A Novel Collision Detection Protocol for Wireless Full-Duplex Networks

Qinglin Zhao, Li Feng, Mengchu Zhou, Haisheng Yu and Yi Sun

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Qinglin Zhao
School of Computer Science and Engineering
Macau University of Science and Technology
Macau, China
qlzhao@must.edu.mo

Li Feng
School of Computer Science and Engineering
Macau University of Science and Technology
Macau, China
lfeng@must.edu.mo

MengChu Zhou
Department of Electrical and Computer Engineering
New Jersey Institute of Technology
Newark, USA
zhou@njit.edu

Haisheng Yu
International Institute of Next Generation Internet
Macau University of Science and Technology
Macau, China
yuhaisheng@must.edu.mo

Yi Sun
Institute of Computing Technology
Chinese Academy of Sciences
Beijing, China
sunyi@ict.ac.cn

Abstract—**Conventional wireless networks are half-duplex and most of them use contention-based protocols. These protocols usually adopt a principle of contention with collision avoidance and infer a collision occurrence very late from the absence of an acknowledgement after data transmission, thus causing low network performance. Wireless full-duplex enables simultaneous transmission (TX) and reception (RX) on the same channel. By exploiting this functionality, this work proposes a novel design that enables contention with collision detection (CCD) to improve the network performance. With this design, in contention, a node exploits its TX antenna to transmit a signal for channel contention, while exploiting its RX antenna to sense if other nodes are transmitting too. By checking the status of TX and RX antennas, the node can detect the contention collision before data transmission and hence obtains an opportunity to avoid data collision effectively. This work then develops a theoretical model to analyze the collision probability of this design. Extensive simulation results verify the effectiveness of our proposed design in improving wireless network performance.**

***Index Terms*—Wireless full-duplex, collision avoidance, collision detection, contention.**

I. Introduction

In IEEE 802.11 wireless networks, contention-based medium access control (MAC) protocols are the most dominant ones for coordinating data transmissions among nodes. In these protocols, a node first contends for the channel and then performs data transmissions. Conventional 802.11 networks are half-duplex (HD), namely, a node either transmits or receives data at the same moment. Therefore, one 802.11 transmission is always unidirectional. In-band full-duplex (FD) wireless technology enables simultaneous transmission (TX) and reception (RX) on the same channel [1]-[3] and hence makes one transmission bidirectional. As a result, it improves the physical transmission rate of nodes significantly and has received growing attention [4]-[8].

To exploit the FD gain, various wireless FD-MAC protocols have been proposed [9]-[15] to improve the transmission efficiency of 802.11 HD-MAC protocols [16]. Most of them can be roughly classified into two categories: FD-CA (collision avoidance) and FD-CD (collision detection). In contention-based protocols, collision is the key factor causing low network performance. To alleviate the adverse impact of collision, HD-MAC always tries its best to *avoid collision before data transmission* due to its HD nature. Specifically, in contention, each HD node adopts the binary exponential backoff (BEB) algorithm and perform *contention with collision avoidance* by exploiting its antenna's RX functionality; that is, each HD node senses the channel status via its RX antenna and then accordingly adjusts the contention time via BEB to avoid contention collision. In data transmission, an HD transmitter keeps transmitting its data until the end by exploiting its antenna's TX functionality, even if it involves a data collision. In contrast, to alleviate the adverse impact of collision, in contention, the FD-MAC protocols inherit the contention mechanism of HD-MAC and hence an FD node performs *contention with collision avoidance* as well by exploiting its antenna's RX functionality only. They differ mainly in data transmission: for FD-CA, the sender-receiver pair exploit FD to keep TX and RX until the end even if a data collision occurs and thus ignore the collision totally; for FD-CD, the sender transmits data by using exploiting TX functionality, while detecting data collision by exploiting its RX functionality and aborting the ongoing TX immediately upon detecting a data collision.

