A Three-way Handshaking Access Mechanism for Point to Multipoint In-band Full-duplex Wireless Networks

Haiwei Zuo[1,2], Yanjing Sun[1,2,*], Changlin Lin[1,2], Song Li[1,2], Hongli Xu[3], Zefu Tan[1,2] and Yanfen Wang[1,2]

[1] School of Information and Electrical Engineering, China University of Mining and Technology
Xuzhou, Jiangsu 221116 - China
[e-mail: yjsun@cumt.edu.cn]

[2] Coal Mine Electrical Engineering and Automation Laboratory in JiangSu Province
Xuzhou, Jiangsu 221116 - China
[e-mail: yjsun@cumt.edu.cn]

[3] School of Computer Science and Technology, University of Science and Technology of China
Hefei, Anhui 230027 - China
[e-mail: xuhongli@ustc.edu.cn]

*Corresponding author: Yanjing Sun

Received December 17, 2015; revised March 21, 2016; revised April 21, 2016; accepted May 31, 2016; published July 31, 2016

Abstract

In-band Full-duplex (IBFD) wireless communication allows improved throughput for wireless networks. The current Half-duplex (HD) medium access mechanism Request to Send/Clear to Send (RTS/CTS) has been directly applied to IBFD wireless networks. However, this is only able to support a symmetric dual link, and does not provide the full advantages of IBFD. To increase network throughput in a superior way to the HD mechanism, a novel three-way handshaking access mechanism RTS/SRTS (Second Request to Send)/CTS is proposed for point to multipoint (PMP) IBFD wireless networks, which can support both symmetric dual link and asymmetric dual link communication. In this approach, IBFD wireless communication only requires one channel access for two-way simultaneous packet transmissions. We first describe the RTS/SRTS/CTS mechanism and the symmetric/asymmetric dual link transmission procedure and then provide a theoretical analysis of network throughput and delay using a Markov model. Using simulations, we demonstrate that the RTS/SRTS/CTS access mechanism shows improved performance relative to that of the RTS/CTS HD access mechanism.

Keywords: In-band Full-duplex, Medium access control, Three-way handshaking, Throughput, Delay

http://dx.doi.org/10.3837/tiis.2016.07.015 **ISSN : 1976-7277**

1. Introduction

IBFD wireless communication networks, which allow nodes to transmit and receive simultaneously in the same frequency band, can theoretically double its spectral efficiency and increase network throughput relative to networks with HD operation [1-3]. To achieve this doubled capability of IBFD wireless transmission networks, a specific and effective medium access control (MAC) mechanism is required.

IBFD wireless transmission can be utilized in PMP wireless networks with a centralized topology so that AP (Access Point) communicates with one station or two stations in IBFD transmission mode. The transmission link between two nodes of AP and one station is a symmetric dual link, and a link among three nodes of AP and two stations is an asymmetric dual link. Advanced self-interference cancellation technologies use a single node to transmit and receive simultaneously, such as antenna cancellation, analog cancellation, and digital cancellation [4-10]. However, when multiple nodes are transmitting simultaneously, for example, when AP communicates with two stations in an asymmetric dual link, the inter-node interference may increase by nearly a factor of two and the total interference at a node also increases [2, 11, 12]. Therefore, the consideration of inter-node interference cancellation in an asymmetric dual link is essential. Tang et al. [13] leveraged capture effect at the station to cancel inter-node interference resulting in an increased opportunity of PMP wireless networks. By utilizing capture effect, a station is able to receive the correct packet from several receiving packets, as long as the SINR (Signal to Interference plus Noise Ratio) of the packet from AP is higher than the packets from other stations [14, 15].

To fully exploit IBFD wireless communication, appropriate MAC protocols and schedule mechanisms are required to support PHY layer communication [16-23]. Strategies based on current HD MAC protocols have been proposed. However, full realization of IBFD capacity has not been realized due to differences in transmission environment and mode.

Current RTS/CTS mechanisms are used in IBFD wireless communication and can support a symmetric dual link between two nodes using one channel access, but two channel accesses are required to establish a link among three nodes for an asymmetric dual link. The RTS frame and CTS frame only provide limited information about the two packets those are transmitted and received simultaneously in IBFD communication. From the returned CTS frame, the source node does not know whether the destination node includes an IBFD transmission or not. On the other hand, some reports ignored the hidden IBFD nodes during the design of MAC protocols, thus neglecting the inter-node interference that the communication nodes experience. Thus, these protocols cannot be utilized practically in a hardware simulation platform to check the feasibility of IBFD wireless transmission.

Using RTS/CTS exchange and three-way handshaking, we propose a novel MAC mechanism RTS/SRTS/CTS for use in PMP IBFD wireless networks. To address the problems mentioned above, this work makes the following contributions. Firstly, we build a PMP IBFD wireless communication network model, in which both symmetric dual link and asymmetric dual link are supported. The asymmetric dual link transmission is classified into two cases based on whether the two packets that are received and transmitted simultaneously by AP are identical or not. Next, we design the RTS/SRTS/CTS mechanism to establish a dual link between two or three nodes. Using this three-way handshaking access mechanism, IBFD two-way packet transmissions require only one channel access. More specifically, the

SRTS frame contains the length of both packets of the IBFD transmission, which allows the IBFD nodes to acquire more information. This takes the busytone out and reduces resources spent for transmission. Finally, to better analyze the performance of the RTS/SRTS/CTS mechanism, a Markov model is leveraged to determine the throughput and delay of PMP IBFD wireless networks.

The remainder of this paper is organized as follows. Section 2 provides the related literature and Section 3 introduces the model of PMP IBFD wireless networks. Section 4 points out the difficulties of using the unmodified RTS/CTS mechanism in IBFD wireless communication and then the specific RTS/SRTS/CTS mechanism for IBFD symmetric/asymmetric dual link transmission is described in Section 5. Section 6 presents the theoretical analysis of our proposed mechanism by leveraging a Markov model. The numerical results are carried out in Section 7, and the conclusions are presented in Section 8.

2. Related Works

In [16, 17], some key mechanisms for the design of IBFD MAC protocols are reviewed. These features include shared random backoff, header snooping, virtual backoffs, and collision avoidance with RTS/CTS exchange. Most previous proposed MAC protocols for IBFD transmission follow one or more of the above mechanisms.

Using the header snooping of IBFD transmission, Wang et al. [18] developed a CSMA/CD-like protocol for OFDMA wireless networks. This protocol improved throughput when the lengths of the packets from two IBFD transmission nodes were the same. However, it does not consider the situation when the packet lengths are of different sizes, which result when the two transmission nodes cannot control the exact timing of sending out a busytone. Singh et al. [19] proposed a ContraFlow protocol where if the destination node has no packet to return, it immediately sends out a busytone to its neighbor nodes at the point of reception. However, transmitting a busytone is energetically wasteful and this method could face high collision problems since the forwarding transmission link is not reserved [2].

