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FULL-DUPLEX TRANSMISSION IN PHY AND MAC LAYERS FOR 5G MOBILE WIRELESS NETWORKS

XI ZHANG, WENCHI CHENG, AND HAILIN ZHANG

ABSTRACT

As the fourth-generation (4G) standards have been successfully deployed in all 4G-based wireless communication industries and mobile devices, research attention and the efforts of academia and industry have already moved onto fifth-generation (5G) technologies. While the frequency-division duplexing (FDD) and time-division duplexing (TDD) are widely used in 4G mobile wireless networks, they have their inherent deficiencies of low spectrum efficiency because FDD and TDD are both based on the half-duplex transmission mode. To overcome these problems existing in 4G systems, in this article we propose novel wireless full-duplex transmission schemes in both the PHY and MAC layers for 5G mobile wireless networks to significantly increase the spectrum efficiency. In particular, we first develop the wireless full-duplex model for both bidirectional transmission and unidirectional transmission, respectively, taking into account self-interference mitigation. Then we analyze the traditional half-duplex FDD and TDD modes and show the superiority of the wireless full-duplex mode over the half-duplex FDD and TDD modes, respectively. Using our developed wireless full-duplex model, we develop and evaluate the efficient full-duplex power allocation scheme at the PHY layer. Corresponding to full-duplex transmission at the PHY layer, we also develop and analyze the full-duplex MAC protocol at the MAC layer to implement full-duplex transmission over the entire 5G mobile wireless network architecture. Through simulation experiments we show that our proposed schemes can significantly enhance spectrum efficiency for 5G mobile wireless networks.

INTRODUCTION

As fourth-generation (4G) wireless communications and networks are becoming more mature and widely implemented in mobile wireless industrial and commercial products, fifth-generation (5G) mobile and wireless communication technologies are rapidly emerging into research fields. While 5G mobile wireless networks create great potential and flexibility supporting various advanced and high-data rate wireless communications, they also impose new challenges not encountered in 4G wireless systems. This is because 5G mobile wireless networks will require a mix of new system concepts to significantly enhance spectrum efficiency, power/energy efficiency, and advanced wireless network design technologies, which can be achieved by advanced wireless techniques, such as spectrum efficiency optimization, massive multiple-input multiple-output (MIMO), cooperative communications, and so on. Compared with the 4G communication systems and networks, several orders of magnitude higher wireless transmission rates/bandwidth are expected to support various statistical delay-bounded quality-of-service (QoS) provisioning [1–3] for the bandwidth-intensive and time-sensitive multimedia services over 5G wireless communications networks, which keeps spectrum-efficiency maximization as one of the central issues in designing and implementing 5G mobile wireless networks.

To overcome the above challenges, in this article we propose advanced full-duplex transmission techniques [4–8] for both physical (PHY) layer and medium access control (MAC) layer protocols as the promising 5G wireless network candidate architectures that can efficiently support 5G mobile wireless communications implementation by significantly boosting spectrum efficiency. This was also motivated by observing the inherent shortcomings of frequency-division duplexing (FDD)-based and time-division duplexing (TDD)-based wireless networks, which are traditionally the two typical half-duplex modes used in current 4G mobile wireless networks. In the half-duplex FDD mode, the uplink and downlink signals are separated by orthogonal frequency-bands, while for the half-duplex TDD mode, the uplink and downlink signals are separated in orthogonal time-slots. Although the FDD mode and the TDD mode[1] are already widely adopted in 4G mobile wireless network standards, they have their inevitable performance constraints. For the FDD mode, the quantization for the channel state information at the transmitter (CSIT), the inflexible bandwidth allocation, and the guard frequency-bands between the uplink and the downlink inevitably affect the optimization of FDD-based wireless networks. On the other hand, for the TDD

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[1] For presentation simplicity, in the rest of this article, we use FDD and TDD to denote the half-duplex FDD and the half-duplex TDD, respectively.

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mode, the duplexing delay in MAC, the out-of-date CSIT, and the guard intervals between the uplink and the downlink can downgrade the performance of TDD-based wireless networks. In contrast, through simultaneous transmission and reception using the same frequency band at the same time, advanced wireless full-duplex transmission technologies can not only overcome the bottlenecks of FDD and TDD, but also significantly increase the spectrum efficiency for 5G mobile wireless networks. The Long-Term-Evolution-Advanced (LTE-A) standards have proposed to use the inband full-duplex relay transmission for wireless networks [9]. The inband full-duplex relay can achieve larger capacity than the outband full-duplex relay if self-interference is significantly mitigated [10]. From LTE/LTE-A to 5G, full-duplex transmission extends from the relay transmissions to point-to-point transmissions.

To efficiently implement the wireless full-duplex transmission mode in 5G mobile wireless networks, self-interference needs to be resolved at the PHY layer and the corresponding higher-layer protocols, which can support the wireless full-duplex transmission mode, also need to be developed. In terms of self-interference mitigation techniques, a great deal of research has been performed, showing the significant feasibility of implementing full-duplex transmissions over wireless communications networks [11, 12]. These works either separately or jointly employ propagation-domain interference suppression (PDIS), analog-domain interference cancellation (AIC), and digital-domain interference cancellation (DIC). PDIS endeavors to mitigate self-interference by avoiding the input of the RF amplifier being overwhelmed due to self-interference [12]. AIC attempts to cancel self-interference to avoid the input of the analog-to-digital converter (ADC) being overwhelmed by self-interference [11, 12]. DIC attempts to cancel residue self-interference due to the non-ideal of the RF amplifier, the nonlinearities in the ADC, and the oscillator phase noise [12]. For presentation convenience, the combined AIC and DIC is denoted by ADIC in this article. However, only solving the self-interference mitigation problem does not warrant the implementation of full-duplex based 5G mobile wireless networks, because a large number of existing schemes/protocols at different protocol layers, such as the power allocation scheme at the PHY layer and the MAC protocol at the MAC layer, are already designed and implemented based on the corresponding FDD and TDD modes at the PHY layer [13]. Therefore, if the full-duplex transmission mode is *only* implemented at the PHY layer, spectrum efficiency cannot be effectively increased because of the constraint caused by the half-duplex transmission mode used at the MAC layer. As a result, we need to develop our full-duplex transmission mode framework across the entire protocol architecture through not only the PHY layer, but also the MAC layer to efficiently implement full-duplex transmission over 5G mobile wireless networks.

