

Chapter 5

Interference Management in Full-Duplex Cellular Networks



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Abstract Despite its promising potential to double the throughput of a point-to-point radio link, a full-duplex (FD) radio has not been comprehensively analyzed in current cellular systems due to the high levels of interference it generates, which significantly degrades its performance. If not carefully planned and managed, an FD operation might lead to much higher interference in both uplink and downlink than existing half-duplex (HD) operation, limiting its potential gains greatly. This chapter provides an overview of the challenges caused by FD radio links in cellular systems as well as the techniques to overcome those challenges to unlock the full potential of FD wireless communications.

5.1 Introduction

The current cellular networks are no longer voice-centric but data-centric, especially with smart-phones leading to a proliferation of data-hungry applications. For example, data traffic in mobile communication systems is expected to increase by around 1000 times by 2020 and by more than 40,000 times by 2030 [1] from 2010. Mobile broadband has been identified as essential to creating jobs, growing economy and benefiting the society because advances in mobile networks will create new opportunities for innovative applications, including devices and services for health, transportation, manufacturing. To support the exponentially growing demand of mobile services to provide high data rates and low latencies, key emerging technologies are being developed in mobile communication systems,

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such as full-duplex (FD) radio, massive multiple-input multiple-output (MIMO), non-orthogonal multiple access (NOMA), etc.

Although great progress has been achieved in designing and implementing FD wireless nodes with the capability of suppressing the self-interference to a sufficiently low level [2–6], the impact of FD transmissions in a wireless network has not been extensively analyzed, especially in a cellular environment, which has a more complicated interference environment. In particular, how to best utilize an FD radio in a wireless cellular network needs sufficient attention. Given the complexity of radio link configurations in a typical cellular network, how to minimize the mutual interferences between FD radio links and/or the performance improvement obtained by the FD communication over the half-duplex (HD) communication are not straightforward for cellular networks.

At the network level, employing FD nodes, such as FD base stations (BSs) creates additional challenges to the existing challenges associated with the HD systems. As seen in Fig. 5.1, compared to HD networks, a single-cell FD cellular network with a BS operating in FD mode and user equipments (UEs) operating in HD mode newly experiences intra-cell UE-to-UE interference (or called as co-channel interference (CCI)) from the uplink users to the downlink users, as well as the self-interference at the BS. Moreover, a multi-cell FD network suffers from even worse interference situation (e.g., inter-cell interference from the BSs and the uplink users in the neighboring cells), which might lead to a severe performance deterioration, even eating up the potential gain of FD networks. Therefore, unless proper interference mitigation techniques are applied, the gain of having FD radios in cellular networks can be severely limited, and thus the use of FD BS in each cell could have a negative impact on the network throughput.

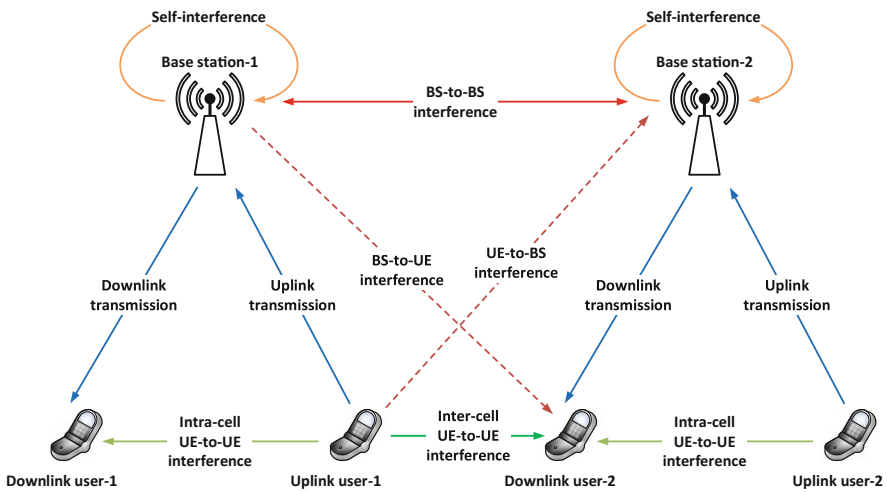


Fig. 5.1 Interference environment in multi-cell full-duplex cellular systems

As cellular networks evolve to become more heterogeneous and to operate independently with less cooperation and less synchronized with each other, intra-cell and/or inter-cell interference become more severe, which are major limiting factors to the spectral efficiency gain from the FD operation. The existence of additional interference terms in FD cellular networks raises the question of whether there is any actual spectral efficiency gain achieved from the FD operation. The authors in [7] have investigated this issue of whether to deploy FD nodes in macro-cells or micro-cells under the additional interference sources generated by FD communication. It has been shown that unless proper countermeasures for interference management are taken, the FD communication is infeasible to operate on the macro-cell networks. On the other hand, when the micro BSs are mounted by a certain distance, the FD communication enhances the spectral efficiency of micro-cell networks. In particular, the actual net gain enabled by the FD operation in cellular networks will strongly depend on interference mitigation/management, network deployments, the density of UEs, and propagation effects in mobile channels. To that end, in this chapter, we will discuss efficient interference management and mitigation methods for FD cellular systems to help realizing the full potential of FD systems.

There have been a significant amount of studies on interference cancellation/coordination in traditional HD systems. For example, various solutions to suppress or coordinate the interference between the interfering neighboring cells have been proposed [8]. However, with the new additional FD interference sources generated in FD mode as shown in Fig. 5.1, uplink and downlink channel resources can no longer be allocated separately, and thus a joint allocation is required in order to support a higher number of simultaneous transmission/reception links with different channel characteristics. Therefore, the existing interference cancellation/coordination techniques proposed for the conventional HD systems cannot be applied readily to the FD systems. The main contributions of this chapter are:

- We discuss interference management and mitigation methods for the base station to base station interference (BS-to-BS interference) in FD cellular networks in Sect. 5.3, which comprises:
 - Elevation beam nulling,
 - Power control based.
- We discuss interference management and mitigation methods for the user-equipment to user-equipment interference (UE-to-UE interference) in FD cellular networks in Sect. 5.4, which comprise:
 - Scheduling-based,
 - Medium access control (MAC) techniques,
 - Interference alignment,
 - Beamforming,
 - Partitioning.
- We discuss interference management and mitigation methods in 3rd Generation Partnership Project (3GPP) from a standardization perspective in Sect. 5.5

- We discuss key interference mitigation technologies, which can be used to suppress the huge surge of interference in FD communications in Sect. 5.6, which comprise:
 - Massive MIMO,
 - Millimeter-Wave (mmWave).

