Medium Access Control Design for Full Duplex Wireless Systems: Challenges and Approaches

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ABSTRACT

Recent advances in self-interference cancellation techniques enable in-band full-duplex (FD) transmission in which a wireless node can simultaneously transmit and receive in the same frequency band. However, to fully exploit the benefits of FD technology in a wireless network, in addition to the physical (PHY) layer issues, medium access control (MAC) layer issues such as inter-node collisions, fairness between half-duplex (HD) and FD users, opportunistic selection of different modes of FD transmission, and synchronization issues need to be resolved. To this end, this article first discusses the fundamental concepts, potential benefits, and primary network topologies of FD transmission. We then highlight immediate challenges (both in the PHY and MAC layers) that need to be addressed in designing FD wireless systems. A qualitative comparison among the existing full-duplex MAC (FD-MAC) protocols is then provided. Finally, the primary requirements and research issues for the design of FD-MAC protocols are discussed, and implications of FD technology in cellular wireless networks are highlighted.

INTRODUCTION

Until very recently, the concept of transmission and reception in the same time and frequency domain (referred to as full-duplex (FD) technology) did not seem to be very promising. The primary reason was the overwhelming nature of the so called self-interference (SI), which is generated by the transmitter to its own collocated receiver. SI is a fundamental bottleneck in the progress of FD technology [1]. Fortunately, with the recent advancements in antenna and digital baseband technologies as well as RF interference cancellation techniques, SI can be reduced close to the level of the noise floor in low-power networks, e.g. cognitive radio networks and Wi-Fi networks [2].

At the physical layer (PHY), considering a point-to-point link and perfect SI cancellation, FD transmission offers twice the spectral efficiency of half-duplex (HD) transmission. Due to this attractive feature, FD technology is rapidly extending its applications in different wireless communications scenarios, especially those with low transmission power and distance requirements [3]. For instance, small cell networks, device-to-device (D2D) communications, cognitive radio networks, and multi-hop relaying are potential areas where FD technology can be practically feasible and implementable in the near future. However, to fully exploit the benefits of FD technology, major PHY and medium access control (MAC) layer issues need to be resolved by devising new PHY layer techniques and by modifying the existing MAC layer protocols. These issues include mitigation of residual self-interference, inter-node interference, inter-cell uplink to downlink/downlink to uplink interference, fairness between HD and FD users, opportunistic selection of different modes of FD transmission, synchronization and time adjustment issues to establish FD transmission, etc. Understanding the role of the PHY and MAC layers is crucial to address these issues.

This article first discusses the fundamental concepts, potential benefits, primary network topologies, and collision domains in FD transmission. Then it highlights the immediate challenges (both in the PHY and MAC layers) that need to be addressed in the design of FD-MAC protocols. A qualitative overview of the existing FD-MAC protocols is then provided. To this end, major issues and approaches for designing FD-MAC are discussed. Finally, implications of FD technology resource and interference management of cellular networks are highlighted.

FUNDAMENTALS OF FULL-DUPLEX WIRELESS SYSTEMS

ANTENNA CONFIGURATIONS FOR FD SYSTEMS

Since FD transmission requires in-band operation of transmitting and receiving RF chains, the conventional duplexers cannot be directly utilized to maintain separation between the two RF transmissions. FD transmission can, however, be realized through the following antenna configurations:

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Shared Antenna Configuration [4]: In this configuration, a single antenna can be used for simultaneous in-band transmission and reception through a three-port circulator. Ideally, the circulator prevents the leakage of signals from the transmit RF chain to the receive RF chain. However, in practice, the transmit signal causes SI to the signals received. Moreover, due to hardware limitations and severe interference, multiple circulators cannot be utilized to enable the use of multiple shared antennas.

Separated Antenna Configuration [5, 6]: In this configuration, the total number of antennas is divided into two groups for transmission and reception. This division of spatial resources, however, introduces a trade-off. As such, a fair comparison between HD and FD transmission should consider the exact number of RF chains/antennas required to establish FD transmission. Also, in the separated antenna configuration, it is crucial to first analyze whether the performance gains of a HD multi-antenna transmission are worth sacrificing with the bidirectional (SI affected) FD transmission?

Transmission Modes in Full-Duplex Systems

The fundamental modes of transmission in FD wireless systems are listed below [7].

Half-Duplex: In this mode RF transmission takes place in a single direction between primary transmitter (PT) (i.e. the node that initiates transmission) and primary receiver (PR) (i.e. the node that decodes the signal from PT) (Fig. 1a). Both nodes operate in HD mode if neither PT receives a signal from a secondary transmitter (ST) (i.e. the node that is allowed to transmit simultaneously with PT), or the PR has to transmit to PT or any other node.

