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Queue-aware scheduling in full-duplex wireless networks

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Abstract

Contemporary progress in telecommunication technologies have made full-duplex wireless communications feasible. The latter promise to double the capacity of wireless networks by allowing devices to concurrently transmit and receive on the same radio resources. In this paper, we devise mathematical optimal formulations for scheduling in full-duplex and hybrid full-duplex/half-duplex orthogonal frequency division multiple access networks. Our optimal models are queue-aware and address the new interferences that arise from working with full-duplex wireless networks: self-interference and intra-cell co-channel interference. We apply these models with different scheduling objectives, tackling issues such as signal-to-interference-plus-noise ratio (SINR) maximization and user fairness. Accordingly, we first propose an optimal full-duplex Max-SINR algorithm and an optimal full-duplex Proportional Fair algorithm. Additionally, and since full-duplex communications may not always be profitable, we introduce an optimal hybrid Max-SINR algorithm and an optimal hybrid Proportional Fair algorithm. These algorithms switch between full-duplex and half-duplex transmissions, so as to enhance network performance. Moreover, to avoid possible intractability with the optimization problems, we propose heuristic versions of our algorithms. We simulate these proposals, showing that they achieve near optimal performances, and asserting the different gains they attain with respect to their half-duplex counterparts: more than a 50% increase in user equipment throughput values alongside a three fold decrease in the average user equipment waiting delay.

Keywords Wireless communications · Scheduling · Full-duplex · OFDMA

1 Introduction

In response to an ever growing demand for higher data rates [1], researchers are now examining the possibility of implementing full-duplex (FD) communications in wireless networks. Current wireless communication networks operate in half-duplex (HD): they assign resources exclusively to one user equipment (UE) for either transmission or reception. In contrast, a full-duplex device can concurrently transmit and receive on the same radio resource making it possible to double a wireless network's capacity.

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In our work, we consider a full-duplex orthogonal frequency division multiple access (FD-OFDMA) network. An FD-OFDMA network is composed of a full-duplex base station (BS) and half-duplex UEs. This keeps the complexities of implementing full-duplex at the BS and away from the terminals. In such networks, a time-frequency resource is allocated to two different UEs: one uplink UE and one downlink UE. The full-duplex BS transmits and receives to and from these UEs on the same resource. The UEs are said to be paired on this radio resource. A full-duplex network's performance is challenged by two main interference sources. First, the transmitted signal from the BS, around 50–110 dB stronger, would leak over the received signal masking it completely. This is known as self-interference, a ramification of full-duplex communications. Second, full-duplex networks suffer from intra-cell co-channel interference resulting from pairs of UEs using the same radio resources within the same cell. In an FD-OFDMA network, self-interference degrades the performance of UEs on the uplink, while intra-cell co-channel interference degrades the performance of UEs on the downlink.

Mitigating self-interference at full-duplex devices is done via a set of advanced analog and digital processes as described in [2]. These technologies are known as self-interference cancellation (SIC) techniques, and their efficiency impacts the gains achievable from full-duplex wireless communications.

Traditionally an inter-cell problem, intra-cell co-channel interference is a new challenge for scheduling in FD-OFDMA wireless networks. Scheduling in the uplink and the downlink can as such no longer be done independently as in half-duplex communications. The scheduler must ensure that the co-channel interference between the UEs of a selected pair does not hinder their performance. This mainly depends on the uplink UE's transmit power, as well as on the channel gain between the pair of UEs.

In this paper, we propose optimal scheduling models for full-duplex and hybrid OFDMA wireless networks. We vary the objectives of these problems with the intent of implementing different scheduling techniques in a full-duplex environment. Our scheduling models encompass a finite buffer traffic model. This is a practical approach that allows us to compute packet level metrics such as the waiting delay.