A. Motivation

Conventional 802.11 HD-MAC protocols adopt a contention mechanism called contention with collision avoidance due to its HD nature. When FD is enabled, it naturally raises a question: should wireless FD-MAC protocols inherit the same contention mechanism of conventional HD-MAC protocols to maximize the FD gain? The inheritance approach favors the compatibility between HD- and FD-MAC protocols, but it has the following drawbacks and hence cannot maximize the FD gain. First, it fails to exploit FD's simultaneous TX and RX functionalities, since the conventional HD-MAC contention mechanism only exploits the RX functionality. Second, it makes FD networks more inefficient than HD networks. It is well known that HD-supporting 802.11 networks are throughput inefficient because of their long contention time. FD networks keep the contention time unchanged when adopting the same contention mechanism but can significantly reduce the transmission time of the same amount of data benefiting from FD's bidirectional transmission, compared with HD networks. Third, it makes FD networks lose more than HD networks, in case a data collision occurs. In HD networks, a data collision only causes the failure of one unidirectional transmission. In contrast, in FD networks, a data collision in one direction will cause transmission failure in another direction since the latter depends on the former's information, thereby doubling the loss. Existing FD-MAC protocols inherit the conventional HD-MAC contention mechanism and hence cannot solve the drawbacks. This motivates us to design a novel contention mechanism for FD networks.

B. Our contributions

This paper aims at designing a new contention mechanism that enables *contention with collision detection (CCD)* for wireless FD networks. Here, we summarize our contributions as follows.

- We propose a novel FD design called FD-CCD for wireless FD networks. With FD-CCD, by checking the TX and RX status of FD antennas and employing the bitwise arbitration algorithm, a node can detect the contention collision while contending for the channel and hence obtains an opportunity to avoid the data collision effectively.
- We develop a theoretical model to analyze the collision probability of FD-CCD.
- We verify via extensive simulations the effectiveness of FD-CCD and the accuracy of the developed theoretical model.

This study provides new insights to better design FD-MAC protocols.

The remainder of the paper is organized as follows. Section II outlines related work. Section III presents the proposed FD-CCD design. Section IV analyzes the collision probability of our design. Section V verifies the effectiveness of our design and the accuracy of our model. Section VI concludes this paper.

II. Related work

Most of FD-MAC protocols adopt the time-domain contention mechanism of 802.11 carrier-sense multiple access with collision avoidance (CSMA/CA) protocols and can be classified into two categories: CSMA/CA-based and CSMA/CD-based. We present these related protocols as follows.

CSMA/CA-based FD-MAC protocols. These protocols mainly inherit conventional 802.11 CSMA/CA contention mechanisms but address different FD problems. For example, the authors in [18] study how FD impacts the performance of CSMA/CA networks theoretically. The authors in [19] aim at solving the hidden terminal problem of FD networks by adopting a request to send / clear to send (for short, RTS/CTS) mechanism. The authors in [20] propose a hybrid HD/FD MAC protocol to fully exploit the channel access opportunity of simultaneous uplink and downlink transmissions. All these protocols do not utilize the TX antenna and generally have a low throughput efficiency due to high contention overhead. In contrast, our design reduces the contention overhead by adopting a novel contention mechanism and removing unnecessary time components.

CSMA/CD-based FD-MAC protocols. These protocols emulate CSMA/CD [17] of wired networks to detect data collision in wireless FD networks. For example, the authors in [21] propose a protocol that lets the sender detect data collision. In the protocol, while transmitting data over the TX antenna, the sender senses the energy change over the RX antenna after cancelling its transmitting signals and infers if there is a collision. Once detecting a collision, the sender aborts the ongoing transmission immediately. The authors in [22] propose a protocol that lets the receiver detect data collision. In the design, upon a collision detection, the receiver notifies the sender of aborting the ongoing transmission immediately. The authors in [13] construct a convolutional neural network to detect data collision. All these protocols cannot detect the contention collision and hence cannot reduce the probability of data collision effectively. Moreover, the former two protocols use the RX antenna to detect data collision instead of receiving data and hence do not conduct bidirectional data transmissions, achieving a very limited throughput improvement. The third protocol introduces costly machine learning modules to detect data collisions. In contrast, in our design, the sender can detect the contention collision and conduct bidirectional data transmissions, thereby outperforming these protocols.