At the PHY layer, one of the most important mechanisms to maximize spectrum efficiency lies in its power allocation scheme. The well known water-filling algorithm can increase spectrum efficiency only for the wireless half-duplex transmission mode. However, due to the impact of self-interference, the traditional water-filling algorithm cannot maximize spectrum efficiency for the wireless full-duplex transmission mode. Therefore, we need to develop an efficient power allocation scheme to maximize spectrum efficiency for the wireless full-duplex transmission mode. On the other hand, at the MAC layer one of the most important mechanisms to support spectrum efficiency optimization relies on the MAC protocol. The widely used MAC protocols, such as the IEEE 802.11 Distributed Coordination Function (DCF) [13] and *p*-persistent Carrier Sense Multiple Access (CSMA) protocols, are both implemented through the *half-duplex* wireless transmission mode. To efficiently implement the full-duplex transmission-mode-based 5G mobile wireless networks, we need to develop a new MAC protocol to support wireless full-duplex transmission.

In this article we first analyze and show the superiority of the wireless full-duplex mode over the FDD and TDD modes. Then we develop the full-duplex power allocation scheme to maximize spectrum efficiency for the full-duplex based 5G mobile wireless networks. We show that full-duplex power allocation follows a *water-filling-like* algorithm when taking into account the impact of self-interference. Corresponding to the full-duplex power allocation scheme at the PHY layer, we also develop a new full-duplex MAC (FD-MAC) protocol at the MAC layer to support both bidirectional (between two wireless nodes) and unidirectional (among three wireless nodes) transmissions, and to resolve the hidden terminal problems in full-duplex based 5G mobile wireless networks.

The rest of this article is organized as follows. We start with a comparison of the wireless full-duplex mode with the FDD and TDD modes, showing the superiority of the former over the latter. Then we develop and evaluate the efficient full-duplex optimal power allocation scheme for full-duplex MIMO transmission at the PHY layer. Corresponding to the developed full-duplex power allocation scheme at the PHY layer, we also develop and analyze the full-duplex MAC protocol at the MAC layer to implement full-duplex transmission over the entire 5G mobile wireless network architecture.

THE FULL-DUPLEX SYSTEM MODEL FOR 5G MOBILE WIRELESS NETWORKS

In this article we consider 5G mobile wireless networks that use full-duplex transmission [14]. The base station (BS) is needed to centrally control the user equipments (UEs) in 5G mobile wireless networks. Thus, we focus on full-duplex technique-based 5G mobile wireless networks, an example of which is shown in Fig. 1 with one BS and six UEs. As illustrated in Fig. 1, the BS communicates directly with the UEs. There are two types of transmissions in full-duplex technique-based 5G mobile wireless networks: the two-node (one of which is the BS node) full-duplex wireless *bidirectional transmission* and the three-node (one of which is the BS node as the relay node) full-duplex wireless *unidirectional transmission*.[2] If the full-duplex transmission is

Several orders of magnitude higher wireless transmission rates/bandwidth are expected to support various statistical delay-bounded quality-of-service (QoS) provisioning for the bandwidth-intensive and time-sensitive multimedia services over 5G wireless communications networks, which makes the spectrum-efficiency maximization remain as one of the central issues in designing and implementing 5G mobile wireless networks.

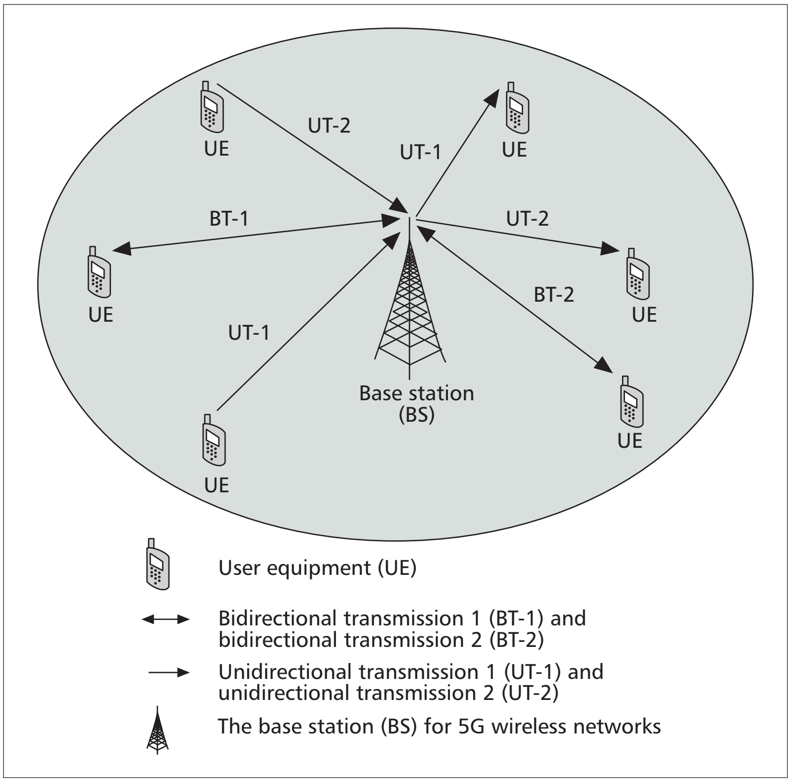

Figure 1. An example of the full-duplex based 5G mobile wireless network.

executed between these two nodes each being equipped with one transmitter and one receiver, we call this type of transmission wireless full-duplex bidirectional transmission (for example, BT-1 between two nodes and BT-2 between two nodes, as shown in Fig. 1). If the first node equipped with one transmitter sends its information to the second node equipped with one transmitter and one receiver while the second node transmits its own information to the third node equipped with one receiver, we call this type of transmission wireless full-duplex unidirectional transmission (for example, two UT-1s across three nodes and two UT-2s across three nodes, as shown in Fig. 1). *All the full-duplex transmissions over 5G mobile wireless networks consist of wireless bidirectional full-duplex transmissions and/or wireless unidirectional full-duplex transmissions*, and thus in the rest of this article we will focus on the wireless bidirectional and unidirectional full-duplex transmissions.