We apply our models with different scheduling objectives, tackling issues such as signal-to-interference-plus-noise ratio (SINR) maximization and user fairness. Accordingly, we first propose an optimal full-duplex Max-SINR scheduling algorithm and an optimal full-duplex Proportional Fair scheduling algorithm. Additionally, and since full-duplex communications may not always be profitable, we introduce an optimal hybrid Max-SINR scheduling algorithm and an optimal hybrid Proportional Fair scheduling algorithm. These algorithms switch between full-duplex and half-duplex transmission modes, so as to enhance network performance. Moreover, to avoid possible intractability with the optimization problems, we introduce heuristic versions of our proposals. As a representation of a random allocation scheme, we put forward a full-duplex Round Robin scheduling algorithm.

The remainder of this paper is structured as follows. Section 2 discusses the state-of-the-art and lists our main contributions. Section 3 introduces the system's radio and traffic models. Our scheduling models are detailed in Sect. 4. We present our proposed optimal algorithms in Sect. 5.1, and discuss the complexity of the optimal solution in Sect. 5.2. We introduce the heuristic versions of our algorithms in Sect. 6.1, and discuss their complexity in Sect. 6.2. Afterwards, we simulate our algorithms versus each other and with respect to half-duplex communications. The results are detailed in Sect. 7. We compare and contrast between our different proposals, and furthermore observe the effect of heterogeneous traffic on our algorithms in Sects. 7.1 and 7.2 , respectively. The impact of UE clustering on performance is studied in Sect. 7.3. In Sect. 7.4, we highlight the need for hybrid algorithms, and in Sect. 7.5 we show the validity of our heuristic proposals. We additionally study the impact of imperfect channel state information on both greedy (Sect. 7.6) and fair (Sect. 7.7) scheduling. Finally, we compare our work to one of the most common approaches to scheduling in full-duplex wireless networks, Sum-Rate Maximization, in Sect. 7.8. The paper is concluded with Sect. 8.

2 Related work and contributions

In this section, we discuss the state-of-the-art related to our work. We cover the different proposals intended to provide scheduling solutions for full-duplex wireless networks in general, and FD-OFDMA networks specifically, and then highlight our main contributions. Several papers in the state-of-the-art are concerned mainly with validating full-duplex technologies and their efficiency. The authors in [3–5] focus their work on proving the possible gains, as well as assessing the limitations of full-duplex wireless networks. Whether by implementing a full-duplex module as in [3], discussing different full-duplex scenarios as in [4], or even with a realistic model implementation in [5], these articles all show that significant rate gains can be achieved with full-duplex communications so long as the self-interference can be contained.

Several other papers in the state-of-the-art focus more on devising scheduling algorithms for full-duplex wireless networks, rather than on validating them. The authors in [6] design an optimal problem for joint power and resource allocation in a multi-carrier non-orthogonal multiple access system (MC-NOMA). They then propose a heuristic solution to avoid the complexity of their initial algorithm. Similarly, but for FD-OFDMA networks, the authors in [7–13] put forward joint power and resource allocation schemes. They propose optimization problems with greedy objectives focused on sum-rate maximization. The joint task of power allocation makes all these optimization problems of the category mixed integer non-linear programming (MINLP) with high complexity and computational intractability. As such, the authors work on heuristic solutions which can produce near optimal performances, but bear less complexity. In this paper, we propose optimal scheduling models for both full-duplex and hybrid OFDMA wireless networks. We then vary the objective of these models to obtain both greedy and fair scheduling algorithms.

These algorithms convey ideas of traditional scheduling techniques. Max-SINR scheduling [14] seeks to allocate resources to UEs with the best radio conditions. This maximizes the network throughput and thus increases the operator's profits. This method of scheduling however, could starve UEs at the boundaries of a cell. Their relatively poor radio conditions would see them deprived of any resources. Other scheduling techniques, such as Round Robin, would allocate resources to UEs in turn regardless of any other factor. Round Robin achieves total equity between the UEs at the cost of decreasing the network's throughput. The bandwidth is thus rendered inefficiently used. As a trade off between contradictory objectives, Proportional Fair [15] seeks to maximize the UE throughput, while at the same time ensuring a minimum level of service to UEs with poor radio conditions. It does so by allocating resources following a UE priority function that factors in a UE's current and historic throughput capabilities. Our devised algorithms, though based on such traditional ideas of scheduling, need to take into account several new factors. Scheduling in full-duplex is done for the uplink and the downlink simultaneously. In addition, the scheduler needs to allocate resources in a manner that takes self-interference into account, and at the same time, minimizes the effects of intra-cell co-channel interference. Inherently, this makes scheduling in full-duplex wireless networks much different than its half-duplex counterpart, even when seeking similar objectives.