Kim et al. [20] proposed a FD-MAC protocol based on the RTS/CTS mechanism. In this mechanism, the source node and destination node transmit their own packet simultaneously. However, the RTS/CTS mechanism cannot establish an asymmetric dual link, which would limit the increase in throughput of wireless networks. Cheng et al. [21] proposed a RTS/FCTS (Full-duplex CTS) mechanism for IBFD wireless communication. This mechanism can solve partial hidden node problems in both the symmetric and asymmetric dual links. However, the RTS/FCTS mechanism does not consider the interference from exposed nodes in an asymmetric dual link and does not present a strategy to avoid inter-node interference.

3. Network model

Here, we consider a PMP IBFD wireless network, as shown in **Fig. 1**(a), based on generally deployed network architecture [18, 24]. It contains n+1 nodes, i.e., one AP node and n station nodes. All the nodes support IBFD wireless communication. A station and AP can communicate with each other, while communication between two stations requires AP forwarding. The communication dual links are IBFD symmetric dual link and asymmetric dual link:

IBFD symmetric dual link: If the destination of the packet from a station is AP itself and

AP also has a packet to return to the station, then AP and the station transmit and receive simultaneously via a bidirectional link, as shown in **Fig. 1**(b).

IBFD asymmetric dual link: If the destination of the packet from a station is AP, but AP has a packet to transmit to another station, or if the destination of the packet from a station is another station and AP needs to forward the packet, then AP receives the packet from the former station and transmits to the latter station simultaneously in an unidirectional link, as shown in **Fig. 1**(c).

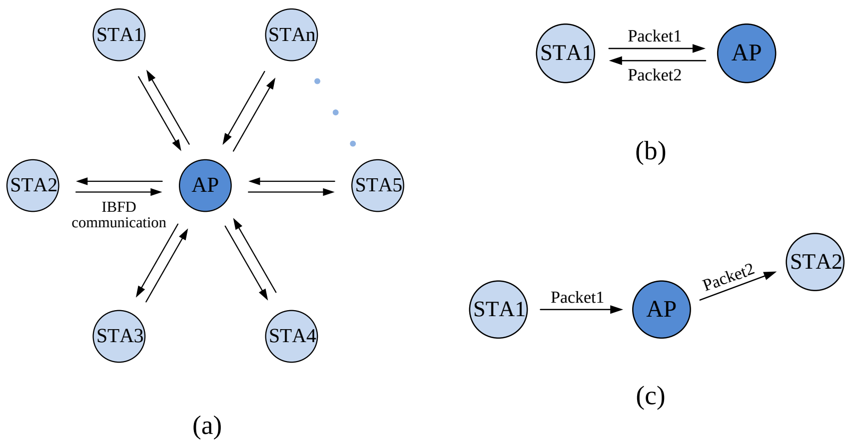


Fig. 1. (a) The PMP IBFD wireless network; (b) IBFD symmetric dual link; (c) IBFD asymmetric dual link

For a IBFD asymmetric dual link, we must consider interference from exposed stations. As shown in **Fig. 1**(c), STA1 transmits Packet1 to AP and AP transmits Packet2 to STA2 simultaneously. If the two stations cannot hear each other, STA2 can only receive Packet2, which is the expected packet. Instead, if the two stations can hear each other, STA2 will receive both Packet1 and Packet2 simultaneously. For STA2, the power of signal from STA1 to AP is too strong so that it results in interference to STA2. Thus, the IBFD asymmetric dual transmission requires the support of inter-node interference cancellation techniques.

Here, we utilize capture effect to solve the inter-node interference in PMP IBFD wireless communication. If the nodes in the PMP wireless networks receive two packets simultaneously, the packet with higher SINR can still be received correctly by capture effect. Since the transmission power is adjustable, we set the signal strength of the packet transmitting from AP to a station to be stronger than the signal strength of the packet transmitting from a station to AP. We use capture effect at stations to allow stations to determine relevant signal strength in the network and recognize the expected packets from AP. Continuing the example above, if STA2 is hidden to STA1, then transmission of Packet1 from STA1 to AP would not affect the ability of STA2 to receive Packet2 from AP. If STA2 is exposed to STA1, then the capture effect allows STA2 to recognize and receive Packet2 correctly when Packet1 and Packet2 arrive simultaneously, given the higher SINR of Packet2 compared to Packet1.

4. RTS/CTS mechanism problem statement

The RTS/CTS access mechanism in HD wireless communication works are presented in **Fig. 2**. In this mechanism, a station (STA1) that wants to transmit a packet to AP waits until the channel is sensed idle for a DIFS (Distributed Inter Frame Space). At that point, STA1 follows the backoff rule and transmits a RTS frame to AP. AP detects the RTS frame and responds with a CTS frame after SIFS (Short Inter Frame Space). If the STA1 receives the CTS frame correctly, it transmits the packet. The channel between STA1 and AP is used for packet transmission. This RTS/CTS access is a two-way handshaking access procedure.

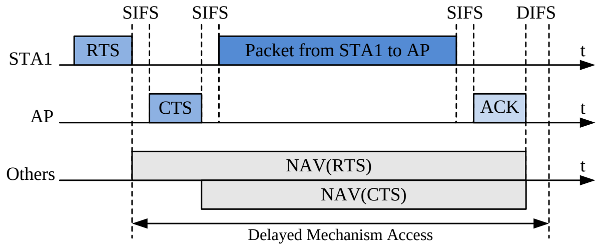


Fig. 2. RTS/CTS mechanism for wireless communication

If we incorporate a RTS/CTS mechanism in PMP IBFD wireless networks, AP and STA1 can transmit packets simultaneously after medium access. When multiple nodes intend to transmit packets simultaneously in IBFD symmetric dual link and asymmetric dual link, there will be the following constraints.

1) When AP initiates a transmission to STA1, the other stations do not know whether STA1 has a packet to AP from the returned CTS frame. The other stations may capture the IBFD opportunity and transmit packet to AP, which will collide with the packet from STA1 to AP.

2) When STA1 sends a packet to another station and AP helps to forward the packet, the channel access between STA1 and AP with RTS/CTS mechanism cannot be used for forwarding transmission.

3) With RTS/CTS mechanism, the asymmetric dual communication among three nodes requires two channel accesses for two-way packet transmissions, and is more complex and time-wasting than using two nodes.

4) If AP has no packet to transmit or has a packet to another station but not to STA1, then the IBFD wireless communication with RTS/CTS mechanism will work equivalently to HD wireless communication.