Bi-Directional Full-Duplex (BFD): In this mode both PT and ST transmit signals to each other at the same time (Fig. 1b). Note that PT and PR becomes secondary receiver (SR) (i.e. the node that decodes signal from ST) and ST, respectively.

Three Node Full-Duplex (TNFD): In this mode a FD node transmits to one node while receiving from another node (Fig. 1c and Fig. 1d). The transmission modes illustrated in Fig. 1c and Fig. 1d are known as destination-based transmission mode (DBTM) and source-based transmission mode (SBTM), respectively.

- DBTM: In DBTM mode, the destination for PR is another node (i.e. not the PT node) which is located in the vicinity of PR's transmission range. Thus, PR becomes the ST and its receiver becomes SR.
- SBTM: The SBTM mode is enabled when PR does not have data to transmit. However, the PT's neighbor node wants to transmit data to PT. In this case, PT's neighbor node becomes ST and PT becomes SR by activating the FD mode.

As an example, in cellular networks where a base station (BS) may not have data packets for a node transmitting to the BS in the uplink or a node receiving transmission from the BS in the downlink may not have data packets for the BS. In such scenarios, the BFD mode cannot be established. However, in the former case, a BS can exploit the FD opportunity by initiating a downlink transmission to another node (DBTM). In the latter case, a BS may initiate receiving data packets from another node in the uplink (SBTM). Note that both SBTM and DBTM may also occur at the same time, and the mode can thus be referred to as *concurrent SBTM and DBTM*.

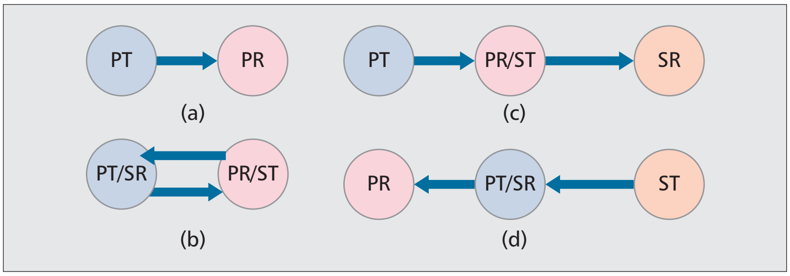

Figure 1. FD transmission modes: a) half-duplex transmission; b) bi-directional FD transmission; c) destination-based FD transmission; d) source-based FD transmission.

Inter-node interference is a crucial factor in TNFD-enabled FD networks depending on the locations and transmit powers of the nodes. Various inter-node interference scenarios are depicted in Fig. 2. The bold circle around the nodes presents the PT's transmission region, whereas the dotted circle denotes the ST's transmission region. Figures 2a and 2b show intra-node collision within a set of nodes operating in DBTM and SBTM, respectively. In DBTM the SR suffers collision from PT if located within the PT's transmission region. In SBTM, the PR suffers collision from ST if located within the ST's transmission region. Similarly, Figs. 2c, 2d, and 2e show the inter-node collisions due to the STs' transmission region overlapping, STs' and PTs' transmission region overlapping, and PTs' transmission region overlapping, respectively.

Fundamental Benefits of FD Technology

In addition to doubling the spectral efficiency, FD technology exhibits several other advantages over conventional HD transmission.

Opportunistic Selection of FD Mode: Radio resources (e.g. resource block (RB) in LTE-A networks) can be opportunistically used for either HD, BFD, or TNFD transmission mode. This mode selection per resource block can be optimized to maximize the overall system utility, considering the prior knowledge of the available data packets and channel/interference conditions of the prospective participating nodes.

Rapid Collision Detection: An FD-enabled wireless device can listen to the RF channel while transmitting to probe the occurrence of other transmissions on the same channel. This would enable fast collision detection, e.g. spectrum sensing in cognitive radio networks.

BFD Mitigates Hidden Terminal[1] Problem [6]: The transmitted signals from both ST and PT can be overheard by their respective neighboring nodes. As a result, the neighboring nodes refrain from initiating transmission until the ongoing BFD transmission is completed. The collisions due to the hidden node problem can thus be eliminated.

[1] Hidden terminals are the wireless nodes that can potentially transmit (and thus introduce interference) during an ongoing transmission. Note that, the hidden nodes cannot be detected by the carrier sensing mechanism.