Furthermore, our algorithms encompass a non-full buffer traffic model. Non-full buffer traffic like streaming and video, would make up to 78% of the global mobile traffic by the year 2021 [1]. This highlights the importance of studying how non-full buffer traffic affects our scheduling algorithms. Full-buffer models were used in the vast majority of the state-of-the-art. These models are far more optimistic than their dynamic counterparts. Assuming that each UE has an infinite stream of bits to transmit/receive allows scheduling algorithms to produce expected results without accounting for many real life wireless network aspects. For instance, the effect of multi-user diversity is exploited with full buffers as the network always has the choice to allocate any radio resource to any select UE. In addition, with all the UEs constantly requesting to transmit or receive, a scheduling model cannot account for cases where the interferences a wireless network exhibits change because of certain UEs emptying their queues. This sets full buffer traffic models apart from reality, sometimes deceivingly anticipating positive results that might not exist in a real network.

Our approach in the traffic model allows us to compute packet level metrics such as the waiting delay, and at the same time enables us to illustrate more accurately the impact of dynamic traffic on the scheduling algorithms. This model is part of the originality of our work, and is a more realistic approach compared to the full buffer traffic assumed in the articles in [4, 7–13].

Finally, the complexity of our proposed algorithms is low compared to the state-of-the-art. This reduced complexity makes our algorithms more efficient and easier to implement in practical wireless networks.

In our work, we seek to both validate the efficiency of full-duplex technologies, as well as propose algorithms for scheduling in full-duplex wireless networks. In what follows, we highlight our main contributions:

(a) We introduce optimal scheduling models for full-duplex and hybrid OFDMA wireless networks. The models have the originality of incorporating non-full buffer traffic, and can be applied with different scheduling objectives. As part of incorporating this realization, we use buffer constraints which help ensure that the radio resources are efficiently distributed among the UEs.

(b) Following the full-duplex model, we propose an optimal full-duplex Max-SINR algorithm that allocates radio resources to pairs of UEs which maximize the total sum of SINR values. We additionally propose an optimal full-duplex Proportional Fair algorithm which balances between the objectives of maximizing the network throughput and ensuring fairness among UEs. Because the optimal model is NP-Complete, we propose heuristic algorithms with the same objectives.

(c) The value of full-duplex scheduling remains tied to the strength of the SIC, and the radio conditions in general (as illustrated in Sect. 7.4). Thus, following the optimal hybrid model, we propose hybrid scheduling algorithms with both greedy and fair objectives. These algorithms allocate resource astutely either in full-duplex to two UEs, or in half-duplex to one. The decision is made depending on which allocation increases the value of the objective function. Similarly, and in order to avoid the complexity of the optimization problem, we introduce heuristic versions of these algorithms.

(d) We address the availability of complete channel state information in a full-duplex network, and assess the necessity of this information in achieving gains from full-duplex wireless communications.

(e) Throughout different simulation scenarios, and via comparisons with the state-of-the-art as well as with half-duplex communications, we highlight the gains full-duplex wireless networks hope to achieve.

3 System model

3.1 Radio model

We consider a single-cell FD-OFDMA wireless network. This network is comprised of a full-duplex BS, and half-duplex UEs. The UEs are virtually divided into two sets: an uplink UE set, denoted by $\mathcal{U}$ and a downlink UE set, denoted by $\mathcal{D}$. The scheduling algorithms would pair between uplink and downlink UEs on the resource blocks (RBs) k of the set $\mathcal{K}$. This network is illustrated in Fig. 1.

