Full Duplex Media Access Control for Wireless Multi-hop Networks

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***Abstract*—Wireless full-duplexing enables a transmission and a reception on the same frequency channel at the same time, and has the potential to improve the end-to-end throughput of wireless multi-hop networks. In the present paper, we propose a media access control (MAC) protocol for wireless full-duplex and multi-hop networks called Relay Full-Duplex MAC (RFD-MAC). The RFD-MAC is an asynchronous full-duplex MAC protocol, which consists of a primary transmission and a secondary transmission. The RFD-MAC increases the full-duplex links by overhearing frames, which include 1-bit information concerning the existence of a successive frame, and selecting a secondary transmission node using the gathered information. The gathered information is also used to avoid a collision between the primary and secondary transmission. Simulation results reveal that the proposed RFD-MAC improves up to 68%, 49% and 56% of end-to-end throughput compared to CSMA/CA, FD-MAC and MFD-MAC, respectively.**

I. Introduction

For many years, wireless communication has been performed through half-duplexing because the signal received from one's own node is stronger than that received from another node. However, recent progress in several technologies, such as analog circuits [1], digital circuits, and interference cancellation [2]–[10], has made wireless full-duplexing possible [7]–[12].

The present paper focuses on the application of wireless full-duplexing to multi-hop networks [13]–[15]. Wireless full-duplexing has the potential to improve the end-to-end throughput of wireless multi-hop networks because a relay node can transmit a frame while receiving another frame from another node. However, existing Full-Duplex Media Access Control (FD-MAC) protocols do not support multi-hop networks. Although multi-hop networks can have relay full-duplexing among three nodes, the existing FD-MAC supports only bidirectional full-duplexing between two nodes. Bidirectional full-duplexing and relay full-duplexing are described in detail in Section II.

In view of this, the present paper proposes a full-duplex media access control protocol for wireless full-duplex and multi-hop networks called Relay Full-Duplex MAC (RFD-MAC). RFD-MAC adds 1-bit information to each frame header. This bit indicates whether the sender node of the frame has a successive frame in its buffer. Each node overhears the frames, which includes the same information and determines whether neighbor nodes have a successive frame. In using the information gathered for successive frames, each node selects a full-duplex link, avoids collisions among other full-duplexing nodes, and increases full-duplex opportunities. We evaluate RFD-MAC through a computer simulation, and the evaluation results reveal that RFD-MAC improves end-to-end throughput compared to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), FD-MAC [9] and MFD-MAC [16].

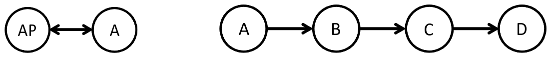
II. Related Research

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. Half-duplex communication can only be used for conventional radio because the transmitting signal is too strong to receive a signal from another node. However, the development of self-interference cancellation has enabled full-duplex communication [2]–[5], [8], [9]. For example, received signals have been successfully cancelled using FPGA on a WARP V2 platform [2]–[5], [10].

Wireless full-duplexing enables wireless multi-hop networks to improve end-to-end throughput because each node can receive a frame from a previous-hop node while transmitting a frame to a next-hop node. In order to realize wireless full-duplex and multi-hop networks, there are two MAC protocol issues to be addressed.

First, the MAC requires timing adjustment. Wireless full-duplexing must cancel self-interference in order to receive a frame from another node. In order to maximize the performance of the self-interference cancellation, a sender node must precisely estimate the signal strength of self-interference and the received signal from another node. Precise estimation requires timing adjustment between uplink and downlink transmission, which suppresses the fluctuation of the signal strength. The FD-MAC has two candidate methods for timing adjustment: synchronous [8] or asynchronous [9]. The present paper uses the asynchronous method for timing adjustment. In the asynchronous method, the destination node of the frame starts to transmit a frame as a secondary transmission when the header of the primary transmission includes the address of the destination node.