Figures 2a and 2b show the PHY layer connections for full-duplex wireless bidirectional and unidirectional transmissions, respectively, in 5G mobile wireless networks. Each UE has one transmitter and one receiver. The transmitter and the receiver can be equipped with a single antenna or multiple antennas according to the applied PDIS schemes [12]. We apply ADIC schemes at each node's receiver to cancel the residual self-interference after being processed by PDIS. As illustrated in Fig. 2a, nodes A and B transmit their data to nodes B and A, respectively, forming a two-node full-duplex wireless bidirectional transmission (as shown in Fig. 2a for nodes A and B's PHY layer connection which also corresponds to, for example, BT-1 and BT-2 in Fig. 1). As shown in Fig. 2b, nodes C and D transmit their data to nodes D and E, respectively, constituting a three-node full-duplex wireless unidirectional transmission (as shown in Fig. 2b for nodes C, D, and E's PHY layer connection which also corresponds to, for example, UT-1 and UT-2 in Fig. 1).

FULL-DUPLEX MODE VERSUS HALF-DUPLEX MODE

We analyze and show the superiority of the wireless full-duplex mode over the FDD and TDD modes.

THE ADVANTAGES OF THE FULL-DUPLEX MODE OVER THE FDD MODE

The wireless full-duplex mode can significantly increase spectrum efficiency compared with the FDD mode. The FDD mode affects the spectrum efficiency in the following aspects.

The Quantization for the CSIT: In the FDD mode, the uplink and the downlink use different frequency-bands (channels). These different channels are orthogonal and have different frequency responses. Thus, to obtain the CSIT, the receiver needs to quantize and feed back the channel state information to the transmitter. The quantization will inevitably degrade the quality of the CSIT. However, for the full-duplex mode with bidirectional transmission, because the same frequency band is used, the uplink channel and the downlink channel responses are reciprocal to each other. By estimating the channel on the return link, the user equipment (UE) can obtain an estimation of the channel, thus avoiding the quantization and delivery for the CSIT.

The Inflexible Bandwidth Allocation: For a large number of data traffic and multimedia services, it is desirable that the bandwidth can be dynamically adjusted according to the traffic demand. In the FDD mode, the uplink and the downlink use fixed bandwidth that cannot be dynamically changed according to the traffic demand. However, in the full-duplex mode, the entire bandwidth can be shared by the uplink and the downlink simultaneously. Also, by adjusting the number of allocated subframes, the bandwidth can be dynamically reallocated.

The Guard Frequency Bands Between the Uplink and the Downlink: In the FDD mode, the guard frequency bands are extra overhead of the frequency resource. However, in the full-duplex mode, since the uplink channel and the downlink channel share the same frequenc bands, there is no need for the guard frequency bands, which saves bandwidth resources.

THE ADVANTAGES OF THE FULL-DUPLEX MODE OVER THE TDD MODE

The wireless full-duplex mode can significantly increase spectrum efficiency compared with the TDD mode because of the following reasons.

The Duplexing Delay in MAC: In the TDD mode, because the uplink transmission and the

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[2] In this article, we use the term of node to represent either the BS or the UE in the full-duplex technique-based 5G mobile wireless network.

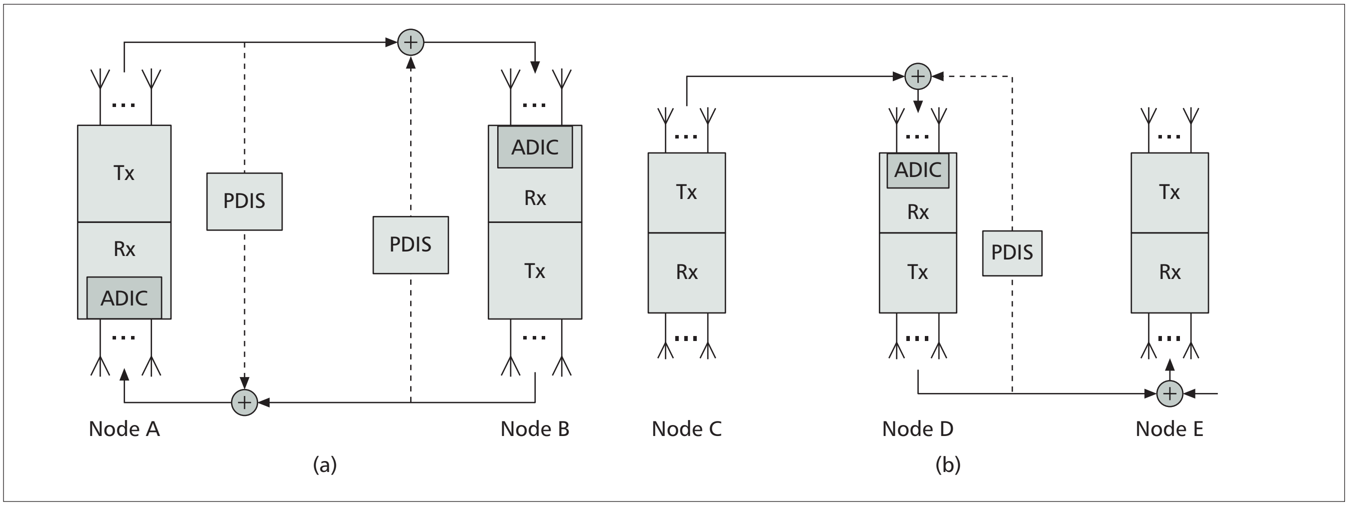

Figure 2. The PHY layer connections for full-duplex wireless bidirectional and unidirectional transmissions, respectively, in 5G mobile wireless networks. a) The PHY layer connection for the two-node full-duplex multiplexing MIMO bidirectional transmission in 5G mobile wireless networks; b) The PHY layer connection for the three-node full-duplex multiplexing MIMO unidirectional transmission in 5G mobile wireless networks.