In our work, we assume that the physical layer is operated using an OFDMA structure. The radio resources are divided into time-frequency RBs. In the time domain, an RB contains an integer number of OFDM symbols. In the frequency domain, an RB contains adjacent narrow-band subcarriers and experiences flat fading. Scheduling decisions for downlink and uplink transmissions are made in every transmission time interval (TTI). At the beginning of each TTI, K RBs are to be allocated. The TTI duration is chosen to be smaller than the channel coherence time. With these assumptions, UE radio conditions will vary from one RB to another, but remain constant over a TTI. The modulation and coding scheme (MCS), that can be assigned to a UE on an RB, depends on its radio conditions. For performance evaluation, we consider LTE like specifications, with an RB being composed of 12 subcarriers and 7 OFDM symbols [14].

Table 1 has a summary of the notations used in this paper. An adapted formula is used to calculate the signal-to-interference-plus-noise ratio (SINR) that takes into consideration the co-channel interference between a UE pair, and the self-interference cancellation performed by the BS. Let $P^u_{i,k}$ denote the transmit power of the ith uplink user, on the kth RB. Similarly, $P^d_{j,k}$ is the transmit power of the BS serving downlink user j, on the kth RB. We denote by $h^u_{i,k}$ the channel gain from the ith uplink user to the BS on RB k, and by and $h^d_{j,k}$ the channel gain from the BS to the jth downlink user, on the kth RB. Furthermore, $h_{ji,k}$ denotes the channel gain between the ith uplink user and jth downlink user, on the kth RB. $P^u_{i,k}|h_{ji,k}|^2$ is thus the co-channel interference on downlink UE j caused by uplink UE i, using the same RB k. The self-interference cancellation level at the BS is denoted SIC. In particular, $\frac{P^d_{j,k}}{SIC}$ represents the residual self-interference power at the BS, on the kth RB. Finally, $N_{0,k}$ and $N_{j,k}$ denote the noise powers at the BS and at the jth downlink user, on the kth RB, respectively. Equations (1) and (2) denote the formulas for SINR calculation for uplink and downlink UEs. For an uplink UE,

$$S^u_j(i,k) = \frac{P^u_{i,k}|h^u_{i,k}|^2}{N_{0,k} + \frac{P^d_{j,k}}{SIC}}, \quad i \in \mathcal{U}, \quad j \in \mathcal{D}. \tag{1}$$

For a downlink UE,

$$S^d_i(j,k) = \frac{P^d_{j,k}|h^d_{j,k}|^2}{N_{j,k} + P^u_{i,k}|h_{ji,k}|^2}, \quad i \in \mathcal{U}, \quad j \in \mathcal{D}, \tag{2}$$

where $S^u_j(i,k)$ is the SINR of uplink UE i on RB k while using the same resources as downlink UE j. Similarly, $S^d_i(j,k)$ is the SINR of downlink UE j on RB k while using the same resources as uplink UE i. Note that the inter-UE channel $h_{ji,k}$ is the focus of our simulation scenarios on channel state information availability.

3.2 Channel state information

Legacy half-duplex wireless networks are concerned mainly with the channel in between the BS and the UEs (i.e., $h^u_{i,k}$ and $h^d_{j,k}$). They rely on feedback from the UEs to determine the current channel state on the downlink. Different techniques are used to determine how often, and on which RBs, would this feedback information be required.

Table 1 Notation summary

Notation	Definition
$S^u_j(i,k)$	SINR of uplink UE i paired with downlink UE j on RB k
$S^d_i(j,k)$	SINR of downlink UE j paired with uplink UE i on RB k
$P^u_{i,k}$	Transmit power of uplink UE i on RB k
$P^d_{j,k}$	BS transmit power on RB k allocated to downlink UE j
$h^u_{i,k}$	Channel between UE i and the BS on RB k
$h^d_{j,k}$	Channel between UE j and the BS on RB k
$h_{ji,k}$	Inter-UE channel between UEs i and j on RB k
SIC	Self-interference cancellation factor
$N_{0,k}$	Noise power at the BS on RB k
$N_{j,k}$	Noise power at UE j on RB k