5.2 Interference Management

In FD systems, the uplink and downlink transmissions/receptions may occur simultaneously at the same time and frequency resources in all cells, resulting in a far more complicated interference environment than that of HD systems. The main challenge in a single-cell FD network, besides the self-interference, is the intra-cell UE-to-UE interference (also called as CCI), which is created from the uplink transmission to the downlink reception as shown in Fig. 5.1. Moving from a single-cell to a realistic multi-cell scenario introduces a huge surge of interferences including both intra-cell UE-to-UE interference and inter-cell interference (both inter-cell UE-to-UE interference and BS-to-BS interference between all BS nodes and UE nodes as shown in Fig. 5.1). In particular, the overall interferences experienced by a downlink user and an uplink user of a cell operating in an FD mode are given, respectively, as:

$$I_{DL} = I_{\text{intra-cell-UE-to-UE}} + I_{\text{inter-cell-UE-to-UE}} + I_{\text{inter-cell-BS-to-UE}}, \quad (5.1)$$

$$I_{UL} = I_{\text{inter-cell-UE-to-BS}} + I_{\text{inter-cell-BS-to-BS}}, \quad (5.2)$$

where the first term in (5.1) denotes the intra-cell UE-to-UE interference from the uplink users of the same cell, the second term denotes the inter-cell UE-to-UE interference from the uplink users of the neighboring cells, and the third term denotes the conventional downlink interference (e.g., BS-to-UE) from the neighboring BSs. Moreover, in (5.2), the first term denotes the conventional uplink interference (e.g., UE-to-BS) from the neighboring uplink users and the second term denotes the BS-to-BS interference from the BSs of the neighboring cells.

As mentioned above and shown in Fig. 5.1, besides the inter-cell BS-to-UE interference and UE-to-BS interference that already exists in HD networks, an FD network experiences an additional inter-cell BS-to-BS interference, and intra- and inter-cell UE-to-UE interference, which we will review below¹:

¹Designing and implementing an FD terminal requires a significant change in the hardware resulting in a higher cost and power consumption. Therefore, it is more practical and less costly to upgrade the infrastructure elements such as BSs to operate in FD mode, while the mobile users (e.g., downlink and uplink users) can still operate in HD mode [3], which we have assumed in Fig. 5.1.

- **Base station to base station interference (BS-to-BS interference):** In FD cellular systems, a downlink transmission of a BS may greatly interfere with an uplink reception of a neighboring cell. As the BSs are deployed at higher elevations with few obstacles/obstructions in between, the channel between the BSs is close to line-of-sight (LoS) resulting in much smaller path-loss between the BSs compared to the path-loss between the BSs and the UEs. Moreover, the transmission power of a BS is much larger than that of a UE which increases the interference further when combined with the small path-loss between the BSs. Therefore, if the BS-to-BS interference is not managed/mitigated properly, it can lead to a poor performance by dominating the weak intended uplink transmission from the uplink UEs. On the other hand, as the BSs are not mobile, the BS-to-BS interference channel is static, which allows static interference mitigation techniques (e.g., elevation beam nulling [9], semi-static uplink/downlink power control [10]) to be applied for the BS-to-BS interference mitigation.
- **User-equipment to user-equipment interference (UE-to-UE interference):** In FD cellular systems, an uplink transmission from an uplink user may generate an interference on a nearby downlink user, called as UE-to-UE interference. The UE-to-UE interference can exist between two UEs in the same cell (e.g., intra-cell UE-to-UE interference) and/or in different cells (e.g., inter-cell UE-to-UE interference). In contrast to static BS-to-BS interference channel, UE-to-UE interference channel is more dynamic as the downlink/uplink users are mobile. Therefore, the UE-to-UE interference mitigation can be realized through smart scheduling which avoids scheduling nearby uplink and downlink users (e.g., creating high UE-to-UE interference) to transmit and receive on the same time/frequency resources so that the potential capacity gain from the FD operation can be achieved. For example, the authors in [11, 12] have proposed uplink user and downlink user pairing based on a *distance* metric, while the authors in [9, 13] have incorporated power control mechanism in their proposed scheduling mechanism.

Interference management techniques are necessary to tackle various types of interference sources and to make sure that FD networks achieve better performance than the HD networks, e.g., in terms of throughput. Therefore, it is critical to carefully design protocols and algorithms to deal with the newly introduced interference in FD networks. In the next two sections, we will discuss practical and efficient interference mitigation methods for the BS-to-BS interference and the UE-to-UE interference in FD cellular systems which limit the exploitation of FD gains in cellular systems.

5.3 BS-to-BS Interference Mitigation

The BS-to-BS interference can be much stronger (e.g., 40 dB [10]) than the conventional uplink interference in HD systems, which requires practical and efficient BS-to-BS interference mitigation techniques to make sure that the uplink reception is not degraded by the BS-to-BS interference, and thus the benefits of FD operation can be realized in FD cellular networks.

In this section, we will discuss two methods to suppress the BS-to-BS interference: (1) Elevation beam nulling and (2) Power control based.

5.3.1 Elevation Beam Nulling

The BSs deployed today can employ elevation antenna down-tilting to optimize the signal strength within their coverage area and create different beam patterns via multiple antennas. The authors in [9] have revisited the same concept of elevation antenna down-tilting to mitigate the BS-to-BS interference (especially the LoS component of the interference channel) in FD cellular networks. Particularly, as the altitudes of BSs are fixed and the incoming direction of the BS-to-BS interference is relatively stable, the authors have proposed to use elevation beam nulling to suppress the BS-to-BS interference, where the BS applies 3D beamforming/beam nulling techniques to null at an arbitrary azimuth angle and elevation angle. It is shown that when every BS has a similar altitude, the BS-to-BS interference can be greatly suppressed by forming nulls at the vicinity of 90° in elevation. For BSs with different altitudes, a wider null width is required to suppress the BS-to-BS interference.

By using the elevation nulling approach, around 70 dB to 80 dB BS-to-BS interference suppression can be achieved for small cell and large cell deployments, respectively [10], which is weaker than the conventional uplink interference level, and thus the benefits of FD operation can be realized.

One drawback of the elevation nulling approach is that it may cause degradation on received power levels of the UEs on the cell edge. Therefore, a cell size reduction may be required while applying elevation nulling to guarantee a fair performance for a UE on the cell edge. Moreover, in a multi-path environment, there may be beams reflected from the main lobe causing strong BS-to-BS interference, which may prevent from achieving the full nulling gain [10]. Therefore, additional interference mitigation methods may be needed to combat the residual BS-to-BS interference.

5.3.2 Power Control Based

The BS-to-BS interference can be further suppressed by power control (e.g., uplink and/or downlink) mechanisms. For example, when an uplink user increases its

transmission power, it can dominate the BS-to-BS interference (e.g., increased uplink signal-to-interference plus noise ratio (SINR)), but at the same time it can also create additional increased interference on a nearby downlink user (e.g., decreased downlink SINR) in addition to increasing its power consumption. In another example, when a BS decreases its downlink transmission power to create less BS-to-BS interference, this may result in a reduced coverage and deteriorated performance for the downlink users.

