Routing Protocol for Directional Full-Duplex Wireless

Katsuhiro Kato† and Masaki Bandai
Dep. of Information and Communication Sciences, Sophia University
7-1 Kioicho, Chiyoda, Tokyo, 102-8554 Japan
†Email: katsuhiro.kato@sophia.ac.jp

Abstract—In this paper, we propose a routing protocol for directional full-duplex wireless (D-FDW) to reduce hidden terminal problems in multi-hop networks. The proposed routing protocol is an on-demand detour routing protocol, which reduces number of cross points among traffic flows. In general, the throughput of a detour route degrades excessively due to increase of the number of hops between source and destination nodes. However, D-FDW has a remarkable benefit that throughput does not degrade excessively as the number of hops between source and destination nodes becomes large. Thus, the proposed detour routing can bring out the potential of D-FDW effectively. We evaluate the performance of the proposed routing protocol via ns-3 computer simulations, and show that the proposed routing protocol can reduce hidden terminal problems and improve end-to-end throughput performance up to 86.4% compared with the conventional AODV in a grid multi-hop network. To the best of our knowledge, this is the first routing protocol for D-FDW.

I. INTRODUCTION

Recently, a novel full-duplex wireless (FDW) technology has been presented in [1]-[3]. FDW is the technology that allows a node to send and receive data simultaneously on a single wireless channel. [2] realizes FDW by using analog and digital cancellations. The analog cancellation uses one receive (RX) antenna, one transmit (TX) antenna and balanced/unbalanced (Balun) transformer. In the analog cancellation, transmission radio wave from the TX antenna and its inverted signal through Balun transformer cancel each other at the RX antenna, which can cancel at least 45 dB across a 40 MHz bandwidth. Digital cancellation technique in addition to the analog cancellation can reduce self-interference by up to 73 dB for 10 MHz OFDM signal. [2] also presents a medium access control (MAC) protocol for FDW. The MAC protocol mitigates hidden terminal problems in access point (AP)-based single-hop networks. Some other MAC protocols have been presented for FDW [4][5]. They are for omni-directional antennas.

It is natural to apply FDW technology to multi-hop networks. Intuitively, FDW would seems to be effective for improving network throughput in multi-hop networks because relay nodes can send and receive data simultaneously thanks to the properties of FDW. However, just only adopting FDW for multi-hop networks does not improve throughput. This is because spatial reuse is limited due to omni-directional transmissions. [6] presents a novel node architecture for realizing directional full-duplex wireless (D-FDW), which introduces directional antennas into FDW nodes. Directional antennas such as switched-beam and adaptive array can control their antenna directivity by software. Basically, the node architecture uses the same analog and digital cancellation mechanisms of [2]. In addition to the FDW mechanism, nodes are equipped with some switched-beam antennas for directional transmissions to reduce interference to other communications and improve spatial reuse. This node architecture can improve end-to-end throughput performance when a single traffic flow exists along a multi-hop line topology. In addition, the throughput performance does not degrade when the number of hops between source and destination becomes large, which is a remarkable benefit of D-FDW. Thus, D-FDW is a promising technique to bring out the complementary advantages of FDW and directional antennas. However, in a multi-hop network with two or more traffic flows, D-FDW incurs severe throughput degradation due to the hidden terminal problem. Therefore, D-FDW should be used with a sophisticated routing protocol that considers hidden terminal problems in multi-hop networks.

In this paper, we propose a routing protocol for D-FDW to reduce hidden terminal problems in multi-hop networks. The proposed routing protocol is an on-demand detour routing protocol, which reduces the number of cross points among traffic flows. The proposed routing protocol mitigates the effect of the hidden terminal problem and improves end-to-end throughput performance in multi-hop networks. In general, the throughput of a detour route degrades excessively due to increase of number of hops between source and destination nodes. However, D-FDW has the remarkable benefit that throughput does not degrade excessively as number of hops between source and destination becomes large. Therefore, the proposed detour routing can bring out the potential of D-FDW effectively. To the best of our knowledge, this is the first work to propose routing protocol for D-FDW. We implement the proposed routing protocol on ns-3, and confirm that the proposed routing protocol with D-FDW can improve the throughput performance in multi-hop networks.

The rest of this paper is organized as follows. In Section II, we show the node architecture, the MAC protocol and fundamental evaluation of D-FDW. The proposed routing protocol is shown in Section III. We evaluate the performance of the proposed routing protocol in Section IV. Finally, Section V concludes this paper.
node can operate the following two modes: TX1 and TX2 cannot be used simultaneously. Therefore, the switch for TX antenna selection. The switch is controlled by software.

