A Distributed MAC Protocol for Full Duplex Radio

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***Abstract*—Recent advances in antenna and circuit design enable radios that operate in full duplex mode on a single channel with very low residual self-interference. In this paper, the use of such full duplex radios in a wireless local area network (WLAN) is explored. Different scenarios in which the full duplex transmission can be exploited are studied. A distributed full duplex MAC design based on IEEE 802.11 DCF that adopts to the traffic conditions is proposed. The proposed MAC design works for both *ad hoc* and *infrastructure* modes of WLAN and takes into consideration new interference and contention during full duplex transmissions. OPNET simulations comparing the performance of the proposed MAC with traditional half duplex based IEEE 802.11 DCF show that the new MAC protocol provides up to 88% throughput gain in a heavily loaded network.**

I. Introduction

Traditional radio transceivers are generally not able to receive and transmit on the same frequency band at the same time because of the crosstalk (self-interference) between transmitter and the receiver circuits. Thus, most of today's bidirectional systems rely on orthogonal signaling dimensions, such as time or frequency. An example of such a system is time division duplex (TDD) or frequency division duplex (FDD). Recent developments in antenna design and analog/digital interference cancellation [1]–[5] have challenged this limitation and resulted in crosstalk cancelation up to 110 dB, which make it feasible to transmit and receive on a common carrier with very low residual self-interference.

In this work, we focus on designing a MAC protocol that enables FD transmission in a wireless local area network (WLAN) system. We first observe the different scenarios in which the FD transmissions can be exploited in a WLAN, where the main challenge is to discover and coordinate a set of stations to participate in FD transmissions in a distributed manner. Further, in some scenarios, FD transmission results in new inter-node interference which needs to be minimized in order to benefit from FD transmission. We propose a MAC design that can enable all scenarios opportunistically in a distributed manner, while taking care of new inter-node interference.

Figure 1 illustrates four possible scenarios with FD enabled nodes in a wireless LAN. In IEEE 802.11 DCF mode, each node that has a non-empty queue contends for the channel according to the CSMA/CA protocol. We call the node that captures the channel to be the primary transmitter (PT), and the intended receiver to be primary receiver (PR). In the case of FD nodes, the next step for the MAC protocol is to find a set of nodes that can simultaneously communicate, for which we denote the transmitter and receiver by secondary transmitter (ST) and secondary receiver (SR), respectively.

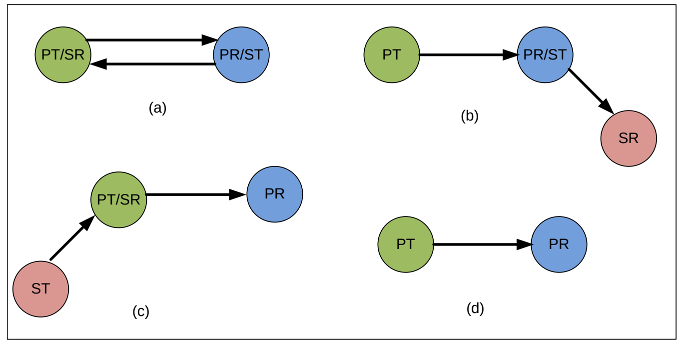

Fig. 1: Different scenarios of exploiting FD capability, (a) Two node FD transmission, (b) Destination based three node FD transmission, (c) Source based three node FD transmission, (d) HD transmission.

According to the traffic condition at the nodes that participate in a FD transmission, four possible cases arise:

1) The PT and PR both have traffic for each other: As shown in Figure 1(a), the system can establish a bi-directional transmission between PT and PR. Thus in this case, the PR and PT also become the ST and SR, respectively.
2) The PR does not have a packet for the PT, however, it has a packet to a third node: As shown in Figure 1(b), the system can group three nodes for destination based FD transmission, where the PR uses its FD radio and starts the secondary transmission to its own receiver. Thus, the PR also becomes the ST and its receiver becomes the SR. This case is important in the infrastructure mode, when for an uplink transmission there is no downlink traffic available for the same station. In that case, the access point (AP) can start a simultaneous transmission to another station (for which it has downlink traffic).
3) The PR does not have any packet to transmit but a third node wants to transmit to PT: Figure 1(c) shows the case of source based three node FD transmission, where a third node becomes the ST transmitting to the PT, and the PT uses its FD feature to also become the SR. In the infrastructure mode, this situation occurs when for a downlink transmission, the station does not have any simultaneous uplink traffic. Then the AP finds another station to transmit to it.
4) Neither the PR has traffic to send to anyone nor the PT finds an another node to transmit data to it: The transmission will happen in only one direction in half duplex (HD) mode, as shown in Figure 1(d).

In the first three cases, all the nodes which do simultaneous transmission and reception get residual self-interference at their reception. Furthermore, in cases 2 and 3, which requires three nodes for FD transmission, an inter-node interference exists (i.e. at SR from PT in Figure 1(b) and at PR from ST in Figure 1(c)). A MAC protocol should schedule the nodes such that inter-node interference can be avoided or minimized.

In the research literature, there have been a few efforts to design FD MAC protocols for WLAN. However, there does not exist a complete distributed MAC design that allows for all the scenarios discussed above. In [1], [6] only two node FD transmissions are considered. In [7], both two node and destination based three node FD transmissions are considered. To mitigate/avoid the inter-node interference from PT to SR, ST uses its past information of successful secondary transmissions in the presence of the given PT. This past information based method is not efficient for a network of nodes with high mobility, where the topology changes rapidly. Our design allows this interference to be measured dynamically based on the latest channel information.

In [8], two node and source based FD transmissions are proposed. In the case of two node FD transmission, a shared random back-off method based on a modification of the standard back-off algorithm is proposed. In general, the time duration by random back-off countdown is much lower than actual data transmission which will prevent their proposed method to enable both nodes to access the channel at the same time and start their FD transmission without any handshaking process. Our MAC design allows a short handshaking process which enables FD transmissions with less overhead. For the source based three node FD transmission, a snooping method is proposed in [7], which enables a new node to become the ST to transmit to the PT. In case of multiple STs, they proposed a probabilistic approach, in which each ST transmits with a different probability based on its current maximum contention window. This method may not be efficient in case of a higher number of such nodes. In our design, we propose a more efficient frequency based contention resolution to handle this situation.

The rest of the paper is organized as follows: Section II presents our proposed MAC design in detail. Section III contains simulation results for the proposed MAC design. Conclusions are presented in Section IV.

II. Components of a Distributed MAC Protocol

As discussed in Section I, a FD capability can be used in different ways based on the traffic conditions. In this section, we describe the complete design of our MAC protocol that exploits all scenarios in a distributed manner. This design is based on IEEE 802.11 CSMA/CA protocol that takes care of the contention between multiple nodes for the primary transmissions.

A. Two node FD transmission

Suppose node A wins the channel and successfully starts the primary transmission to its destination, node B. Node A, after sending MAC header, waits for node B's reply that indicates what kind of FD transmission (based on the categorization in Section I) can be enabled. For this, we introduce a new two bit signal/notification called *full duplex acknowledgment* (FDA).

TABLE I: Different values of FD acknowledgment (FDA)

Value	Description
0	Receiver has packets for the transmitter
1	Receiver has packets for a different node (not the transmitter)
2	No FD from receiver at all
3	Transmission is not allowed

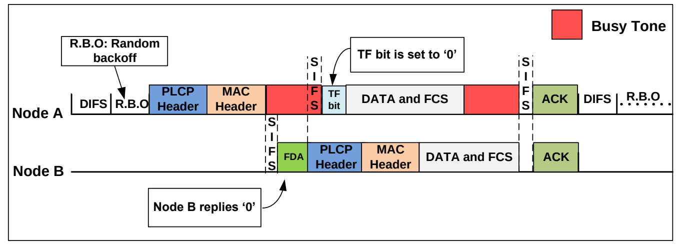

Fig. 2: Two node FD transmission.