Although the authors in [14] have proposed a power control algorithm to suppress the BS-to-BS interference, they have not considered the impact of their power control mechanism on the downlink users as they have not taken the UE-to-UE interference into account in their proposed power control algorithm. In [10], an open-loop uplink power control mechanism has been proposed for FD cellular systems which considers both the BS-to-BS interference and the UE-to-UE interference in the power control design to minimize the uplink SINR degradation. In particular, the authors propose to boost the target received power level used in Long-Term Evolution (LTE) systems (e.g., P_0) based on the distribution of the BS-to-BS interference over conventional uplink UE-to-BS interference, and conventional downlink BS-to-UE interference over UE-to-UE interference. For example, as each BS may experience different levels of BS-to-BS interference, as the BS-to-BS interference increases (decreases), a higher (lower) target uplink received power (i.e., P_0) may be selected by each cell independently, which is dynamic.

5.4 UE-to-UE Interference Mitigation

In this subsection, we discuss the efficient and practical methods to mitigate the UE-to-UE interference in FD cellular networks.² Handling the UE-to-UE interference is much more challenging than handling the BS-to-BS interference as it is between distributed users, who cannot share data information without sacrificing bandwidth resources. As the level of UE-to-UE interference depends on the UE locations and their transmission powers, coordination mechanisms are needed to mitigate the negative effect of the interference on the spectral efficiency of the system [13].

Below, we will discuss various methods, such as scheduling, interference alignment, beamforming, partitioning, etc., to mitigate/suppress the UE-to-UE interference.

²Note that some of the techniques discussed in this section can also be applied to mitigate the BS-to-BS interference.

5.4.1 Scheduling-Based

Scheduling has been a commonly used approach in multi-user communication systems to optimize system performance such as link data rate, network capacity, and coverage. In conventional orthogonal frequency division multiple access (OFDMA)-based cellular systems operating in HD mode, the scheduling decision at a BS is made independently for uplink and downlink transmissions. Moreover, users served by the same cell are allocated orthogonal resource blocks (RBs) and/or time slots so that there exists no interference between them.

As mentioned in Sect. 5.2, as the uplink and downlink transmissions are coupled and simultaneous in FD systems, a scheduling-based interference management is required. In particular, a scheduling problem in an FD system boils down to pair one uplink UE and one downlink UE properly from all active UEs and to select a frequency channel (e.g., RB, subcarrier, sub-band) to determine which UEs should be scheduled for simultaneous uplink and downlink transmissions over the same frequency channels. The existing scheduling methods used in HD cellular networks, such as proportional fairness (PF) and round-robin, can also be used in the FD cellular networks directly. For example, the scheduler in the FD network can employ the well-known PF procedure for an independent selection of the downlink and uplink UEs and pair them for simultaneous transmission and reception. However, the ignorance of the UE-to-UE interference in such a method could degrade the performance. For example, when an uplink user creating strong UE-to-UE interference on a downlink user is selected to be served on the same RB for a simultaneous transmission, the downlink SINR of the downlink user is highly degraded. Therefore, interference awareness in scheduling should be an important feature for the UE pairing process.

Within each selected pair, the transmission of the uplink user will cause CCI to the downlink user, and this interference varies largely with the mutual distance between the uplink and downlink users of each pair and transmission powers, etc. The uplink and downlink user pairing, subcarrier, and power allocation among different pairs of users need to be properly managed to achieve the optimal performance in the network. In particular, frequency channel (e.g., RB, subcarrier) allocation involves allocating the different subsets of subcarriers (or RBs or bands) to different users by taking into account the self-interference at the BS and the CCI between the uplink and downlink users within each user pair. This is significantly different from the traditional subcarrier allocation problem and presents further research challenges in resource allocation. For example, a scheduler selecting the best pair of uplink and downlink users based on a joint scheduling metric optimizing both uplink and downlink transmissions is required. When the joint scheduling metric which takes the UE-to-UE interference into account is optimized, the UE-to-UE interference is directly managed by selecting the best pair of users creating the least UE-to-UE interference on the frequency channel (e.g., subcarrier, RB). However, due to the combinatorial nature of pairing multiple uplink users, downlink users, and subcarriers, and also the complexity of optimal power allocation to each

subcarrier-transceiver pair, resource allocation in such an FD OFDMA network can be very challenging [15].

The joint scheduling metric can be PF scheduler, which is generally used in current cellular systems, or a maximum-sum-throughput scheduler, or a maximum-minimum-throughput scheduler. Since an FD BS schedules both uplink and downlink transmissions, the objective function (e.g., a function of achievable downlink and uplink data rates) should consider the performance of both uplink and downlink. When the scheduler selects a pair of uplink and downlink users on an RB, the scheduler searches across all candidate uplink and downlink user pairs on the RB and selects the pair achieving the highest joint scheduling metric (or with the lowest interference level for transmission and reception on the same scheduling RB). The selection procedure can be an exhaustive search or an optimization algorithm (e.g., greedy search, dynamic programming, Hungarian algorithm, etc.).

The authors in [10] show that when the inter-cell interference dominates the intra-cell interference, a scheduler that independently schedules the uplink and downlink transmission directions can provide the FD gain. On the other hand, when the intra-cell interference dominates the inter-cell interference, a scheduler that jointly schedules the uplink and downlink transmission directions by avoiding a pair of downlink and uplink users with a high UE-to-UE interference being paired together can improve the downlink SINR.

The management of the UE-to-UE interference caused by the intra-cell and inter-cell users may require extra signaling, feedback, and coordination between BSs. For example, to deal with both intra- and inter-cell interference, each cell first selects or pairs the appropriate users to maximize its spectral efficiency, then the scheduler coordinates with other cells to allocate the power levels of selected users such that the aggregate network spectral efficiency is maximized. This may result in a high computational complexity and signaling overhead diminishing the gains obtained by the FD operation. Therefore, distributed scheduling algorithms are required to mitigate the UE-to-UE interference [10].

5.4.1.1 Related Work

In [16], the authors study the joint subcarrier and power allocations to maximize the sum rate in FD OFDMA networks. In [17], a suboptimal user pairing and resource allocation algorithm that maximizes the sum achievable rate while guaranteeing a quality-of-service (QoS) of each user have been proposed. An application of an opportunistic interference suppression technique at the user side to both mitigate the UE-to-UE interference and maximize the system spectral efficiency has been proposed in [18]. A simple opportunistic joint uplink and downlink scheduling algorithm has been proposed in [19], which suppresses, asymptotically, the UE-to-UE interference in a single-cell MIMO FD network as if there were no UE-to-UE interference. In [20], the problem of pairing uplink and downlink users with the joint power allocation along with the consideration of user fairness has been studied. Moreover, a resource allocation method using matching theory to optimally allocate

the subcarriers among uplink/downlink user pairs for a single-cell FD OFDMA network was proposed in [21].

In these works, the authors have only considered FD communication in a single-cell scenario and ignored the inter-cell interference in their analysis. However, in the multi-cell scenario, it is not clear how much throughput gain can be achieved by the FD communication as the number of interference links increases.

Recently, several works have investigated the usage of FD communication in a multi-cell scenario. For example, to mitigate the UE-to-UE interference, a scheduling approach maximizing the achievable sum-rate in FD multi-cellular networks has been proposed in [13, 22]. A suboptimal joint user selection and power allocation strategy has been proposed in [13, 22], which can yield around 65% throughput gain over the traditional HD system. A radio resource allocation algorithm assigning uplink and downlink transmissions jointly has been proposed in [23], by taking both intra-cell and inter-cell interference into consideration. In [24], the authors have obtained closed-form throughput expressions for the FD multi-cell networks with the help of stochastic geometry tools.