A Node Architecture for D-FDW

We show the node architecture for D-FDW. D-FDW node has \( N_{\text{ant}} \) directional TX antennas and one omni-directional RX antenna, and can transmit directionally and receive omnidirectionally.

Fig. 1 shows an example of the node architecture for D-FDW when \( N_{\text{ant}} = 2 \). TX1 and TX2 are placed on the node surrounding the omni-directional RX antenna. TX1 is used to transmit for the direction 0 to \( \pi \). TX2 is used to transmit for the direction \( \pi \) to 2\( \pi \). Each TX antenna connects to a switch for TX antenna selection. The switch is controlled by software. TX1 and TX2 cannot be used simultaneously. Therefore, the node can operate the following two modes:

- Mode 1: Directional transmission by TX1 and Omni-directional reception by RX simultaneously,
- Mode 2: Directional transmission by TX2 and Omni-directional reception by RX simultaneously.

In the architecture, a node needs only one set of the digital and analog cancellation circuits. Thus, it does not depend on the number of directional antenna elements \( N_{\text{ant}} \) and is almost the same circuit scale and complexity as the conventional omni-directional FDW node presented in [2].

B MAC protocol for D-FDW

We show the MAC protocol for the node architecture for D-FDW presented in Section II-A. The MAC protocol is based on CSMA/CA. The following two points are modified:

1) Modifying condition for data transmission,
2) No ACK frame.

The first modification is the condition for data transmission for the node architecture for D-FDW. Since CSMA/CA is designed for half-duplex wireless, full-duplex operations are hardly adopted in D-FDW because a node’s data transmission is prohibited when the node detects carrier in CSMA/CA. The customized MAC protocol for D-FDW allows a node to transmit data if a node detects carrier and the destination MAC address of the detected data is the node itself. Adopting this condition increases the opportunity for full-duplex operations. A sample operation of the MAC protocol is illustrated in Fig. 2. This example assumes a three-node line topology. After waiting DIFS and not detecting carrier during the random contention window period, Node 1 initiates to transmit DATA to Node 2. Node 2 initiates to receive the frame header, and if the destination MAC address of the incoming DATA is Node 2 itself, Node 2 is allowed to transmit DATA to another node, which means starting a full-duplex operation at Node 2.

The second modification is about ACK frames. The MAC protocol for D-FDW removes ACKs from CSMA/CA to reduce frame collisions. In the situation of Fig. 2, if Node 3 transmits ACK to Node 2 after receiving DATA from Node 2, the ACK incurs a collision with another DATA from Node 1. Therefore, the MAC protocol for D-FDW removes ACKs not to occur this kind of frame collisions.

MAC protocol for D-FDW presented in this paper considers contention window, as well as the conventional CSMA/CA, for mitigating collisions in general multi-hop networks.

C Fundamental evaluation of D-FDW

We implement the node architecture and MAC protocol for D-FDW on the network simulator ns-3 [5] to evaluate a fun-
damental performance of the D-FDW. Simulation parameters are shown in Table I.

We consider two models in fundamental evaluation.

- D-FDW: Directional antenna + full duplex wireless
- O-HDW: Omni directional antenna + half duplex wireless

Fig. 3 shows \( N \)-hop line topology in simulations. Node 1 is the source; Node \( N \) is the destination. 1 Mb/s constant bit rate (CBR) traffic flow is generated at Node 1. We evaluate the end-to-end average throughput over twenty simulation trials. In D-FDW, the transmission range and carrier sense distance are 443 meters. In O-HDW, the transmission range and carrier sense distance are 626 meters. The transmission distance of O-HDW is longer than that of D-FDW because self-interference never occurs in O-HDW. In O-HDW, CSMA/CA without RTS/CTS is adopted as its MAC protocol.

Fig. 4 shows the average end-to-end throughput between Node 1 and Node \( N \). As shown in this figure, the throughput of D-FDW does not degrade excessively as number of hops between source and destination nodes becomes large. This is because all nodes can communicate simultaneously thanks to the FDW and directional antennas, MAC protocol for D-FDW. On the other hand, the throughput of O-HDW degrades as the number of hops between source and destination nodes becomes large. This comes from the following two reasons: The first reason is that O-HDW cannot send and receive data simultaneously due to the use of half-duplex wireless. The second reason is that O-HDW prohibits the transmission of data to neighbor nodes due to the use of omni-directional antenna.

From this result, we confirmed that D-FDW has the remarkable benefit that the throughput of D-FDW does not degrade excessively as number of hops between source and destination nodes becomes large.

