Chapter 9
Full-Duplex Non-Orthogonal Multiple Access Networks

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9.1 Introduction

In conventional wireless networks, resources are assumed to be allocated exclusively to users by considering half-duplex (HD) transmissions in serving uplink (UL) and downlink (DL) requests. Operating simultaneously in UL and DL over the same frequency band, known as in-band full-duplex (IBFD) or more commonly as full-duplex (FD), has been avoided for a long time, due to the inability to suppress the self-interference in the full-duplex radio to a feasible operating point. Furthermore, orthogonal multiple access techniques, such as orthogonal frequency-division multiple access (OFDMA), is used in multi-carrier settings to allocate subcarriers to users in an exclusive manner. This restriction is imposed to avoid the multi-user interference (MUI) resulting from scheduling multiple users/messages over the same subcarrier. The unprecedented growth in data rate requirement and the number of connected devices mandates going beyond the traditional ways of handling the scarcity of bandwidth in future wireless networks. A fundamental shift in the in the way wireless resources are allocated and managed is thus necessary.

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Full-duplex (FD) is ideally a spectrum efficiency doubler. By relaxing the constraint of orthogonal UL and DL transmissions, transceivers in the user and base station nodes can exploit the non-orthogonality to boost the spectral efficiency [21]. However, HD was adopted as the default setting in wireless networks for multiple reasons. First, FD radios can experience self-interference leaked from the UL transmitter to the DL receiver when operating in the same time–frequency resource. Recent advances in self-interference cancellation techniques have challenged this assumption. By using a combination of analogue and digital cancellation techniques, self-interference can be reduced to a level close to the receiver noise floor. Second, operating in FD results in increased inter-user interference due to the larger number of transmissions per resource. In particular, DL base station to UL base station and UL user to DL user interference will occur when operating simultaneously in UL and DL in the same frequency resource. Furthermore, this interference can occur at the intra-cell level, unlike the orthogonal resources per cell associated with OFDMA-based HD systems.

Another way of boosting the cellular network bandwidth utilization is the use of non-orthogonal multiple access (NOMA) technique to schedule users with potentially overlapping resources [11]. NOMA has been recently discussed as a promising way to boost the network spectral efficiency as compared to orthogonal multiple access (OMA) techniques. NOMA provides diversity in the power domain by transmitting different messages to/from different users using the same time–frequency resource. If the different signals are received with enough power disparity, the signals can be decoded for example using successive interference cancellation (SIC) techniques.

Hence, incorporating both FD and NOMA into current wireless networks will pose different challenges in terms of interference and network management. Different solutions are needed to address these challenges, ranging from smart resource scheduling, power allocation, duplex and multiple access mode switching. This chapter sheds light on both FD and NOMA network operation and discusses potential future research directions for this topic. First, preliminaries on FD, self-interference, and the interplay between FD and NOMA are discussed in Sect. 9.2. The objectives and tools used for FD and NOMA networks are discussed and surveyed in Sect. 9.3. Numerical results on the performance of FD-NOMA networks are presented in Sect. 9.4. Finally, Sect. 9.5 concludes the chapter and discusses some open problems.

9.2 Full-Duplex NOMA Networks

9.2.1 Preliminaries

Here, we provide the basics of FD and NOMA that can be helpful to the reader. We particularly define the basic concepts of FD and self-interference cancellation and then briefly introduce FD and NOMA network operation challenges.

9.2.1.1 Full-Duplex

Conventional wireless networks operate in HD mode, meaning that one direction of transmission is allowed at any given time and frequency resource. Different duplexing techniques have been considered in HD networks to duplex the UL and DL transmissions. In particular, time division duplex (TDD) and frequency division duplex (FDD) are both used commonly in today's networks. FDD dedicates frequency resources to UL and DL where communication in both directions is orthogonal in the frequency domain. TDD splits the time resources between UL and DL transmissions either in a static manner (fixed UL and DL duty cycles on each time frame) or a dynamic manner (where UL and DL duty cycles can change to match the network UL and DL load conditions [14].

Alternatively, bidirectional transmissions can be used simultaneously, namely full-duplex communication. FD can ideally double the spectrum efficiency by relaxing the constraint on UL and DL orthogonality [21]. This has been an ideal assumption for a long time. However, taking it into practice was hindered by the complexity of removing the self-interference leaked from the transmitter to the receiver of the same device. The transmitted signal is much stronger than the received one, as the latter is significantly weakened by the path and propagation losses. Hence, the transmitted signal saturates the receiver radio chains and prevents signal reception. Self-interference has been seen as the major impairment to FD operation. Ideally, self-interference should be cancelled to the same level as the receiver noise floor such that the received signal is decoded in the same level as in HD. Otherwise, the residual interference is added to the received signal and hence decreases the receive SNR and throughput.

9.2.1.2 Self-Interference Cancellation

Cancelling the self-interference from the transmitted signal of a FD radio is not as easy as it might sound. Although the transmitter knows what it is transmitting, this knowledge is of the signal in the baseband level [12, 20]. The baseband signal experiences several linear and nonlinear in the analogue radio chain before it is converted into a transmitted signal. Hence, subtracting the baseband signal does not help in removing the self-interference.