5. RTS/SRTS/CTS mechanism

As shown in Section 4, two nodes with two packets to transmit require two channel accesses by RTS/CTS, especially in asymmetric dual link communication. To support both symmetric and asymmetric dual link transmission, we propose a three-way handshaking RTS/SRTS/CTS MAC mechanism for IBFD wireless communication. In our method, IBFD wireless communication only requires one channel access for two-way packet transmission. Then the destination node can transmit a packet while receiving from the source node. We add the other request frame (SRTS) between RTS and CTS access to complete a three-way handshaking. The SRTS frame serves both a response role and a request one. Using the

SRTS frame, the source node obtains not only the response that the RTS has been received successfully by the destination node, but also the request that the destination node has a packet to transmit. It allows the nodes to exactly determine the communication status in the PMP IBFD wireless network. The specific access mechanism is described as the following.

5.1. RTS/SRTS/CTS design

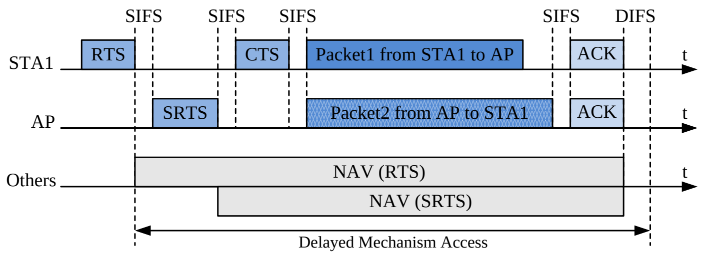
The RTS/SRTS/CTS has similar frame structures as the 802.11 RTS/CTS standard. We design the SRTS frame based on the RTS frame that includes source address, destination address, data duration of the packet (Packet2) that is going to be transmitted by the node and the source address, and data duration of the packet (Packet1) that is going to be received by the node, as shown in **Fig. 3**. The frame length of SRTS is 8 bytes longer than that of RTS.

Frame Control	Packet2 Duration	Packet1 Duration	Packet2 Destination Address	Packet2 Source Address	Packet1 Source Address	FCS
2 bytes	2 bytes	2 bytes	6 bytes	6 bytes	6 bytes	4 bytes

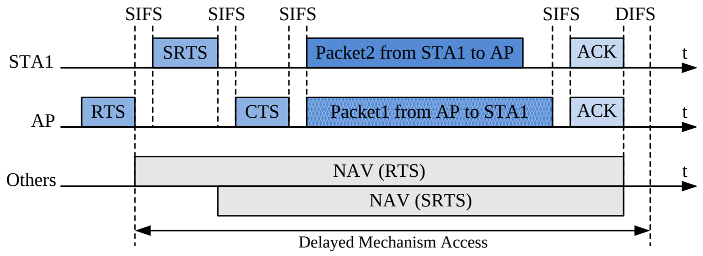
Fig. 3. The frame structure of SRTS before adding the PHY header

Each node can sense the channel status and the other nodes status in the PMP IBFD wireless network, irrespective of whether it is transmitting or not. AP and all the stations will contend for transmissions. If a node senses that the channel is idle for a time of DIFS, it starts the backoff procedure and initiates a transmission while the backoff counter decreases to 0. If the node senses that the channel is busy, it freezes its backoff counter and waits.

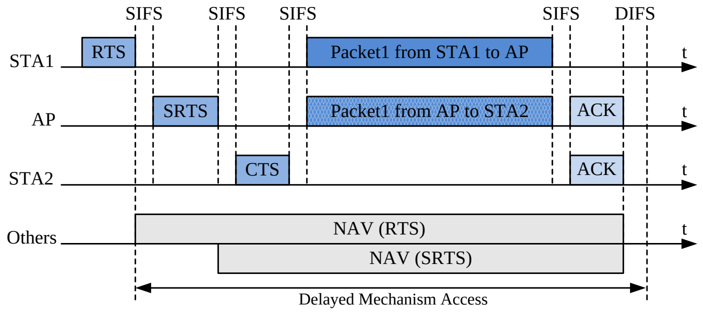
To better analyze the designed access mechanism of PMP IBFD wireless communication, we separately examine cases of symmetric dual link and asymmetric dual link. For symmetric dual link transmission, both stations and AP are capable of IBFD wireless communication. As shown in **Fig. 4**(a) and (b), after three-way handshaking of RTS/SRTS/CTS, a station (STA1) and AP transmit packets simultaneously in the symmetric dual link. For asymmetric dual link transmission, we only consider AP for IBFD wireless communication, since only AP can transmit a packet while receiving another packet and stations work in HD mode. As shown in **Fig. 4**(c) and (d), after three-way handshaking of RTS/SRTS/CTS, two stations (STA1 and STA2) and AP transmit packets simultaneously in the asymmetric dual link. The specific access procedure and data transmission in IBFD symmetric and asymmetric dual link are described as follows.



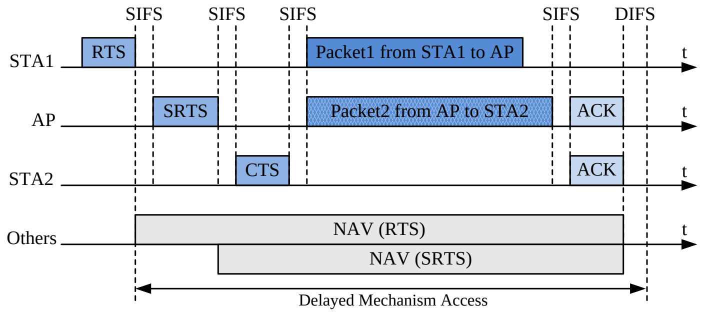
(a) A station initiates a transmission in IBFD symmetric dual link



(b) AP initiates a transmission in IBFD symmetric dual link



(c) A station initiates a transmission in IBFD asymmetric dual link transmission and AP forwards the packet of the station



(d) A station initiates a transmission in IBFD asymmetric dual link transmission and AP transmits its own packet to another station

Fig. 4. Successful IBFD wireless transmissions with RTS/SRTS/CTS mechanism

5.2. IBFD symmetric dual link transmission

Fig. 4(a) shows the IBFD symmetric dual link transmission that a station initiates a RTS to AP and AP requests for IBFD communication by SRTS frame. STA1 wins the contention and then starts to transmit a RTS to AP. As soon as AP receives the RTS, it reads the RTS and knows that it is the target destination. If AP has no packet to transmit to STA1, it sends a CTS to STA1 after a SIFS time. If AP also has a packet (Packet2) to transmit to STA1, it captures an IBFD opportunity and sends a SRTS to STA1 after a SIFS time. This SRTS contains the source (AP) address, destination (STA1) address, duration of Packet2, and the source (STA1) address and duration of Packet1. Thus, from the received SRTS, STA1 learns that AP not only has received the RTS successfully but also requests to send packet to STA1 in the IBFD symmetric dual link. STA1 then waits for a SIFS time and sends a CTS back to AP to finish the three-way handshaking.