III. Proposed FD-CCD protocol

In this section, we first outline the proposed FD-CCD protocol, and then present its MAC designs. Our designs are based on IEEE 802.11g, which is widely implemented in almost all commercial devices and is compatible with almost all subsequent standards and amendments including 802.11ax [25]. Below, we mainly present the difference between FD-CCD and 802.11g.

A. Protocol overview

We consider an infrastructure-based FD wireless local area network (LAN), as shown in Fig. 1(a). The network consists of one access point (AP) and multiple nodes. The AP and each node adopt two antennas for wireless FD communications: one for TX and another for RX.

Our design requirements are: (i) FD nodes should detect the contention collision before data transmission, (ii) FD-CCD should support priority-based contention like IEEE 802.11 enhanced distributed channel access (EDCA), and (iii) FD-CCD should be compatible with conventional 802.11 protocols.

By compatibility, we mean that FD-CCD nodes and conventional 802.11 nodes can work together without issues arising. To meet these requirements, we divide one FD communication into three stages sequentially: trigger frame (TF) stage, contention stage, and data-transmission stage, as shown in Fig. 1(b). The FD communication is either node-initiated or AP-initiated. Below, we present these three stages of the former.

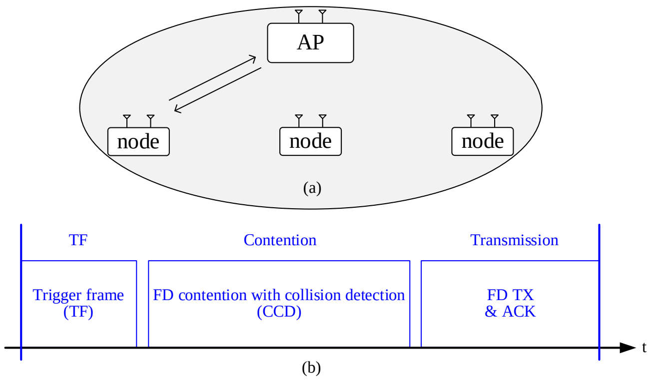
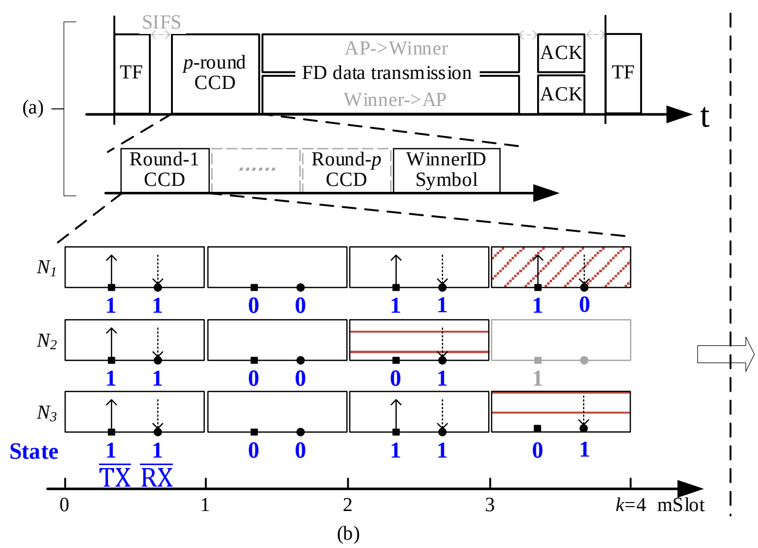


Fig. 1. (a) An FD wireless LAN, and (b) overview of FD-CCD.

In the TF stage, the AP broadcasts a TF to announce the beginning of one FD communication and convey contention parameter values, etc. Also, this stage is for meeting the design requirement (iii), i.e., compatibility. Consider the coexistence scenario of FD-CCD nodes and conventional 802.11 nodes. In our design, the AP and all conventional 802.11 nodes adopt the same contention protocol as that in 802.11 DCF or EDCA. When wining the contention, the AP may broadcast a TF which inactivates 802.11 nodes but triggers the contention of FD-CCD nodes; otherwise, the AP transmits data as in conventional 802.11protocols while FD-CCD nodes are inactivated. In this way, both FD-CCD nodes and conventional 802.11 nodes can work normally.