The different possible values of FDA are given in Table I. For example, in the two node FD case, where node B also has data for node A, it replies FDA with value '0' to node A. After this, node B starts the secondary transmission by transmitting its data to node A. Node A, after sending the MAC header to node B, sends a busy tone during the FDA reception from node B to prevent other nodes to start its transmission during this period. This is illustrated in Figure 2.

We also introduce a one bit signal/notification called *transmission flag* (TF) to be used at PT during the source based three node FD transmission (Section II-C). In the two node FD case, this bit is set to '0' which prevents node A's neighbors to start any new transmission to node A during its communication to node B. After the TF, node A starts its data transmission to node B as shown in Figure 2. This allows for simultaneous reception and transmission. If say from PT to PR as shown in Figure 2, one transmission finishes before the other transmission, the node whose transmission ends earlier starts sending a busy tone to protect its reception. Once the data transmission from both nodes are completed, they send their ACKs simultaneously.

B. Destination based three node FD transmission

As in Section II-A, consider a PT (node A) and PR (node B). When node B does not have data for node A, but has data for another node (node C), it notifies this to node A through an FDA reply with value '1' as shown in Figure 3. Node B then starts the secondary transmission by sending its packet to the node C. Node A first uses the busy tone and TF bit '0' to stop any other neighboring node from transmitting, and then transmits its data to node B. Note that in this case there is an inter-node interference from node A to node C. To handle that, node C measures the interference from node A to make sure that the transmission from node B to node C can take place successfully in the presence of node A's transmission. Node B, after sending its MAC header to node C, waits for its response. At node C, the signal to interference ratio (SIR) is measured based on the transmission power strength, overheard from node A during the node A's transmission to node B (PLCP header and MAC header) and the power of the signal received from

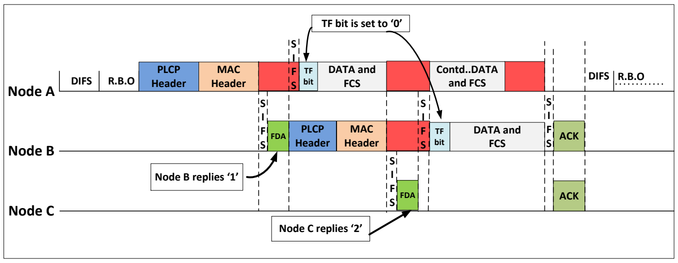

Fig. 3: Destination based three node FD transmission.

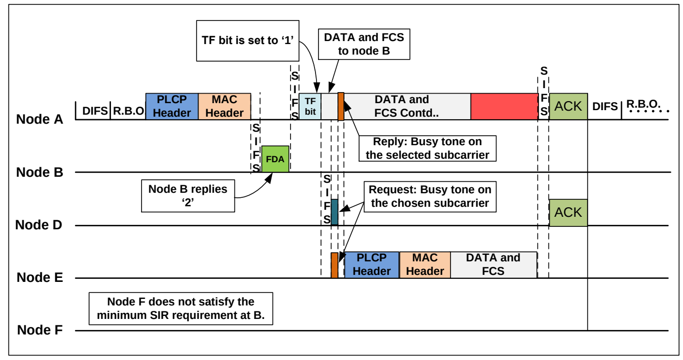

Fig. 4: Source based three node FD transmission.

node B. Suppose h_{AC} denotes the channel gain between node A and C, and h_{BC} is the channel gain between node B and C. The power of node A is P_A, and node B is P_B, resulting in the SIR at node C

$$SIR_C = \frac{P_A|h_{AB}|^2}{P_B|h_{BC}|^2}. \tag{1}$$

If SIR_C is above the minimum threshold γ_{th}, determined so that the minimum data rate can be sustained then node C sends an FDA reply with value '2' to node B, which notifies node B to continue its transmission. Then, node B starts sending its data to node C, while simultaneously receiving data from node A. In this case, both nodes A and B send busy tones to prevent other nodes in their neighborhood to start their transmission during the FDA transmission from node C to node B. Here, we assume that the busy tone signal from node A is known at node B, so it can decode the FDA reply from node C correctly in the presence of node A's busy tone. Moreover, in this case, TF bit is set to '0' at both node A and node B. In the other case, when SIR_C does not satisfy the minimum threshold constraint, node C sends an FDA with value '3' to node B, which stops node B from transmitting further to node C, and only one successful transmission (node A to node B) takes place.