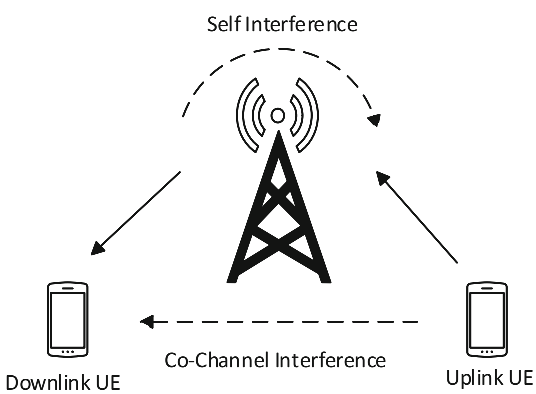

Fig. 1 Network model and interferences

The more periodic the feedback, the more accurate the channel estimation is.

Full-duplex communications add to the complexity of determining the channel state information (CSI). In full-duplex networks, additional information on the channel in between the UEs of a certain pair (i.e., $h_{ji,k}$) is required. Not only do current wireless networks not count for such information, there is also no implemented method for which a UE can estimate such UE–UE channels. Additionally, it is perceivable that measuring and continuously updating such information by the UEs would cause excessive overhead and loads that UEs cannot handle. Consequently, precisely estimating inter-UE channels might not be feasible. In our work, we statistically model the inter-UE channel as follows:

$$h_{ji,k} = G_t G_r L_p A_s A_f \tag{3}$$

G_t and G_r are the antenna gains at the transmitter and the receiver, respectively. L_p represents the path loss, or equivalently the median attenuation the signal undergoes in this channel. A_s and A_f are two random variables that respectively represent the shadowing effect, and the fast fading effect.

3.3 Traffic model

Queue-awareness is incorporated into our scheduling model (Fig. 2). Each UE has a predefined throughput demand which determines the rate at which the UE will transmit or receive. A downlink UE has a queue at the BS, denoted Q_j^d, that it wants to receive. An uplink UE has a queue of bits it wants to transmit to the BS, denoted Q_i^u. UE queues are updated each TTI. They are filled according to a random process with a number of bits/s equal, on average, to the UE throughput demand. Once the scheduling is done for a certain TTI, the scheduler computes the number of bits each UE can transmit or receive, and the UE queues are deducted accordingly. Any bits remaining in a UE queue at the end of a TTI are carried on to the next.

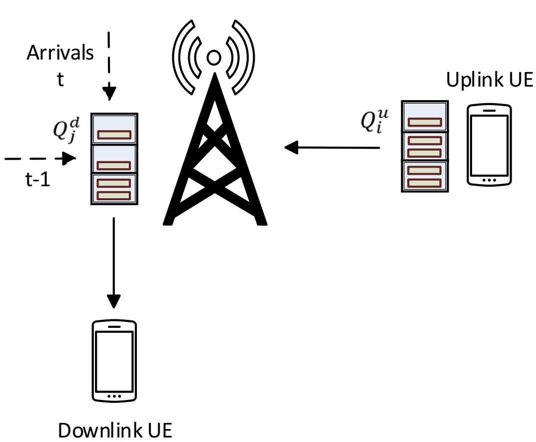

Fig. 2 Traffic model: UE pair i–j

4 Optimal scheduling model

4.1 Queue-aware full-duplex scheduling model

We propose an optimal scheduling model for FD-OFDMA networks. We define the UE pair-RB assignment variable $z_{ijk}, \forall\, k \in \mathcal{K}, \forall\, i \in \mathcal{U}, \forall\, j \in \mathcal{D}$. z_{ijk} is equal to one if uplink UE i is paired with downlink UE j on RB k. It is equal to zero otherwise. In the following problem, $F_j^u(i,k)$ is the utility function of uplink UE i on RB k, while it is paired with downlink UE j. Likewise, $F_i^d(j,k)$ is the utility function of downlink UE j on RB k, while it is paired with uplink UE i. We will use this utility function to vary the objective of our problem. We formulate the optimization problem as follows:

$$\text{Maximize} \quad \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}\left(F_j^u(i,k) + F_i^d(j,k)\right), \tag{4a}$$

$$\text{Subject to} \quad \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk} \le 1, \;\; \forall k \in \mathcal{K}, \tag{4b}$$

$$\alpha_p \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} z_{ijk} T_{ijk}^u \le D_i^u, \;\; \forall i \in \mathcal{U}, \tag{4c}$$

$$\alpha_p \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} z_{ijk} T_{ijk}^d \le D_j^d, \;\; \forall j \in \mathcal{D}, \tag{4d}$$

$$z_{ijk} \in \{0,1\}, \;\; \forall i \in \mathcal{U}, \forall j \in \mathcal{D}, \forall k \in \mathcal{K}. \tag{4e}$$

T_{ijk}^u is the number of bits uplink UE i can transmit on RB k while paired with downlink UE j. Similarly, T_{ijk}^d is the number of bits UE j can receive on RB k while paired with UE i. T_{ijk}^u and T_{ijk}^d depend mainly on the radio conditions of the UEs. In addition, D_i^u is the demand of UE i i.e., the number of bits in its queue. Likewise, D_j^d is the demand of UE j. Equation (4a) expresses the objective of our problem, which consists of maximizing the total sum of the utility of the pairs that are allocated RBs. According to (4b), each RB should be allocated to a maximum of one pair. Constraints (4c) and (4d) ensure that a UE will transmit or receive at least α_p of the bits it can on the resources allocated to it. If $\alpha_p = 1$, then a UE is allocated an additional resource if the number of bits in its queue is greater than or equal to the number of bits it can transmit or receive on the resources allocated to it. If $\alpha_p = 0.8$, then a UE will efficiently utilize at least 80% of the resources allocated to it, or in other terms the number of bits in its queue is greater than or equal to 80% of the number of bits it can transmit or receive on the resources allocated to it. As we devise a queue-aware model, the number of bits that each UE would receive or transmit in a certain TTI varies and these buffer constraints are as such necessary to ensure that the resources are distributed efficiently. α_p is a constraint on resource usage regardless of, as well as adaptive to, the number of bits in a UE queue. The optimization problem is run every TTI to determine how the resources will be allocated to the UEs.

4.2 Queue-aware hybrid scheduling model

The feasibility of full-duplex communications is related to the cell radio conditions, as well as the resulting interference problems. This hybrid model allows the scheduler to choose between allocating the RBs in full-duplex or half-duplex, depending on which yields a higher sum of the UE utility functions (5a).

Let y^u_{ik}, $\forall\ k \in \mathcal{K}$, $\forall\ i \in \mathcal{U}$ be the uplink UE-RB half-duplex assignment variable. It is equal to one if uplink UE i is allocated RB k in half-duplex. It is equal to zero otherwise. Similarly, y^d_{jk} is the downlink UE-RB half-duplex assignment variable. The hybrid optimization problem is formulated as follows:

$$\text{Maximize} \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}(F^u_j(i,k)+F^d_i(j,k)) + \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} y^u_{ik}F^u(i,k) + \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} y^d_{jk}F^d(j,k), \tag{5a}$$

Subject to

$$\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk} + \sum_{i\in\mathcal{U}} y^u_{ik} + \sum_{j\in\mathcal{D}} y^d_{jk} \le 1,\ \ \forall k\in\mathcal{K}, \tag{5b}$$

$$\alpha_p\left(\sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} z_{ijk}T^u_{ijk} + \sum_{k\in\mathcal{K}} y^u_{ik}T^u_{ik}\right) \le D^u_i,\ \ \forall i\in\mathcal{U}, \tag{5c}$$

$$\alpha_p\left(\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} z_{ijk}T^d_{ijk} + \sum_{k\in\mathcal{K}} y^d_{jk}T^d_{jk}\right) \le D^d_j,\ \ \forall j\in\mathcal{D}, \tag{5d}$$

$$z_{ijk}, y^u_{ik}, y^d_{jk} \in \{0,1\},\ \ \forall i\in\mathcal{U}, \forall j\in\mathcal{D}, \forall k\in\mathcal{K}. \tag{5e}$$