downlink transmission alternate in the time domain, the service is discontinuous, thus causing duplexing delay between different uplink/downlink frames. To avoid long duplexing delay, the length of the frame cannot be very large. However, if the frame is too short, the overhead of the transmit/receive transition gap (TTG) and receive/transmit transition gap (RTG) will be too large. Thus, the duplexing delay cannot be avoided in the TDD mode. By contrast, in the full-duplex mode, since the uplink frames and the downlink frames are continuous, there is no duplexing delay.

The Out-of-Date CSIT: In the TDD mode, because of the duplexing delay, the CSIT may be out-of-date. In particular, for the time-varying channels where channel states vary quickly, the CSIT will deviate from the actual channel state during the delay time between two uplink/downlink frames, thus becoming out-of-date. However, in the full-duplex mode, there is no duplexing delay, and thus there is no CSIT outdating problem, which also helps enhance spectrum efficiency.

The Guard Intervals Between the Uplink and the Downlink: The TDD mode needs the guard intervals (TTG to switch from transmit mode to receive mode; RTG to switch from receive mode to transmit mode) to implement the transmit-receive mode switching. The overhead in the TTG is large when the wireless cells are too large. Thus, the guard intervals waste time-slot resources in TDD-based wireless networks. However, in the full-duplex mode, there is no need for the guard intervals, which saves time-slot resources.

The above analyses show that the full-duplex mode has a number of significant advantages over the FDD and TDD modes. To maximize spectrum efficiency, in the following we develop the efficient schemes/protocols in both the physical (PHY) layer and the medium access control (MAC) layer, respectively, for full-duplex mode based 5G mobile wireless networks.

FULL-DUPLEX POWER ALLOCATIONS

In this section we build the full-duplex transmission models and the self-interference mitigation model, respectively. Then, based on this self-interference mitigation model, we formulate spectrum efficiency optimization problems and solve them to derive the optimal full-duplex power allocation schemes for two-node full-duplex wireless bidirectional transmission and the three-node full-duplex wireless unidirectional transmission, respectively.

FULL-DUPLEX MULTIPLEXING MIMO BIDIRECTIONAL AND UNIDIRECTIONAL TRANSMISSIONS MODELS

We build a model for two-node full-duplex wireless bidirectional transmission [2] and three-node full-duplex wireless unidirectional transmission [1], as illustrated in Fig. 2, where nodes A, B, and D need to mitigate self-interference from the local transmitter. The transmit power of nodes A, B, C, and D for the *i*th singular-value channel are denoted by $P_a^{(i)}$, $P_b^{(i)}$, $P_c^{(i)}$, and $P_d^{(i)}$, respectively. Under our proposed full-duplex multiplexing MIMO scheme, we suppose that nodes A, B, C, D, and E employ N_t transmit antennas and N_r receive antennas, respectively (see Figs. 2a and 2b).

SELF-INTERFERENCE MITIGATION MODELING

We define κ ($0 < \kappa \leq 1$) as the self-interference mitigation coefficient for the node with full-duplex wireless transmission. The value of κ depends on a number of factors, such as system bandwidth, antenna displacement error, transmit signal amplitude difference, and so on [12]. When κ approaches 0, it implies that self-interference causes large interference on wireless full-duplex transmission. When κ approaches 1, it means that self-interference causes little interference on wireless full-duplex transmission.

The self-interference mitigation coefficients characterize the effect of self-interference mitigation jointly using the propagation-domain

> When the residual self-interference is very large, the effective received signal power at the receiver of full-duplex node becomes very small. When the residual self-interference is very small, the effective received signal power at the receiver of full-duplex node gets very large.

interference suppression (PDIS) technique, the analog-domain interference cancellation (AIC) technique, and the digital-domain interference cancellation (DIC) technique. For example, if we jointly use the PDIS (30 dB self-interference mitigation), the AIC (25 dB self-interference mitigation), and the DIC (20 dB self-interference mitigation) techniques for full-duplex wireless transmission, the self-interference mitigation coefficient should be 1/(75 dB), which explicitly shows the entire effectiveness of self-interference mitigation by jointly using the PDIS, the AIC, and the DIC techniques.

For two-node full-duplex wireless bidirectional transmission, both nodes (nodes A and B) need to tolerate residual self-interference after being processed by PDIS and ADIC. For three-node full-duplex wireless unidirectional transmission, only the node that is transmitting and receiving (node D) needs to tolerate residual self-interference after being processed by PDIS and ADIC. The parameters κ_a, κ_b, and κ_d denote the self-interference mitigation coefficients for nodes A, B, and D, respectively.

