RTS/FCTS Mechanism Based Full-Duplex MAC Protocol for Wireless Networks

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***Abstract*—As an attractive and challenging transmission mode, the wireless full-duplex transmission can potentially double the system throughput if the self-interference can be efficiently cancelled or suppressed as compared with that of the wireless half-duplex transmission. Recently emerged advanced self-interference cancellation and suppression techniques have shown the possibility of avoiding the overwhelmed self-interference of the wireless full-duplex transmission. However, to achieve the double system throughput in wireless full-duplex networks, not only the efficient self-interference cancellation and suppression techniques in the physical-layer is necessary, but also the practical full-duplex medium access control (MAC) protocol is highly demanded in the datalink layer. In this paper, we propose a novel request to send (RTS)/full-duplex clear to send (FCTS) based MAC protocol which can support both bidirectional and unidirectional links in wireless full-duplex networks. Then, we develop the analytical model to characterize the performance of our proposed full-duplex MAC protocol in wireless full-duplex networks. Also conducted is a set of numerical evaluations showing that our proposed full-duplex MAC protocol can achieve superior system throughput as compared with that of the conventional half-duplex MAC protocol for wireless networks.**

***Index Terms*—Wireless networks, full-duplex MAC protocol, FCTS, throughput, bidirectional links, unidirectional links, self-interference.**

I. Introduction

By simultaneous transmission and reception over a single wireless link, the wireless full-duplex transmission mode has the potential to double the throughput as compared with the wireless half-duplex transmission mode where the transmission and reception are orthogonally separated by frequency or time slots [1]. Over the past few decades, however, the wireless full-duplex transmission mode has not been widely implemented in wireless networks since the transmission of wireless full-duplex nodes will cause the overwhelmed self-interference at their own receivers.

Recently, a great deal of research works have shown the possibility of using the wireless full-duplex transmission in wireless networks by developing the advanced self-interference cancellation and/or suppression techniques [2]–[10]. These works separately or jointly employ propagation-domain interference suppression, analog-domain interference cancellation, and digital-domain interference cancellation. Propagation-domain interference suppression endeavors to mitigate the self-interference to avoid the input of the RF amplifier overwhelmed by the self-interference [2], [4], [6], [8]. Analog-domain interference cancelation attempts to cancel the self-interference to avoid the input of the analog-to-digital converter (ADC) overwhelmed by the self-interference [3]–[5]. Digital-domain interference cancelation attempts to cancel the residue self-interference due to the non-ideal of the RF amplifier, the non-linearities in the ADC, and the oscillator phase noise [2], [4], [5].

However, to enable the full-duplex transmission in wireless networks, the medium access control (MAC) protocol which can support the wireless full-duplex transmission is also highly demanded. Some full-duplex MAC (FD-MAC) protocols have been proposed for wireless networks [4], [11], [12]. The authors in [4] proposed a simple centralized FD-MAC protocol which is only suitable for wireless bidirectional links based on their mainly developed the Balun circuit and digital cancellation technique. In [11], another centralized full-duplex MAC protocol has been proposed by introducing three protocol elements: shared random back-off, snooping to discover full-duplex opportunities, and virtual contention resolution. For decentralized access networks, the authors in [12] proposed the CONTRA FLOW protocol for wireless full-duplex networks. However, both the authors in [11] and [12] do not derive any analytical model for wireless full-duplex networks and do not consider the possible hidden terminal problem for wireless unidirectional links.

To design and analyze an efficient full-duplex MAC protocol, we need to solve the problems not only for bidirectional links, but also for unidirectional links in wireless networks. Also, all hidden terminal problems in wireless full-duplex networks should be avoided. Furthermore, to analyze the per-

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formance of the FD-MAC in wireless networks, an analytical model needs to be developed to derive the system throughput of wireless full-duplex networks. We summarize and evaluate these three challenges and our contributions as follows:

1). Supporting both bidirectional links and unidirectional links: Since the links in wireless full-duplex networks consist of bidirectional and/or unidirectional links, our proposed full-duplex MAC protocol can support both bidirectional link and unidirectional link transmissions. (Reference [4] only considers the bidirectional link).