Recently, the self-interference cancellation capability has significantly evolved. The study in [20] has shown simultaneous transmission and reception (with a single antenna) is achievable using analogue and digital cancellation techniques to cancel the self-interference. The leaked self-interference is reduced to the noise floor such that the received signal is not degraded. This breakthrough in the self-interference cancellation capability motivated the consideration of full-duplex in future networks for user scheduling [17] as well as relaying [38]. Furthermore, the shift from traditional macrocells to low-power small-cell networks eases the process of integrating FD into future networks. As compared to 46 dBm transmit power of macrocells, femtocells operate in power levels as low as 20 dBm, which makes the self-interference process feasible.

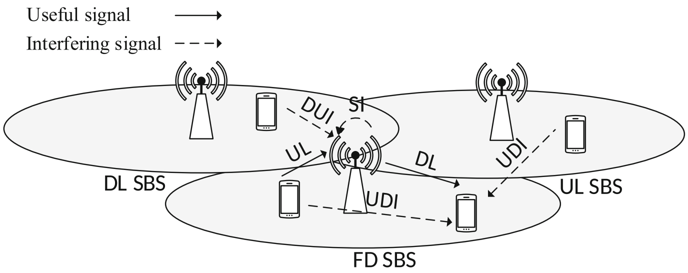

Fig. 9.1 An illustration of the different types of interference in multi-cell FD operation (UDI: UL-to-DL interference, DUI: DL-to-UL interference and SI: self-interference.)

9.2.1.3 FD Network Operation

Once the self-interference is cancelled, the link throughput of FD can potentially double that of an HD link. However, as FD operates in a network level, another issue arises which is the inter-link interference due to having simultaneous transmission and reception, as illustrated in Fig. 9.1. This interference situation is similar to that of dynamic TDD networks, where base stations operate with different TDD configurations to satisfy their individual UL and DL traffic requirements, resulting in additional inter-link inter-cell interference. In addition to that, FD networks will suffer intra-cell interference between the user pairs operating in UL and DL. Therefore, intelligent user pairing methods are needed to select the appropriate pairs of users to be scheduled in each time–frequency resource such that this interference is avoided.

9.2.1.4 FD-NOMA Network Operation

FD-NOMA refers to the concept of operating in IBFD mode and using NOMA to serve multiple requests. It is shown in the literature that NOMA can operate in both UL and DL. To reap the benefits promised by NOMA over OMA, power disparity has to be guaranteed. In UL, decoding the signals of multiple users sharing the time–frequency resource will occur in the base station level. It is intuitive therefore to select users with different receive power levels to be scheduled simultaneously. For example, scheduling a pair of cell-centre and cell-edge users is a convenient approach. In DL, different power levels should be allocated to the messages of different users, according to the decoding order they are going to select. This is essential to ensure a successful SIC process to cancel the intra-cell interference.

When FD is combined with NOMA, additional levels of interference are introduced generated from the opposite direction [3]. Different approaches can be considered to mitigate the effect of this unwanted interference. One approach [13] is to select between operating in FD while using an OMA technique or operating in HD and using NOMA. The scheduling and power allocation schemes play a key role in finding the optimal operating methods given the network conditions and optimization objectives. Prioritizing the serving of users in certain link direction means that NOMA should be selected to operate. On the other hand, FD can be selected to simultaneously serve UL and DL requests. While this approach restricts operation to FD-OMA or HD-NOMA at a certain time instant, it avoids the additional intra-cell interference of FD on NOMA operation and hence allows for more users to be served by NOMA in a certain link direction.

Another way to blend the use of FD and NOMA together is to allow the network to operate in FD and NOMA in a given time instant. In this regard, the inter-link interference can be treated as noise [35] and will affect the NOMA performance. In particular, DL users will experience high UL-to-DL interference from multiple users operating in UL-NOMA. This interference can be handled by limiting the maximum number of users allowed to operate in UL-NOMA if the performance of DL users is degraded.

9.2.2 Challenges of FD-NOMA Resource Optimization

As discussed above, resource optimization is a key role in reaping the benefits of FD-NOMA operation. Since the challenges of implementing them in practice are similar, there are common tools that can be used to optimize the resource and power allocation when either or both of them are considered. In this chapter, we focus on two main optimization problems that are fundamental for enabling NOMA, which are user pairing/scheduling and power allocation. Furthermore, we discuss the impact of the different objective functions on the resource optimization.