Finally, in [25], a UE-to-UE interference coordination approach based on geographical context information (e.g., provided by radio maps and user positions) has been provided, which exploits the signal attenuation from obstacles between UEs so that UE-to-UE interference is minimized by assigning simultaneous uplink and downlink transmissions to UEs in areas that are separated by large obstacles.

5.4.1.2 Space-Time Power Scheduling

Another promising idea for interference management is space-time-frequency power scheduling, also known as space-time (or space-temporal) power scheduling [26–28]. Despite its previous applications in ad hoc networks, the space-time power scheduling idea is particularly useful for small cells, where the channel state information (CSI) of various channels can be jointly exploited. The key idea behind space-time power scheduling is to best distribute the interferences within the (complete) space-time physical world that we have. In other words, channels with weak interferences should be exploited, channels with strong interferences should be avoided, and all interferences should be optimally distributed via a well-designed algorithm for optimal space-time power scheduling. The idea of space-time power scheduling has also recently been applied to FD systems [29–31]. Further research of space-time power scheduling for FD cellular networks should be of a promising direction.

5.4.2 Medium Access Control (MAC) Techniques

Apart from the aforementioned physical-layer solutions, FD research opportunities have also been explored in the context of efficient MAC protocols for addressing the

challenges of long end-to-end delays of network congestion and the hidden terminal problems. As the FD networks generate new additional inter-node collisions, conventional MAC protocols such as the carrier-sense multiple access with collision avoidance (CSMA/CA)-based HD MAC protocols cannot be readily applied to reduce these additional inter-node collisions.

To that end, the authors in [32] propose an optimal location-aware node selection algorithm minimizing the intra-node interference while still maintaining the signal strength of the intended link. Moreover, transmitting RTS/CTS (Request to Send/Clear to Send) signaling or busy tones before establishing the FD connection has been proposed to reduce the inter-node collisions due to the hidden nodes.

The authors in [33] propose a simple method that avoids the UE-to-UE interference by selecting nodes that are completely hidden from each other. Another method in [34] optimizes user pairing by considering the UE-to-UE interference based on the information about the UE-to-UE interference and traffic demands reported from all pairs of users. Goyal et al. in [35] develop a centralized MAC protocol by taking the UE-to-UE interference between two users into account. In [36], the UE-to-UE interference is managed by a random access MAC protocol using distributed power control.

It is more practical to develop an adaptable MAC protocol based on the channel/network conditions (e.g., inter-cell, intra-cell interference) to switch to the desired (FD or HD) transmission mode opportunistically. To that end, Chen et al. [37] have proposed a distributed FD MAC protocol for a BS that can adaptively switch between FD and HD modes based on the channel conditions so that the negative impact of the (intra- and inter-cell) interference can be removed. In particular, when intra-cell interference is low (high), the BS selects FD (HD) mode for transmission [11, 22].

Another MAC technique that can be applied for interference mitigation is clustering in small cell networks. An FD operation is more suitable for small cells due to low transmission power at the BSs resulting in a relatively easy self-interference cancellation. However, as the small cells are densely deployed, the uplink to downlink and downlink to uplink inter-cell interference become even more critical. Therefore, efficient clustering methods/techniques that allow nearby small cells to coordinate their FD transmissions need be designed. In an example, a cluster of small cells may coordinate such that each small cell within the cluster operates in the FD mode in a sequential manner, while the other small cells operate in the HD mode until their turns come up. This would alleviate the additional interference sources generated in FD mode [32].

Another MAC technique that can be applied for interference mitigation can be cooperative FD device-to-device (D2D) transmission. While D2D links, which enable direct communication between nearby users, are utilized for HD data transmissions, they may also be utilized for interference suppression in an FD mode. In an example, a D2D transmitter can overhear interference signals on an FD receiver and can feed back/forward the interference information to its intended receiver along with the data packets for an interference suppression [32].

5.4.3 *Interference Alignment*

Another technique that is used for mitigating the intra- and inter-cell interference is interference alignment (IA) [38, 39]. Initially proposed by the seminal works in [40, 41], IA is a coding technique that efficiently deals with interference and is known to achieve the optimal degrees-of-freedom (DoF) for various interference networks [42]. Especially, it is shown that IA can be successfully applied to mitigate interference in various cellular networks [42].

The authors in [38, 39] employ signal space IA schemes optimized for FD networks to manage inter-user interference and fully utilize the wireless spectrum with FD operation. In particular, in [38, 39], transmit beamformers, on the uplink channel, are designed for aligning the UE-to-BS interference, and intra- and inter-cell UE-to-UE interference. On the other hand, on the downlink channel, each BS designs the transmit beamformers to align the downlink multi-user interference, BS-to-UE interference, and BS-to-BS interference. It is shown that the achievable sum-DoF obtained with the IA technique in an FD multi-cell system increases with the number of cells, users, and BS antennas. In particular, the key idea of the proposed schemes is to carefully allocate the uplink and downlink information streams using IA and beamforming techniques. The uplink data is sent to the BS using IA such that the inter-user interference is confined within a tolerated number of signal dimensions, while the BS transmits in the remaining signal dimensions via IA beamforming or zero-forcing beamforming for the downlink transmission. This would result in nulling out the downlink and uplink intra-cell and inter-cell interferences.

To suppress the UE-to-UE interference in FD communication systems, the authors in [43] propose an interference management strategy enabling the network to suppress the UE-to-UE interference while obtaining achievable rate gains. In their following work, the authors propose an IA scheme to suppress the UE-to-UE interference for MIMO FD communication systems in order to achieve rate gains over conventional cellular systems in terms of DoF [44]. As the downlink mobile user observes a MAC of two users (e.g., BS and the uplink user) in FD systems, the authors in [45] propose to apply successive interference suppression (SIC) so that the downlink user has an opportunity to remove the UE-to-UE interference according to the transmission rates and its received powers. In their following work, the authors in [46] reuse the interference suppression method applied for the X-interference channels for a superposition coding based UE-to-UE interference suppression.

Although IA does not reduce the spectral efficiency, it requires accurate CSI between communicating and interfering users. Such CSI comes at the cost of high signaling overhead. Since interference alignment operates on a number of time slots that depends on the CSI, it also adds a non-deterministic transmission delay.

5.4.4 Beamforming

One of the techniques used for mitigating the intra- and inter-cell UE-to-UE interference and/or BS-to-BS interference is beamforming design. In FD systems, the uplink and downlink transmission optimization problems can no longer be separated due to the joint dependency of throughput functions on the uplink and downlink transmissions. Therefore, the uplink and downlink transmissions in FD networks have adverse effects on each other's performance. For example, if the downlink transmit power increases to combat the UE-to-UE interference at the downlink users, the self-interference also increases at the BS, and thus the uplink sum rate decreases. On the other hand, if the uplink users increase their transmit powers to dominate the self-interference at the BS, the UE-to-UE interference increases at the downlink users. Thus, in an FD multi-user network, transmission strategies at the BS and the uplink users are coupled, and thus have to be designed to address both UE-to-UE interference and self-interference simultaneously, which poses a jointly coupled optimization problem.