THE OPTIMAL POWER ALLOCATIONS FOR FULL-DUPLEX MULTIPLEXING MIMO 5G WIRELESS NETWORKS

In contrast to the power allocation for wireless half-duplex transmission, the full-duplex wireless power allocation scheme needs to take into account self-interference, which is characterized by the self-interference mitigation coefficient. There exist some initial research works on optimizing transmit power to maximize the transmission rate in bidirectional [15, 16] and unidirectional [17, 18] full-duplex wireless networks. For bidirectional and unidirectional topologies, the authors of [15, 17] derived the bounds on the achievable transmission rate of bidirectional and unidirectional full-duplex transmissions under the standard isotropic Rayleigh-fading model for wireless signal propagation. For full-duplex wireless-powered communication networks, the optimal resource allocation can maximize the weighted sum-rate [16]. For cognitive-radio unidirectional full-duplex wireless networks, the optimal power allocation scheme (the outage constrained power allocation) can minimize the overall outage probability in the cognitive-radio unidirectional full-duplex networks without requiring the instantaneous CSI across the wireless links between the primary and secondary users [18]. However, these works mainly focus on specialized channel models. The optimal full-duplex power allocation scheme required for the more generic and more practical wireless channel models remains an open and challenging problem.

We define the transmission rates for the two-node full-duplex wireless bidirectional (unidirectional) transmission as the sum of the transmission rates from node A (C) to node B (D) and from node B (D) to node A (E). Under our proposed multiplexing MIMO-based full-duplex 5G mobile wireless networks, we can derive the transmission rate for the two-node full-duplex wireless bidirectional transmission as $R_b = \Sigma_{i=1}^{N_t} [\log_2(1 + \kappa_a \gamma_{ba}^{(i)} P_b{}^{(i)}) + \log_2(1 + \kappa_b \gamma_{ab}^{(i)} P_a^{(i)})]$ and the transmission rate for the three-node full-duplex wireless unidirectional transmission as $R_u = \Sigma_{i=1}^{N_t} [\log_2(1 + \kappa_d \gamma_{cd}^{(i)} P_c{}^{(i)}) + \log_2(1 + \gamma_{de}^{(i)} P_d^{(i)})]$, respectively, where N_t is the number of transmit antennas, N_r is the number of receive antennas, and i denotes the ith transmit antenna (we suppose all channels are full rank, $1 \leq i \leq N_t$, and $N_t \leq N_r$), $\gamma_{ba}^{(i)}$, $\gamma_{ab}^{(i)}$, $\gamma_{cd}^{(i)}$, and $\gamma_{de}^{(i)}$ denote the power gains of the ith singular-value channel corresponding to channels from node B to node A, from node A to node B, from node C to node D, and from node D to node E, respectively. Then we can formulate the spectrum efficiency optimization problem for the two-node full-duplex MIMO wireless bidirectional transmission, denoted by ***P*1**, as follows:

$$\mathbf{P1:} \quad \max_{(P_a, P_b)} \{\mathbb{E}_\gamma[R_b]\} \qquad \text{s.t.} \quad \mathbb{E}_\gamma \left\{ \sum_{i=1}^{N_t} \left[P_a^{(i)} + P_b^{(i)} \right] \right\} \leq \bar{P} \tag{1}$$

where i denotes the ith transmit antenna, $\mathbb{E}_\gamma\{\cdot\}$ denotes the expectation over γ, and $\bar{P}$ denotes the average transmit power constraint. Because full-duplex wireless transmission consists of different data flows from different nodes using the same frequency band at the same time, we use the average power constraint over multiple nodes.

Using the powerful Lagrangian method, we can solve problem ***P*1** to derive the optimal power allocation scheme for the two-node full-duplex MIMO bidirectional transmission as follows:

$$\begin{cases} P_a^{(i)} = \dfrac{1}{\gamma_0} - \dfrac{1}{\kappa_b \gamma_{ab}^{(i)}}; \\ P_b^{(i)} = \dfrac{1}{\gamma_0} - \dfrac{1}{\kappa_a \gamma_{ba}^{(i)}}; \end{cases} \tag{2}$$

where i denotes the ith transmit antenna, κ_a and κ_b denote the self-interference mitigation coefficients of node A and node B, respectively, and γ_0 is the cut-off SNR threshold and can be numerically obtained by taking Eq. 2 into

$$\mathbb{E}_\gamma \left\{ \sum_{i=1}^{N_t} \; P_a^{(i)} + P_b^{(i)} \; \right\} = \bar{P}.$$

From Eq. 2 we can observe that the optimal power allocations for the two-node full-duplex bidirectional transmission still follow the tendency of a water-filling algorithm. However, the self-interference imposed by κ_b affects the full-duplex transmission performance, which results in a decrease of the cut-off SNR threshold and an increase of the power allocations at the high channel SNR region when κ_b decreases. The power allocation for node B follows a similar tendency as the power allocation for node A.

Replacing R_b, $P_a^{(i)}$, and $P_b^{(i)}$ by R_u, $P_c^{(i)}$, and $P_d^{(i)}$ in problem ***P*1**, respectively, we can formulate the spectrum efficiency optimization problem for three-node full-duplex wireless unidirectional transmission. Then we can derive the optimal power allocation scheme for three-node full-duplex MIMO wireless unidirectional transmission as follows:

$$\begin{cases} P_c^{(i)} = \dfrac{1}{\gamma_0} - \dfrac{1}{\kappa_d \gamma_{cd}^{(i)}}; \\ P_d^{(i)} = \dfrac{1}{\gamma_0} - \dfrac{1}{\gamma_{de}^{(i)}}; \end{cases} \tag{3}$$

where i denotes the ith transmit antenna and κ_d denotes the self-interference mitigation coefficient of node D. From Eq. 3 we can observe that self-interference only affects the effective received power of the full-duplex node (node D) in three-node full-duplex wireless unidirectional transmission.

Different from the half-duplex power allocation scheme where there is no self-interference impact, the design of a full-duplex power allocation scheme needs to take into account the impact of self-interference, which is characterized by the self-interference mitigation coefficients: κ_a, κ_b, and κ_d. When residual self-interference is very large (the self-interference mitigation coefficient is very close to 0), the effective received signal power at the receiver of the full-duplex node becomes very small. When residual self-interference is very small (the self-interference mitigation coefficient is very close to 1), the effective received signal power at the receiver of the full-duplex node becomes very large.