In the contention stage, a node contends for the channel and detects the contention collision by exploiting its TX & RX functionalities and adopting a weighted bitwise-arbitration algorithm (instead of BEB as in 802.11). In each contention slot, each node detects contention collision, according to the number of nodes who transmit the contention symbol simultaneously. Specifically, each node randomly chooses a k-bit binary number in a different range according to its traffic type, a bit corresponding to a mini contention slot (called mSlot). The node then performs bitwise arbitration mSlot by mSlot. That is, in an mSlot, if the node chooses bit 1 (0), it transmits (does not transmit) one mini contention symbol (called mSym) via its TX antenna. Meanwhile it always infers if other nodes are transmitting too via its RX antenna, after cancelling its own transmitting mSym via the self-interference cancellation (SIC) technique [1]-[3]. According to its TX status and RX inference, the node may know if it wins, loses, or ties in the mSlot. In case that the node experiences a contention collision, namely, the node and other nodes still tie after k-slot, it may choose to launch a new round of contention to avoid a data collision, which will be caused when these tied nodes transmit data simultaneously. Further, different nodes choose different ranges of random numbers and hence are of different contention priorities. In this way, our contention mechanism meets the design requirements (i)-(ii).

In the data-transmission stage, the winner initiates one uplink transmission to the AP and the AP then triggers one downlink transmission to the winner. In this way, the AP and the winner perform bidirectional communications by exploiting their TX and RX functionalities. The design of this stage follows the one in [26].



State		Contention result	Next action
$\overline{TX}$	$\overline{RX}$		
1	1	Tie	Contention
0	0	Tie	Contention
0	1	Lose	Exit
1	0	Win	Win-declare

(c)

Fig. 2. (a) Overview of MAC protocol, (b) one example of one-round CCD (k = 4) and (c) state, contention result, and next action per mSlot in one-round CCD.

B. MAC design

In the MAC layer, one complete FD communication consists of 3 stages: TF stage, p-round CCD stage, and FD data transmission & ACK stage, as shown in Fig. 2(a). Below, we mainly present the p-round CCD stage.

In our design, each node performs at most p-round CCD, where each round time consists of mSlots 1 to k from left to right, as shown in Fig. 2(b). At the beginning of each round, each node randomly chooses bits 1 to k from left to right by the

CW size of its traffic category, and then performs CCD mSlot by mSlot from left to right by its corresponding bit value and its TX & RX antenna statuses. In each mSlot, a node may win, lose, or tie. In Fig. 2(c), we summarize the per-mSlot state, contention result and next action. If the node wins (i.e., the node is the unique winner who chooses the maximum decimal number), it transmits a winnerID symbol containing its ID, which announces that the CCD stage ends, and next prepares to transmit data. If the node loses, it exits the contention and subsequent data-transmission stages. If the node ties with other nodes, it continues contention in the next mSlot. After k mSlots, if the node still ties with other nodes, we say that it experiences a contention collision. In this case, the node enters the next-round CCD and repeats the above process until the end of round p CCD. After p rounds, if the node still experiences a collision, all collided nodes transmit a data and hence cause a data collision.

Below, assume p=1 & k=4, and consider an example of three nodes: N_1, N_2, and N_3. These three nodes choose 1011 (11 in decimal), 1001 (9 in decimal), and 1010 (10 in decimal), respectively. In this example, N_1 finally wins since it chooses the maximum decimal number. With the help of Fig. 2(b) and (c), we detail the CCD process mSlot by mSlot.

In mSlot 1, all these three nodes are in state [1,1] since their corresponding bit values are all 1. Hence the contention result is tie and all these nodes will continue contention in the next mSlot, according to the second line of Fig. 2(c).

In mSlot 2, all these three nodes are in state [0, 0] since their corresponding bit values are all 0. Hence the contention result is tie and all these nodes will continue contention in the next mSlot, according to the third line of Fig. 2(c).

In mSlot 3, N_1 and N_3 are in state [1,1] since their corresponding bit values are all 1 and hence will continue contention in the next mSlot. However, N_2 is in state [0,1] since its corresponding bit value is 0 and it will detect an mSym from N_1 and N_3. Then N_2 exits according to the fourth line of Fig. 2(c).