The other nodes in the network can hear RTS, SRTS, or CTS and defer self-transmission until the packet transmission between STA1 and AP is finished to avoid collisions caused by hidden stations. When STA1 broadcasts the RTS, all its neighbor stations can receive and read the RTS. Recognizing that STA1 will communicate with AP, the neighbors of STA1 suspend their backoff counters and wait according to Packet1 duration. When AP broadcasts the SRTS, all its neighbor stations including the hidden stations of STA1 can receive and read the SRTS. Knowing that AP will have an IBFD symmetric dual link communication with STA1, the neighbors of AP freeze their backoff counters and wait based on the length of the longer one of Packet1 and Packet2.

During packet transmission, both STA1 and AP wait for a SIFS time and then transmit their respective packets to each other. The time of the packet transmission lasts for the longer duration of Packet1 and Packet2. Next, after a SIFS time, both STA1 and AP send an ACK to each other to finish IBFD symmetric dual link transmission. Moreover, all the neighbors of STA1 and AP receive the ACK and know that the communication between STA1 and AP is over. At this point, they can start their backoff counters and contend the channel again after a DIFS time. As shown in **Fig. 4**(a), the length of Packet2 is longer than that of Packet1, which is known by STA1. Therefore, even if STA1 finishes transmitting Packet1, it will wait until Packet2 transmission is complete rather than sending ACK to AP immediately. Thus in RTS/SRTS/CTS mechanism, it is unnecessary for STA1 to broadcast a busytone to reserve channel.

Fig. 4(b) shows the IBFD symmetric dual link transmission in which AP initiates a RTS to a station and the station requests for IBFD communication by SRTS frame. After three-way handshaking, AP and STA1 transmit packet simultaneously in the symmetric dual link. The access mechanism and data transmission are similar to what occurs when STA1 initiates a RTS to STA1 as shown in **Fig. 4**(a).

5.3. IBFD asymmetric dual link transmission

Fig. 4(c) and (d) show the IBFD asymmetric dual link transmissions that occur when STA1 sends a packet to AP and AP sends a packet to another station (STA2) simultaneously. By leveraging the capture effect at stations, we ignore the inter-node interference in the analysis of IBFD asymmetric dual link transmission. According to the destination address of Packet1 that is transmitted by STA1, we analyze the IBFD asymmetric dual link transmission for two cases. *Case* 1: If the destination of Packet1 is STA2, AP only needs to forward Packet1, as shown in **Fig. 4**(c). *Case* 2: If the destination of Packet1 is AP, and AP also has its own packet (Packet2) to transmit to STA2, AP receives Packet1 from STA1 and transmits Packet2 to STA2 simultaneously, as shown in **Fig. 4**(d). Since the two stations cannot communicate directly, the situation where AP initiates a RTS to a station while the station transmits its own packet to another station cannot occur, for example AP-STA1-STA2.

***Case* 1**. As shown in **Fig. 4**(c), STA1 transmits Packet1 to AP and AP forwards Packet1 to STA2 immediately in the IBFD asymmetric dual link. After contenting the channel, STA1 starts to transmit a RTS to AP. From the RTS, AP knows that the destination address of Packet1 is STA2 and it only needs to forward Packet1. Then AP sends a SRTS to STA2 after a SIFS time, where the SRTS includes the source address, destination address, duration of Packet1 from AP to STA2, and the source address and duration of Packet1 from STA1 to AP. After receiving and reading SRTS, STA2 knows that STA1 has a packet to send to itself and that the packet will be forwarded by AP. Moreover, STA1 responds by SRTS that AP not only has received the RTS successfully but also will forward Packet1 as soon as AP has received it. At last, STA2 waits for a SIFS time and returns a CTS back to AP to finish the three-way handshaking.

Using RTS/SRTS/CTS medium access, AP knows the communication link between AP and STA2 has been reserved. Thus, during asymmetric dual link transmission, AP starts forwarding Packet1 to STA2 as soon as it receives the header of Packet1. The time of the packet transmission lasts for the duration of Packet1, which consumes only half the time compared to the PMP HD asymmetric dual link. After a SIFS time, STA2 sends an ACK to AP and AP sends an ACK to STA1 simultaneously to complete the IBFD asymmetric dual link transmission.

***Case* 2**. As shown in **Fig. 4**(d), STA1 has a packet (Packet1) to transmit to AP while AP transmits another packet (Packet2) to STA2 in IBFD asymmetric dual link. STA1 wins the contention and then transmits a RTS to AP. AP does not gain the channel but still wants to transmit Packet2 to STA2. While receiving the RTS from STA1, AP realizes that it can capture an IBFD opportunity for Packet2 transmission. Thus it sends a SRTS to STA2 for medium access after a SIFS time. The SRTS includes the source (AP) address, destination (STA2) address, duration of Packet2, and the source (STA1) address and duration of Packet1. After receiving and reading SRTS, STA2 knows that AP will transmit a packet to itself. Moreover, STA1 responds by SRTS that AP not only has received the RTS successfully but also will transmit a packet to STA2 at the same time of Packet1 transmission. Finally, STA2 waits for a SIFS time and returns a CTS back to AP to finish the three-way handshaking.

During packet transmission, STA1 transmits Packet1 to AP and AP transmits Packet2 to STA2 simultaneously. The time of packet transmission lasts for the longer duration of Packet1 and Packet2. After a SIFS time, STA2 sends an ACK to AP and AP sends an ACK to STA1 simultaneously to complete the IBFD asymmetric dual link transmission. As shown in **Fig. 4**(d), the length of Packet1 is shorter than that of Packet2, which is known by STA1. Thus, when STA1 finishes transmitting Packet1, it will not send ACK to AP right now but will wait until Packet2 transmission is complete.

The delay mechanism of the other networked stations during IBFD asymmetric dual link transmission is similar to that of IBFD symmetric dual link transmission, as shown in Section 5.2.

6. Theoretical analysis

In order to analyze the performance of RTS/SRTS/CTS mechanism for PMP IBFD wireless networks, we study the behavior of a single node with a discrete-time Markov model [25, 26] and analyze the throughput and delay of IBFD wireless communication. We assume that the PMP wireless network consists of n+1 nodes (one AP and n stations). All the nodes can listen to the channel, allowing them to perfectly capture IBFD opportunities and detect collisions with RTS/SRTS/CTS mechanism.