THE FULL-DUPLEX MAC PROTOCOL

The optimal full-duplex power allocation can maximize the spectrum efficiency of full-duplex transmission at the PHY-layer. However, to minimize the collisions among all full-duplex transmissions in the full-duplex technique-based 5G mobile wireless networks, the full-duplex MAC protocol, which can significantly reduce the collision probability among all full-duplex transmissions in the full-duplex technique-based 5G mobile wireless networks, is also highly demanded [19, 20]. Jointly optimizing the full-duplex power allocation scheme and the full-duplex MAC protocol, the spectrum efficiency and throughput of full-duplex wireless networks can be maximized. The full-duplex MAC protocol needs to support not only bidirectional full-duplex transmissions, but also unidirectional full-duplex transmissions in full-duplex based 5G mobile wireless networks. Also, the traditional hidden terminal problem [13] in full-duplex based 5G mobile wireless networks needs to be resolved.

To overcome these challenges, we further propose the RTS/CTS-based full-duplex MAC protocol, called the RTS/full-duplex clear-to-send (FCTS) mechanism, to achieve the following goals:

- Both bidirectional and unidirectional transmissions can be supported.
- All hidden terminal problems in wireless full-duplex networks have been resolved.

We denote the first transmission (corresponding to the transmission from node A to node B in Fig. 2a, and the transmission from node C to node D in Fig. 2b, respectively) and the second transmission (corresponding to the transmission from node B to node A in Fig. 2a, and the transmission from node D to node E in Fig. 2b, respectively) in one time full-duplex transmission by FD-T1 and FD-T2, respectively.

Before developing the FD-MAC protocol, we need to choose the basic mechanism between the ACK mechanism and the RTS/CTS mechanism. Clearly, since the destination node needs to keep on receiving while some neighbors do not know that the node is receiving, the hidden terminal problem exists in wireless half-duplex networks. The RTS/CTS mechanism is introduced to efficiently avoid the hidden terminal problem. In wireless full-duplex networks, it seems that there is no need for the RTS/CTS mechanism to avoid the hidden terminal problem since the node can send signals when the node is receiving data. However, notice that for wireless unidirectional links, since node E only works in the half-duplex transmission mode and it does not send any signal in the ACK mechanism, the hidden terminal problem is still present in wireless full-duplex networks if we employ the ACK mechanism. The hidden terminal problem of full-duplex transmission arises from three-node wireless unidirectional transmission. For wireless unidirectional transmission with nodes C, D, and E, node C and node E may be out of radio range of each other. If node C starts a full-duplex transmission (node C sends its own data to node D while node D transmits its own data to node E) while node E starts another full-duplex transmission (node E sends its own data to node D while node D transmits its own data to node C) simultaneously. In this case, node D is forced to "transmit two signals" and "receive two signals," thus causing collisions on node D. Therefore, we turn to developing the RTS/CTS based FD-MAC protocol for wireless full-duplex networks.

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

Then we can classify the nodes participating in full-duplex transmission into three categories as follows:[3]

Type 1: the node starts with sending an RTS.

Type 2: the node starts with having received an RTS when the destination address in the RTS is the address of this node.

Type 3: the node starts with having received a FCTS.

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

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

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[3] **Type 1** corresponds to nodes A and C in Fig. 2a and Fig. 2b, respectively; **Type 2** corresponds to nodes B and D in Fig. 2a and Fig. 2b, respectively; **Type 3** corresponds to node E in Fig. 2b.

The full-duplex MAC protocol needs to support not only the bidirectional full-duplex transmissions, but also the unidirectional full-duplex transmissions in full-duplex based 5G mobile wireless networks. Also, the traditional hidden terminal problem in full-duplex based 5G mobile wireless networks needs to be resolved.

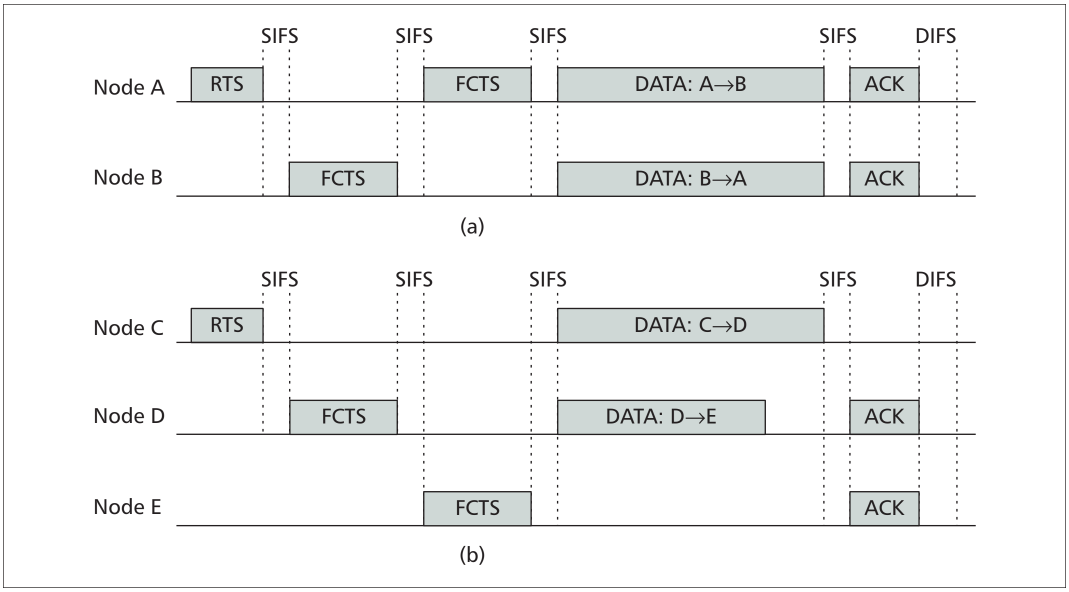

Figure 3. The timing sequences for the example cases of bidirectional and unidirectional transmissions controlled by our proposed FD-MAC protocol. a) The example of bidirectional transmission; b) The example of unidirectional transmission.