9.2.3 User Pairing and Power Optimization

To illustrate the problem of user scheduling FD-NOMA networks, we assume a general multi-cell wireless network that comprises a set $\mathscr{B}$ of B FD-capable base stations, with self-interference cancellation capability of ζ, and a set $\mathscr{U}$ of U users requesting either UL or DL service. Furthermore, we assume that both base stations and users can operate in NOMA scheme, where the resulting multi-user interference can be cancelled by performing SIC at the receiver side. The user scheduling parameters in UL and DL at time instant t are defined using the binary parameters $x_{bu}^{\mathrm{UL}}(t) \in X^{\mathrm{UL}}$, $x_{bu}^{\mathrm{DL}}(t) \in X^{\mathrm{DL}} \forall b \in \mathscr{B}, u \in \mathscr{U}$. Let f_b be the allocated bandwidth, $\boldsymbol{v}_b^{\mathrm{UL}}(t)$ and $\boldsymbol{v}_b^{\mathrm{DL}}(t)$ be the vectors of the UL and DL successive ordering index of all the users in base station b, where $\nu_{bu}^{(.)}(t) \in \boldsymbol{\nu}_b^{(.)}(t)$ is the decoding order of user u when it is scheduled by base station b, and R_{bu}^{UL} and R_{bu}^{DL} be the UL and DL data rates between base station b and user u, then for a general network with open-access policy, the UL and DL service rates of user u can be expressed using the Shannon formula as:

$$\begin{aligned} r_u^{\mathrm{UL}}(t) &= \sum_{b \in \mathscr{B}} x_{bu}^{\mathrm{UL}}(t) R_{bu}^{\mathrm{UL}}(t), \\ &= \sum_{b \in \mathscr{B}} x_{bu}^{\mathrm{UL}}(t) f_b \log_2(1 + \Gamma_{bu}^{\mathrm{UL}}(t)), \end{aligned} \tag{9.1}$$

$$\begin{aligned} r_u^{\mathrm{DL}}(t) &= \sum_{b \in \mathscr{B}} x_{bu}^{\mathrm{DL}}(t) R_u^{\mathrm{DL}}(t), \\ &= \sum_{b \in \mathscr{B}} x_{bu}^{\mathrm{DL}}(t) f_b \log_2(1 + \Gamma_{bu}^{\mathrm{DL}}(t)). \end{aligned} \tag{9.2}$$

Assuming that the information to be transmitted is encoded based on a Gaussian distribution and a zero-mean additive white Gaussian noise with variance N_0, the UL and DL signal-to-interference-plus-noise ratios (SINRs) between base station b and user u at time instant t are given by:

$$\Gamma_{bu}^{\mathrm{UL}}(t) = \frac{p_u^{\mathrm{UL}}(t) h_{bu}(t)}{N_0 + I_b^{\text{UL-UL}}(t) + I_b^{\text{DL-UL}}(t) + I_{bu}^{\text{NOMA-UL}}(t) + p_b^{\mathrm{DL}}(t)/\zeta}, \tag{9.3}$$

$$\Gamma_{bu}^{\mathrm{DL}}(t) = \frac{p_{bu}^{\mathrm{DL}}(t) h_{bu}(t)}{N_0 + I_u^{\text{DL-DL}}(t) + I_u^{\text{UL-DL}}(t) + I_{bu}^{\text{NOMA-DL}}(t)}, \tag{9.4}$$

where p_u^{UL} is the UL transmit power of user u, and $p_b^{\mathrm{DL}} = \sum_{u \in \mathscr{U}} p_{bu}^{\mathrm{DL}}$ is the total DL transmit power of base station b, $h_{x,y}(t) = |g_{x,y}(t)|^2$ is the channel gain between the two nodes x and y, $g_{x,y}(t)$ is the propagation channel between nodes x and y, and the interference terms in (9.3) and (9.4) are expressed as follows[1]:

$$\begin{aligned} I_b^{\text{UL-UL}}(t) &= \sum_{u' \in \mathscr{U} \setminus \{u\}} p_{u'}^{\mathrm{UL}}(t) h_{bu'}(t), \\ I_b^{\text{DL-UL}}(t) &= \sum_{b' \in \mathscr{B} \setminus \{b\}} p_{b'}^{\mathrm{DL}}(t) h_{b'b}(t), \\ I_u^{\text{DL-DL}}(t) &= \sum_{b' \in \mathscr{B} \setminus \{b\}} p_{b'}^{\mathrm{DL}}(t) h_{b'u}(t), \\ I_u^{\text{UL-DL}}(t) &= \sum_{u' \in \mathscr{U}} p_{u'}^{\mathrm{UL}}(t) h_{u',u}(t), \end{aligned}$$

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[1] Note that the term $I_{\text{UL-DL}}$ includes the intra-cell interference, to account for the interference due to FD operation.

$$I_{bu}^{\text{NOMA-UL}}(t) = \sum_{\substack{u' \in \mathcal{U} \setminus \{u\} | x_{bu'}^{\text{UL}}=1, \\ v_{bu}^{\text{UL}}(t) < v_{bu'}^{\text{UL}}(t)}} p_{u'}^{\text{UL}}(t) h_{bu'}(t),$$

$$I_{bu}^{\text{NOMA-DL}}(t) = \sum_{\substack{u' \in \mathcal{U} \setminus \{u\} | x_{bu'}^{\text{DL}}=1, \\ v_{bu}^{\text{DL}}(t) < v_{bu'}^{\text{DL}}(t)}} p_{bu'}^{\text{DL}}(t) h_{bu}(t),$$

$p_b^{\text{DL}}(t)/\zeta$ is the leaked self-interference.