2). Using the ACK-based mechanism or the RTS/CTS-based mechanism: The request-to-send (RTS)/clear-to-send (CTS) mechanism can more efficiently avoid the hidden terminal problem as compared with the acknowledgement (ACK) mechanism in wireless half-duplex networks. Thus, we propose to develop the RTS/CTS-based mechanism in wireless full-duplex networks. (References [4], [11], [12] assume that the ACK mode can solve all hidden terminal problems in wireless full-duplex networks).

3). The analytical model for the FD MAC: To characterize the proposed FD-MAC protocol and analyze its performance, the analytical model for the FD-MAC protocol is needed (There is no analytical model in references [4], [11], [12]).

To overcome the above-mentioned challenges, in this paper we propose the RTS/CTS-based full-duplex MAC protocol, named as RTS/full-duplex clear-to-send (FCTS) mechanism to achieve the following goals: 1). Both the bidirectional and unidirectional transmissions can be supported. 2). All hidden terminal problems in wireless full-duplex networks have been solved. 3). We develop an accurate analytical model for using and analyzing our proposed FD-MAC protocol in wireless networks.

The rest of this paper is organized as follows. Section II describes the system model where we discuss the link models and define the full-duplex efficiency. Section III proposes and illustrates our FD-MAC protocol. Then, we develop the novel analytical model for our proposed FD-MAC protocol in Section IV. Section V conducts numerical analyses to evaluate our proposed FD-MAC protocol and compare its performances with those when using convention half-duplex MAC protocols. The paper concludes with Section VI.

II. System Model

A. The Bidirectional and Unidirectional Links

There are two type of links in wireless full-duplex networks: the bidirectional link [13] and the unidirectional link [14], as shown in Fig. 1, where Tx and Rx denote the transmitter and receiver at the wireless full-duplex node, SI denotes the self-interference from the transmitter to the receiver. If the wireless full-duplex transmission happens on the link between two nodes each equipped with one transmitter and one receiver, we name this kind of link as the two nodes wireless full-duplex bidirectional link (B-link), as shown in Fig. 1(a). If the first node equipped with one transmitter sends its information to the second node equipped with one transmitter and one receiver while the second node transmits its own information to the third node equipped with one receiver, we call this kind

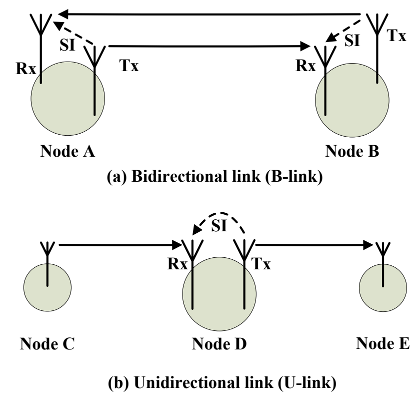


Fig. 1. The bidirectional link and the unidirectional link.

of link as three nodes wireless full-duplex unidirectional link (U-link), as shown in Fig. 1(b). Any wireless full-duplex link can be converted to the combination of the two nodes wireless full-duplex bidirectional link and/or the three nodes wireless full-duplex unidirectional link [15].

B. The Full-Duplex Efficiency

To analyze the performance of wireless full-duplex networks, we need to define the full-duplex efficiency for one wireless full-duplex node, denoted by η, as the ratio of the effective received packet payload to the packet payload. The full-duplex efficiency η can be derived as follows:

$$\eta = \frac{\int_0^{\infty} \log_2(1+\kappa\gamma) p_{\Gamma}(\gamma) d\gamma}{\int_0^{\infty} \log_2(1+\gamma) p_{\Gamma}(\gamma) d\gamma}, \tag{1}$$

where γ is the instantaneous received SNR at the wireless full-duplex node, $p_{\Gamma}(\gamma)$ is the probability density function of the channel, and $\kappa (0 < \kappa \leq 1)$ is defined as the cancellation coefficient [14] for the wireless full-duplex node. The value of cancellation coefficient κ depends on a number of factors, such as system bandwidth, antenna displacement error, and transmit signal amplitude difference, etc. When κ approaches 0, it represents that the self-interference causes large interference on the full duplex transmission. When κ approaches 1, it denotes that the self-interference causes little interference on the full duplex transmission.