$F^u(i,k)$ and $F^d(j,k)$ are the utility functions for half-duplex uplink UE i and half-duplex downlink UE j, respectively. T^u_{ik} is the number of bits uplink UE i can send on RB k if it gets it in half-duplex. Similarly, T^d_{jk} is the number of bits downlink UE j can receive on RB k if it gets it in half-duplex. The constraint in (5b) imposes that an RB is allocated only once, either in full-duplex to two UEs, or in half-duplex to one. The constraints (5c) and (5d) serve the same purpose as (4c) and (4d), with the possibility of a half-duplex allocation considered. These constraints ensure the resources are allocated efficiently in an environment with dynamic traffic arrivals. In what follows we will change the utility function, and thus the objective of the problem, generating algorithms that are either greedy or fairness oriented.

5 Optimal resource allocation

5.1 Our proposals

In this section, we present our optimal algorithms for scheduling in FD-OFDMA wireless networks. By changing the utility functions in both the full-duplex and hybrid models, we are able to propose four algorithms with different scheduling objectives. We change the objective function in (4a) such that the utility function F is equal to the UE SINR:

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}(S^u_j(i,k)+S^d_i(j,k)), \tag{6}$$

This algorithm, full-duplex Max-SINR, calculates the SINR, on every RB, for each possible pair between an uplink UE and a downlink UE. It then proceeds to allocate each RB to the UE pair that maximizes the objective function. This approach favors the best performing UEs, leading to an increase in the network's overall throughput. Nonetheless, UEs with bad radio conditions could experience bandwidth starvation.

Full-duplex Max-SINR is as such greedy and opportunistic. While such an approach could lead to the most efficient utilization of resources, it is generally unfair. We are interested in taking a different, and more fair advance on the scheduling task. Therefore, we propose an optimal full-duplex Proportional Fair algorithm. We change the utility function in (4a) to be equal to the UE priority. This yields the objective function presented by our second proposal, full-duplex Proportional Fair.

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}(\rho^u_j(i,k)+\rho^d_i(j,k)), \tag{7}$$

where $\rho^u_j(i,k)$ is the priority of uplink UE i, and $\rho^d_i(j,k)$ is the priority of downlink UE j, when paired with each other. The priority of a UE is defined as a function of its current radio conditions, represented by the number of bits a UE can transmit on the selected RB, and its historic radio conditions, represented by the number of bits it has already transmitted. The priority for an uplink UE i while paired with downlink UE j on RB k, for example, is defined as:

$$\rho^u_j(i,k) = \frac{T^u_{ijk}}{T_i}, \tag{8}$$

where T_i is the number of transmitted bits within a certain time window. The priority of a UE thus decreases as it transmits more. This gives higher priority to UEs which have not transmitted in a while, while still factoring in the current radio conditions of the UEs.

Making the algorithms hybrid guarantees that the network is always working in the transmission mode that enhances its performance. Depending on the radio conditions, and the quality of the SIC available, full-duplex communications might not always even be viable. For low values of SIC, uplink UEs could be totally denied access to the network resources. We thus seek to allow the scheduler to astutely choose between allocating an RB to a single UE (half-duplex) or to a pair of UEs (full-duplex).

We change the utility function F in Eq. (5a) to be equal to the UE SINR to yield a hybrid Max-SINR algorithm.

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}\left(S_j^u(i,k)+S_i^d(j,k)\right) + \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} y_{ik}^u r^u(i,k) + \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} y_{jk}^d r^d(j,k), \tag{9}$$

where $r^u(i,k)$ and $r^d(j,k)$ are the SINR of UEs i and j in half-duplex. Similarly, replacing F with the UE priority yields a hybrid Proportional Fair algorithm.