As mentioned above, it is attractive and useful to analyze the mutual effect of uplink and downlink transmissions in FD networks by designing precoding matrices for both uplink and downlink transmissions to manage the newly generated interference sources. In a beamforming design, an interference management can be performed without explicitly avoiding the UE-to-UE interference in the sense that the BSs and the users use their multiple antennas for interference mitigation. The scheduler collects all the required CSI and then maximizes the various optimization metrics (e.g., sum power, harmonic sum, sum rate, etc.) of the network by employing optimal transmit and receiver beamformers [47–57] for mitigating the self-interference and the UE-to-UE interference in the FD multi-user systems.

Finding a feasible point for the various optimization metrics is already challenging due to the nonconvexity and disconnectivity of the feasible set. The authors in [58] exploit the well-known duality between broadcast channel (BC) and MAC and reformulate the sum-rate maximization problem in the BC as an equivalent optimization problem for MAC, resulting in a concave function.

Channel Estimation The mitigation of the BS-to-BS interference and the UE-to-UE interference requires accurate knowledge of the channel(s) between the BSs and the UEs (between uplink and downlink users), respectively, so that a joint power-rate optimization [9, 13] or a joint transmit/receive beamforming [12] can be performed by the scheduler. Estimation of an interference channel requires pilot (e.g., preamble) transmissions and/or feedback of the estimated interference measurement.

The levels of interference awareness for scheduling and/or beamforming may vary. For example, tracking the UE-to-UE interference channel which is dynamic and fast varying results in a knowledge of a short-term interference giving the best performance, but at the same time resulting in the highest overhead and signaling, especially as the number of users increases. On the other hand, tracking long-term statistics of the UE-to-UE interference channel (e.g., the path-loss, large-scale fading)

ing terms) can be obtained easily from the relative positions of the UEs, converting the scheduling problem into a distance-aware scheduling problem [59, 60]. Tracking long-term statistics of the BS-to-BS interference channel with low overhead and less signaling is also realistic due to the static channel between the BSs.

For the joint scheduling and/or beamforming, the scheduler has to obtain an accurate downlink data rate estimate which can be acquired via feedback of rank indicator (RI), precoding matrix indicator (PMI), and channel quality indicator (CQI). As the UE-to-UE interference has less impact on the transmit direction and rank for beamforming at the BS, the same RI and PMI feedback mechanisms in legacy systems (e.g., LTE) can be reused for FD networks. However, the CQI report reflects the received downlink SINR, which is highly based on and sensitive to the UE-to-UE interference. Therefore, for every downlink and uplink user pair, the scheduler must acquire an accurate CQI reflecting the UE-to-UE interference [10].

In LTE, the BSs require sounding reference signals (SRS) regularly to estimate the uplink channel quality at different frequency bands for uplink scheduling. The authors in [22] propose to reuse the uplink SRS at the downlink UEs for the UE-to-UE interference channel estimation between themselves and nearby UEs [61]. All UEs within a cell are informed about the subframes that will be used for SRS. The biggest challenge in reusing the SRS in FD systems as a neighbor discovery is to distinguish between different (both in the same and in the different cell) UEs during SRS transmission. One way to help the UEs distinguish different UEs is to assign different SRS combination sets to neighboring cells while assigning orthogonal combinations to UEs within the same cell which are scheduled to transmit simultaneously [22]. In addition, this allocation of SRS combinations can be passed to UEs through the downlink shared channel [61].

There are other ways to design neighbor discovery, such as the ones used in D2D communications [62, 63]. In an example, each UE can estimate the (interference) channels from strong UE interferer, and in response to completing the estimation, the UE can forward this estimation to its serving BS at the beginning of each scheduling slot. When the serving BS receives this information from many UEs, it can make its scheduling decision at each scheduling time slot.

5.4.5 Partitioning

To reduce the effect of the UE-to-UE interference and maximize the spectral efficiency, an intelligent scheduler is required to pair the uplink and downlink users as well as to compute the optimal transmit powers of the BS and users. A natural and efficient UE-to-UE interference mitigation approach is to separate the uplink and downlink users as far as possible. To that end, the authors in [64] propose the use of cell sectorization for the separation. As shown in Fig. 5.2, the uplink and downlink users are scheduled in two opposite (e.g., 120°) sectors of time-frequency resources to avoid scheduling an uplink user and a downlink user on a same time-frequency resource, reducing, if not eliminating, the UE-to-UE interference.

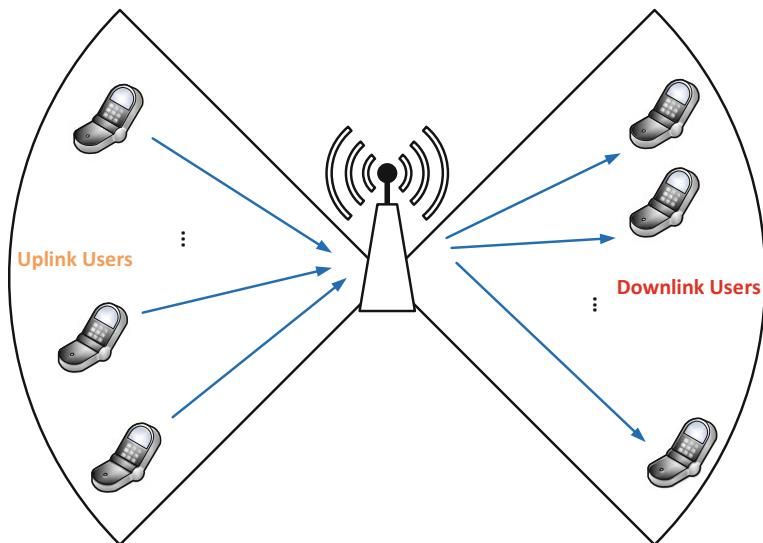


Fig. 5.2 Cell sectorization to reduce the UE-to-UE interference. ©2018 IEEE. Reprinted, with permission, from [64]

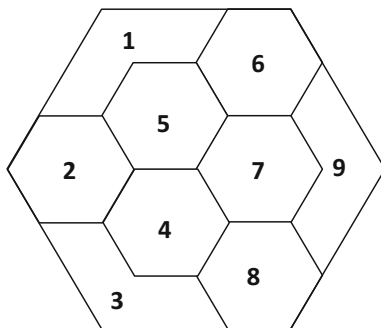


Fig. 5.3 Cell partitioning to reduce the UE-to-UE interference

Once user scheduling in opposite sectors is performed, the optimal powers can be computed for the BS and uplink users.