Before sending packets on the channel, each node sets a random back-off number from the contention window based on transmission history. We define the minimum contention window as W, and the maximum backoff stage as m. The contention window is defined as (0, W_i), where $W_i=2^iW$, $i=0,2,\ldots,m$. From this, the maximum contention window can be calculated as $CW_{max}=W_m=2^mW$. For the n+1 nodes in the PMP wireless network, the transmission probability and the conditional collision probability can be calculated based on the Markov model of the backoff window size [25]. Let τ be the probability of a node transmitting in a random chosen slot time, which can be expressed as (1):

$$\tau = \frac{2}{1+W+pW\sum_{i=0}^{m-1}(2p)^i}, \tag{1}$$

where p is the conditional collision probability. If a node transmits a packet, a collision happens when at least one of the other n nodes is currently transmitting. Thus p is obtained as (2):

$$p = 1-(1-\tau)^n. \tag{2}$$

6.1. Throughput analysis

Let S be the normalized system throughput, defined as the fraction of time the channel is used to successfully transmit payload bits, or the payload successfully transmitted during a given slot time. Then, S is expressed as (3):

$$S = E_P / E_T. \tag{3}$$

Here, E_T is the length of a slot time and E_P is the payload information transmitted during this time period.

To compute S, we divide a slot time into three parts: idle time, successful transmission time, and collision time, calculated as the following. P_{tr} is defined as the probability that there exists at least one transmission during the time period. It can be calculated as (4):

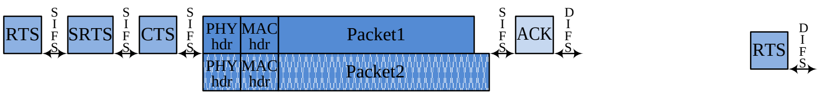
$$P_{tr} = 1-(1-\tau)^{n+1}. \tag{4}$$

Thus, 1-P_{tr} is the probability of idle time during a slot time. The duration of the idle time is denoted as σ.

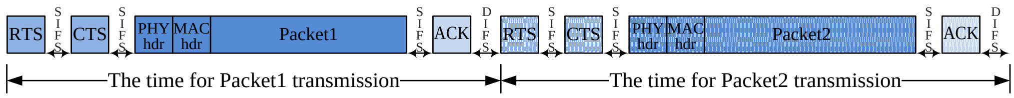
To calculate the successful IBFD transmission in a slot time, we consider a station and AP both initiating a transmission. When a station initiates a transmission to AP, AP and the other stations are listening, AP will capture an IBFD opportunity, as shown in **Fig. 4**(a), (c) and (d). When AP initiates a transmission to a station, all the stations are listening. The destination station will capture an IBFD opportunity, as shown in **Fig. 4**(b). This total successful transmission probability, denoted as P_s, is calculated as (5):

$$P_s = \binom{n+1}{1}\tau(1-\tau)^n. \tag{5}$$

The successful transmission time is defined as T_s: T_s = RTS + SIFS + SRTS + SIFS + CTS + SIFS + H + $E[P]_{longer}$ + SIFS + ACK + DIFS, where H = PHY_{hdr} + MAC_{hdr} is the packet header and $E[P]_{longer}$ is the longer payload size of Packet1 and Packet2, as shown in **Fig. 5**(a).



(a) (b)



(c)

Fig. 5. T_s and T_c for RTS/SRTS/CTS mechanism in IBFD wireless communication and RTS/CTS mechanism in HD wireless communication. (a) The successful transmission time for the RTS/SRTS/CTS mechanism in IBFD wireless communication; (b) The collision time of both RTS/SRTS/CTS and RTS/CTS mechanisms; (c) The successful transmission time of RTS/CTS mechanism in HD wireless communication.

The failed IBFD transmission in the slot time happens when more than one of the nodes transmit RTS simultaneously. This probability, denoted as P_c, is given as (6):

$$P_c = 1 - (1-\tau)^{n+1} - \binom{n+1}{1} \tau (1-\tau)^n . \tag{6}$$

The collision time is defined as T_c: T_c = RTS + DIFS, as shown in **Fig. 5**(b).

Thus, the throughput S in (3) can be denoted as (7):

$$S = \frac{P_s E[P]}{(1-P_{tr})\sigma + P_s T_s + P_c T_c}, \tag{7}$$

where $E[P]$ is the total packet payload size of the two simultaneously transmitted packets, i.e., the amount of payload information successfully transmitted within a slot time.

6.2. Delay analysis

Frame delay is defined as the duration from the generation of a frame to its successful reception. As shown in **Fig. 5**(c), in order to successfully transmit Packet1 and Packet2 via HD wireless communication, the RTS/CTS access mechanism must contend for the channel, establish access, and send the packet, with each step being conducted twice. In IBFD wireless communication, the destination node of Packet1 can transmit Packet2 while receiving Packet1. Thus, the frame delay will be close to half that of HD wireless communication with RTS/CTS mechanism. Let D be the frame delay of IBFD wireless communication with RTS/SRTS/CTS mechanism and $E[D]$ be the average value of D. Here $E[D]$ can be given as (8):

$$E[D] = N_c (T_{bd} + T_c + T_o) + (T_{bd} + T_s) , \tag{8}$$

where N_c is the number of collisions of a frame until its successful reception, T_{bd} is the average backoff delay that a node uses before accessing the channel again, T_o is the time that a node has to wait before sensing the channel again when the frames collide during transmission, T_s and T_c are described above.

The average number of retransmissions is given as $1/P_s$. Then the number of collisions N_c can be calculated as (9):

$$N_c = \frac{1}{P_s} - 1. \tag{9}$$

The average backoff delay T_{bd} is determined based on the value of the node counter and the duration during which the counter freezes and the node detects the channel as busy. The value of a node counter is calculated based on the Markov model without considering the counter stop [25]. The value of the counter is defined as a random variable X, and its average value is given as (10):

$$E[X] = \frac{\tau(1-p)}{6}\left[\sum_{i=0}^{m-1} p^i (W_i^2 - 1) + \frac{p^m}{1-p}(W_m^2 - 1)\right]. \tag{10}$$

We denote the time that the counter freezes as F, and the average time of F as $E[F]$. When the counter freezes, at least one frame is transmitting on the channel. Then $E[F]$ can be given as (11):

$$E[F] = E[N_F](P_s T_s + P_c T_c), \tag{11}$$

where $E[N_F]$ is the average number of times that a node detects transmissions from the other nodes before its counter reaches 0. The counter keeps continuously working until it freezes. The idle time is defined as σ, thus the mean number of a consecutive idle slot time before a freeze occurs can be given as $(1-P_{tr})\sigma$. The sum of the average consecutive idle slot time is the average value of the node counter $E[X]$. Then, $E[N_F]$ is given as (12):

$$E[N_F] = \frac{E[X]}{\max((1-P_{tr})\sigma, 1)} - 1. \tag{12}$$

From Eqs. (10) and (11), we can calculate the average backoff delay as $T_{bd} = E[X] + E[F]$.

Finally, the time T_o depends on the access mechanism and is given as T_o = SIFS + CTS_timeout. Combining the above equations, the average frame delay $E[D]$ in (8) can be determined.