For bidirectional links, we need to take the full-duplex efficiency into account for both two nodes (such as nodes A and B in Fig. 1(a)) since both two nodes will be impacted by the self-interference from their own transmitters to their own receivers. For unidirectional links, we only need to take the full-duplex efficiency into account for the node (such as node D in Fig. 1(b)) where the transmission and reception simultaneously happen. Without loss of generality, in this paper we assume that all nodes in the wireless full-duplex networks have the same full-duplex efficiency.

III. Our Proposed FD-MAC Protocol

We develop our FD-MAC protocol based on the classical RTS/CTS mechanism. In this section, first, we propose our FD-MAC protocol. Second, we detailed illustrate the process of using our FD-MAC protocol for wireless full-duplex networks.

A. Overview

In wireless full-duplex networks, each node is equipped with one transmitter and one receiver. Although the receiver needs to endure the self-interference from the transmitter, the transmission and the reception at the node can happen simultaneously. We denote the first transmission (corresponding to the transmission from node A to node B in Fig. 1(a) and the transmission from node C to node D in Fig. 1(b), respectively) and the second transmission (corresponding to the transmission from node B to node A in Fig. 1(a) and the transmission from node D to node E in Fig. 1(b), respectively) in one time full-duplex transmission as FD-T1 and FD-T2, respectively.

Before developing the FD-MAC protocol, we need to discuss that whether we develop the FD-MAC protocol based on the ACK-based mechanism or the RTS/CTS-based mechanism. As we know, since the destination node keeps receiving while some neighbors do not know that the node is receiving, the hidden terminal problem may happen in wireless half-duplex networks. The RTS/CTS mechanism is introduced to efficiently avoid the hidden terminal problem. In wireless full-duplex networks, it seems that we do not need the RTS/CTS mechanism to avoid the hidden terminal problem since the node can send a signal while receiving. However, notice that for wireless unidirectional links, since node E only works in the half-duplex transmission mode and it does not send any signal in the ACK mechanism, the hidden terminal problem still exists in wireless full-duplex networks if we employ the ACK mechanism. Thus, we turn to developing the RTS/CTS based FD-MAC protocol for wireless full-duplex networks.

In our FD-MAC protocol, we use the RTS and the FCTS frames to finish the handshake process. The RTS frame includes the source address of the FD-T1, the destination address of the FD-T1, and the data length of the FD-T1. The FCTS frame includes the source addresses of the FD-T1 and the FD-T2, the destination addresses of the FD-T1 and the FD-T2, and the data lengths of the FD-T1 and the FD-T2.

Then, we can classify the nodes participated in the full-duplex transmission into three categories as follows:[1].

Type 1: the nodes start with sending a RTS;

Type 2: the nodes start with received a RTS when the destination address in the RTS is this node;

Type 3: the nodes start with received a FCTS;

We denote the nodes of Type 1, Type 2, and Type 3 as X, Y, and Z, respectively. The definitions of the short inter-frame space (SIFS) and the distributed inter-frame space (DIFS) are the same as IEEE 802.11 distributed coordination function and p-persistent carrier sense multiple access protocols [16].

Then, we describe the pseudo code for our proposed FD-MAC protocol as follows (we omit the transmission delay in our FD-MAC protocol):

Our proposed FD-MAC protocol

Code for nodes of Type 1

1) X sends the RTS to the destination Y, then waits for the FCTS from Y;
2) **If** (the destination address of FD-T2 in the FCTS is X)
3) After X received the FCTS from Y, X waits for a SIFS time and then sends another FCTS to Y, then waits for a SIFS time to start the FD-T1 and FD-T2 transmissions with Y;
4) **Else** (the destination address of FD-T2 in the FCTS is another node Z)
5) X waits for a (2SIFS+FCTS) time and then starts the FD-T1 and FD-T2 transmissions with Y and Z;
6) **End if**;
7) After the transmissions of the FD-T1 and the FD-T2 (the transmissions will last for the longer time between the FD-T1 and the FD-T2), X waits for a SIFS time and then sends a ACK frame to Y.