C. Source based three node FD transmission

In this section, we discuss the case when PR, node B, does not have any data to send to anyone. Figure 4 illustrates this case, where node B sends FDA reply with value '2' through FDA to the PT, node A, which means that node B does not want to enable any secondary transmission. Node A then looks for the possibility of enabling FD transmission to itself by finding a node that can become an ST, and which can start a simultaneous transmission to it. Node A notifies its other neighbors that a new transmission can be started to node A by setting the TF bit to '1', and after that continues its data transmission to node B.

In this case, there will be an inter-node interference from the new node (ST) to node B. Only those nodes whose transmissions do not affect the communication from node A to node B that is satisfying the minimum SIR requirement at node B, are qualified to transmit to node A. Suppose node K wishes to transmit to node A, has power P_K and channel gain h_{KB} towards node B, then the SIR at node B should satisfy

$$SIR_B = \frac{P_A|h_{AB}|^2}{P_K|h_{KB}|^2} > \gamma_{th}. \tag{2}$$

All the neighbors of node A, who want to transmit to node A after getting TF bit of value '1' need to satisfy the above constraint. To meet this requirement, a method by using inverse power echo signal proposed in [9] is used. In this case, node B, which receives the power $P_A|h_{AB}|^2$ from node A, sets its power for the FDA reply to

$$P_B = \frac{Z}{P_A|h_{AB}|^2}, \tag{3}$$

where Z is a well-defined system constant [9]. Node K receives node B's FDA reply at power level

$$P_{RK} = P_B|h_{BK}|^2 = \frac{Z|h_{BK}|^2}{P_A|h_{AB}|^2}. \tag{4}$$

To satisfy the the constraint given in (2), received power at node K should be such that

$$P_{RK} < \frac{Z}{\gamma_{th}P_K}. \tag{5}$$

Here, we assumed that $h_{KB} = h_{BK}$. All neighbors which satisfy the above constraint are qualified to transmit to node A. Since there may be multiple such nodes, all nodes which satisfy the above constraint must take part in the contention to transmit. The protocol reserves a frequency-time resource block for the contention resolution. The complete frequency band is divided in to several subcarriers. Each node who wants to transmit to node A randomly chooses a subcarrier and sends a busy tone on that subcarrier. If node A hears the busy tone on multiple subcarriers, it randomly chooses one out of those multiple subcarriers and replies with busy tone on the chosen subcarrier. Thus, only the node who chose the subcarrier on which node A sends a busy tone will start its transmission to node A. Other nodes become silent and do not attempt to transmit to node A during its current transmission. This design reduces collisions in the case in which node A's neighbors do not listen to each other's transmissions and start to transmit even after one of the transmissions to node A has already started. Note that this case is not handled in [8]. For example, as shown in Figure 4, there are three neighbors, node D, E, and F of node A, which want to transmit to node A, after getting the TF bit of '1' from it. Only nodes D and E satisfy the constraint (5), and they randomly choose a subcarrier to send a busy tone. As illustrated in Figure 4, node A chooses node E's subcarrier and only node E starts its transmission to node A.