Similarly, Shao et al. [60] propose partitioning method that the whole cell is divided into several partitions where the same frequency resource is assigned/allocated properly to the two users who are far enough from each other. For example, as shown in Fig. 5.3, by dividing the frequency resources into nine groups, group 1 can be assigned to use frequency-1 on the uplink and frequency-2 on the downlink, while frequency-2 can be reused in the uplink for the group 9 while frequency-1 can be reused in the downlink in the group 4. This would alleviate the intra-cell UE-to-UE interference between users in the FD cellular system as the

co-channel reverse links are apart enough from each other. However, this method may not work when the cell gets smaller.

The existing inter-cell interference coordination (ICIC) methods are used to suppress the inter-cell interference in HD systems to improve the performance of cell-edge users in LTE systems [65] via static, semi-static, or dynamic resource coordination, and cannot be directly used in FD cellular systems to suppress the additional interference sources. Therefore, in [65], the authors have proposed new ICIC designs to mitigate the inter-cell UE-to-UE interference in FD cellular systems. In particular, for the inter-cell UE-to-UE interference suppression, the total available bandwidth is divided into multiple (e.g., three) orthogonal sub-bands (zones) under different interference levels in each zone. For example, the first zone can be an uplink-only zone, in which only uplink transmission can be performed, which is beneficial for weak uplink UEs; the second zone can be downlink-only zone, in which only downlink transmission can be performed, which is beneficial for downlink users exposed to high interference levels from uplink users; and the third zone is downlink-centric and uplink-centric zones where major downlink-victims are restricted to transmit only in downlink-centric sub-bands and the uplink-aggressors can only transmit in orthogonal uplink-centric sub-bands. In addition, the proposed ICIC algorithm allows adjustable BS transmission power in different zones. In an example, the BS can set its power to a higher level in downlink-centric zone, and to a lower level in uplink-centric zone to further improve the throughput of downlink-victims and uplink-aggressors.

5.5 Interference Mitigation in the 3GPP

In this section, we discuss technical solutions for an LTE-compatible FD cellular network, featuring intra- and inter-cell interference mitigation techniques.

5.5.1 Frame Structure

Frame structure is the basic uplink/downlink operation framework in wireless communication systems specifying the timing and location of the transmission of the control signaling and uplink/downlink data. Due to the additional interference sources in an FD cellular system, the existing frame structure needs to be tailored for interference mitigation capabilities in an FD communication.

In the LTE/LTE-Advanced (LTE-A) systems, reference signals (RSs) such as cell-specific reference signals (CRSs), SRS, and downlink channel-state-information RS (CSI-RS) are designed for channel estimation [66]. However, since the current frame structures for LTE and LTE-A were originally designed for the HD modes such as frequency division duplexing (FDD) and time division duplexing (TDD), the resource elements (REs) carrying the downlink RSs (e.g.,

CRSSs, CSI-RSSs) are interfered by the REs in the uplink channel co-located with the downlink RSSs, and thus self-interference channel estimation and/or BS-to-BS interference based on the downlink RSSs is degraded.

To deal with this problem, the authors in [67] propose an uplink nulling technique that prevents a certain portion of REs allocated to, for example, the downlink RSSs (e.g., CRSSs), the physical broadcast channel (PBCH), the primary synchronization signal (PSS), and/or the secondary synchronization signal (SSS), being used by the REs in the uplink in order not to degrade the self-interference and BS-to-BS interference channel estimation. Since some of the uplink resources are not used, this will result in a throughput loss and resource waste. However, the loss will not be significant due to the traffic asymmetry between the downlink and uplink [67]. After the self-interference channel and/or BS-to-BS interference channel is estimated, the BS can perform the self-interference cancellation. Moreover, the BS-to-BS interference channel information can be feedback to the adjacent BSs, which pre-nulls the BS-to-BS interference via transmit beamforming. The uplink nulling technique requires minimal frame structure changes to the existing LTE and LTE-A standards. Moreover, accurate self-interference channel and/or BS-to-BS interference channel estimations require frame synchronization between the downlink and uplink, which can be achieved by using the existing uplink timing alignment mechanism in LTE/LTE-A systems which limits the uplink–downlink misalignment within the cyclic prefix [67].

A more general downlink and uplink frame structure utilizing both an uplink nulling and downlink nulling techniques is illustrated in Fig. 5.4, where the regions are defined as [60]:

- Downlink common control region (uplink blank region): The downlink cell common control information, e.g., for initial access, such as PSS, SSS, and PBCH, physical downlink control channel (PDCCH), and RSSs are transmitted in this region. Therefore, the uplink transmission needs to be nulled to avoid any interference that can be caused by an uplink UE.
- Downlink UE specific control region (uplink opportunistic data region): The UE specific control information such as downlink/uplink data scheduling is transmitted in this region. The wireless device may perform an opportunistic uplink transmission if the level of interference can be tolerated or is below a threshold.
- Uplink control region (downlink opportunistic data region): In this region, the UE may transmit a physical uplink control channel (PUCCH) or a physical uplink shared channel (PUSCH). The BS may schedule a downlink transmission opportunistically as long as the UE-to-UE interference can be managed by an intelligent scheduler.
- Uplink special control region (downlink blank region): The UE transmits important signals/channels such as physical random access channel (PRACH), SRS, demodulation RS (DM-RS) in this region. Therefore, the downlink transmission needs to be nulled to avoid any interference that can be caused by a BS. This nulling can also be used to estimate the UE-to-BS interference channel.

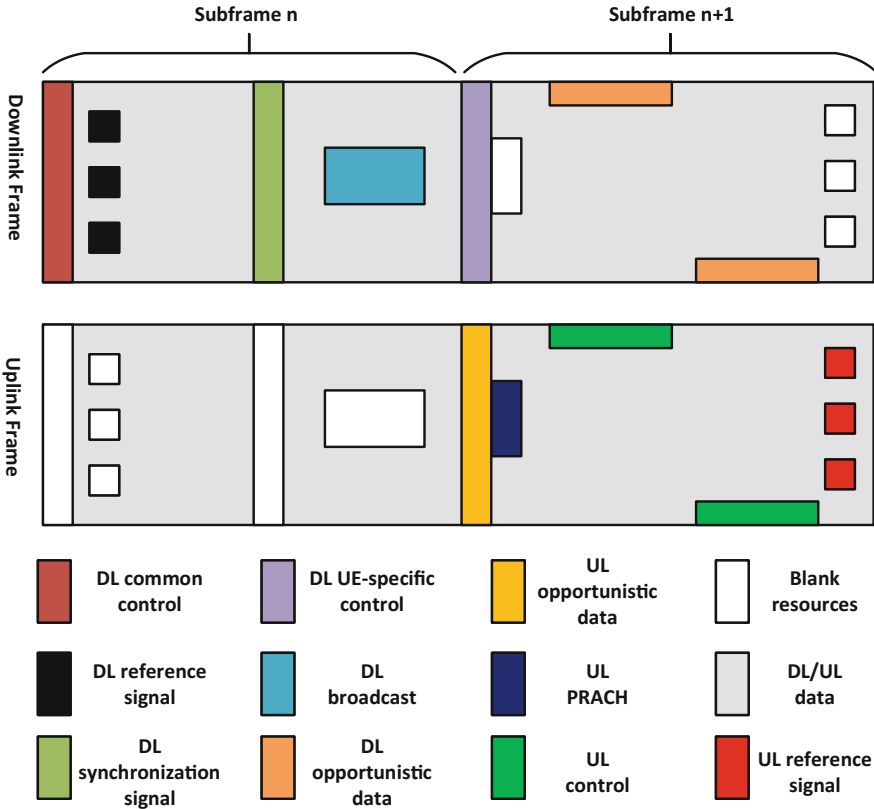


Fig. 5.4 Frame structure in full-duplex systems. ©2014 IEEE. Reprinted, with permission, from [59]

- Downlink data region (uplink data region): In this region, the BS can serve both uplink and downlink users at the same time and frequency resources.