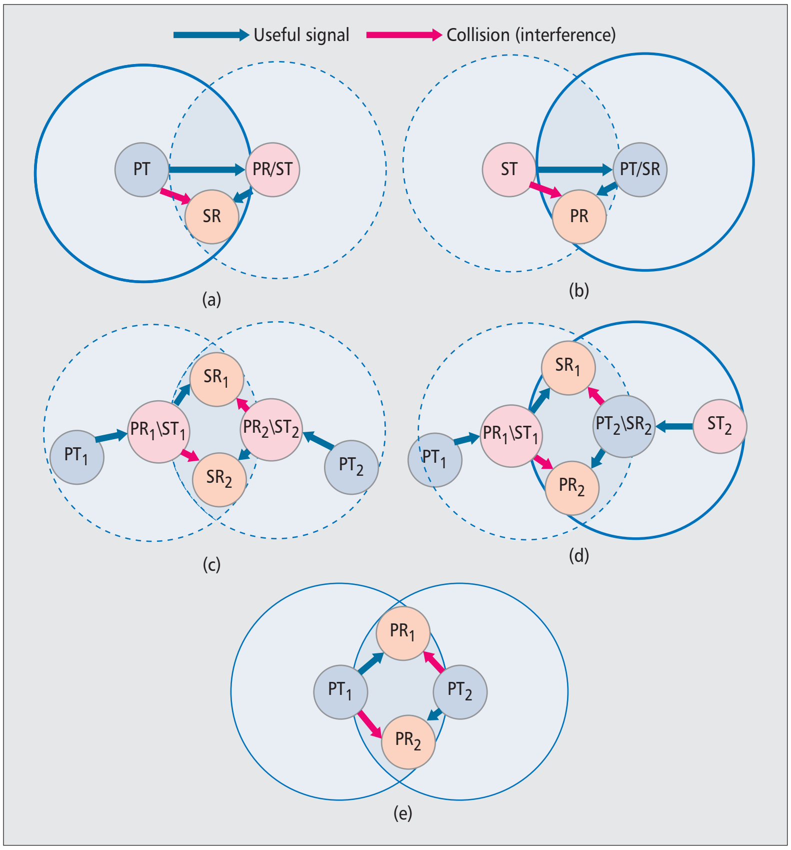

Figure 2. Fundamental inter-node collision possibilities in FD transmission.

Channel Selection: An FD-enabled node can assist nearby nodes in the channel selection process. For instance, if a PR has nothing specific to transmit to PT or any other node, the PR may assist its nearby nodes by informing them about the interference on a channel. This may help the nearby nodes in selecting a channel.

Reduced Latency: FD technology exhibits reduced latency by enabling the reception of feedback signals from the receiver (i.e. channel state information (CSI), control signaling for ARQ and/or network management, ACK, etc.) during transmission.

Secure Transmission: Due to the simultaneous transmission and reception in FD networks, the eavesdroppers receive mixed signals that are difficult to decode.

RF Energy Transfer During Transmission [8]: FD technology enables a wireless node to perform wireless charging while performing an uplink transmission.

Challenges in the Design of FD Wireless Systems

Fundamental Challenges

Residual Self-Interference (SI): SI is caused by the coupling of the transceiver's own transmit signal to the receiver while attempting to receive a signal sent by another wireless node. The key challenge arises from the large power level difference between the transceiver's own transmission and the signal of interest coming from a distant source. To achieve considerable SI cancellation, several antenna, RF, and baseband cancellation techniques [2, 9] are currently under investigation. Even with the several stages of SI cancellation (passive, active analog, and active digital), a certain amount of SI remains in the system, which is referred as residual SI. To achieve the theoretical performance limit of FD transmission, efficient SI cancellation techniques are required that can eliminate residual SI.

Intracell Interference: In a TNFD-based SBTM transmission, a PT communicates with two nodes using HD transmission, i.e. the PR in the downlink and the ST in the uplink. There exists two types of interference in this case: residual SI from the PT to the SR and intra-node interference from the ST to the PR (Fig. 2b). Since the PT and SR are collocated, the SI signal is known and can possibly be canceled at the SR. However, the signal that is the source of the intra-node interference is not known at the PR and thus cannot be canceled on reception. This intra-node interference can significantly degrade the performance of PT-PR transmission depending on the vicinity of the ST with the PR.

Uplink to Downlink and Downlink to Uplink Inter-Cell Interference: In multiuser cellular networks, additional inter-cell interference will be experienced by a node (whether operating in HD, BFD, or TNFD mode) depending on its direction of transmission. For instance, if a node is transmitting in the uplink, it will receive interference from the uplink transmitters of the neighboring cells (conventional) as well as the neighboring BSs who are transmitting in the downlink (additional). This additional interference is therefore referred to as downlink to uplink inter-cell interference. On the other hand, if a node is transmitting in the downlink, it will receive interference from the neighboring BSs (conventional) as well as the uplink transmitters of the neighboring cells, which is referred to as uplink to downlink inter-cell interference. By analyzing these two specific scenarios, it can be concluded that the users who want to operate in HD mode may suffer considerably as the potential gains of FD technology are not applicable to them. Moreover, due to the high transmit power of BSs, downlink to uplink interference becomes more severe than uplink to downlink interference.