TABLE II: Simulation Parameters

Parameter	Value
Bandwidth	20 MHz
Path loss exponent	3.0
Propagation Model	ITU-T Indoor Model and Rayleigh fading
Received E_s/N_0 (in dB) at edge	3
PHY layer data rates	6, 9, 12, 18, 24, 36, 48, 54 Mbps
Modulation	BPSK, QPSK, 16-QAM, 64-QAM
Channel coding	Convolutional 1/2, 2/3, 3/4
Acceptable MAC Layer PER	10%
MAC Layer PDU size	1024 bytes
Contention window size	0-1023

In this design, two or more neighbors of node A who want to transmit may select the same subcarrier. Moreover, if node A selects that subcarrier to reply, the transmissions of those multiple nodes will collide at node A. They may also corrupt the ongoing transmission of node A to node B. Nevertheless, having a large number of subcarriers reduces the probability of choosing the same subcarrier at two or more nodes and at node A.

III. Performance Evaluation

In order to evaluate the performance of the proposed MAC protocol, we developed a simulation model in OPNET. We compare the proposed MAC with the standard IEEE 802.11 DCF with only HD transmissions. Although the proposed MAC design can be applied to both ad-hoc and infrastructure modes of WLAN, for simulation purposes, we only show the results for the infrastructure mode. As discussed in Section I, in the infrastructure mode, source based three node FD transmission can be enabled when the primary transmission is in downlink (AP to STA) direction; similarly, destination based three node FD transmission can be enabled when the primary transmission is in the uplink direction (STA to AP).

We assume that each node is capable of transmitting and receiving at rates specified in the IEEE 802.11g standard, and the cell radius is 100 meters. Independent slow Rayleigh fading among each pair of stations and additive white Gaussian noise is adopted as the channel model. The simulated system consists of one AP at the center of a cell with N mobile stations. All other simulation parameters are shown in Table II.

First we consider a heavily loaded system where each station has at least one packet to transmit at anytime. Figure 5 shows the average system throughput for different self-interference cancellation capabilities. In this paper, we consider a basic self-interference model in which the cancellation capability does not vary with the transmission power, so for the given transmission power P_T and the self-interference cancellation value C_{SI}, the residual self-interference power is given by

$$R_{SI} = \frac{P_T}{C_{SI}}. \tag{6}$$

Figure 5 shows that the proposed MAC design provides a significant throughput gain over the standard IEEE 802.11 DCF. As the self-interference cancellation capability is improved, the throughput of the system increases. We observe more than 85% improvement over HD system for FD systems

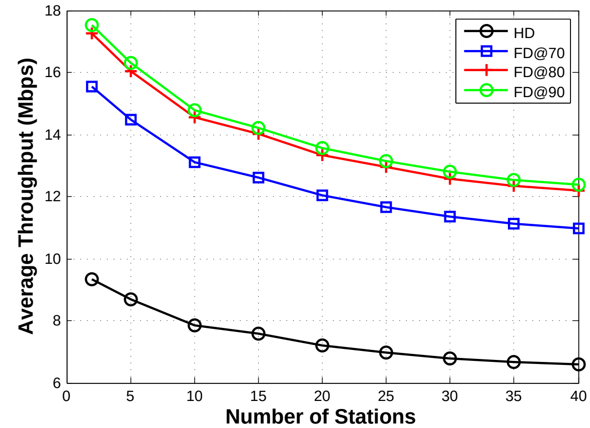

Fig. 5: Throughput as a function of number of stations for different self-interference cancellation levels (FD@x means the FD node is capable of canceling self-interference by x dB).

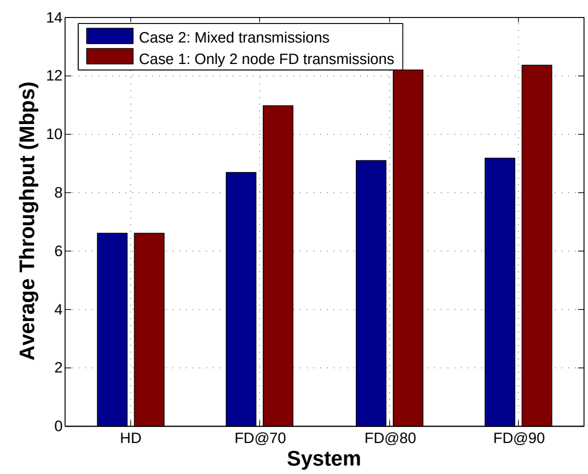

Fig. 6: Throughput for mixed FD (both two node and three node FD transmissions) and only two node FD transmissions for different self-interference cancellation levels (FD@x means the FD node is capable of canceling self-interference by x dB).