Code for nodes of Type 2

1) Y received a RTS from X;
2) **If** (the destination address of the packet from Y is X)
3) Y waits for a SIFS time and then sends the FCTS to X, then Y waits for another FCTS from X;
4) After Y received the FCTS from X, Y waits for a SIFS time and then starts the FD-T1 and FD-T2 transmissions with X;
5) **Else** (the destination address of the packet from Y is another node Z)
6) Y waits for a SIFS time and then sends the FCTS to X and Z, then Y waits for the FCTS from Z;
7) After Y received the FCTS from Z, Y waits for a SIFS time and then starts the FD-T1 and FD-T2 transmissions with X and Z;
8) **End if**;
9) After the transmissions of the FD-T1 and the FD-T2 (the transmissions will last for the longer time between the FD-T1 and the FD-T2), Y waits for a SIFS time and then sends a ACK frame to X.

Code for nodes of Type 3

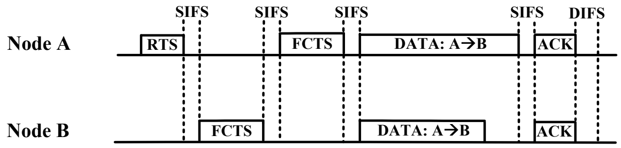
1) After Z received a FCTS, Z waits for a SIFS time and then sends a FCTS to Y.
2) After Z sent the FCTS to Y, Z waits for a SIFS time and then starts the FD-T1 and FD-T2 transmissions with X and Y;
3) After the transmissions of the FD-T1 and FD-T2 (the transmissions will last for the longer time between the FD-T1 and the FD-T2), Z waits for a SIFS time and then sends a ACK frame to Y.

B. Illustration of Our Proposed FD-MAC Protocol

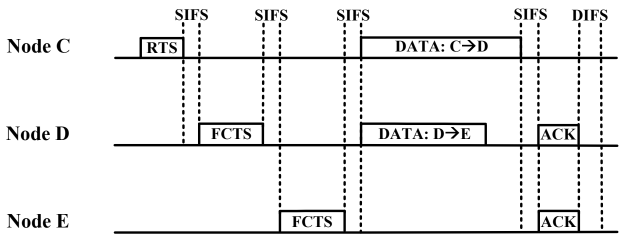
To detailed illustrate our proposed FD-MAC protocol, Figs. 2(a) and 2(b) show the negotiation and transmission process with our proposed FD-MAC protocol for bidirectional and unidirectional links, respectively.

As shown in Fig. 2(a), node A, which has its packet to send to one of its neighborly node B, senses the channel idle and when its back-off counter reaches zero, it starts broadcasting the RTS to its neighbors. As soon as the destination node B received the RTS from node A, node B will wait for a SIFS time and then broadcasts the FCTS to its neighbors. If node B has no packet to transmit to node A, the FCTS is the same as the CTS used in wireless half-duplex networks. If node B has its packet to send to node A, the FCTS needs to be added the destination address (node A) of the packet from node B and the length of the packet from node B to node A. The neighbors of node B will receive this FCTS and back off corresponding to the data length of the packet from node B to node A. As soon as node A received the FCTS, node A waits for a SIFS time and broadcasts another FCTS to notice the neighbors of

[1]Type 1 corresponds to nodes A and C in Figs. 2(a) and 2(b); Type 2 corresponds to nodes B and D in Figs. 2(a) and 2(b); Type 3 corresponds to node C in Fig. 2(b)



(a) Example of bidirectional transmission



(b) Example of unidirectional transmission

Fig. 2. The cases for bidirectional and unidirectional transmissions with our proposed FD-MAC protocol.

node A that it will receive the packet from node B. Then, after a SIFS time, both node A and node B will transmit their packets to each other. The time of the packets transmission will last for the longer time between the FD-T1 and the FD-T2. Then, after a SIFS time, the ACKs (from node A to node B and from node B to node A, respectively) will be sent and this bidirectional transmission ends.

The case for three nodes wireless full-duplex transmissions is shown in Fig. 2(b), where node C first starts its transmitting to node D while node D also has its own data to transmit to node E. In this case, node C senses the channel idle and when its back-off counter reaches zero, it starts to broadcast the RTS to its neighbors. As soon as node D received the RTS from node C, it waits for a SIFS time and then broadcasts the FCTS to its neighbors, where the FCTS includes the destination address (node E), the length of the packet from node D to node E, and the length of the packet from node C to node D. The node E will receive the FCTS from node D. Then, after a SIFS time, node E will broadcast another FCTS to its neighbors. After another SIFS time, node C and node D will send their packets to node D and node E simultaneously. After the transmission of the data and a SIFS time, node D sends the ACK to node C and node E transmits the ACK to node D, respectively.