Asynchronous TNFD Transmission: While BFD mode may possibly enable a perfectly synchronized transmission between two nodes, it may not be straightforward in TNFD transmission mode, because the emergence of the third node may not occur at the same time when a single-hop HD transmission is initiated. Thus, the primary question arises about the feasibility and performance limit of the asynchronous TNFD systems, i.e. can a new node be added once a HD transmission starts? If yes, then how much gain can be achieved practically?

There can be two possible scenarios, i.e. a PT starts receiving a packet while initiating a transmission, or a PR starts a new transmission while receiving a packet. In the former case, the PT can suppress its own SI while transmitting to the

PR in order to decode new transmission from the ST. Also, correct decoding of new reception requires the PT to estimate the channel between the ST and itself in the presence of the SI. On the other hand, initiating a new transmission at the PR while receiving from the PT is not reliable enough as the process of estimating the channels to establish a canceling signal causes a self-collision at the receiver [6].

CHALLENGES AT THE MAC LAYER

FD networks allow several transmission modes that can result in a new kind of inter-node collisions other than the SI as mentioned previously. As such, minimizing the additional inter-node collisions with traditional MAC protocols such as the carrier-sense multiple access with collision avoidance (CSMA/CA)-based HD-MAC protocols is not straightforward. This section focuses on characterizing the main challenges that need to be considered while designing MAC protocols for FD transmission.

Selecting FD Transmission Modes and Nodes: In FD networks, nodes can operate in any of the transmission modes that are illustrated in Fig. 1. Hence, selecting a set of nodes and an FD transmission mode to maximize the overall utility of FD transmission is crucial. The basic approaches that are currently used in FD-MAC protocols to exploit proper nodes and modes for FD transmission are shared random backoff, header snooping, and request-to-send (RTS)/clear-to-send (CTS) mechanisms. These will be discussed in the next section.

Fairness: Due to the bidirectional communication capabilities in FD networks, the fairness among nodes may degrade by a factor of two compared to HD communication. For instance, assume that there are three sets of potential BFD nodes located parallel to each other. The BFD nodes in the corners can use the same channel without interfering with each other as they are not located in the coverage area of one another. However, the FD set located within the coverage of both FD sets is highly unlikely to start its transmission since both the FD nodes in the middle sense that the channel is busy most of the time. The possibility of this case is double for a FD device located in the coverage of two FD sets. Hence, designing efficient and fair MAC protocols for FD networks is a crucial task. This unfairness is penalized by tuning the channel access probability of nodes as a function of proportion of time in which their transmission has been active [10].

Exploiting FD Opportunities via Buffer: In the existing MAC standards, the head-of-line (HOL) packet of the buffer always gets transmitted irrespective of the buffer length, type of packets, and their respective destinations. For instance, if node PT is capable of performing BFD transmission with node PR but PR has no HOL packet for PT (although some packets are available in the buffer), then PT needs to either wait until the HOL packet of PR is transmitted, or initiate an HD transmission. Later, the PR will need to do an HD transmission to the PT. It can thus be concluded that exploiting the right packets from the buffer that can enable FD transmission opportunities may possibly reduce the overall latency at the cost of delays for the destinations of HOL packets [6].

Residual Hidden Node Problem: In practice, the primary and secondary transmitted packets are offset in time and may have different packet lengths. Therefore, the transmission of all nodes will not end up at the same time. Hence, relying only on FD data transmission (even in BFD mode) does not completely solve the hidden node problem. The hidden node problem in FD transmissions due to asymmetric data packets at the transmitter and the receiver can be referred to as the residual hidden node problem. However, the node that finishes data transmission earlier can resolve this issue by transmitting busy tone signals until the other node completes its transmission [11].

Contention in Asynchronous TNFD Mode: Asynchronous TNFD mode occurs when a transmitter, say the PT, has already started transmission and a new transmitting node emerges who wants to transmit to the PT. In this case, the traditional RTS/CTS mechanism cannot be implemented as the PT is transmitting already. Thus the new node has no way to know about the other nodes who may be trying to transmit to the PT at the same time. Therefore, resolving a contention becomes a challenging task in asynchronous TNFD mode [10].