Remark 1 To guarantee a successful NOMA operation in the DL, a user u' should decode the data of user u with an SINR level $\Gamma_{bu}^{u'\text{DL}}(t)$ that is at least equal to the user u received SINR $\Gamma_{bu}^{\text{DL}}(t)$. Otherwise, the data rate of user u is higher than what user u' can decode. Accordingly, the inequality $\Gamma_{bu}^{u'\text{DL}}(t) \geq \Gamma_{bu}^{\text{DL}}(t)$ must hold, where:

$$\Gamma_{bu}^{u'\text{DL}}(t) = \frac{p_{bu}^{\text{DL}}(t) h_{bu'}(t)}{p_{bu'}^{\text{DL}}(t) h_{bu'}(t) + N_0 + I_{u'}^{\text{DL-DL}}(t) + I_{u'}^{\text{UL-DL}}(t) + I_{bu'}^{\text{NOMA-DL}}(t)}.$$

This condition is met if the following metric is greater or equal to zero:

$$Y_{uu'} = \mathbb{1}_{v_{bu}^{\text{DL}}(t) < v_{bu'}^{\text{DL}}(t)} x_{bu}^{\text{DL}} x_{bu'}^{\text{DL}} (\Gamma_{bu}^{u'\text{DL}} - \Gamma_{bu}^{\text{DL}}).$$

Note that the above condition is satisfied by default in the UL, since all users' signals are decoded in the base station's receiver.

A general FD-NOMA resource optimization problem can be defined to be optimizing user scheduling, NOMA decoding ordering, and UL and DL power allocations, i.e., the scheduling matrices $X^{\text{UL}} = [x_{bu}^{\text{UL}}]$ and $X^{\text{DL}} = [x_{bu}^{\text{DL}}]$, the decoding ordering vectors $\boldsymbol{v}_b^{\text{UL}}$ and $\boldsymbol{v}_b^{\text{DL}}$, and the power allocation vectors, $\boldsymbol{p}^{\text{UL}} = [p_1^{\text{UL}}, ..., p_U^{\text{UL}}]$ and $\boldsymbol{p}_b^{\text{DL}} = [p_{b1}^{\text{DL}}, ..., p_{bU}^{\text{DL}}]$. Note that the selection of the scheduling parameters essentially includes the problems of user association, UL/DL mode selection, and OMA/NOMA mode selection. Accordingly, a general optimization problem can be cast as follows:

$$\textbf{P1:} \quad \max_{\substack{X^{\text{UL}}, X^{\text{DL}}, \\ \{\boldsymbol{v}_b^{\text{UL}}\}, \{\boldsymbol{v}_b^{\text{DL}}\} \\ \boldsymbol{p}^{\text{UL}}, \{\boldsymbol{p}_b^{\text{DL}}\}}} \quad U\big(\{r_u^{\text{UL}}\}, \{r_u^{\text{DL}}\}\big) \tag{9.5a}$$

$$\text{subject to} \quad p_u^{\text{UL}} \leq P_{\max}^{\text{UL}}, \ \forall u \in \mathcal{U}, \tag{9.5b}$$

$$p_u^{\text{DL}} \leq P_{\max}^{\text{DL}}, \ \forall b \in \mathcal{B}, \tag{9.5c}$$

$$\sum_{b \in \mathcal{B}} x_{bu}^{\text{UL}} + x_{bu}^{\text{DL}} \leq 1, \ \forall u \in \mathcal{U}, \tag{9.5d}$$

$$\sum_{u \in \mathcal{U}} x_{bu}^{\text{UL}} \leq q^{\text{UL}}, \sum_{u \in \mathcal{U}} x_{bu}^{\text{DL}} \leq q^{\text{DL}} \ \forall b \in \mathcal{B}. \tag{9.5e}$$

$$Y_{uu'} \geq 0 \ \ \forall u, u' \in \mathcal{U}. \tag{9.5f}$$

Constraints (9.5b) (9.5c) limit the UL and DL transmit powers to their maximum values $P_{\max}^{\mathrm{UL}}$ and $P_{\max}^{\mathrm{DL}}$, respectively. Constraint (9.5d) restricts the connection of a user to one base station in either UL or DL. The number of users a base station can simultaneously serve in UL or DL-NOMA is limited to a quota of q^{UL} and q^{DL} users, respectively, by constraint (9.5e).[2] Constraint (9.5f) guarantees a successful SIC in the DL.

The utility in (9.5) should be selected to reflect the objective of the network optimization problem. The work in [35] considers a utility that maximizes the sum rate in a multi-carrier setting. In this regard, the resource allocation includes the subcarrier allocation. In [13], a weighted rate maximization utility was developed from a stochastic optimization problem, where the user weights are derived from the user traffic queue and virtual queue backlogs.[3]

9.2.4 Optimization Tools

Rate-based utility maximizations are often combinatorial and non-convex optimization problems that are computationally complex to solve optimally. In particular, the user scheduling problem is a combinatorial problem whose complexity will increase exponentially as the number of base stations and users increase.