IV. Analysis of Our Proposed Full-Duplex MAC Protocol

In this section, we develop the p-persistent CSMA based scheme for wireless full-duplex transmission and propose an analytical model to analyze the throughput of our proposed FD-MAC protocol under the saturation networks case, where each node has a non-empty queue.

We can derive the effective packet payload using our proposed FD-MAC protocol in wireless networks, denoted by E_{FD}, as follows:

$$E_{FD} = \begin{cases} E_B = \eta(E_{T1} + E_{T2}), & \text{for B-link;} \\ E_U = \eta E_{T1} + E_{T2}, & \text{for U-link,} \end{cases} \quad (2)$$

where E_B and E_U are the effective packet payloads for bidirectional and unidirectional links, respectively, E_{T1} and E_{T2} denote the packet payloads for the FD-T1 and the FD-T2, respectively. For fairly comparing the FD-MAC and the HD-MAC for wireless networks, we assume that the packet load (also the effective packet load) of the half-duplex link, denoted by E_{HD}, as follows:

$$E_{HD} = \frac{E_{T1} + E_{T2}}{2}. \quad (3)$$

Our p-persistent CSMA based scheme is similar to the conventional p-persistent CSMA scheme except that the node starts with a wireless full-duplex transmission, not a wireless half-duplex transmission. Under our p-persistent CSMA based scheme, if the channel is detected as busy, the node waits until channel becomes idle, and then starts the wireless full-duplex transmission with probability p.

If we denote T_{S}, T_{C1}, and T_{C2} as the time spent by a successful full-duplex transmission, the time spent by an unsuccessful transmission when the collision happens during the RTS frame transmission of the FD-T1 transmission, and the time spent by an unsuccessful transmission when the collision happens during the FCTS frame transmission of the FD-T2 transmission (in this case, the wireless full-duplex transmission degrades to the wireless half-duplex transmission with only the FD-T1 transmission), respectively, then we have

$$\begin{cases} T_{\mathrm{S}} = RTS + SIFS + FCTS + SIFS \\ \qquad +FCTS + SIFS + H + E_{FD} \\ \qquad +SIFS + ACK + DIFS; \\ T_{\mathrm{C1}} = RTS + DIFS; \\ T_{\mathrm{C2}} = RTS + SIFS + FCTS + DIFS + H \\ \qquad +E_{HD} + SIFS + ACK + DIFS, \end{cases} \quad (4)$$

where RTS is the length of a RTS frame, $FCTS$ is the length of a FCTS frame, $SIFS$ is the time interval of SIFS, H is the length of a packet header including the MAC header and the physical-layer header (PHY header), ACK is the length of a ACK frame, and $DIFS$ is the time interval of DIFS.

The packet destination of all nodes in wireless networks follows different distributions according to the various types of data such as the voice-data where the bidirectional transmission often generate and the multimedia-data where the unidirectional transmission often happen. Without loss of generality, we assume that the ratio of the number of B-links to all links (including B-links and U-links) in the wireless networks as α (α can be obtained based on the distribution of the services' destinations in wireless full-duplex network). We assume that α falls into the region $[0, 1]$ which makes our analytical model be suitable for wireless networks with various types of data.

Then, denoting P_{I}, P_{SB}, P_{SU}, P_{C1}, and P_{C2} as the probability that the channel for the FD-T1 transmission is idle, the probability that a bidirectional transmission succeeds, the