that have 80 dB or more self-interference cancellation capability, which is well in the realm of the systems proposed in the literature [4], [8]. In this topology, we set the carrier sensing threshold such that each station can sense any other transmissions. As we increase the number of stations, throughput decreases because of higher collision probability due to higher number of stations that want to start their transmission at the same instant, which is the beginning of primary transmission. This is the primary cause of collisions and will happen in both legacy IEEE 802.11 and our proposed MAC. Thus, throughput decreases for both systems as the number of stations increases.

Figure 6 considers a system with 40 stations and compares a heavily loaded system that always works in the two node FD transmissions mode with a system in which 50% of the stations have full buffered data and the remaining 50% of the stations have only either uplink or downlink traffic. In the latter case, both three node FD transmissions and HD transmissions could occur. Table III shows the FD throughput gain over

TABLE III: FD throughout gain over the HD system (FD@x means the FD node is capable of canceling self-interference by x dB).

	FD@70	**FD@80**	**FD@90**
Case 1	67%	85%	88%
Case 2	32%	38%	39%

HD for both cases. It shows lower gain in the system if only some of the nodes perform two node FD transmissions. There are two primary reasons for this: (1) extra overhead in the three node FD transmission design, (2) different data rates for the uplink and downlink links in three node FD transmission, where system performance is limited by the slower link of the two.

IV. Conclusion

In this work, we have considered the use of common carrier FD radios in IEEE 802.11 based WLANs. We have proposed a MAC design that enables bi-directional and three nodes transmissions using FD radios. Our MAC design is able to accommodate all scenarios in which FD transmission could take place, which is determined by traffic conditions. At the same time, our design takes into account several other practical issues such as inter-node interference in the three node FD transmissions, and contention in source based three node FD transmissions. An OPNET modeler based simulation shows that the proposed MAC provides upto 88% throughput gain over the standard IEEE 802.11 DCF based MAC in a heavily loaded network.

References

[1] M. Jain, J. I. Choi, T. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practical, real-time, full duplex wireless," in *MOBICOM*, 2011, pp. 301–312.

[2] M. Duarte and A. Sabharwal, "Full-duplex wireless communications using off-the-shelf radios: Feasibility and first results," in *Forty Fourth Asilomar Conference on Signals, Systems and Computers (ASILOMAR)*, 2010, pp. 1558–1562.

[3] M. Knox, "Single antenna full duplex communications using a common carrier," in *IEEE 13th Annual Wireless and Microwave Technology Conference (WAMICON)*, April 2012, pp. 1 –6.

[4] D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in *SIGCOMM*, August 2013, pp. 375–386.

[5] A. K. Khandani, "Methods for spatial multiplexing of wireless two-way channels," Oct. 19 2010, US Patent 7,817,641.

[6] M. Duarte, A. Sabharwal, V. Aggarwal, R. Jana, K. Ramakrishnan, C. Rice, and N. Shankaranarayanan, "Design and characterization of a full-duplex multi-antenna system for wifi networks," *arXiv preprint arXiv:1210.1639*, 2012.

[7] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. V. Balan, and P. Key, "Efficient and fair MAC for wireless networks with self-interference cancellation," in *IEEE International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, 2011, pp. 94–101.

[8] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," *arXiv preprint arXiv:1107.0607*, 2011.

[9] X. Wu, S. Tavildar, S. Shakkottai, T. Richardson, J. Li, R. Laroia, and A. Jovicic, "Flashlinq: A synchronous distributed scheduler for peer-to-peer ad hoc networks," in *48th Annual Allerton Conference on Communication, Control, and Computing (Allerton)*, 2010, pp. 514–521.