Our proposed FD-MAC protocol

Pseudo code for nodes of **Type 1**:

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

Pseudo code for nodes of **Type 2**:

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

Pseudo code for nodes of **Type 3**:

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

To better elaborate on our proposed FD-MAC protocol, we use the bidirectional transmission and unidirectional transmission examples to show the negotiation and transmission processes controlled by our proposed FD-MAC protocol for bidirectional and unidirectional transmissions in terms of the timing sequences as illustrated in Figs. 3a and 3b, respectively.

As shown in Fig. 3a, if node A, which has the packet to be sent to node B, senses that the channel is idle, the node A starts broadcasting the RTS signal to its neighbors when its back-off counter reaches zero. As soon as the destination node B received the RTS from node A, node B will wait for a SIFS time and then broadcasts the FCTS signal to its neighbors. If node B has no packet to transmit to node A, the FCTS is the same as the CTS used in wireless half-duplex networks. If node B has its packet to send to node A, the FCTS needs to be added with the destination address (node A) of the packet from node B and the length of the packet from node B to node A. The neighbors of node B will receive this FCTS and back off according to the data length of the packet from node B to node A. As soon as node A received the FCTS, node A waits for a SIFS time and broadcasts another FCTS to notify the neighbors of node A that it will receive the packet from node B. Then, after a SIFS time, both node A and node B will transmit their packets to each other. The duration of the packet transmission will last for the longer time between the FD-T1 and the FD-T2. Then, after a SIFS time, the ACKs (from node A to node B and from node B to node A, respectively) will be sent and then the current bidirectional transmission ends.

The case for three-node wireless full-duplex unidirectional transmission is shown in Fig. 3b, where node C first starts its transmitting to node D while node D also has its own data to be transmitted to node E. In this case, node C senses that the channel is idle, and when its back-off counter reaches zero it starts to broadcast the RTS to its neighbors. As soon as node D received the RTS from node C, it waits for a SIFS time and then broadcasts the FCTS to its neighbors, where the FCTS includes the destination address (node E), the length of the packet from node D to node E, and the length of the packet from node C to node D. The node E will receive the FCTS from node D. Then, after a SIFS time, node E will broadcast another FCTS to its neighbors. After another SIFS time, node C and node D will send their packets to node D and node E simultaneously. After the transmission of the data and a SIFS time, node D sends the ACK to node C, and node E transmits the ACK to node D, respectively.

Please note that under the full-duplex MAC protocol, system synchronization is guaranteed through the three-way handshakes protocol using one RTS frame and two FCTS frames. After the successful three-way handshakes, the two way transmissions (for the two-node bidirectional transmission, from node A to node B and from node B to node A; for the three-node unidirectional transmission, from node C to node D and from node D to node E) are synchronized at the end of the third SIFS of one full-duplex transmission. When the two way transmissions end, because all nodes "know" the longer duration between the two way transmissions, after two SIFSs time periods and the ACK frame interaction, the two-way transmissions are synchronized.

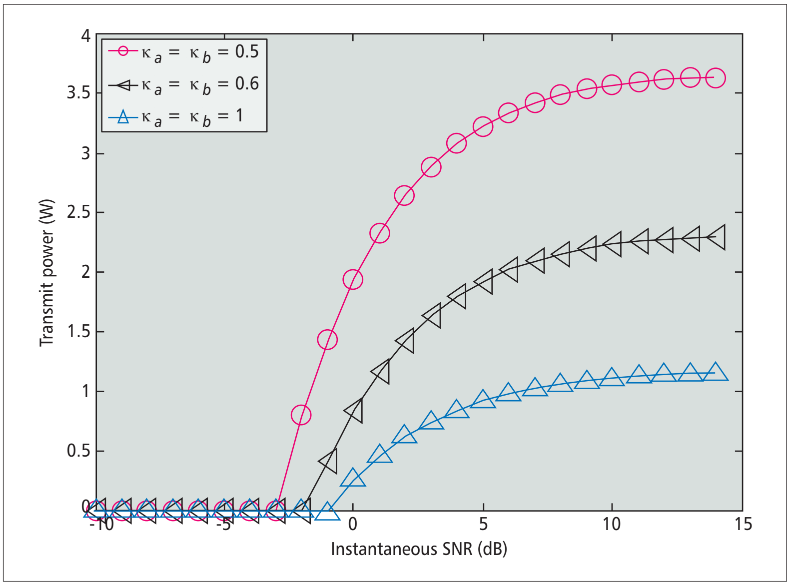

Figure 4. The optimal power allocation for node A with the two-node full-duplex wireless bidirectional transmission.

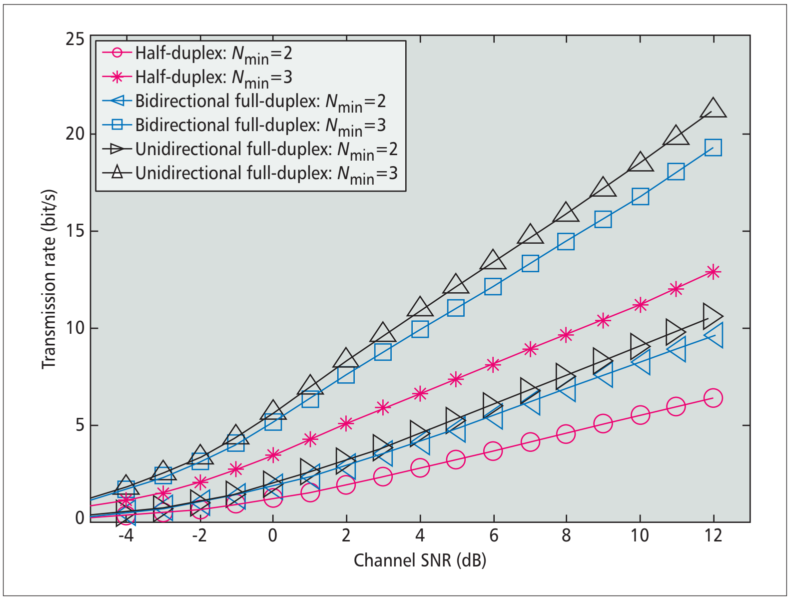

Figure 5. The effect of optimal power allocations on the full-duplex wireless transmission rate ($\kappa_a = \kappa_b = \kappa_d = 0.95$).