In many cases, the optimization problem has to be solved dynamically. For example, if the weighted rate maximization based on user's queue state is considered as the objective, both the user pairing and power allocation will need to be dynamically adjusted. Efficient and local solutions tools are therefore needed. Matching is a powerful tool that can solve the user scheduling problem [26]. Matching theory is a framework that provides solutions for the combinatorial problem of matching members of two disjoint sets of players in which each player is interested to associate with one or more player the other set. Matching is performed on the basis of preference profiles defined by the players of each side, providing a low-complexity stable matching. Although matching does not necessarily guarantee finding the optimal solution, its suitability for dynamic systems and local implementations made it a popular solution to reduce the complexity of the combinatorial problems [18, 19, 31]. Matching can also be used with other game-theoretic tools, such as cooperative game theory [28, 29], to further solve user grouping problems. Matching should be performed assuming an initial feasible power allocation policy. Subsequently, the power allocation is performed for the selected matching setting. The decoupling of the user scheduling and power allocation problems simplifies both problems, since power allocation is performed to the reduced set of scheduled users [13].

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[2] Note that, in theory, the number of users that can be served simultaneously using NOMA is unrestricted. However, we impose a quota to avoid high-complexity SIC in the receiver side if a high number of users are scheduled.

[3] Virtual queues result from applying the Lyapunov framework to convert the time-averaged constraints into virtual queues such that the constraints are met as the virtual queues are stabilized.

In addition to the complexity of the user scheduling problem, the power allocation problem is non-convex, due to having interference terms in the denominator of the SINR in the rate expression. Several approaches have been proposed in the literature to deal with the non-convexity of the problem. In [35], the global optimal solution of the joint problem of resource and power allocation is solved using monotonic optimization. The solutions are, however, with high computational complexity. The authors provide a lower complexity solution to solve the problem using successive convex approximation (SCA), which is shown to achieve a close to global optimal solution. SCA and similar tools to convexify the non-convex terms in the optimization problem are used in several works [13, 15, 24, 35, 36]. In this case, the convexified problem is solved iteratively using convex optimization tools until some convergence criterion is met.

The NOMA decoding order significantly affects the user performance in both UL and DL. In DL-NOMA, decoding users with the lower channel strength first is optimal in the single-cell scenario [11]. In UL-NOMA, the opposite decoding order based on the user channel strength is shown in [6] to result in a gain over OMA based on users channel gain disparity. The decoding ordering in a multi-cell scenario is a challenging task, especially in the DL where different users might experience different inter-cell interference levels.

9.3 State of the Art in FD and NOMA Resource Optimization

This section surveys the recent works in the problem of wireless resource optimization in FD and NOMA networks. First, with the promises of doubling the link throughput, the study of the when and how the potential gains can be achieved in a network level is surveyed. Following that, we overview the studies of resource optimization in NOMA networks in UL and DL. Finally, we highlight the works that combine both FD and NOMA schemes.

9.3.1 FD Resource Optimization

In [16], a hybrid HD/FD scheduler for a single-cell network is proposed. The scheduler assigns FD resources only when it is advantageous over HD resource assignment. The joint problem of subcarrier and power allocation are optimized in [36] using an SCA algorithm. An auction-based algorithm to pair UL and DL users in a single-cell IBFD network is proposed in [33]. Subcarrier and power allocation is optimized using a heuristic algorithm with polynomial complexity for a single-cell IBFD network in [37]. The study also considers the case of imperfect self-interference cancellation on the performance of FD as compared to HD. It concludes that a higher number of users can be served using FD as the cancellation capability increases. In [17], the authors extended the work in [16] to multi-cell networks. To reduce the complexity of a centralized solution, a distributed resource allocation scheme is developed where each base station selects locally which user to serve, and then, it coordinates with the neighbouring base stations to coordinate their transmission powers such that the inter-cell interference is minimized. The study shows that FD can achieve up to double the throughput of HD in indoor scenarios and 65% throughput gain in outdoor scenarios. The work in [34] also considered the FD resource and power allocation in multi-cell FD networks but with frequency reuse allowed only once among different cells. Matching theory is leveraged in [7] to develop a resource allocation algorithm. A matching algorithm is proposed to assign subcarriers to UL and DL user pairs. In [5], the user scheduling in FD ultra-dense-networks is optimized using different schemes with and without power optimization. The scheduling is carried out locally assuming no knowledge of the inter-cell interference. Table 9.1-a summarizes the contributions on the FD resource allocation.

Remark 2 A common assumption in FD scheduling is that the base station knows the individual channel between its own users. This assumption is necessary to select FD pairs that do not significantly interfere on each other [16]. The assumption should be practical as FD is expected to be feasible in low-power small-cell networks where a low number of users are served by each base station.

9.3.2 NOMA Resource Optimization

Recently, several works have looked into the resource optimization in UL and/or DL-NOMA networks. Here, we shed light on the papers focusing on the scheduling and power optimization in NOMA networks. The authors in [8] propose a many-to-many algorithm to assign subcarriers to users in a single DL-NOMA network. Many-to-many matching is used in [9] for a multi-cell DL-NOMA scenario. Matching is also used for DL-NOMA resource allocation in [15] with a focus on energy efficiency. The power allocation problems are convexified and solved using difference of convex functions (DC) programming. DC programming is also used in [24] to optimize the power allocation in OFDM-based DL-NOMA networks, whereas a greedy algorithm is proposed for the user selection problem. A greedy approach is also used for the user scheduling in a multiple-input multiple-output (MIMO) DL-NOMA network in [32], and a minimum mean squared error (MMSE)-based power allocation is considered.