TABLE I
THE PARAMETERS FOR OUR FD-MAC PROTOCOL

packet payload for FD-T1(FD-T2)	8184 bits
MAC header	272 bits
PHY header	128 bits
RTS	288 bits
CTS	240 bits
FCTS	528 bits
ACK	240 bits
channel bit rate for FD-T1(FD-T2)	1Mbit/s
slot time	50 μs
SIFS	28 μs
DIFS	128 μs

probability that a unidirectional transmission succeeds, the probability that the collision occurs during the RTS packet transmission of the FD-T1, and the probability that the collision occurs during the FCTS packet transmission of the FD-T2, respectively, we can derive them as follows:

$$\begin{cases} P_{\rm I} \ =(1-p)^n; \\ P_{\rm SB} =\binom{n}{1}p(1-p)^{n-1}\alpha = np(1-p)^{n-1}\alpha; \\ P_{\rm SU} =\binom{n}{1}p(1-p)^{n-1}(1-\alpha) = np(1-p)^{n-1}(1-\alpha); \\ P_{\rm C1} =\binom{n}{2}p^2(1-p)^n = \frac{n(n-1)p^2(1-p)^n}{2}; \\ P_{\rm C2} =\binom{n}{1}p(1-p)^{n-1}\binom{n}{2}p^2(1-p)^n = \frac{n^2(n-1)p^3(1-p)^{2n-1}}{2}, \end{cases} \tag{5}$$

where n is the number of wireless full-duplex nodes in the wireless full-duplex networks. Then, we can calculate the normalized system throughput, denoted by T_{FD}, as follows:

$$T_{FD} = \frac{P_{\rm SB}E_B + P_{\rm SU}E_U}{(P_{\rm SB}+P_{\rm SU})T_{\rm S} + P_{\rm C1}T_{\rm C1} + P_{\rm C2}T_{\rm C2} + P_{\rm idle}T_{ms}} \tag{6}$$

where T_{ms} is the duration of an empty slot time. In fact, since the wireless full-duplex transmission can complete the two-direction packets transmission (from node A to node B and from node B to node A for the B-link; or from node C to node D and from node D to node E for the U-link) simultaneously, the normalized system throughput for the wireless full-duplex transmission T_{FD} should be larger than 0 and less than 2.

The analysis for the conventional MAC protocol can be found in many existing works. To compare the performance of our proposed FD-MAC protocol for the wireless full-duplex network with that of the conventional half-duplex MAC (HD-MAC) protocol for the wireless half-duplex network, we employ the analytical model of the conventional HD-MAC protocol proposed in [17] which is extensively used for the wireless half-duplex networks.

V. NUMERICAL RESULTS

We compare the performance of our proposed FD-MAC protocol with that of the conventional HD-MAC protocol in wireless networks using numerical results. The parameters for our FD-MAC protocol are summarized in Table I.

Figure 3 compares the normalized system throughput versus the transmission probability using our proposed FD-MAC protocol and the conventional HD-MAC for the wireless network with different numbers of users, where we assume that all wireless full-duplex nodes can fully cancel the self-interference. Since all wireless full-duplex nodes in the wireless networks can fully cancel the self-interference, this figure also shows the upper-bounds of the normalized system throughput of using our proposed FD-MAC protocol for wireless full-duplex networks (showing with the three solid curves for $n = 10$, $n = 20$, and $n = 30$, respectively).

As shown in Fig. 3, the FD-MAC protocol can help the wireless full-duplex network achieve larger throughput than that of the wireless half-duplex network using the HD-MAC protocol. Due to the consuming of negotiation frames such as RTS, FCTS, and ACK, the wireless full-duplex network with our proposed FD-MAC protocol cannot obtain the expected double gain as compared with the wireless half-duplex network using the HD-MAC protocol. However, the normalized system throughput gain of the wireless full-duplex network to the wireless half-duplex network is very close to double. Therefore, the wireless full-duplex network outperforms the wireless half-duplex network not only in the physical-layer which is verified and evaluated by many existing works [4], [11], [15], but also in the MAC-layer if using our proposed FD-MAC protocol.

Since existing self-interference cancellation and suppression techniques cannot fully cancel the self-interference, we need to investigate the normalized system throughput of using our proposed FD-MAC for the wireless full-duplex network with imperfect self-interference cancellation and suppression. Because the imperfect self-interference cancellation and suppression impacts the reception of the nodes which are simultaneously transmitting and receiving in wireless full-duplex networks, it decreases the reception of all nodes in bidirectional links (for example, node A and node B) and the reception of the nodes which are simultaneously transmitting and receiving in unidirectional links (for example, node D). Thus, for different α's, the normalized system throughput of the wireless full-duplex network will be different.