PERFORMANCE EVALUATIONS

We evaluate the performance of our developed full-duplex power allocation schemes and the FD-MAC protocol, respectively. We set the self-interference mitigation coefficients $\kappa_a = \kappa_b = \kappa_d = 0.95$. For the FD-T1 and the FD-T2, we set the packet payload and the channel bit rate to 8184 bits and 1 Mbit/s, respectively. Adopting some values of protocol parameters from the IEEE 802.11 standard and its extended new components (including the FCTS frame) which are suitable for 5G mobile wireless networks, we set the lengths of the MAC header, the PHY header, the RTS frame, the CTS frame, and the ACK frame to 272 bits, 128 bits, 288 bits, 240 bits, and 240 bits, respectively. Based on the new FCTS frame proposed for 5G mobile wireless networks, the length of the FCTS frame is set to be 528 bits. We also set the duration of one time slot, the SIFS frame, and the DIFS frame to be 50 µs, 28 µs, and 128 µs, respectively.

Figure 4 shows the optimal power allocation for node A with two-node full-duplex wireless bidirectional transmission. As illustrated in Fig. 4, under the different settings of $\kappa_a = \kappa_b = 1$, 0.6, and 0.5, respectively, the optimal transmit power allocation schemes reflect the water-filling structure. However, when κ_a and κ_b become smaller (for example, $\kappa_a = \kappa_b = 0.5$), the threshold γ_0 gets smaller correspondingly, because the transmit power needs to be increased to compensate for the decrease of the date rate due to large self-interference caused by full-duplex transmission.

Figure 5 plots the transmission rates using our

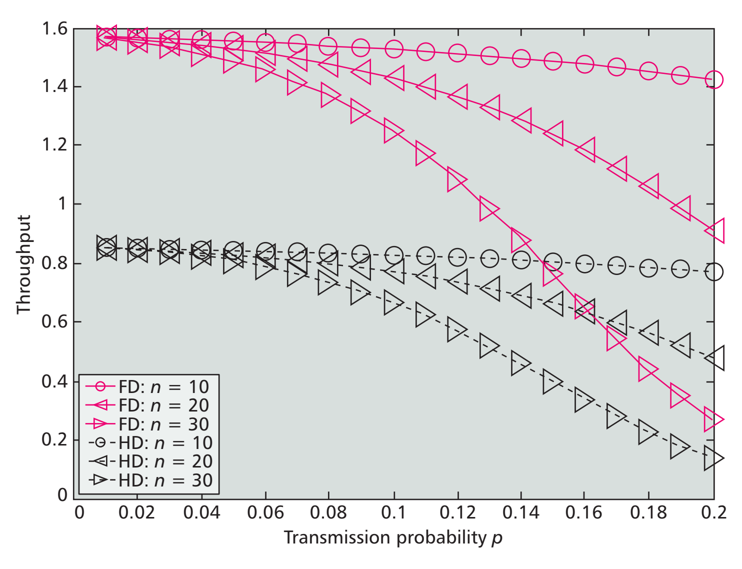

Figure 6. The throughputs of FD-MAC and HD-MAC protocols versus transmission probability (p) of each UE with perfect self-interference cancellation (FD: full-duplex; HD: half-duplex).

developed full-duplex power allocation schemes for two-node full-duplex wireless bidirectional transmission and three-node full-duplex wireless unidirectional transmission, where $N_{\min} = \min\{N_t, N_r\}$ denotes the minimum value between N_t and N_r. As shown in Fig. 5, both bidirectional transmission and unidirectional transmission achieve almost double the rate compared with half-duplex transmission. Unidirectional transmission achieves larger transmission rate than that of bidirectional transmission because self-interference affects only one node (node D) with unidirectional transmission while self-interference affects these two nodes (node A and node B) with bidirectional transmission.

Figure 6 compares the normalized system throughputs versus the transmission probability (p) of each UE using our proposed FD-MAC protocol and the conventional HD-MAC for the wireless network with different numbers of users, where we assume that all full-duplex wireless nodes can fully cancel self-interference. The parameter n is the number of full-duplex wireless nodes in full-duplex wireless networks. Since all full-duplex wireless nodes in the wireless networks can fully cancel self-interference, Fig. 6 also shows the upper-bounds of the normalized system throughputs of using our proposed FD-MAC protocol for full-duplex based 5G mobile wireless networks (the three solid plots are for $n = 10$, $n = 20$, and $n = 30$, respectively).

CONCLUSIONS

We proposed to use the wireless full-duplex transmission mode to overcome the deficiencies of the half-duplex modes used in 4G systems and thus significantly increase the spectrum efficiency for 5G mobile wireless networks. The full-duplex mode has a number of significant advantages over the FDD and TDD modes. To implement full-duplex based 5G mobile wireless networks, we developed and analyzed not only self-interference mitigation schemes, but also a full-duplex wireless power allocation scheme and a full-duplex wireless MAC protocol. In particular, we developed a full-duplex wireless power allocation scheme and a full-duplex wireless MAC protocol to maximize the spectrum efficiency of 5G mobile wireless networks, respectively. The obtained simulation results show that our proposed full-duplex wireless power allocation schemes and full-duplex wireless MAC protocol can efficiently increase the spectrum efficiency for 5G mobile wireless networks.

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