Deafness in Directional Antennas: If FD systems use directional antennas, then the neighboring nodes around the PT and the ST are unable to detect these transmissions. This scenario is known as the deafness problem in directional transmission [12]. Due to the deafness problem, the neighboring nodes try to access a particular channel assuming that it is available for their transmission. This might end up with a collision in the ongoing transmission. A centralized MAC protocol can therefore be useful in avoiding such collisions as the central coordinator might know the locations of its registered nodes and their corresponding transmission directions.

EXISTING FD-MAC PROTOCOLS

The existing FD-MAC protocols in the literature can be classified based on their operation, handshaking mechanism, transmission mode, time synchronization, and number of channels used for resource allocation, as illustrated in Table 1. In this section we will discuss three key mechanisms that can be utilized in the design of FD-MAC protocols [6]: shared random backoff; header snooping; and collision avoidance with RTS/CTS exchange. In order to execute these mechanisms, the basic structure of the HD packet does not need to be modified significantly, i.e. all the basic fields in the HD packet header (i.e. source/destination address, packet duration, fragmentation, etc.) remain the same. However, to exchange the basic information among the FD nodes, the following unique fields/identifiers are required.

The basic approaches that are currently used in FD-MAC protocols to exploit proper nodes and modes for FD transmission are shared random backoff, header snooping, and request-to-send (RTS)/clear-to-send (CTS) mechanisms.

Scenario	Technique
Network architecture	Centralized [13] or distributed [7, 14, 15]
Control information exchange	RTS/CTS [1, 14] or ACK [5, 9, 10] in data transmission channel, dedicated or dynamically configurable control channel
Spectrum access	Contention [11, 16], time slotted [13], or hybrid
Transmission mode	Bi-directional FD [6, 7] or three node FD [6, 7]
Time adjustment (synchronous or asynchronous)	RTS/CTS [1, 14], ACK [5, 9, 10], or beacon [13]
Channel usage	Single channel [5–7] and multiple channel [11, 16]

Table 1. Classification of FD-MAC protocols.

FD Transmission Mode (FDM) Field: At a given time, the set of nodes selected to initiate FD transmission can operate in either one of the four transmission modes depicted in Fig. 1. To indicate/select/suggest a mode, the FD packet thus needs a separate field with the length of two bits (i.e. '00' for HD-mode, '01' for BFD-mode, '10' for DBTM, and '11' for SBTM).

Full-Duplexing Duration (FDDUR): A two bytes field to indicate the duration of FD transmission is also required. Otherwise, the nodes participating in FD transmission may not synchronize and increase the collision rates.

Complex FD-MAC protocols may require further information exchange among the nodes [6].

Shared Random Backoff (SRB)-Based FD-MAC [6]

In SRB-based protocols, all nodes that have performed handshaking for FD communications and have transmitted at least a data packet delay their transmission for a common duration with the intention of allowing other nodes to utilize the channel. Information about this duration needs to be sent to other nodes in the network by including an additional field in the FD packet header known as the SRB field. SRB-based MAC protocols are well-suited for BFD when participating nodes have many packets to exchange, because the problems in the backoff counter countdown mechanism turn out to be significant in TNFD mode and degrades performance due to the lack of synchronization. SRB protocols are implicitly synchronous due to the common backoff and allow FD nodes to spare channel for other starving nodes.

Illustration: Let us assume that there are two nodes and they want to exchange data between them. Let one node win the contention (PT) and start transmission to the intended receiver (PR). Since the PT has a large amount of data to transmit to the PR, the PT sets the FDM field in the FD header to '01' and the SRB field to a random backoff value. After the PR successfully decodes this packet, it knows that the PT has more packets to transmit and the preferred transmission mode is bidirectional transmission. Since the PR also has many packets to transmit to the PT, the PR sends an ACK to the PT by setting the FDM field in the FD header to '01'. Then, both the PT and PR start their transmissions simultaneously after waiting for the random backoff time that was informed by the PT. This scenario is a *forced shared random backoff* since PR has to follow the backoff time informed by the PT. Otherwise, the PR also can propose a backoff time to the PT by setting the SRB field in the ACK packet. In this scenario, either minimum or maximum backoff time should be selected by both the nodes, and this selection should be set by the MAC protocol a priori. Note that in any SRB-based MAC protocol the first transmission is a half-duplex one.

Header Snooping-Based FD-MAC [6]

In header snooping-based MAC protocols, the primary transmitted packet header is decoded by at least single registered node in the network, excluding the primary receiver. Due to this header snooping, the FD nodes transmit in different time stamps, which results in asynchronous transmission. The header snooping-based MAC protocols are well-suited for applications where nodes operate in SBTM since the PT transmitted packet can be snooped by other nodes located withing the PT's transmission region (Fig. 1d).

