum use of opportunities for full-duplexing; however, it suffers from the secondary transmission collision problem mentioned in Section II-B. Because of the secondary transmission problem, the collision ratio of the MFD-MAC is the largest among all the others. We use MFD-MAC as the baseline for evaluating performance without suppression of the secondary transmission collision problem.
4) DAFD-MAC
DAFD-MAC is the proposed approach shown in Section III. DAFD-MAC avoids the secondary transmission collision problem and the deafness problem by using the directional antennas and the 5-way handshake. We use the beam angle when transmissions and receptions of data and ACK frames are at $\frac{\pi}{6}$ rad. Note the beam angle is a reference angle and may not be the optimal angle. This angle should be determined by taking into account the influence of interference [15].

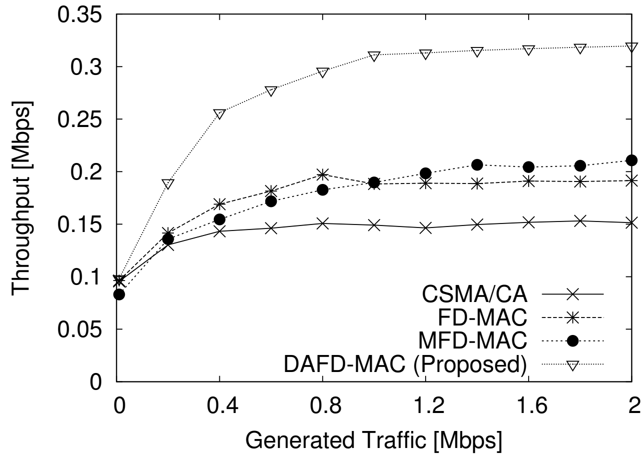


Fig. 6. End-to-end throughput vs. generated traffic

The common simulation parameters are as follows. The physical rate is 2 [Mbps], the radio range is 250 [m], the frame size is 1,500 [bytes], the area size is 1,500 [m] $\times$ 1,500 [m], the number of nodes is 100, the number of flows is 5, and the simulation time is 300 [sec]. We use Dynamic Source Routing (DSR), which is an on-demand routing protocol that makes use of source routing, as the routing protocol [20].

B. Throughput vs. Generated Traffic

We evaluate end-to-end throughput by changing the generated traffic. The aggregate end-to-end throughput versus the generated traffic is shown in Figure 6. Figure 6 shows the following:

1) The throughput of the proposed DAFD-MAC achieves the highest throughput among the others. The reason it has the highest throughput is as follows: DAFD-MAC has full-duplex communication compared to that of CSMA/CA. While FD-MAC only supports bidirectional full-duplexing, DAFD-MAC supports not only bidirectional full-duplexing but also relay full-duplexing. DAFD-MAC suppresses the secondary transmission collision problem even though MFD-MAC does not.
2) The throughput of CSMA/CA is the lowest among all the others. This is because CSMA/CA does not support full-duplexing.

C. Collision Rate vs. Generated Traffic

To verify the suppression of the secondary collision problem in DAFD-MAC, we also evaluate the collision ratio by changing the generated traffic. The aggregate collision ratio versus the generated traffic is shown in Figure 7. Figure 7 shows the following:

1) The collision ratio of the proposed DAFD-MAC is lower than that of FD-MAC and MFD-MAC. This is because DAFD-MAC succeeds in suppressing the secondary transmission collision problem by using the directional antennas and the 5-way handshake.
2) The collision ratio of CSMA/CA is the lowest among all the others. This is because it has the lowest collision ratio for the following reason:. in CSMA/CA,

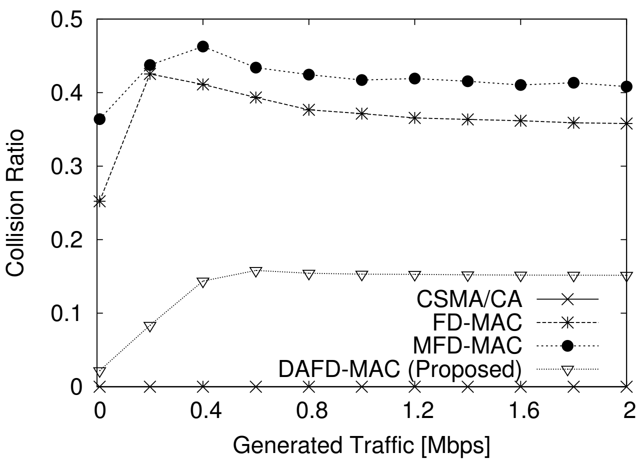


Fig. 7. Collision ratio vs. generated traffic

every node belonging to a wireless network initiates its transmission after exchanging RTS/CTS frames, and the exchange of RTS/CTS frames prevents collisions in half-duplex communication.