Figure 4 depicts the normalized system throughput of using our proposed FD-MAC MAC protocol for the wireless full-duplex network and using the conventional HD-MAC protocol for the wireless half-duplex network versus the full-duplex efficiency η and the ratio of the number of B-links to the number of all links α, where we set the transmission probability $p = 0.02$ and the number of nodes $n = 10$. As illustrated in Fig. 4, the normalized system throughput of the wireless half-duplex network with the conventional HD-MAC protocol is a plane since it is un-related to η and α. We can also observe that 1). The normalized system throughput of the wireless full-duplex network with our proposed FD-MAC protocol is very close to zero when α is very close to 1 and η is very close to zero. This is because when α is very close to 1, it indicates that the links in the wireless full-duplex network are almost all B-links, where the full-duplex efficiency impacts all nodes. Together with η is very close to zero (very large self-interference at the wireless full-duplex node), we can know that the normalized system throughput in this case is very close to zero. 2). The normalized system throughput of the wireless full-duplex network with our proposed FD-MAC protocol is larger than that of the wireless half-duplex network with the HD-MAC protocol when the full-duplex efficiency is close to

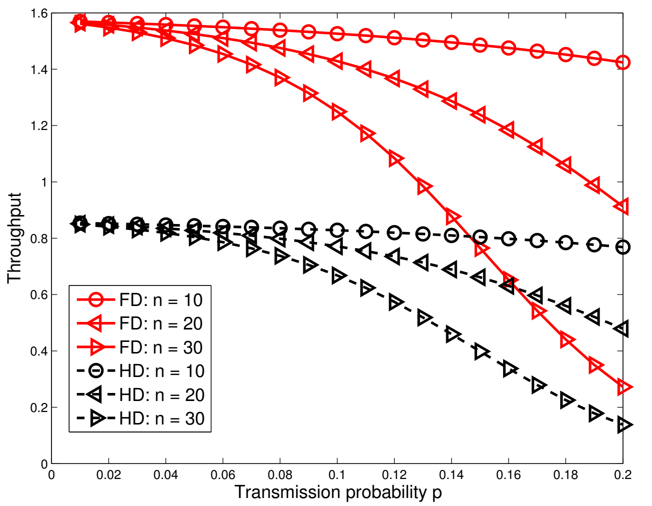


Fig. 3. The throughput of FD-MAC and HD-MAC protocols versus transmission probability with perfect self-interference cancellation.

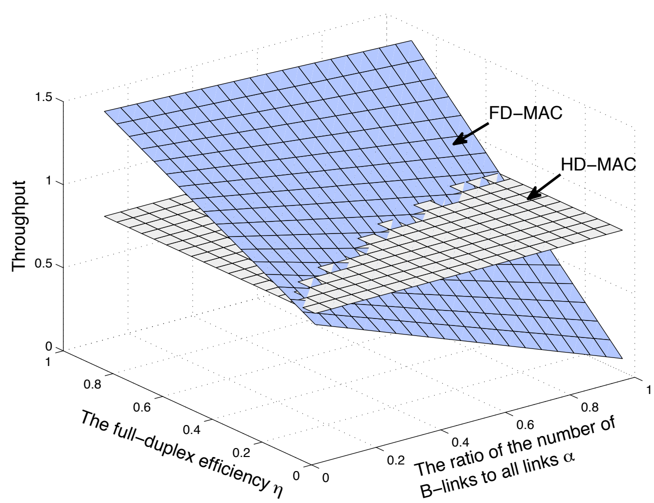


Fig. 4. The throughput of FD-MAC and HD-MAC protocols versus full-duplex efficiency and bidirectional links to all links ratio.

1. From 1). and 2)., we can know that there definitely exists the crossover for the curves of the normalized system throughput of the wireless full-duplex network with our proposed FD-MAC protocol and the throughput of the wireless half-duplex network with the HD-MAC protocol. Thus, once the cancellation coefficient κ is larger than a specified threshold (which is guaranteed by the self-interference cancellation and suppression techniques), the normalized system throughput of the wireless full-duplex network with our proposed FD-MAC protocol can be larger than the normalized system throughput of the wireless half-duplex network with the conventional HD-MAC protocol.