Illustration: Let us assume that there are three nodes in the network and one node wins the contention (PT). Then the PT sets its FDM field in the FD packet header to '01' and transmits its packet to the PR indicating its preferred transmission mode as bidirectional transmission. The PR sets its FDM field in the FD ACK header to '00' and it indicates that only HD is possible. This indirectly conveys to the PT that the PR does not have any packet to transmit. Meanwhile, another node (ST) in the network, which wants to transmit packets to the PT, snoops the PT's packets and knows that the PT requests a bidirectional transmission from the PR. However, the ST does not have any idea about the PR's response if the ST is located outside the PR's transmission region. Since the PR does not have any packet to transmit to the PT, the PT sets its FDM field in the FD packet header to '11' and this packet is snooped by the ST. After the ST notices that the FDM field in the PT's packet header is '11,' it starts its transmission simultaneously with the PT. Note that the first packet transmission in the header snooping-based MAC protocol does not utilize full-duplexing.

RTS/CTS-Based FD-MAC [14]

The RTS/CTS mechanism that is used in HD transmission can be utilized even in FD transmission to mitigate the hidden node problem. In FD communication, the FD RTS/CTS headers are obtained by adding a FDM and FDDUR field to the HD RTS/CTS headers. Additionally, another address field is added to the HD CTS header that indicates SR's or ST's address. Let us denote that address field as the STorSRAddress field. Hence, the basic operation of the RTS/CTS-based FD-MAC protocols can be illustrated as follows.

MAC protocol	Mechanism	Application	Benefits	Drawbacks	Transmission modes
Distributed MAC [7]	Header snooping	Cellular, D2D, relay, WLAN	Low overhead in handshaking, considers inter-node interference, select nodes for TNFD based on the signal-to-interference ratio (SIR)	Busy tone signaling required, duration of header snooping period cannot be used for data transmission	BFD, DBTM, SBTM
RCTC MAC [15]	Signature based RTS/CTS	Cellular, D2D, rxelay networks	Low overhead signaling, identify nearby transmissions to maximize system throughput	Vulnerable to collision	BFD, DBTM, SBTM
ContraFlow [10]	Header snooping	Cellular, D2D, relay networks	Does not reserve a channel, fairness is considered	Busy tone signaling, no handshake before transmitting packets	BFD, DBTM, SBTM
Distributed MAC [2, 5]	Header snooping	Cellular, D2D networks	Lower signaling overhead	No handshake before transmitting packets	BFD
Wormhole switching-based MAC [9]	Header snooping	Multi-hop networks	Lower signaling overhead	No handshake before transmitting packets	DBTM
Directional antenna [12]	Header snooping	Multi-hop networks	No ACK frame of contention window	Vulnerable to collision	Multi-hop networks-based on DBTM
RFD-MAC [17]	Header snooping	Relay networks	Asynchronous approach with low signaling overhead	Higher collision period in contention	DBTM
JANUS [13]	Header snooping	Relay networks	Achieve higher throughput by eliminating random backoff, nodes transmit multiple packets with a single set of control packets	Higher collision period in contention	DBTM
SRB-based MAC [6]	SRB	Cellular, D2D	Both the nodes fully utilized data transmission duration	Independent backoff counter count down of different nodes	BFD

Table 2. Qualitative overview of existing FD-MAC protocols.

Illustration: Let us assume there are three nodes and one wins the contention without loss of generality. Then the node that wins the contention (PT) sets its FDM field in the FD RTS header to '01' and transmits a packet to the intended receiver (PR) indicating that its preferred transmission mode is a bidirectional transmission. Let us assume that the PR does not have any packet to transmit to the PT but it has many packets to transmit to another node in its transmission range. Then the PR (ST) sets its FDM field in the FD CTS header to '10' and the STorSRAddress field in the CTS header, which is the address of the node to whom the PR (ST) wants to transmit its data. With the reception of this packet, the PT knows in which transmission mode it is going to operate and waits for another CTS duration. Note that this CTS packet acts as an RTS to the SR. Hence, within this waiting CTS time duration, the SR transmits a CTS packet to the ST (PR) after setting the FDM field to '00.' The nodes around the SR receive this packet and know that a transmission is going on that channel. After the SR's CTS transmission, both the PT and ST start to transmit their data to the intended receivers simultaneously.

Comparative Analysis

A qualitative comparison among the existing FD-MAC protocols is shown in Table 2. The characteristics of each protocol are captured in terms of their underlying mechanism (SRB, header snooping, and RTS/CTS), their application in different transmission modes (BFD, SBTM, and DBTM) and network topologies, benefits, and drawbacks. Note that, keeping in view the unique characteristics of various kinds of FD-MAC protocols, hybrid protocols can also be developed.