Several works have looked into NOMA in the UL direction. The performance of NOMA in the UL is investigated in [2] using an iterative channel allocation algorithm. In [30], the problem of user pairing in UL-NOMA for users with single and multi-antennas is optimized. User grouping and power optimization in UL-NOMA is studied in [6] where the impact of user ordering and imperfect SIC is

Table 9.1 Summary of existing literature in FD- and NOMA-based resource allocation problems

(a) FD

References	Network scenario	Implementation	FD scheduling	Power allocation
[16]	Single-cell	Local	HD/FD mode selection	×
[36]	Single-cell	Local	Joint subchannel and power allocation	✓
[33]	Single-cell	Local	FD user pairing and channel allocation	✓
[37]	Single-cell	Local	OFDMA channel allocation	✓
[17]	Multi-cell	Local	Suboptimal HD/FD user selection	✓
[34]	Multi-cell (subcarrier is reused once)	Central	Mode selection and subcarrier allocation	✓
[7]	Multi-cell	Central	Matching subcarriers to user pairs	✓
[5]	Multi-cell	Local	Local scheduling	✓

(b) NOMA

References	Link scenario	Network scenario	Scheduling and power allocation scheme
[8]	DL	Single-cell	Matching algorithm
[15]	DL	Single-cell	Subchannel assignment and power allocation
[24]	DL	Single-cell	User selection and power optimization
[32]	DL	Single-cell	User pairing and power allocation
[9]	DL	Multi-cell	Matching algorithm and power allocation
[30]	UL	Single-cell	User pairing for multi-antenna systems
[2]	UL	Single-cell	Iterative subcarrier and power allocation
[6]	UL	Heterogeneous	User clustering and power allocation
[4]	UL + DL	Multi-cell	Optimal power allocation for a limited number of users

(c) FD-NOMA

References	Network scenario	Scheduling and power allocation scheme
[35]	Single-cell	Joint subchannel and powerallocation
[13]	Multi-cell	Joint user scheduling and power allocation

investigated. In [4], the authors consider a multi-cell UL and DL-NOMA system where a user grouping and power optimization scheme are proposed. The optimal power allocation is derived for a single macro-cell and a limited number of users.

9.3.3 FD-NOMA Resource Optimization

Two recent studies have looked into the incorporation of FD into NOMA networks and the impact on the scheduling and power allocation. In [35], the authors proposed an FD-NOMA approach in which users can be scheduled simultaneously in UL and DL in the same time–frequency resource and NOMA can be used in both directions. SIC is used in UL and DL to decode the messages of different users, whereas the inter-link interference due to FD is treated as noise. The joint subcarrier and power optimization problem is formulated, and the global optimal solution is found using monotonic optimization. Due to the high complexity of finding the global optimal solution, a low-complexity solution based on SCA is found. The results have shown that FD-NOMA improves the spectral efficiency as compared to HD-NOMA. Moreover, the effect of imperfect SIC is shown to impact the performance of the FD scheme.

In [13], FD-NOMA is investigated in a dynamic multi-cell scenario where a stochastic optimization problem based on the Lyapunov framework is considered. The benefits of operating in HD or FD, as well as in OMA or NOMA modes, depending on traffic conditions, network density, and self-interference cancellation capabilities are investigated. The optimization problem is decomposed into two subproblems that are solved independently per small-cell base station. User association and mode selection are formulated as a many-to-one matching problem. A distributed matching algorithm aided by an inter-cell interference learning mechanism is proposed which is shown to converge to a pairwise stable matching. The matching algorithm allows small-cells to select between HD and FD and to operate either in OMA or NOMA schemes to serve their users. Subsequently, the UL/DL power optimization problem is formulated as a sequence of convex problems, and an iterative algorithm to allocate the optimal power levels for the matched users and their base stations is proposed. It was shown that using matching theory, the network can dynamically select when to operate in HD or FD and when to use OMA or NOMA to serve different users, which yields significant gains in UL and DL user throughput and packet throughput, as compared to HD-NOMA, FD-OMA, and HD-OMA schemes.