VI. Conclusions

Based on the proposed RTC/FCTS mechanism, we developed the FD-MAC protocol for wireless full-duplex networks. Our developed FD-MAC protocol can efficiently support both B-links and U-links, and can change to support the half-duplex transmission if the collision happens during the first FCTS frame. We also proposed the analytical model to characterize the normalized system throughput for using our developed FD-MAC protocol in wireless full-duplex networks. We perfectly solved the three key problems when designing the MAC protocols for wireless full-duplex networks proposed in the introduction of this paper. Extensive numerical results well evaluated our proposed FD-MAC protocol and showed that there are superior normalized system throughput gains when using our proposed FD-MAC protocol as compared with the conventional HD-MAC protocol for wireless networks.

References

[1] D. W. Bliss, P. A. Parker, and A. R. Margetts, "Simultaneous transmission and reception for improved wireless network performance," in *IEEE Workshop Statist. Signal Process*, Aug. 2007, pp. 478–482.

[2] R. Bozidar, R. Dinan, K. Peter, P. Alexandre, S. Nikhil, B. Vlad, and D. Gerald, "Rethinking indoor wireless mesh design: low power, low frequency, full-duplex," in *The Fifth IEEE Workshop on Wireless Mesh Networks (WIMESH 2010)*, Jun. 2010, pp. 1–6.

[3] S. Gollakota and D. Katabi, "Zigzag decoding: combating hidden terminals in wireless networks," in *Processinds of the ACM SIGCOMM 2008 conference on Data communications*, New York, NY, USA, 2008, pp. 159–170.

[4] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. 16th ACM MOBICOM*, Chicago, Illinois, USA, Sep. 2010.

[5] M. Jain, J. I. Choi, T. M. Kim, D. Bharadia, S. Seth, K. Srinivasan, P. Levis, S. Katti, and P. Sinha, "Practival, real-time, full duplex wireless," in *Proc. 17th ACM MOBICOM*, Las Vegas, nevada, USA, Sep. 2011.

[6] E. Everett, M. Duarte, C. Dick, and A. Sabharwal, "Empowering full-duplex wireless communication by exploiting directional diversity," in *45th Asilomar Conference on Signals, Systems and Computers*, Nov. 2011, pp. 2002–2006.

[7] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Transactions on Wireless Communications*, vol. 10, no. 9, pp. 3074–3085, Sep. 2011.

[8] D. Senaratne and C. Tellambura, "Beamforming for space division duplexing," in *IEEE ICC 2011*, June 2011, pp. 1–5.

[9] W. Cheng, X. Zhang, and H. Zhang, "Full duplex spectrum sensing in non-time-slotted cognitive radio networks," in *IEEE MILCOM 2011*, 2011, pp. 1029–1034.

[10] W. Cheng, X. Zhang, and H. Zhang, "Imperfect full duplex spectrum sensing in cognitive radio networks," in *ACM Mobicom 2011, 3rd ACM workshop on cognitive radio networks*, 2011.

[11] A. Sahai, G. Patel, and A. Sabharwal, "Pushing the limits of full-duplex: Design and real-time implementation," Tech. Rep., Rice University, http://arxiv.org/pdf/1107.0607.pdf, July 2011.

[12] 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 *2011 International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt)*, May 2011, pp. 94–101.

[13] W. Cheng, X. Zhang, and H. Zhang, "QoS driven power allocation over full-duplex wireless links," in *IEEE ICC 2012*, Ottawa, Canada, June 2012.

[14] W. Cheng, X. Zhang, and H. Zhang, "Full/half duplex based resource allocations for statistical quality of service provisioning in wireless relay networks," in *IEEE 31st INFOCOM*, Orlando, Florida, USA, Mar. 2012.

[15] W. Cheng, X. Zhang, and H. Zhang, "Optimal dynamic power control for full-duplex bidirectional-channel based wireless networks," in *IEEE 32st INFOCOM*, Turin, Italy, Apr. 2013.

[16] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio wireless networks," *IEEE Journal on Selected Areas in Communications*, vol. 26, no. 1, pp. 118–129, 2008.

[17] G. Bianchi, "Performance analysis of the IEEE 802.11 distributed coordination function," *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, pp. 535–547, Mar 2000.