Figure 3 depicts the normalized throughput of FD nodes for different FD-MAC protocols when multiple nodes contend for a given channel. As expected, the system performance deteriorates with the increasing number of nodes in the network due to the increasing collisions during contention. This figure reveals that the SRB-based FD-MAC protocol with RTS/CTS outperforms all other approaches because both the nodes (PT and ST) fully utilize the transmission duration from beginning to end for data transmission simultaneously. Surprisingly, both the bi-directional-SRB and SBTM-header snooping methods without RTC/CTS show close per-

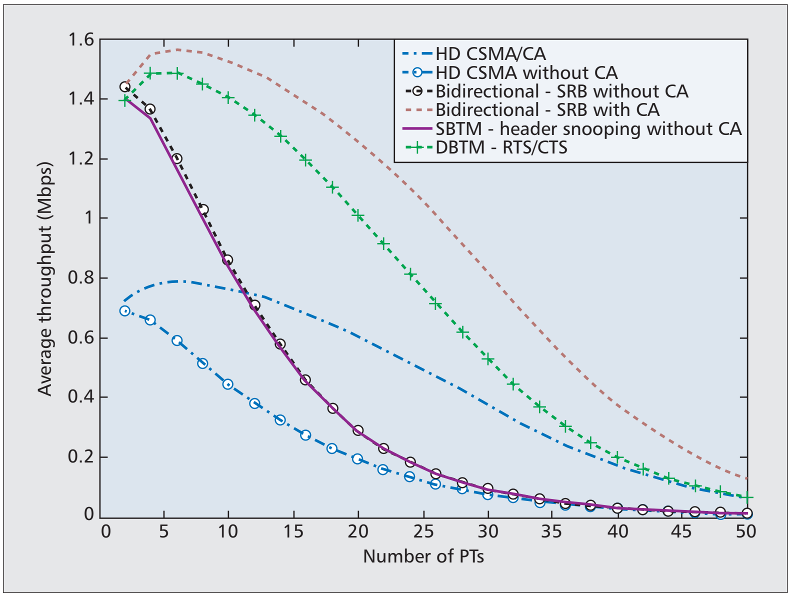

Figure 3. Throughput as a function of the number of PTs for different MAC protocols. Simulation parameters: PHY header = 128 bits, MAC header = 272 bits, RTS = 160 + PHY header, CTS = 128 + PHY header, Short inter-frame space (SIFS) = 28, Payload = 1042 bytes, mini-slot = SIFS + RTS+ SIFS + CTS and contention window size = 16.

formance because the signaling overhead in the header snooping approach is not significant compared to the packet size. However, Fig. 3 clearly reveals that the RTS/CTS-based MAC approach for DBTM outperforms all other approaches (except SRB with CA) even with higher signaling overhead due to the collision avoidance nature of RTS/CTS.

Design Challenges for FD-MAC and Open Research Issues

In this section we highlight design issues in existing FD-MAC and discuss possible solution techniques that can be incorporated with the design of existing FD-MAC. To this end, implications of FD technology on resource and interference management in cellular networks are also discussed.

Design Challenges for FD-MAC Protocols

Node Selection: Existing FD-MAC protocols are designed for a predefined set of nodes (i.e. two or three node set) and thus do not address the challenge of node selection in multi-node FD networks while considering the overall utility of FD transmission and the inter-node collisions. Note that node selection is even more challenging for TNFD modes due to intra-node/inter-node collisions. A straightforward approach is to perform location-aware selection of nodes, i.e. considering the distance from the PT to the SR in DBTM, and considering the distance from the ST to the PR in SBTM. However, this might increase the performance loss of the secondary link due to far-away distances. In this context, optimal location-aware node selection algorithms need to be developed that can minimize intra-node interference without causing excessive degrading of the signal strength of the corresponding link. Further, the inter-node collisions due to the hidden nodes can be alleviated by transmitting RTS/CTS signaling before establishing the FD connection or by transmitting busy tones.

Fairness in the Secondary Link: In existing FD-MAC protocols, the node that wins the contention (e.g. PT) starts its transmission on its best channel without considering the quality of the secondary link. The channel that is selected for primary transmission might be the worst channel for the secondary link. Therefore, designing a MAC protocol that considers both primary and secondary link conditions is highly desirable to improve the overall utility of FD transmission.

Channel Selection: The channel selection in FD-MAC protocols is challenging due to multiple transmission modes and different interference scenarios.