9.4 Numerical Results

In this section, we present some numerical results to assess the performance of the queue-aware FD and NOMA resource optimization. We consider a continuous utility function of time-averaged UL and DL service rates. The problem can be decomposed using the Lyapunov framework into an instantaneous weighted rate maximization in which the user weights are their queue backlogs. The network consists of small-cell base stations with a varying self-interference cancellation capability, serving multiple users in an open-access manner. Scheduling can be in HD or FD modes, and in HD mode, users can be scheduled in OMA or NOMA. To cancel the resulting multi-user interference, base stations or users operating in NOMA can perform SIC at the receiver side. The decoding ordering is assumed to be done in a descending order of channel strength in DL-NOMA, and an ascending order of channel strength in UL-NOMA. We assume that the user's mean packet arrival rate and mean packet size follow Poisson and exponential distributions, respectively. To satisfy queue stability requirements, base stations need to ensure that user's traffic queues are mean rate stable. Equivalently, constraints are imposed to ensure that the average service rate is higher or equal to the average arrival rate. The resource optimization problem consists of the scheduling problem (which includes the mode selection) and the power allocation problem. To reduce the complexity of the combinatorial scheduling problem, a many-to-one matching algorithm based on the *deferred acceptance (DA)* matching [13] is considered to dynamically schedule one or more users to each base station at each time instant. Preference profiles for users and base stations are selected as to maximize their individual weighted rates. The matching algorithm can be performed locally at each base station, which significantly reduce the amount of signalling exchange. After the matching is performed, each base station coordinates with its neighbours to optimize the allocated power, such that a feasible policy is achieved and inter-cell interference is minimized. The multi-cell power optimization is non-convex. Hence, the DC programming is used to convexify the problem, which is guaranteed to converge to a local optimal solution. System level simulations are carried out to show the gains brought by FD and NOMA, as well as to investigate the impact of queue stability constraints on the network performance. Simulation parameters are presented in Table 9.2. For the sake of comparison, the following schemes are considered in the simulation:

1. *HD-OMA scheme*: users are associated to the nearest base station and are allocated orthogonal resources for UL and DL. Requests are served using a round robin (RR) scheduler.
2. *HD-NOMA only scheme*: users are associated to the nearest base station, and RR scheduler is used to serve UL and DL queues. If there are multiple users in a scheduling queue, they are ranked according to their channel gains and are served using NOMA if the ratio between their channel gains is at least 2; otherwise, OMA is used. Power is allocated to NOMA users based on their channel ranking, in a uniform descending order for UL-NOMA and a uniform ascending order for DL-NOMA. Base stations operate either in UL or in DL depending on the queue length on each link direction.
3. *FD-OMA scheme*: users are associated to the nearest base station, and a pair of users is served in FD mode if the channel gain between them is greater than a certain threshold; otherwise, users are served in HD mode using RR scheduler.
4. *Uncoordinated scheme*: in this scheme, users can be served in either HD or FD and in OMA or NOMA modes. The many-to-one matching algorithm is used for mode selection and user scheduling, with the user queues taken into account in the weighted rate maximization. Power is assumed to be fixed for OMA and is similar to that of scheme 2 for NOMA. No inter-cell interference coordination is considered.

Table 9.2 Simulation parameters

Parameter	Value
System bandwidth	10 MHz
Duplex modes	TDD HD/ FD
Multiplexing mode	OMA/NOMA
Subframe duration	1 ms
Network size	500×500 m^2
Number of base stations	10
Avg. number of users per base station	10
Small-cell radius	40 m
Max. base station transmit power	22 dBm
Max. user transmit power	20 dBm
Path loss model	Multi-cell pico scenario [1]
Shadowing standard deviation	4 dB
Penetration loss	0 dB
Self-interference cancellation	110 dB
Packet arrival rate per user	10 packet/s
Max. quota of NOMA users q^{UL}, q^{DL}	5

5. *Proposed scheme*: In this scheme, the many-to-one matching algorithm is used for mode selection and user scheduling as in scheme 4. In addition, inter-cell interference coordination is considered by optimizing the UL and DL power allocation using DC programming.

We begin by evaluating the performance of the proposed scheme under different traffic intensity conditions. Traffic intensity is varied by changing the mean packet size between 50 and 400 kb. In Fig. 9.2, we show the impact of traffic intensity on the normalized UL and DL user throughput. The normalized user throughput is defined as the user service rate divided by its data arrival rate. Figure 9.2a shows that in the UL, all schemes but the proposed one achieve lower UL throughput as compared to the HD-OMA scheme. The performance drop is due to the DL-to-UL interference that has a significant impact on the uncoordinated schemes due to the higher transmitting power of base stations and the lower path loss between the base station and user. The proposed scheme outperforms the different schemes by mitigating the DL-to-UL interference through power optimization.

In Fig. 9.2b, we can see that, in the DL case, the effect of UL-to-DL interference is less significant, as it can be avoided within each cell through the pairing process. By leveraging both matching and the UL and DL power optimization, the proposed scheme outperforms the baseline schemes, with UL and DL gains of 10 and 20% over the HD-OMA scheme. The figure also shows that the coordination gain (over the uncoordinated scheme) is even more evident in the UL as in the DL due to the dominance of the DL-to-UL interference in the uncoordinated scenario.