With the new frame structure, the UE-to-UE interference channel can be mitigated via (1) an interference channel measurement, and (2) large-scale fading (or relative locations) [60]. The steps of the first technique, which is based on the interference channel measurement, are described below:

1. The BS broadcasts the number of uplink UEs (e.g., N_1) transmitting orthogonal RS sequences to distinguish between different UEs.
2. Uplink UEs transmit the uplink RSs and the BS transmits the downlink RSs in the same time slot, but on orthogonal frequency resources such that downlink users can measure uplink RSs and downlink RSs simultaneously to calculate their corresponding SINRs.
3. Based on the measurements in Step 2, a downlink UE feeds back the lowest N_2 ($N_2 < N_1$) interference power measurement and the corresponding uplink RS

index broadcasted in the Step 1. In some cases, uplink RSs may not be received at a downlink UE due to high path-loss, which will have an interference power of zero (e.g., 0).

4. The BS performs a joint uplink/downlink scheduling and power allocation based on the downlink UEs' feedback in Step 3.

The second technique (e.g., based on large-scale fading) has a lower overhead. The steps of the second technique can be described as below:

1. The BS first estimates the distance from an uplink UE to itself (Distance-UL) and from itself to a downlink UE (Distance-DL) based on existing techniques.
2. Based on the estimations in Step 1, the BS computes the minimum distance between an uplink UE and a downlink UE by computing an absolute value of (Distance-UL minus Distance-DL), which is associated with the highest UE-to-UE interference level.
3. Based on the computations in Step 2, the BS schedules the UE pairs that can transmit simultaneously on the same time/frequency resources, where the UEs with the minimum distance are not paired.

The drawback of the second technique is that slow-fading channel characteristics are not taken into account in the scheduling decision at the BS, which lessens the scheduling flexibility.

5.5.2 Flexible Duplexing

The fifth-generation (5G) is expected to support various services, such as voice over IP (VoIP), online video, virtual reality, social networking, real-time video sharing, etc. As each of these services requires different uplink and downlink traffic demand, which cannot be supported with the existing semi-static uplink/downlink configuration in LTE, during Release-14 new radio (NR) study item, flexible duplexing (e.g., dynamic TDD) has been studied, and a flexible frame structure is agreed to be supported in Release-15, which enables both semi-static and dynamic TDD operation (e.g., dynamic uplink and downlink assignments), latter of which allows dynamic change of uplink/downlink transmission direction per slot [68–70]. With the flexible duplexing, the ratio between uplink and downlink traffic can change over time (e.g., over each slot, subframe) dynamically which allows support of different services. For example, a symmetric downlink/uplink partitioning in a TDD mode of LTE may not be effective to address an ultra-reliable and low latency communication (uRLLC) service when the partitioning is either downlink heavy or uplink heavy.

As each cell may have a different instantaneous traffic condition, the transmission direction of a cell can be dynamically changed in flexible duplexing, resulting in cross-link interference (CLI) when the transmission directions of neighboring cells in the network are misaligned (e.g., transmitting in opposite links/directions),

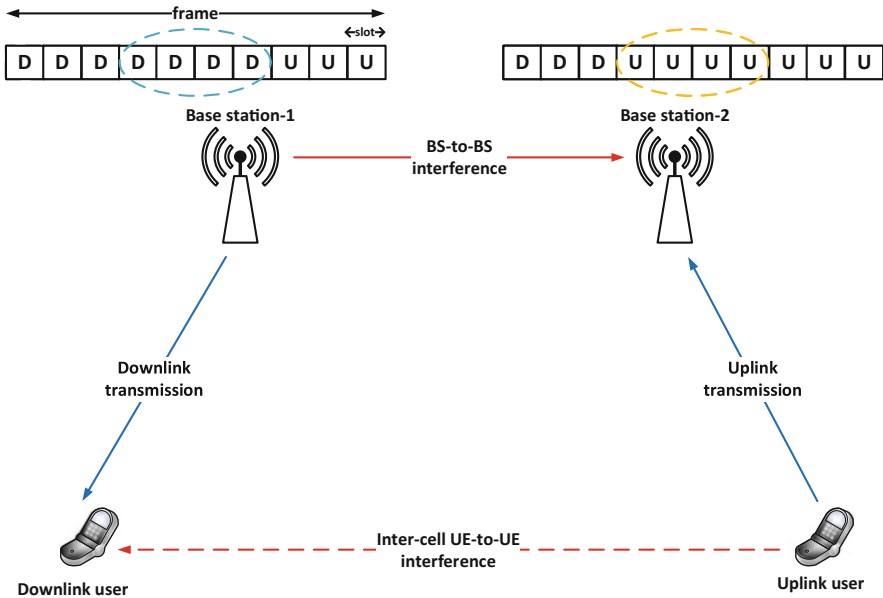


Fig. 5.5 Flexible duplexing

which may severely degrade uplink and/or downlink performance. For example, in Fig. 5.5, from fourth slot to seventh slot of cell-1 and cell-2 may be downlink and uplink, respectively, which are not aligned. While base station of cell-1 is scheduling downlink, the base station of cell-2 is scheduling uplink resulting in UE-to-UE interference from cell-2 to cell-1 and BS-to-BS interference from cell-1 to cell-2, which is similar to interference terms in FD cellular networks discussed for Fig. 5.1.

Interference management is crucial for flexible duplexing to provide performance improvement over semi-static TDD operation, and thus various CLI mitigation schemes, such as interference sensing, scheduling and link adaptation, the advanced receiver (e.g., minimum mean square error interference rejection combining (MMSE-IRC), maximum likelihood (ML), and iterative ML, etc.), coordinated beamforming, and power control have been discussed in [68, 70]. In the next subsections, we will discuss interference sensing/measurement and link adaptation as the other interference mitigation techniques have been already discussed in the previous sections.

5.5.2.1 Interference Sensing

As sensing/listen-before-talk (LBT)-like based mechanisms have proven to be effective distributed protocols for minimizing channel access collision for spectrum sharing scenarios, e.g., Wi-Fi, licensed assisted access (LAA), etc., CLI can be

mitigated by channel sensing (such as energy detection and/or signal detection) performed by the transmitting nodes (e.g., by the base station for the BS-to-BS interference and/or by the UE for the UE-to-UE interference) before transmission [70].