- As mentioned earlier, selecting a common channel becomes more crucial in TNFD mode. The best common channel for TNFD mode can be obtained using a graph based approach. After the channel is selected the process of handshaking among the FD set is also a challenge that needs to further exploit the conventional approaches, e.g. common hopping sequence, control channel, and rendezvous scheme.
- To enhance the fairness between primary and secondary links as mentioned earlier, selecting a common channel that considers the overall utility of the primary and secondary link is crucial and not an easy task due to the signaling overhead. To mitigate this effect, all the participating nodes have to handshake before finalizing their transmit channel. In this context, studying a low overhead FD-MAC protocol is also required.

Backoff Counter Countdown Mechanism: In SRB-based MAC protocols [6], FD-enabled nodes select a common backoff time to start their next transmission simultaneously. However, different nodes independently count down their backoff counters since each node may observe the selected channel's idleness differently due to the heterogeneity of the network. As a result, the nodes that handshake for full-duplexing with a common backoff start their transmission in two different timestamps. This degrades the system performance due to the lack of synchronization in SRB-based MAC protocols.

Control Signaling Overhead: In the existing HD communications, data and control information is exchanged in different frequency bands/time-slots. FD communication is a very good solution to moderate the affirmation issues in HD communication. FD-MAC protocols can potentially exploit the simultaneous transmission and reception to reduce the signaling overhead by discovering the transmission mode and its corresponding nodes, coordination of participating nodes, full-duplexing time slots, and channel identification, etc.

Exploiting FD Opportunities via the Buffer: As discussed earlier, the performance of FD networks can be improved by exploiting FD opportunities via the buffer. However, blindly delaying the HOL packet is not feasible, so a FD-MAC protocol should be developed that optimally decides the duration of the delay for the HOL packet.

Performance Analysis of FD-MAC: As in other MAC protocols, the analysis of FD-MAC protocols is also crucial to understand the fundamental performance limits and to gain design insights. However, analysis of FD-MAC is challenging due to the simultaneous transmission, multiple transmission modes, different packet sizes, busy tones, time adjustments, and signaling overhead.

IMPLICATIONS OF FD IN CELLULAR NETWORKS

Cooperation in Cellular Networks: To mitigate uplink to downlink and downlink to uplink inter-cell interference issues, all nearby BSs need to cooperate and optimize the proportion of FD transmission events in a coordinated manner.

Traffic Load-Aware FD Networks: The asymmetry of uplink and downlink data traffic may not directly affirm the significance of FD transmission in cellular networks. Typically, downlink traffic is much more significant compared to the uplink traffic. It is thus of immense importance to optimize the proportion of FD transmissions considering the uplink/downlink traffic load intensities.

Clustering in Small Cell Networks: FD transmission can be applied more frequently in low power small BSs due to the high prospects of SI cancellation. However, uplink to downlink and downlink to uplink inter-cell interference becomes even more critical in densely deployed small cell networks. Efficient clustering methods/techniques need to be adopted that can allow nearby small-cells to coordinate their FD transmissions. For instance, a cluster of small-cells may coordinate the execution of FD transmissions such that all small-cells within that cluster select FD mode in a sequential manner. In this way, the aforementioned interference issues can possibly be minimized. In this regard, inter-cluster cooperation may also be exploited.

Cooperative FD-D2D Transmissions: Device-to-device (D2D) communications allow nearby users to establish a direct link to communicate with each other. While D2D links are typically exploited for HD data transmissions, they may be used for interference mitigation or channel selection if exploited in FD mode. For instance, a D2D transmitter can hear interference signals on the FD receiver and can provide the interference information to its intended receiver along with the data packets. In addition, any downlink cellular user can also exploit the FD-D2D communication to forward interference knowledge to a nearby user. This knowledge can help nearby users in either interference cancellation or channel selection.

CONCLUSION

Full-duplexing will be one of the main candidate technologies for future wireless communication systems to exploit spectrum, and this will practically enable applications such as cognitive radios. We believe that the maximum gain due to full-duplexing can only be achieved through a smart FD-MAC protocol that jointly addresses the physical layer and MAC layer aspects. In this article we have highlighted the major challenges that need to be considered in designing smart FD-MAC protocols. The possible approaches to solve these challenges have been discussed. Also, the interference management challenges that arise in cellular networks due to the adoption of FD technology have also been discussed.

Full-duplexing will be one of the main candidate technologies for future wireless communication systems to exploit spectrum and this will practically enable applications such as cognitive radios. We believe that the maximum gain due to full-duplexing can only be achieved through a smart FD-MAC protocol that jointly addresses the physical layer and MAC layer aspects.

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BIOGRAPHIES

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