7. Numerical results

In order to evaluate the performance of RTS/SRTS/CTS mechanism for PMP IBFD wireless communication, we provide the numerical results of the mechanism performance by MATLAB simulation and validate our analytical model. The basic wireless communication parameters for the simulation are listed in **Table 1** [25]. We compare the performance of our mechanism to that of RTS/CTS mechanism for HD wireless communication and also compare other mechanism for IBFD wireless communication [21].

Table 1. Basic simulation parameters for RTS/SRTS/CTS mechanism

Packet1 payload	8184 bits
Packet2 payload	8184 bits
PHY header	128bits
MAC header	272 bits

RTS	160 bits + PHY header
SRTS	224 bits + PHY header
CTS	112 bits + PHY header
ACK	112 bits + PHY header
Channel Bit Rate	1 Mbit/s
Slot Time (σ)	50 μs
SIFS	28 μs
DIFS	128 μs
CTS_timeout	300 μs

In our analysis of RTS/SRTS/CTS mechanism, we consider the situation where both AP and stations always have packets to transmit. **Fig. 6** shows that the throughput depends on the number of stations in IBFD wireless communication. Here the maximum backoff stage m is set to 6. We can see that with the RTS/SRTS/CTS mechanism, the throughput of IBFD wireless network is significantly improved. For instance, for the case of minimum contention window W = 16, the throughput S of RTS/SRTS/CTS mechanism is about 1.61, nearly twice the throughput of RTS/CTS mechanism (S = 0.83). Compared with the RTS/FCTS mechanism, the RTS/SRTS/CTS mechanism achieves higher throughput. Additionally, the throughput of RTS/SRTS/CTS mechanism changes little as the number of stations increases. That is to say, the throughput of RTS/SRTS/CTS mechanism is less sensitive to the number of stations than that of the RTS/CTS or RTS/FCTS mechanisms. Thus, our proposed mechanism is more scalable based on network size. However, the variation trend of throughput is related to the minimum contention window size. For W = 16, as the number of stations increases, the throughput decreases slowly. At W = 256, the throughput continues to increase. Therefore, an appropriate contention window size is important to expand the network scale. However, this requires the proper contention window for different network scales in order to achieve the maximum throughput. To determine the appropriate minimum contention window size, we next simulate the relationship of the throughput and the minimum contention window size for the IBFD wireless communication with the RTS/SRTS/CTS mechanism, as shown in **Fig. 7**. For 10 stations in the IBFD wireless network, we use 32 as the most appropriate minimum contention window size, when the throughput achieves 1.61.

Fig. 8 compares the throughput for different mechanisms and shows that the throughput depends on the transmission probability τ. The maximum throughput of RTS/SRTS/CTS mechanism reaches 1.61, which is double of the throughput of the RTS/CTS mechanism. Furthermore, the throughput decreases as the transmission probability increases. When more and more stations try to contend the channel in IBFD wireless communication, the throughput of RTS/SRTS/CTS mechanism decreases rapidly but remains nearly twice that of the RTS/CTS mechanism. Under the same conditions, the throughput of RTS/SRTS/CTS mechanism is always higher than that of RTS/FCTS mechanism.

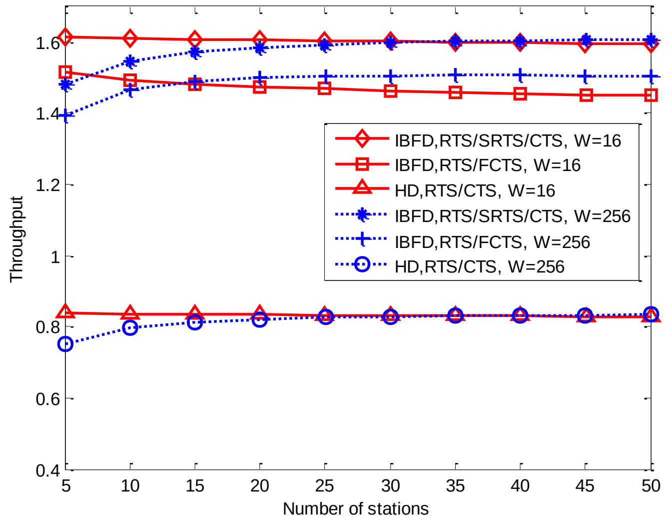


Fig. 6. The throughput versus the number of stations for different access mechanisms and minimum contention window sizes

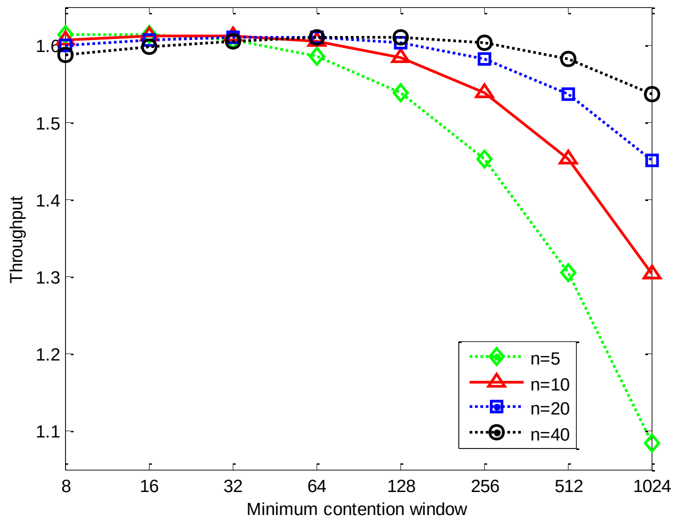


Fig. 7. The throughput versus the minimum contention window size for the IBFD wireless communication with RTS/SRTS/CTS mechanism

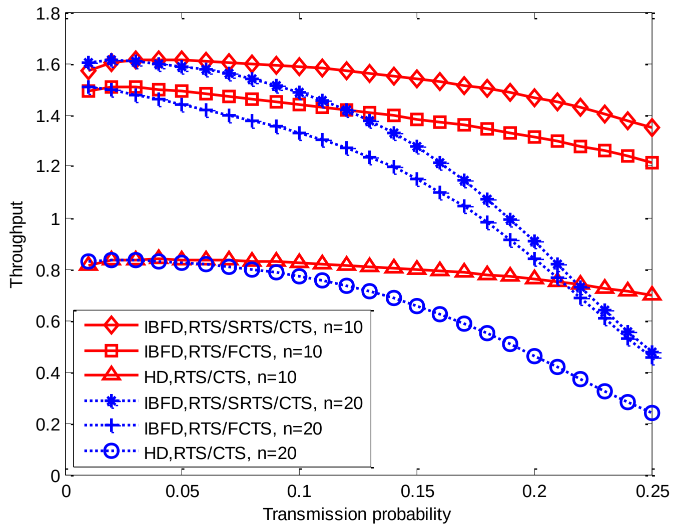


Fig. 8. The throughput versus the transmission probability for different access mechanisms and numbers of stations

Fig. 5(a) and (c) show the time used in a successful transmission. The time required to transmit two packets by IBFD wireless communication is nearly half the time required for HD wireless communication. To better understand this difference, we analyze the delay versus the number of stations for different access mechanisms and minimum contention window sizes, as shown in **Fig. 9**. Here the maximum backoff stage m is set to 6. The delay of RTS/SRTS/CTS mechanism is much lower than that of RTS/CTS mechanism. As the minimum contention window size is increased, the delay of RTS/SRTS/CTS mechanism is nearly half that of the RTS/CTS mechanism. Comparison of the two mechanisms shows that the delay for RTS/SRTS/CTS is slightly longer in small-scale networks. But as the number of stations increases, the delay of RTS/SRTS/CTS mechanism is less than that of RTS/FCTS mechanism. Thus, RTS/SRTS/CTS mechanism does better in large-scale networks.