### III. PROPOSED ROUTING PROTOCOL FOR D-FDW

We propose a routing protocol for D-FDW to improve end-to-end throughput in wireless multi-hop networks. The proposed routing protocol is an on-demand detour routing protocol, which reduces number of cross points among traffic flows. The proposed routing protocol mitigates the effect of hidden terminal problems and improves end-to-end throughput performance in multi-hop networks thanks to the remarkable benefit of D-FDW as shown Section II-C. The proposed routing protocol is based on the ad hoc on demand distance vector (AODV), and adds the following three functions:

- Function 1: Each node has a flow counter. When a node receives a route reply (RREP), the node increments the flow counter by one. In addition, the destination node also increments the flow counter by one when the node transmits a RREP.
- Function 2: A new field called counter field is added to the header of route request (RREQ).
- Function 3: A destination node waits for a RREQ whose counter field is zero.

The initial value of the flow counter at each node is zero. The initial value of the counter field of RREQ is also zero. The operation of the proposed routing protocol is shown as follows:

1) A source node broadcasts a RREQ to find a route to the destination node.
2) When a node receives a RREQ, the node sums the value of the node’s flow counter to that of the counter field of the received RREQ, overwrites the counter field of the RREQ as the summation, and rebroadcasts the RREQ.
3) If a destination node receives a RREQ whose counter field is zero, it unicasts a RREP to the source node. A destination node waits for at most \( M \)-th RREQ until receiving a RREQ whose counter field is zero. If a destination node does not receive a RREQ whose counter field is zero until it receives \( M \)-th RREQ, it unicasts a RREP based on the information of the \( M \)-th RREQ for simplicity.
4) When a node receives RREP, the node increments the flow counter. In addition, the destination node also increments the flow counter when the node transmits a RREP.
5) When a source node receives a RREP, the source node starts to transmit data to the destination node.

When a routing entry is deleted from the routing table, the value of the flow counter is decremented by one.

#### Table I

**SIMULATION PARAMETERS**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation time</td>
<td>100 seconds</td>
</tr>
<tr>
<td>Packet size</td>
<td>1,500 byte</td>
</tr>
<tr>
<td>Channel rate</td>
<td>1 Mb/s</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Path loss exponent</td>
<td>2 (free space)</td>
</tr>
<tr>
<td>Standard</td>
<td>IEEE 802.11b</td>
</tr>
<tr>
<td>Frame reception model</td>
<td>SINR-based model [6]</td>
</tr>
</tbody>
</table>
D-FDW allows all the traffic flows to communicate without cross points with each other. It also has the potential of D-FDW complementary and effectively. In general, the throughput of a detour route degrades excessively due to increase of the number of hops between source and destination nodes. However, D-FDW has a remarkable benefit that throughput does not degrade excessively as the number of hops between source and destination becomes large as shown in Fig. 4. This benefit is come from the following two reasons: The first reason is that D-FDW can improve spatial reuse thanks to the use of directional transmissions, which can decrease the interference from/to the other communication pairs. The second one is that D-FDW can improve temporal efficiency thanks to the full duplex wireless. Therefore, the proposed detour routing can bring out the potential of D-FDW complementary and effectively.

Fig. 5 illustrates a sample operation of the proposed routing protocol. There are nine nodes in the network. Each node can communicate with its neighbor nodes, but cannot communicate with diagonal neighbors. Initially, there is a traffic flow from Node 4 to 5. We consider how Node 2 finds a route to Node 8 by using the proposed routing protocol with $M = 3$. As shown in Fig. 5a, the flow counters of Node 4 and 5 are one, respectively. In Fig. 5a, Node 2 broadcast a RREQ. In Fig. 5b, when a node receives a RREQ, the node sums the value of the node’s flow counter to that of the counter field of the received RREQ, and overwrites the counter field of the RREQ as the summation, and rebroadcasts the RREQ. We see the change of the counter field of three RREQs as follows:
- RREQ 1 (Node 2→1→4): counter field is 1 ($0 + 0 + 1$)
- RREQ 2 (Node 2→5): counter field is 1 ($0 + 1$)
- RREQ 3 (Node 2→3→6): counter field is 0 ($0 + 0 + 0$)

In Fig. 5c, Node 8 firstly receives RREQ 2 from Node 5. Node 8 waits for next RREQ. After that Node 8 receives RREQ 3 from Node 9. Since the counter field of the RREQ 3 is zero, Node 8 unicasts a RREP along the reverse route to Node 2 as illustrated in Fig. 5c. In Fig. 5d, Nodes 8, 9, 6, 3 and 2 increase their flow counters by one. When Node 2 receives the RREP, it starts to transmit data to Node 8.