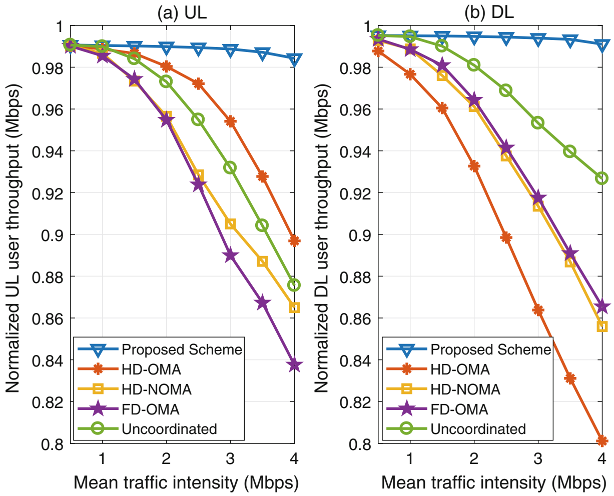

Fig. 9.2 Normalized **a** UL and **b** DL user throughput performance for different schemes as the user traffic intensity increases, for a network of ten base station and an average of ten users per base station

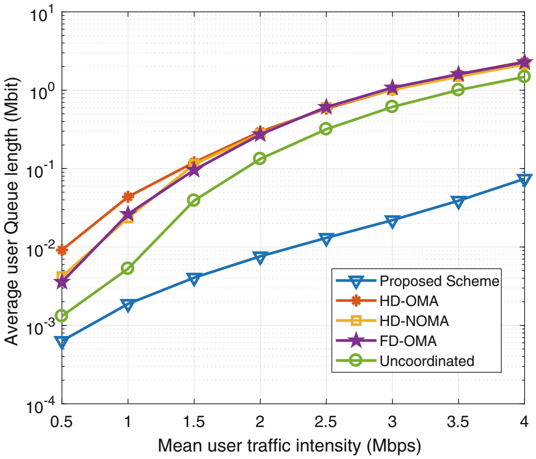

Fig. 9.3 Average user queue length performance for different schemes as the user traffic intensity increases, for a user of ten base station and an average of ten users per base station

Next, we investigate the queue behaviour of the different schemes as the traffic intensity varies. In Fig. 9.3, the average queue length is shown as function of the traffic intensity. Figure 9.3 shows that the average queue length grows as the traffic intensifies. In low traffic conditions, FD-OMA and HD-NOMA have smaller queue lengths as compared to the HD-OMA scheme. Also, the uncoordinated FD-NOMA scheme maintains a smaller queue length, since coordination is not crucial in low traffic intensity conditions. As the traffic intensity increases, we can see that the queue length grows significantly for the uncoordinated schemes. The proposed scheme

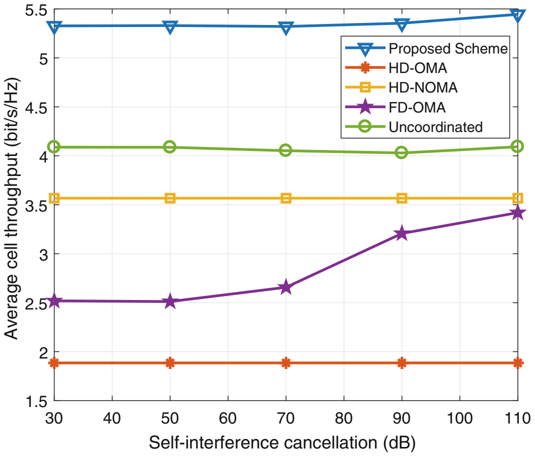

Fig. 9.4 Average cell throughput (in bit/s/Hz) performance for different schemes as the base station self-interference cancellation capability varies, for a network of ten base stations, an average of ten users per base station, and a mean traffic intensity rate of 3 Mbps per user

maintains small queue lengths as it seeks to stabilize the user queues through the weighted rate maximization.

Finally, we show the impact of the self-interference cancellation capability on the performance of the FD schemes. Figure 9.4 compares the average cell throughput (in bit/s/Hz) of the different schemes as the self-interference cancellation capability varies from 30 to 110 dB, which is the highest reported value [20]. As shown in the figure, the throughput of the FD schemes degrades with lower self-interference cancellation levels due to the interference leakage on the UL signal. It is also shown that only a slight degradation in the throughput of the proposed FD-NOMA is observed. As the proposed scheme optimizes the mode selection between HD/FD and OMA/NOMA, it can select more frequently the UL-NOMA instead of FD to serve UL users, such that it avoids high interference from the base station's DL. This shows that enabling both FD and NOMA has the potential to enable higher network spectral efficiency in different network conditions.

9.5 Conclusions and Open Problems

This chapter has provided an overview of the topic of full-duplex (FD) non-orthogonal multiple access (NOMA) from a network optimization point of view. Different challenges on the optimization of FD-NOMA networks are discussed. It has highlighted the particular importance of the user pairing and scheduling in both FD and NOMA networks. Several directions are still open for research. As was mentioned throughout the chapter, the decoding ordering is a key factor in the performance of the NOMA systems. Some studies are carried out on the optimal ordering of users, most of which are assuming single-cell operation and focus on the optimal solution from the point of sum rate maximization. Finding the optimal decoding ordering is a challenging task in a multi-cell scenario and is even challenging in FD networks in which both intra-cell and inter-cell interference impact the network performance. The objective of the decoding order optimization should also take into account the notion of fairness between the users with different channel and queue state conditions. Moreover, enabling NOMA for emerging 5G systems, such as vehicle-to-everything (V2X) networks [10, 25] and networks with unmanned aerial vehicles [22, 23, 27], poses a wide range of open problems. Finally, looking into different objectives beyond the average rate maximization problems is necessary, especially in the context of ultra-reliable and low latency communication (URLLC), which brings further challenges to the system design.

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