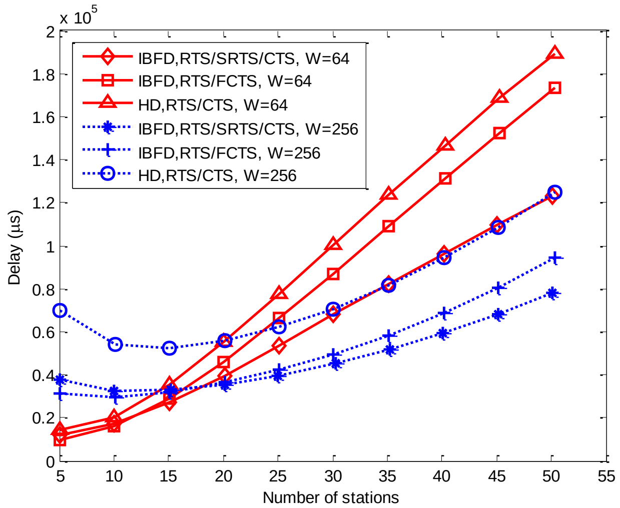


Fig. 9. The delay versus the number of stations for different access mechanisms and minimum contention window sizes

The delay versus the number of stations for different access mechanisms and maximum backoff stages is shown in **Fig. 10**, which also illustrates the lower delay of the RTS/SRTS/CTS mechanism for IBFD wireless communication. The minimum contention window *W* is set to 32. Combining these results with those presented in **Fig. 9**, we can observe that when the backoff procedure includes a larger backoff stage *m* and minimum contention window *W*, the RTS/SRTS/CTS mechanism suffers longer delays, which is the expense of higher throughput.

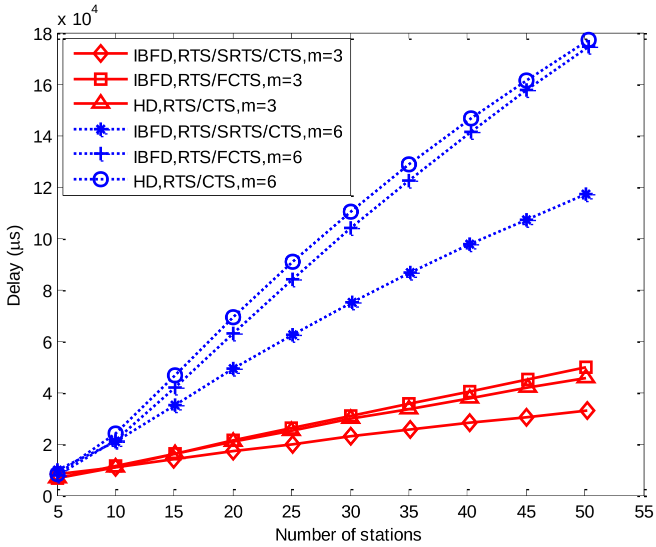


Fig. 10. The delay versus the number of stations for different access mechanisms and maximum backoff stages

8. Conclusion

In this paper, we proposed a novel RTS/SRTS/CTS access mechanism to establish both symmetric and asymmetric dual links in the PMP IBFD wireless network with three-way handshaking. Compared with the RTS/CTS mechanism, our proposed mechanism only requires one channel access for two way packet transmissions. RTS/SRTS/CTS access improves the knowledge of all the nodes in the network to know the status of the transmitting nodes, thus avoiding collisions caused by hidden stations. Moreover, this mechanism reduces costs in transmitting packets by eliminating the busytone after shorter packet transmission is complete. Using a Markov model, we provided theoretical analysis and evaluated achievable throughput and delay. The results show improved performance for our proposed mechanism.

Acknowledgment

This work is supported by the Fundamental Research Funds for the Central Universities under Grant(2013RC11), National Natural Science Foundation of China, the Colleges and Universities in Jiangsu Province Plans to Graduate Research and Innovation.

References

[1] A. Sabharwal, P. Schniter, D. Guo, D. Bliss, S. Rangarajan and R. Wichman, "In-band full-duplex Wireless: challenges and opportunities," *IEEE Journal on Selected Areas in Communications*, pp. 1637-1652, 2014. Article (CrossRef Link)

[2] D. Kim, H. Lee and D. Hong, "A survey of in-band full-duplex transmission from the perspective of PHY and MAC layers," *IEEE Communications Surveys & Tutorials*, pp. 1-31, 2015. Article (CrossRef Link)

[3] D. Bharadia, E. Mcmilin and S. Katti, "Full duplex radios," in *Proc. of 2013 ACM Special Interest Group on Data Communication*, vol. 43, no. 4, pp. 375-386, August 12-16, 2013. Article (CrossRef Link)

[4] 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 *Proc. of 17th Annual International Conference on Mobile Computing and Networking*, pp. 301-312, September 19-23, 2011. Article (CrossRef Link)

[5] A. Balatsoukas-Stimming, P. Belanovic, K. Alexandris and A. Burg, "On self-interference suppression methods for low-complexity full-duplex MIMO," in *Proc. of 2013 Asilomar Conference on Signals, Systems and Computers*, pp. 992-997, November 3-6, 2013. Article (CrossRef Link)

[6] D. Korpi, S. Venkatasubramanian, T. Riihonen, L. Anttila, S. Otewa, C. Icheln, K. Haneda, S. Tretyakov, M. Valkama and R. Wichman, "Advanced self-interference cancellation and multiantenna techniques for full-duplex radios," *Tampere University of Technology*, 2014. Article (CrossRef Link)

[7] M. Duarte, C. Dick and A. Sabharwal, "Experiment-driven characterization of full-duplex wireless systems," *IEEE Transactions on Wireless Communications*, vol. 11, no. 12, pp. 4296-4307, 2012. Article (CrossRef Link)

[8] T. Riihonen and R. Wichman, "Analog and digital self-interference cancellation in full-duplex MIMO-OFDM transceivers with limited resolution in A/D conversion," in *Proc. of 46th Annual Asilomar Conference on Signals, Systems, and Computers*, pp. 45-49, 2012. Article (CrossRef Link)