Second, the MAC must decide which node performs a primary transmission or a secondary transmission. The existing



(a) Bidirectional full-duplexing

(b) Relay full-duplexing

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

TABLE I
CHARACTERISTIC OF VARIOUS MACS

	single-hop	multi-hop
synchronous	[8]	[17]
asynchronous	[9]	proposed MAC, [16], [18]

FD-MAC protocols [8], [9] are designed for the bidirectional full-duplexing in Figure 1(a). Bidirectional full-duplexing has only a bidirectional link such as AP and node A shown in Figure 1(a). The wireless full-duplex and multi-hop network can handle not only bidirectional full-duplexing but also relay full-duplexing. A full-duplex situation, referred to as relay full-duplexing, occurs for the case in which node B receives a frame from node C while transmitting a frame to node A in Figure 1(b). In order to make maximum use of both bidirectional full-duplexing and relay full-duplexing, the MAC protocol must properly select a secondary transmission node. For example, in Figure 1(b), node B has two candidates for a secondary transmission node: nodes A and C. If the MAC protocol selects a node that does not have a frame, then full-duplexing does not occur.

The MAC protocol must also take into account a collision between a primary transmission and a secondary transmission. Figure 2 illustrates a collision between a primary transmission and a secondary transmission. In Figure 2, P denotes a primary transmission node, and S denotes a secondary transmission node. Moreover, R denotes the destination node of nodes P and S. The solid line depicts the transmission range of the primary transmission node, and the dotted line depicts the transmission range of the secondary transmission node. Whenever a destination node of a primary transmission node is located within the transmission range of a secondary transmission node, a collision occurs at the destination node.

We classify the existing full-duplexing MAC in Table I. As mentioned previously, FD-MAC [8], [9] supports only single-hop networks. Multi-hop Full-Duplex MAC (MFD-MAC) applies wireless full-duplexing to a wireless multi-hop network [16]. The MFD-MAC selects the secondary transmission node by monitoring traffic on adjacent nodes. However, MFD-MAC does not take into account collisions between primary and secondary transmissions. [17], [18] propose full-duplexing MAC protocols using directional antennas. For example, [17] achieved a throughput that was three times higher than that of half-duplexing . However, the wireless full-duplexing devices considered herein do not assume directional antennas. Instead, the present study assumes the same full-duplexing device as in [2], [3], [7]–[9], [12].

III. RELAY FULL-DUPLEX MAC

Based on the discussion in Section II, we propose the Relay Full-Duplex MAC (RFD-MAC) protocol, which enables bidirectional full-duplexing and relay full-duplexing. The RFD-MAC protocol is designed based on a synchronous method [9], which is composed of a primary transmission and a secondary transmission. The RFD-MAC protocol enables relay full-duplexing and avoids a collision between a primary transmission and a secondary transmission.

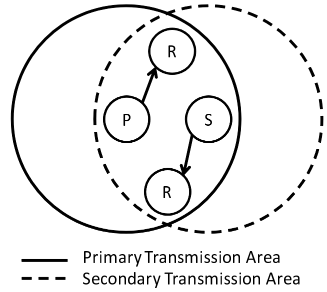


Fig. 2. Collision between a primary transmission and a secondary transmission

RFD-MAC adds 1-bit information to each frame. The 1-bit information indicates whether the node that sent the frame has a successive frame. Whenever a node overhears a transmission from its surrounding nodes, the node records the 1-bit information into a surrounding node table. The surrounding node table is described in detail in Section III-A. When a node starts the primary transmission, the node also selects the secondary transmission node and attaches the address of the secondary transmission node. The selection algorithm is described in detail in Section III-B. The secondary transmission node, which received the header of the primary transmission, starts a secondary transmission.

A. Surrounding Node Table

RFD-MAC uses two types of frame: a primary transmission frame and a secondary transmission frame. RFD-MAC uses the same frame header format of IEEE 802.11. However, the following two fields are used for different purpose: ‘Address 3’ and ‘More Data’. Figure 3 shows a IEEE 802.11 MAC frame header [19]. The primary transmission node places the designated secondary transmission node address into ‘Address 3’. Both the primary transmission frame and the secondary transmission frame use the ‘More Data’ field for the 1-bit information related to a successive frame. In the ‘More Data’ field, 1 indicates that the source node of the frame has a successive frame, and 0 indicates that the source node does not have a successive frame.