The channel sensing may be performed based on instantaneous measurement, which is more accurate for a dynamic environment and efficient than statistical measurement, which can recognize the temporal channel state. In an instantaneous measurement performed based on the energy detection, the transmitting node can perform the sensing of the CLI in a pre-defined time slot dynamically. The length of the pre-defined slot may depend on the QoS and/or the priority of the service, where the service with a higher priority has a shorter time slot. In an instantaneous measurement performed based on the signal detection, the transmitting node can perform the sensing of the CLI based on pre-defined RSs (e.g., SRS, CSI-RS, DM-RS, etc.) carrying some information (e.g., cell index, transmission direction (uplink or downlink), etc.) transmitted by the other BSs and/or UEs. Based on the sensing results, power control, scheduling coordination, and beamforming may be adjusted to reduce the CLI.

5.5.2.2 Link Adaptation

Link adaptation is another method to mitigate CLI, which can be based on the sensing results discussed in Sect. 5.5.2.1. For example, if the transmitting node detects a strong CLI, the transmitting node can drop the transmission of the data on the scheduled slot. In another example, if the transmitting node detects a strong CLI, the scheduling of the data can be adjusted to mitigate CLI by reducing the transmit power, changing the carrier or the transmitting beam, adjusting the modulation and coding scheme (MCS) or the transport block size (TBS), etc. [70]. For example, based on the sensing result, the BS can transmit another downlink control information (DCI) to the UE adjusting the initial scheduling parameters (e.g., MCS, TBS, beam, etc.) to mitigate the CLI.

5.6 Key Technologies for Interference Mitigation

5.6.1 Massive MIMO

The huge surge of interference in FD communications can be further suppressed by using the massive MIMO technology as the increased number of antennas help to form highly directional beams [71] and help to exploit the very large DoF [72].

When the number of simultaneous (e.g., at the same time/frequency resource) active uplink and downlink users increases, the level of the UE-to-UE interference from uplink users to downlink users increases accordingly. The authors in [56] have shown that multi-user precoding is an efficient approach for the UE-to-UE

interference control. However, as the number of users is envisioned to be much larger in the massive MIMO systems, the acquisition and the estimation of the UE-to-UE interference channels via the cooperation among the users becomes challenging. Moreover, as the numbers of BS antennas and users increase, the high computational complexity in the computation of multi-user precoding hinders the application of FD technology in massive MIMO systems. Therefore, new interference mitigation methods taking the high number of BS antennas and users into account must be developed for FD massive MIMO systems [64].

For example, the authors in [64] have studied a joint user scheduling and power control algorithm to suppress the UE-to-UE interference that maximizes the achievable spectral efficiency. The key point of the proposed algorithm is that it requires only the knowledge of the slow time-varying channel which makes it practical in the massive MIMO systems as it reduces the overhead and computational complexity. In particular, the proposed algorithm exploits the fact that the instantaneous uplink/downlink SINR converges to its deterministic equivalent approximation, which is a function of slow time-varying parameters, e.g., the large-scale fading of channels [73].

In [74], the authors study the region of DoF under the assumption that BSs have full coordination, which transforms the multi-cell problem into a tractable single-cell problem. This transformation would enable the utilization of the IA method to obtain the highest possible DoF. Although the proposed algorithm provides insights and theoretical maximum limits of DoF, as it assumes full coordination among the BSs, it is impractical and challenging to develop in practice due to high overhead and high signaling. To that end, the authors in [72] consider the scenario when there is no BS coordination among the BSs, which does not allow the transformation from the multi-cell problem to a single-cell problem and study the use of a large number of antennas for intra- and inter-cell interference management in FD cellular networks. It has been shown that as the number of BS antennas increases, the transmit power of BSs and UEs can be reduced proportionally to maintain a fixed asymptotic rate (e.g., QoS). Moreover, the additional interference terms (e.g., residual self-interference, intra-cell and inter-cell interference) in the multi-cell multi-user MIMO FD cellular systems disappear as the number of BS antennas becomes infinitely large. Finally, the authors show that the FD system asymptotically achieves two times spectral efficiency gain over the HD system when the CSI knowledge is perfect or when the users also operate in FD mode under the imperfect CSI knowledge assumption.

The centralized scheme may be useful for sparse scenario with few users. However, it incurs a significant amount of overhead as the number of users grows, with the inter-node interference being the dominant bottleneck. Therefore, a distributed power control method for the UE-to-UE interference management in a single FD massive MIMO cell has been proposed in [75].

5.6.2 *Millimeter Wave*

MmWave is an emerging technology that improves the spectral efficiency of wireless networks by exploiting an enormous amount of spectrum. In mmWave bands, the signals suffer from huge propagation loss and are sensitive to blockage, which requires highly directional beams in achieving high SINR (or high antenna gain) at the user. In the omni-directional case, the signal is transmitted in all directions and, as a result, interferes with all other terminals in the network. Therefore, focusing the signal to a certain direction reduces the number of terminals that are affected by the interfering signal, i.e., the terminals that lie in the transmitted direction. Furthermore, compared to the omni-directional case, the directed transmitted signal can achieve a longer distance with the same power and can also reach the receiver with a higher power. As the beamwidth decreases, the gain of the signal increases and the possibility of interfering with other terminals decreases.

Hence, combining the mmWave technology with FD technology reduces the self-interference significantly because a highly directional beam from a transmitter antenna has a weak LOS component suffering from higher attenuation towards its own receiver antennas. This would result in the uplink users transmitting with a reduced power leading to a reduction of the intra-cell UE-to-UE interference [76], which is dominant when compared with inter-cell UE-to-UE interference [22]. Furthermore, FD small cell-based networks can benefit from the employment of mmWave communications, since the distances that signals have to travel as well as the transmissions powers reduce, resulting in a reduced interference compared to legacy systems in microwave bands [77].

5.7 Conclusion

This chapter discusses several key design issues in FD cellular networks (e.g., both in single-cell and multi-cell scenarios) and provides a brief overview of the state-of-the-art developments in FD cellular communications. Firstly, the newly introduced interference terms (e.g., intra- and inter-cell interference) were analyzed, including BS-to-BS interference and UE-to-UE interference. Secondly, various promising interference mitigation schemes for the intra- and inter-cell UE-to-UE interference and BS-to-BS interference have been discussed, with particular attention given to elevation beam nulling and joint uplink/downlink power control for the BS-to-BS interference; and scheduling, MAC protocols, interference alignment and beamforming for the UE-to-UE interference. With the growing research interests and efforts in the upcoming years in FD technology, FD technology is very likely to become one of the key technologies studied/specified in 5G standardization. Therefore, we have discussed technical solutions for an LTE-compatible FD cellular network from a 3GPP standardization perspective. Although FD cellular networks have a complicated interference environment compared to existing HD cellular net-

works, the techniques discussed in this chapter can help to resolve the complicated interference environment to fully unlock the potential of FD communication, which can increase the achievable rates, reduce latency, and enable flexible scheduling.

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