In the proposed routing protocol, each node counts the number of traffic flows being transmitted or received at the node, and records it in its flow counter. Therefore, the counter field in RREQ indicates total number of traffic flows where the nodes in the route transmit or receive. The proposed routing protocol selects the RREQ with zero counter field, which means that the route has no cross points with the other traffic flows. This concept reduces hidden terminal problems.

In general, the throughput of a detour route degrades excessively due to increase of the number of hops between source and destination nodes. However, D-FDW has a remarkable benefit that throughput does not degrade excessively as the number of hops between source and destination becomes large as shown in Fig. 4. This benefit is come from the following two reasons: The first reason is that D-FDW can improve spatial reuse thanks to the use of directional transmissions, which can decrease the interference from/to the other communication pairs. The second one is that D-FDW can improve temporal efficiency thanks to the full duplex wireless. Therefore, the proposed detour routing can bring out the potential of D-FDW complementary and effectively.

### IV. PERFORMANCE EVALUATION
We evaluate the performance of the proposed routing protocol for D-FDW in multi-hop networks. Based on the evaluations, we show that the routing protocol mitigates the effect of hidden terminal problems and improves end-to-end throughput performance in multi-hop networks.

Fig. 6 shows the network topology in simulations. The network topology is 5×7 grid topology. Each node can communicate with its neighbor nodes, cannot communicate with diagonal neighbors. Initially, there is a traffic flow from Node S1 to D1. We consider how Node S2 finds a route to Node D2 by using routing protocols. We use the same simulation parameters as shown TABLE I. In addition, we assume the following:
- 1Mb/s CBR traffic flows are generated at the nodes S1 and D1.
- We evaluate average of values over twenty simulation trials.
- In D-FDW, transmission and carrier sense distance are 443 meter.
- The beamwidth is 30 degrees.
- We select AODV for comparison.

Fig. 7 shows the average throughput performance of the proposed routing protocol. In all the cases, the proposed routing protocol archives higher throughput than AODV. This is because a detour route is set up by using the proposed routing protocol, and hidden terminal problem is mitigated. On the other hand, AODV incurs hidden terminal problem because the flows cross. As a result, data collide at cross points among traffic flows, and throughput degrades. Moreover, when $M = 5$, the highest throughput can be obtained. As compared with AODV, throughput of the proposed routing protocol
improves 86.4%. This is because the probability that the destination node receives the RREQ whose counter field is zero becomes high when $M$ is large. In other words, it is easier to make a detour where traffic flows do not cross.

Fig. 8 shows the average number of hops between S2 and D2. We can find that the proposed routing protocol leads to more hops than AODV in all the cases. Moreover, the number of hops increases as $M$ increases due to making detours. This increase does not cause a negative impact to the throughput performance because D-FDW has the benefit as shown Fig. 4. Therefore, the proposed detour routing can bring out the potential of D-FDW effectively.

Fig. 9 shows the average route setup delay. Route setup delay is defined as the time from when a source node transmits RREQ until it receives RREP. When $M = 5$, the proposed routing protocol has the largest route setup delay. There are two reasons for long route setup delay. The first reason is that the delay increases because a destination node waits for $M$ to receive RREQs. The second reason is that the delay increases because there are more hops about RREP by making a detour. On the other hand, average route setup delay of AODV is the smallest because a destination node transmits RREP immediately when a destination node receives RREQ.

From these results, the proposed routing protocol has positive and negative features. The positive feature is that it mitigates the effect of hidden terminal problems and improves end-to-end throughput performance in multi-hop networks. The negative feature is that average route setup delay is large. So we should select appropriate $M$ carefully considering these two features. We confirm the effectiveness of the proposed routing protocol.

V. CONCLUSION

In this paper, we have proposed a routing protocol for D-FDW to reduce hidden terminal problems in multi-hop networks. The proposed routing protocol is an on-demand detour routing protocol, which reduces number of cross points among traffic flows. We have shown that the proposed detour routing can bring out the potential of D-FDW. We have implemented the proposed routing protocol on ns-3, and confirmed that the proposed routing protocol with D-FDW can improve the throughput up to 86.4% in a grid multi-hop network. As the future work, we plan to implement D-FDW node and the proposed detour routing protocol in a real system such as WARP v3.

ACKNOWLEDGMENT

This work is partly supported by KAKENHI Grant-in-Aid for Young Scientists (B) No. 24700074 and the Telecommunications Advancement Foundation.

REFERENCES