Each node overhears primary transmission frames and secondary transmission frames from neighbor nodes and builds a surrounding node table. Table II shows the surrounding node table. The surrounding node table has the following columns: Node Address, Has Frame, and Next Hop. The Node Address column contains the source address of the overheard frame. The Has Frame column contains the value in the ‘More Data’ subfield in the overheard frame. The Next Hop column contains 1 when the destination address of the overhead frame is its own address and 0 when the destination address is some

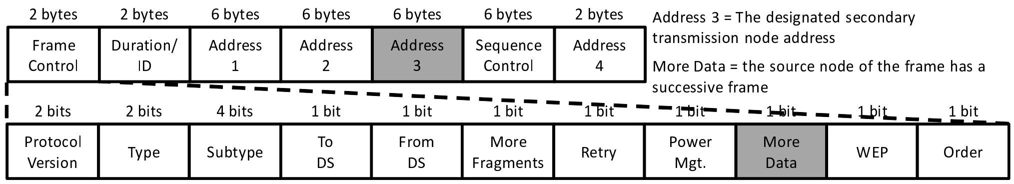


Fig. 3. IEEE 802.11 header

other address.

In addition, each node updates the surrounding node table when the node succeeds in transmitting a frame. If the recipient of the frame is not the final destination in the network layer, the sender node of the frame updates the Has Frame column of the corresponding recipient node to 1. The recipient not being the final destination indicates that the recipient node will hold the frame until the node transmits the frame.

B. Selection of a Secondary Transmission

As mentioned in Section II, whenever the destination node of a primary transmission (or the destination node of a secondary transmission) is located within the transmission range of a secondary transmission (or the transmission range of a primary transmission), a collision occurs at the destination node. In particular, a collision occurs when a primary transmission node selects a secondary transmission node on another flow. In order to avoid such collisions, the primary transmission node selects a secondary transmission node from the same flow. Generally speaking, a routing protocol in wireless multi-hop networks selects a route with the least hop. The same flow and the least hop ensure that the destinations of the primary and secondary transmissions are different.

Figure 4 shows examples of collision and no collision between nodes. In Figure 4, the solid line depicts the transmission range of the primary transmission node and the dotted line depicts the transmission range of the secondary transmission node. Figure 4(a) shows a collision between destination nodes B and E. In Figure 4(a), node A, which is a primary transmission node, and node D, which is a secondary transmission node, belong to different flows. Figure 4(b) shows the situation in which there is no collision between destination nodes B and C. In Figure 4(b), node A, which is a primary transmission node, and node B, which is a secondary transmission node, belong to the same flow.

The primary transmission node uses the surrounding node table, which is described in Section III-A, for the selection of a secondary node. The priority of the selection is as follows:

1) The next-hop node that has a frame
2) The previous-hop node that has a frame
3) The previous-hop node that does not have a frame
4) The next-hop node that does not have a frame

TABLE II
EXAMPLE OF A SURROUNDING NODE TABLE

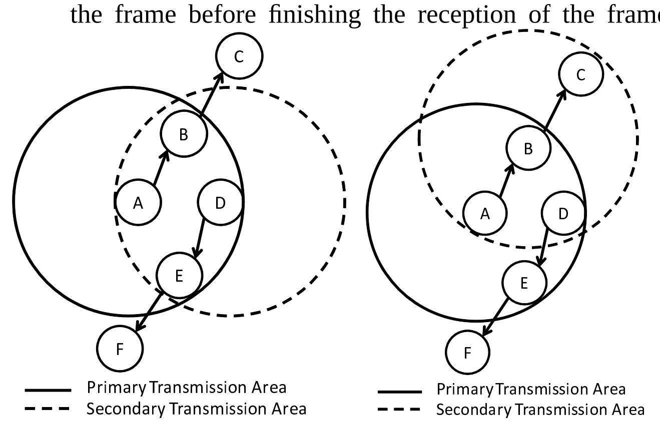
Node Address	Has Frame	Next Hop
A	1	1
C	1	0

RFD-MAC prioritizes the node that has a frame and belongs to the same flow. There are two types of nodes in the same flow: an upstream node and a downstream node. If both the upstream node and the downstream node have a frame, the downstream node has higher priority because frames jam the flow if the downstream node does not transmit any frames. If neither the upstream node nor the downstream node have a frame, RFD-MAC prioritizes the upstream node because the upstream node might have received a frame from a node upstream of the upstream node. The surrounding node table cannot know the reception from the upstream node of the upstream node. If more than one candidate node has the same priority, then RFD-MAC randomly selects among the candidate nodes.