In mSlot 4, N_1 is in state [1, 0] but N_3 is in state [0, 1], since N_1 transmits an mSym but N_3 does not transmit. As a result, N_1 is the unique winner according to the fifth line of Fig. 2(c).

IV. Theoretical analysis

In contention-based protocols, the collision probability governs all performance metrics such as throughput and delay. In this section, we develop a theoretical model to analyze the collision probability of our FD-CCD.

In our model, we consider a single-cell FD-CCD-enabled network and the node-initiated FD communication. Assume two types of traffic: high priority (HP) traffic such as voice and low priority (LP) traffic such as best-effort traffic. We call a node who transmits HP (LP) traffic an HP (LP) node. In the network, there is one AP, m_1 HP nodes and m_2 LP nodes, where m_1+m_2=m. An HP node and an LP node respectively choose one random decimal number from $2^{k_1} \sim 2^k$-1 and $2^{k_2} \sim 2^k-1$, where $k_2 \le k_1 \le k$. Then $N_1 = 2^k - 2^{k_1}$ and $N_2 = 2^k - 2^{k_2}$ denote the total number of the decimal numbers that an HP and an LP node may choose, respectively. Like [28]-[30], to investigate the performance of the MAC layer of our FD-CCD, we assume saturated traffic (i.e., each node and the AP always have packets to transmit) and ideal channel conditions and perfect physical-layer technology such as perfect SIC and collision detection. We note that modern physical layer SIC techniques can almost perfectly cancel SI. For example, in [27], the SIC technique with three-stage (i.e., antenna isolation, analog and digital SI cancellations) can cancel 100 dB of SI when TX power is up to +10 dBm. Further, these modern SIC techniques make collision detection fairly reliable.

Below we model the collision probability. According to our p-round CCD mechanism, the winner is the unique node that chooses the maximum decimal number. In each CCD round, if more than one nodechooses the same maximum decimal number, a contention collision will happen. The contention collision probability governs the system performance of FD-CCD. Here, we calculate the collision probability.

Let r be the chosen maximum decimal number. We have $r \in [2^{k_1}, 2^k\text{-}1]$ for m_1>0 and $r \in [2^{k_2}, 2^k\text{-}1]$ for m_1=0. Let $P(r)$ denote the collision probability that two or more nodes choose r. Let P_c be the collision probability in each CCD round. Then, we have

$$P_c = \sum\nolimits_r P(r). \qquad (1)$$

To calculate $P(r)$, we consider the three cases: case 1 where r is chosen by HP nodes only, case 2 where r is chosen by HP and LP nodes, and case 3 where r is chosen by LP nodes only.

Let $\Pr_1(r) \triangleq \Pr[\text{case 1}]$. We have

$$\Pr_1(r) = \sum\nolimits_{j=2}^{m_1} \binom{m_1}{j} \left(\frac{1}{N_1}\right)^j \left(\frac{r\text{-}2^{k_1}}{N_1}\right)^{m_1\text{-}j} \left(\frac{r\text{-}2^{k_2}}{N_2}\right)^{m_2} \qquad (2)$$

Here, $\frac{1}{N_1}$ denotes the probability that one HP node chooses r. $\frac{r\text{-}2^{k_1}}{N_1}$ denotes the probability that one HP node chooses a random number from $2^{k_1} \sim r\text{-}1$. $\frac{r\text{-}2^{k_2}}{N_1}$ denotes the probability that one LP node chooses a random number from $2^{k_2} \sim r\text{-}1$. Then $\left(\frac{1}{N_1}\right)^j \left(\frac{r\text{-}2^{k_1}}{N_1}\right)^{m_1\text{-}j} \left(\frac{r\text{-}2^{k_2}}{N_2}\right)^{m_2}$ denotes the probability that only j HP nodes choose r, and all other HP nodes and all LP nodes choose a number less than r. Considering that these j nodes are from m_1 HP nodes and j may take a value from 2 to m_1, we obtain the expression of $\Pr_1(r)$.