[9] Q. Xu, X. Quan, Z. Zhang, Y. Tang and Y. Shen, "Analysis and experimental verification of digital self-Interference cancelation for co-time co-frequency full-duplex LTE," *International Journal of Signal Processing, Image Processing and Pattern Recognition*, vol. 7, no. 1, pp. 299-312, 2014. Article (CrossRef Link)

[10] A. Sahai, G. Patel, C. Dick and A. Sabharwal, "On the impact of phase noise on active cancellation in wireless full-duplex," *IEEE Transactions on Vehicular Technology*, vol. 62, no. 9, pp. 4494-4510, 2013. Article (CrossRef Link)

[11] D. Kim, S. Park, H. Ju and D. Hong, "Transmission capacity of full-duplex-based two-way Ad Hoc networks with ARQ protocol," *IEEE Transactions on Vehicular Technology*, vol. 63, no. 7, pp. 3167-3183, 2014. Article (CrossRef Link)

[12] J. Bai and A. Sabharwal, "Distributed full-duplex via wireless side-channels: Bounds and protocols," *IEEE Transactions on Wireless Communications*, vol. 12, no. 8, pp. 4162-4173, 2013. Article (CrossRef Link)

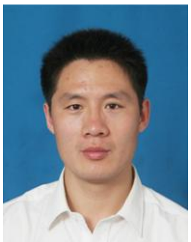
[13] A. Tang, X. Wang, "Medium access control for a wireless LAN with a full duplex AP and half duplex stations," in *Proc. of 2014 IEEE Global Communications Conference*, pp. 4732-4737, December 8-12, 2014. Article (CrossRef Link)

[14] W. Christopher, J. John, C. Joe and D. Eryk, "Unfairness and capture behavior in 802.11 ad hoc networks," *IEEE International Conference on Communications*, vol. 1, pp. 159-163, June 20-22, 2000. Article (CrossRef Link)

[15] K. Whitehouse, A. Woo, F. Jiang, J. Polastre and D. Culler, "Exploiting the capture effect for collision detection and recovery," in *Proc. of 2nd IEEE Workshop on Embedded Networked Sensors*, pp. 45-52, May 30-31, 2005. Article (CrossRef Link)

[16] K. Thilina, H. Tabassum, E. Hossain and D. Kim, "Medium access control design for full duplex wireless systems: challenges and approaches," *IEEE Communications Magazine*, vol. 53, no. 5, pp. 112-120, 2015. Article (CrossRef Link)
[17] A. Sahai, G. Patel and A. Sabharwal, "Pushing the limits of full duplex: design and real-time implementation," *Rice University Technical Report TREE*1104, 2011. Article (CrossRef Link)
[18] X. Wang, A. Tang and P. Huang, "Full duplex random access for multi-user OFDMA communication systems," *Ad Hoc Network*, vol. 24, no. A, pp. 200-213, 2015. Article (CrossRef Link)
[19] N. Singh, D. Gunawardena, A. Proutiere, B. Radunovic, H. Balan and P. Key, "Efficient and fair MAC for wireless networks with self-interference cancellation," in *Proc. of International Symposium of Modeling and Optimization of Mobile, Ad Hoc, and Wireless Networks*, pp. 94-101, May 9-13, 2011. Article (CrossRef Link)
[20] S. Kim and W. E. Stark, "On the performance of full duplex wireless networks," in *Proc. of 47th Annual Conference on Information Sciences and Systems*, pp. 1-6, March 20-22, 2013. Article (CrossRef Link)
[21] W. Cheng, X. Zhang and H. Zhang, "RTS/FCTS mechanism based full-duplex MAC protocol for wireless networks," in *Proc. of 2013 IEEE Global Communications Conference*, pp. 5017-5022, December 9-13, 2013. Article (CrossRef Link)
[22] W. Choi and H. Lim, "Immediate acknowledgement for single-channel full-duplex wireless networks," in *Proc. of 2012 IEEE 9th International Conference on Mobile Adhoc and Senser Systems*, pp. 477-478, October 8-11, 2012. Article (CrossRef Link)
[23] E. Askari and S. Aissa, "Single-band full-duplex MAC protocol for distributed access networks," *IET Communications*, vol. 8, no. 10, pp. 1663-1673, 2014. Article (CrossRef Link)
[24] J. Choi, M. Jain, K. Srinivasan, P. Levis and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. of 16th Annual International Conference on Mobile Computing and Networking*, pp. 1-12, September 20-24, 2010. Article (CrossRef Link)
[25] 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, 2000. Article (CrossRef Link)
[26] E. Ziouva and T. Antonakopoulos, "CSMA/CA performance under high traffic conditions: throughput and delay analysis," *Computer Communications*, vol. 25, no. 3, pp. 313-321, 2002. Article (CrossRef Link)

Haiwei Zuo received the B.S. degree in Information and Communication Engineering from China University of Mining and Technology in 2012. She is currently pursuing the Ph.D. degree at School of Information and Electrical Engineering, China University of Mining and Technology. Her research interests include IBFD communication and wireless networks.



Yanjing Sun is a professor in School of Information and Electrical Engineering, China University of Mining and Technology since July 2012. He received the Ph.D. degree in Information and Communication Engineering from China University of Mining and Technology in 2008. He is also a vice director of Coal Mine Electrical Engineering and Automation Laboratory in JiangSu Province. His current research interests include IBFD communication, Embedded real-time system, Wireless sensor networks, Cyber-physical system and so on.

Changlin Lin received the B.S. degree in Information and Communication Engineering from China University of Mining and Technology in 2014. He is currently working toward the M.S. Degree at the School of Information and Electrical Engineering, China University of Mining Technology. His research interests include wireless communication, and wireless networks.

Song Li is a lecture in School of Information and Electrical Engineering, China University of Mining and Technology since July 2012. He received the Ph.D. degree in signal and information processing from Beijing University of Posts and Telecommunications in 2012. His current research interests are full duplex communication, cyber-physical system and cooperative communication.

Hongli Xu is an assistant research fellow in the School of Computer Science and Technology at the University of Science and Technology of China. He received the Ph. D. degree in Computer Science from the University of Science and Technology of China in 2007. His current research interests are cooperative communication, vehicular ad hoc network and software defined networks.

Zefu Tan received M.S. degree in electromagnetic field and microwave technology from Beijing University of Posts and Telecommunications. He is currently pursuing the Ph.D. degree at School of Information and Electrical Engineering, China University of Mining and Technology. His research interests include wireless communication and signal processing.

Yanfen Wang is a professor in School of Information and Electrical Engineering, China University of Mining and Technology. She received the Ph.D. degree in Information and Communication Engineering from China University of Mining and Technology in 2009. Her current research interests include ultra-wide band wireless communication, channel modeling, signal processing and so on.