C. Example of Operation of RFD-MAC

Figure 5 shows the time sequence of RFD-MAC, and an example of operation of RFD-MAC is as follows:

1) A node, that has a frame to transmit uses CSMA/CA to resolve the contention. The node that wins the contention transmits a frame as a primary transmission. We define this node as the primary transmission node.
2) The primary transmission node selects another node designated to transmit a frame as a secondary transmission node. The selection algorithm is described in Section III-B. We define the selected node as the secondary transmission node.
3) The secondary transmission node starts if the secondary transmission node has a frame. The other nodes set the network allocation vector (NAV) and defer transmission.
4) Whenever the primary transmission node or the secondary transmission node finishes the transmission of the frame before finishing the reception of the frame,



(a) Collision (b) No Collision

Fig. 4. Collision and no collision between nodes

the node transmits a busytone until the reception ends. The busytone ensures that surrounding nodes do not start the next transmission until the current transmission has finished.

5) The primary and secondary transmission nodes exchange ACK frames at the same time with full-duplexing after ending the primary and secondary transmissions.

IV. Performance Evaluation

A. Simulation Environment

We conduct a computer simulation to evaluate the RFD-MAC. We compare the obtained end-to-end throughput and full-duplexing ratio (FD ratio) with the following three MAC protocols:

1) CSMA/CA
CSMA/CA is a contention-based MAC protocol. The CSMA/CA is a baseline for performance without full-duplexing.
2) FD-MAC
FD-MAC [9] uses full-duplex communication. However, FD-MAC is restricted to bidirectional full-duplexing. We use FD-MAC as a baseline for comparing relay full-duplexing to bidirectional full-duplexing.
3) MFD-MAC
MFD-MAC [16] has a mechanism in which the primary node specifies a secondary transmission node that is likely to have a frame to transmit. Although this mechanism is designed to make maximum use of opportunities for full-duplexing, it suffers from collisions among different flows, as mentioned in Section II. As a result of these collisions, the collision ratio of the MFD-MAC will be the largest among the MACs considered herein. We used MFD-MAC as a baseline for performance evaluation without suppressing collisions between primary and secondary transmissions.
4) RFD-MAC
RFD-MAC is the proposed MAC protocol as shown in Section III. RFD-MAC supports bidirectional full-duplexing and relay full-duplexing while avoiding collisions between primary and secondary transmissions.

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 2,000 (m) $\times$ 2,000 (m). The number of nodes is 100. The number of source-destination pairs (flows) is 3 or 7, and the simulation time is 300 (s). The topology is a random network topology in which the nodes are randomly distributed inside the area. The number of simulation trials is 10. We use Dynamic Source Routing (DSR) [20] as the routing protocol.

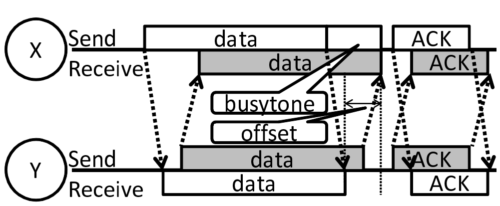


Fig. 5. RFD-MAC time sequence

B. Throughput vs. Sending Rate

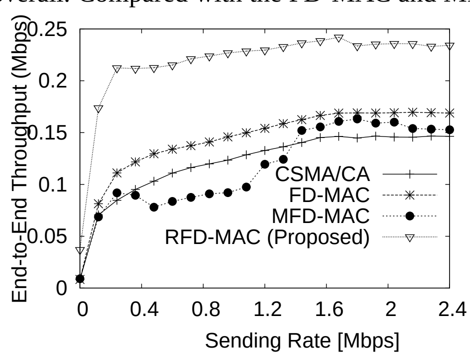
We evaluated the end-to-end throughput by varying the sending rate. The aggregate end-to-end throughput versus the sending rate is shown in Figure 6(a) (♯ of flows = 3) and 6(b) (♯ of flows = 7). The vertical and horizontal axes denote the throughput and traffic generation rate, respectively.