Let $\Pr_2(r) \triangleq \Pr[\text{case 2}]$ and $\Pr_3(r) \triangleq \Pr[\text{case 3}]$. Following the calculation method of $\Pr_1(r)$, we have

$$\Pr_2(r) = \sum_{j=1}^{m_1} \binom{m_1}{j} \left(\frac{1}{N_1}\right)^j \left(\frac{r\text{-}2^{k_1}}{N_1}\right)^{m_1\text{-}j} \sum_{i=1}^{m_2} \binom{m_2}{i} \left(\frac{1}{N_2}\right)^i \left(\frac{r\text{-}2^{k_2}}{N_2}\right)^{m_2\text{-i}}$$

$$\Pr_3(r) = \left(\frac{r\text{-}2^{k_1}}{N_1}\right)^{m_1} \sum\nolimits_{i=2}^{m_2} \binom{m_2}{i} \left(\frac{1}{N_2}\right)^i \left(\frac{r\text{-}2^{k_2}}{N_2}\right)^{m_2\text{-i}} \qquad (3)$$

When m_1>0, we have

$$P(r) = \Pr_1(r) + \Pr_2(r) + \Pr_3(r)$$
$$P_c = \sum\nolimits_{r=2^{k_1}}^{2^k\text{-}1} P(r) \qquad (4)$$

When m_1=0, we have

$$P(r)=\sum_{i=2}^{m_2}\binom{m_2}{i}\left(\frac{1}{N_2}\right)^i\left(\frac{r\text{-}2^{k_2}}{N_2}\right)^{m_2\text{-i}}$$
$$P_c=\sum_{r=2^{k_2}}^{2^{k}\text{-}1}P(r) \quad (5)$$

V. PERFORMANCE EVALUATION

In this section, we evaluate the collision probability of FD-CCD via our developed Matlab simulator. Table 1 lists the default parameter settings according to IEEE 802.11g. In addition, by default, we set the number of nodes, m, to 30, and set one WinnerID symbol time, T_{wSym}, to $4\mu s$.

TABLE 1
DEFAULT PARAMETER SETTINGS IN SIMULATION

	FD-CA/FD-CD/ HD-CA	FD-CCD
T_{SIFS}	10µs	8µs
T_{DIFS}	28µs	T_{TF}=28µs
T_{Slot}	9µs	T_{mSlot}=2.6µs
R	54Mbps	54Mbps
CW_{min}	32	k=8
CW_{max}	1024	p=2
T_{phy}	20µs	20µs
T_{mac}	28B/R	28B/R
$T_{payload}$	3000B/R	3000B/R
T_{ack}	14B/R	14B/R

In all figures, the curves with labels "ana" and "sim" represent the analytical and simulation results, respectively. The curves with labels "FD-CCD ($p=1$)" and "FD-CCD ($p=2$)" represent the results of FD-CCD with 1-round and 2-round CCDs, respectively. For Fig. 3, we assume that HP and LP nodes coexist. For Fig. 4, we assume that all nodes have the same contention priority and choose a random number from 2^0 to 2^k-1. Each simulation result is an average of over 5 simulation runs, where each run lasts for 100 seconds.

Fig. 3 plots the collision probability P_f vs. the number of mSlots per contention round k when HP and LP nodes coexist, where k varies from 1 to 10, and the number of CCD rounds p=1, 2. For each k, we set the CW sizes of HP and LP nodes to k_1=floor(2k/3) and k_2=floor(k/3), respectively, and set the number of HP and LP nodes to $[m_1, m_2]$=[8, 8] or [10, 20], respectively. From this figure, we have the following observations. First, given p and m, P_f decreases with k since a large k reduces the probability that different nodes choose the same number. Second, given m and k, P_f when p=2 is lower than that when p=1 since increasing the number of CCD rounds reduces the collision probability further. Third, given p and k, P_f increases as the total number of HP and LP nodes increases. Fourth, each simulation curve (i.e., the sim curve) well matches the corresponding analytical curve (i.e., the ana curve), implying that our collision-probability model is very accurate.