3) The collision ratio of MFD-MAC is the highest among all the others. This is because MFD-MAC does not have any mechanisms to suppress the secondary transmission collision problem, as shown in Section II-B.
4) The collision ratio of FD-MAC is lower than that of MFD-MAC. This is because FD-MAC has fewer full-duplex opportunities, and so the collision ratio of FD-MAC is lower than that of MFD-MAC. FD-MAC only supports bidirectional full-duplexing, and MFD-MAC supports not only bidirectional full-duplexing but also relay full-duplexing.

V. Conclusion

In this paper, we proposed the DAFD-MAC protocol that avoids the secondary transmission collision problem by using directional antennas. The secondary collision problem occurs when combining wireless full-duplexing with multi-hop communication. We evaluated the proposed DAFD-MAC by computer simulation. The evaluation results show that DAFD-MAC achieves higher throughput than do CSMA/CA, FD-MAC, and MFD-MAC.

References

[1] R. Ramanathan and R. R. Hain, "Topology control of multihop wireless networks using transmit power adjustment," in *Proceedings of 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'00)*, 2010, pp. 404–413.

[2] J. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proceedings of the 16th Annual International Conference on Mobile Computing and Networking (MobiCom'10)*, 2010, pp. 1–12.

[3] E. Everett, M. Duarte, C. Dick, and A. Sabharwal, "Empowering full-duplex wireless communication by exploiting directional diversity," in *Proceedings of 45th Asilomar Conference on Signals, Systems, and Computers (ACSSC'11)*, 2011, pp. 2002–2006.

[4] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," Rice University TREE1104, Tech. Rep., 2011.

[5] M. Jain, J. Choi, T. M. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *Proceedings of the 17th Annual International Conference on Mobile Computing and Networking (MobiCom'11)*, 2011, pp. 301–312.

[6] K. Tamaki, A. Raptino, Y. Sugiyama, M. Bandai, S. Saruwatari, and T. Watanabe, "Fundamental evaluation of full-duplex communication in multi-hop networks," in *Proceedings of the 11th International Conference on Global Research and Education (iA'12)*, 2012, pp. 395–404.

[7] 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 (MobiCom'02)*, 2002, pp. 23–28.

[8] Quellan Inc., "QHX220 Active Isolation Enhancer and Interference Canceller," http://www.intersil.com/products/deviceinfo.asp?pn=QHX220.

[9] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Proceedings of 44th Asilomar Conference on Signals, Systems, and Components (ACSSC'10)*, 2010, pp. 1558–1562.

[10] Rice University WARP Project, http://warp.rice.edu.

[11] T. S. Ho and K. C. Chen, "Performance analysis of IEEE 802.11 CSMA/CA medium access control protocol," in *Proceedings of the 7th IEEE International Symposium Personal, Indoor and Mobile Radio Communications (PIMRC'96)*, 1996, pp. 407–411.

[12] R. Ramanathan, "On the performance of ad hoc network with beamforming antennas," in *Proceedings of the 2nd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'01)*, 2001, pp. 95–105.

[13] Y. B. Ko, V. Shankarkumar, and N. H. Vaidya, "Medium access control protocols using directional antennas in ad hoc networks," in *Proceedings of 19th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'00)*, 2000, pp. 13–21.

[14] T. Korakis, G. Jakllari, and L. Tassiulas, "A MAC protocol for full exploitation of directional antennas in ad-hoc wireless networks," in *Proceedings of the 4th ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc'03)*, 2003, pp. 98–107.

[15] A. Spyropoulos, "Capacity bounds for ad-hoc networks using directional antennas," in *Proceedings of IEEE International Communications Conference (ICC'03)*, 2003, pp. 348–352.

[16] H. Dai, K. W. Ng, and M. Y. Wu, "An overview of MAC protocols with directional antennas in wireless ad hoc networks," in *Proceedings of the International Multi-Conference on Computing in the Global Information Technology (ICCGI'06)*, 2006, pp. 477–491.

[17] A. P. Subramanian and S. R. Das, "Addressing deafness and hidden terminal problem in directional antenna based wireless multi-hop networks," *Wireless Networks*, vol. 16, pp. 1557–1567, 2010.

[18] K. Miura and M. Bandai, "Node architecture and MAC protocol for full duplex wireless and directional antennas," in *Proceedings of the 23th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC'12)*, 2012, pp. 385–390.

[19] D. Niculescu and B. Nath, "Ad hoc positioning system (APS) using AOA," in *Proceedings of 22th Annual Joint Conference of the IEEE Computer and Communications Societies (INFOCOM'03)*, 2003, pp. 1734–1743.

[20] D. B. Johnson and D. A. Maltz, "Dynamic source routing in ad hoc wireless networks," in *Mobile Computing*, T. Imielinski and H. F. Korth, Eds. Kluwer Academic Publishers, 1996, pp. 153–181.