In Figure 6, the proposed RFD-MAC achieves the highest throughput overall. Compared with the CSMA/CA, FD-MAC and MFD-MAC, RFD-MAC improves up to 68%, 49% and 56% of end-to-end throughput, respectively. The reasons for this are as follows. Unlike CSMA/CA, RFD-MAC uses full-duplexing. FD-MAC supports only bidirectional full-duplexing whereas RFD-MAC supports both bidirectional and relay full-duplexing. The RFD-MAC suppresses collisions between primary and secondary transmissions by selecting the secondary transmission node from the same flow, whereas MFD-MAC does not take into account such collisions.

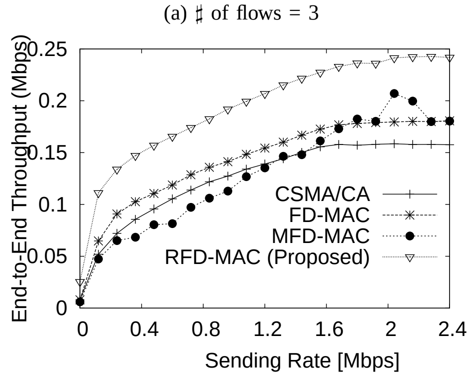
C. Full-duplexing Ratio vs. Sending Rate

In order to verify that RFD-MAC increases full-duplexing opportunities, we evaluated the full-duplexing ratio by varying the sending rate. Figure 7(a) (♯ of flows = 3) and 7(b) (♯ of flows = 7) show the aggregate full-duplex ratio versus the sending rate. The vertical and horizontal axes denote the full-duplex ratio and the traffic generation rate, respectively.

The full-duplex ratio of the proposed RFD-MAC is the highest overall. Compared with the FD-MAC and MFD-MAC,

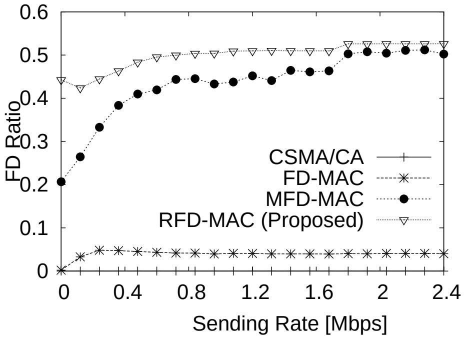


(a) ♯ of flows = 3

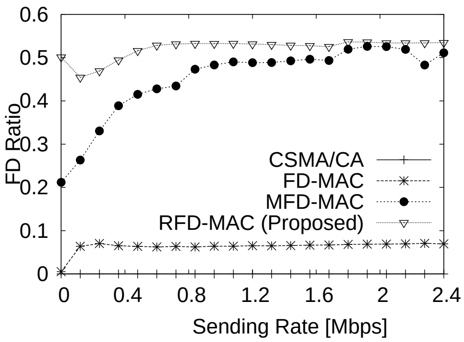


(b) ♯ of flows = 7

Fig. 6. End-to-end Throughput



(a) ♯ of flows = 3



(b) ♯ of flows = 7

Fig. 7. Full-duplex ratio

RFD-MAC improves up to 815% and 22% of full-duplex ratio, respectively. The reasons for this are as follows. CSMA/CA is a half-duplex protocol, which results in a full-duplex ratio of 0. FD-MAC supports only bidirectional full-duplexing. RFD-MAC supports both bidirectional and relay full-duplexing and yields a higher full-duplex ratio than FD-MAC. The MFD-MAC improves full-duplexing opportunities by monitoring the adjacent nodes traffic, although the mechanism is not as effective as the information exchange of the RFD-MAC with respect to finding full-duplexing opportunities. In addition, the full duplex ratio of RFD-MAC does not depend on the traffic. In Figure 7, RFD-MAC achieves a high full-duplex ratio when the sending rate is low, although other MACs achieve a low full-duplex ratio.

V. Conclusion

In the present paper, we proposed a full-duplex MAC protocol for the RFD-MAC multi-hop network. We evaluated the proposed RFD-MAC through a computer simulation. The evaluation results reveal that the proposed RFD-MAC achieves a higher throughput than CSMA/CA, FD-MAC, or MFD-MAC.

Acknowledgement

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