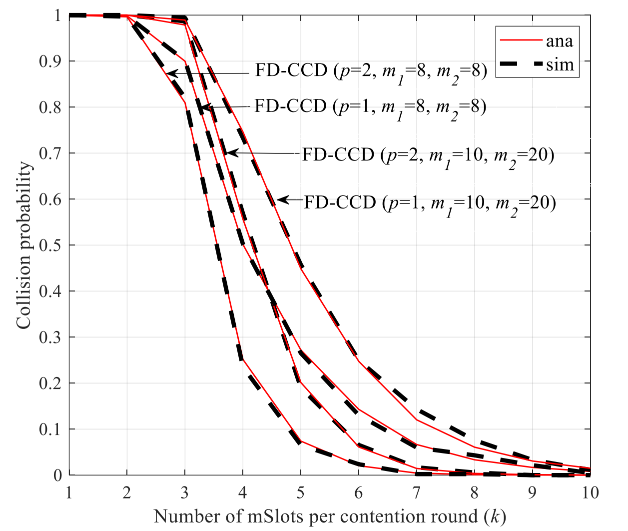


Fig. 3. Collision probability P_f vs. k when HP and LP nodes coexist.

Fig. 4 plots the collision probability of our p-round FD-CCD, FD-CA [18], FD-CD [21] and HD-CA (i.e., CSMA/CA [16]) as the number of nodes, m, varies from 1 to 30. The diamond curve presents the theoretical collision probability of FD-CA, FD-CD, and HD-CA since these protocols adopt the same contention protocol. The other curves represent the simulation or theoretical collision probability of FD-CCD with 5 cases: case 1 where $k=8$ and $p=1$, case 2 where $k=8$ and $p=2$, case 3 where $k=8$ and $p=3$, case 4 where $k=8$ and $p=4$, case 5 where $k=16$ and $p=1$. From this figure, we have the following observations. First, the collision probability of each protocol increases as m increases. Second, given m, the collision probability of these related protocols is far higher than that of FD-CCD due to the difference in contention mechanisms. Third, for FD-CCD, the collision probabilities of cases 2 to 4 are neglectable compared with that of case 1. This implies that our CCD algorithm does not require many CCD rounds to reduce the collision probability.

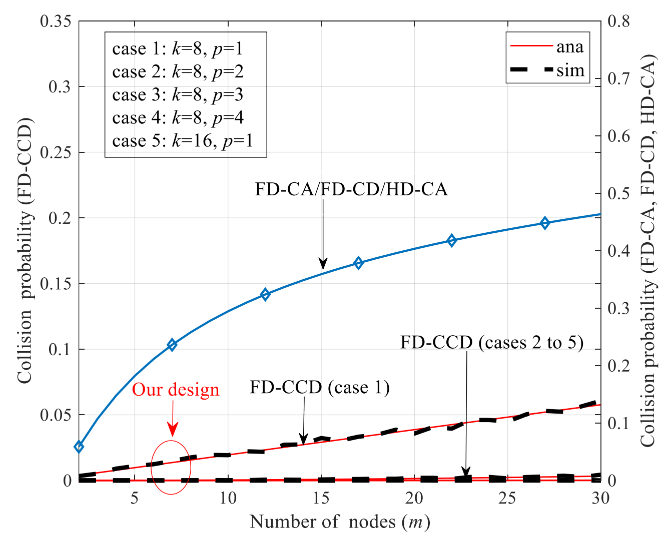


Fig. 4. Comparison of the collision probability among FD-CCD, FD-CA, FD-CD, and HD-CA.

VI. Conclusion

In wireless contention-based protocols, a contention mechanism is among the most fundamental. Conventional contention mechanisms only exploit the reception functionality of antennas to contend for the channel and avoid the contention collision due to the limit of the half-duplex nature. Wireless full-duplex enables simultaneous transmission and reception on the same channel. This paper proposes exploiting the full-duplex capability to redesign the contention mechanism for wireless full-duplex networks. The most salient feature of our design is to allow a node to detect the contention collision while contending for the channel and hence provides an opportunity to avoid the data collision effectively. We then analyze the collision probability of the proposed design and finally run extensive simulations to verify the effectiveness of our design and the accuracy of our model.

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