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}\left(\rho_j^u(i,k)+\rho_i^d(j,k)\right) + \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} y_{ik}^u \rho^u(i,k) + \sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} y_{jk}^d \rho^d(j,k), \tag{10}$$

$\rho^u(i,k)$ and $\rho^d(j,k)$ are the half-duplex priorities of UEs i and j i.e, their priorities if they were to be allocated resources solely. In both algorithms, the scheduling decision is done following the allocation mode that would maximize the objective function (5a). In hybrid Max-SINR for example, if the maximum half-duplex UE SINR value on a certain RB is higher than the corresponding full-duplex highest sum of SINR values, the resource is allocated in half-duplex. Otherwise, it is allocated in full-duplex. Note that in case of half-duplex scheduling the SINR for an uplink UE i on an RB k is calculated as:

$$r^u(i,k) = \frac{P_{i,k}^u |h_{i,k}^u|^2}{N_{0,k}}, \quad i \in \mathcal{U}. \tag{11}$$

And for a downlink UE j,

$$r^d(j,k) = \frac{P_{j,k}^d |h_{j,k}^d|^2}{N_{j,k}}, \quad j \in \mathcal{D}, \tag{12}$$

As for the priorities of the half-duplex UEs, they are calculated as a function of the number of bits a UE can transmit or receive on an RB. For example, for an uplink UE i transmitting solely on an RB k, the half-duplex UE priority can be written as:

$$\rho^u(i,k) = \frac{T_{ik}^u}{T_i}, \tag{13}$$

In presence of sufficient self-interference cancellation at the BS, our full-duplex algorithms will perform identically to our hybrid algorithms, albeit with less complexity. The hybrid algorithms would always be allocating the RBs in full-duplex, because the network conditions will always make it the more lucrative choice. However, if that was not the case, the hybrid algorithms would be trading more complexity for better resource allocation. A practical evaluation of the complexity is presented in the following section.

5.2 Complexity of the optimal problem

5.2.1 Full-duplex scheduling model

The variables in this optimization problem are all integers. The objective function and the constraints, which depend on the binary value of z_{ijk}, are linear. The problem is thus of type integer linear (ILP), and specifically of the type binary linear programming (BLP). The number of constraints and variables are important factors when estimating if this problem is tractable. These problems can, in principle, be solved by complete enumeration of candidate solutions. This method is known as branch and bound [16], where the set of candidate solutions is thought of as forming a rooted tree with the full set at the root. The branch and bound algorithm explores the branches of this tree, which represent subsets of the solution set. Before enumerating the candidate solutions of a branch, the branch is checked against upper and lower estimated bounds on the optimal solution, and is discarded if it cannot produce a better solution than the best one found so far by the algorithm. Theoretically speaking, the branch and bound technique has no limitations on the number of variables, but it would be taking more time to solve the problem as their numbers increase. The problem would eventually become computationally intractable. Our estimation is that that would occur when the number of UEs is in the hundreds.

Our optimal scheduling formulation can be classified as an NP-Hard problem. We can do this by reducing the Graph Coloring problem (whose optimization is a well-known NP-Hard problem) into our scheduling problem. Graph Coloring [17] is the problem of assigning colors to the elements of a graph (edges and vertices) subject to certain constraints. In its simplest form, it is a way of coloring the vertices of a graph such that no two adjacent vertices are of the same color; this is called a vertex coloring. Alternatively, edge coloring assigns a color to each edge in a manner that no two adjacent edges are of the same color.

Edge coloring can indeed be used to model scheduling problems. The details of the latter will therefore define the structure of the graph. Let the vertices of the graph be the RBs and the edges be the UE pairs. Adjacent edges cannot have the same color i.e., no two pairs can be allocated the same RB.

Finally, in his seminal work in [18], Karp detailed 21 NP-Complete problems which include binary linear programming. This means that our scheduling model can be further classified as NP-Complete.

5.2.2 Hybrid scheduling model

This model is similar in form to the full-duplex model. All the variables are binary, and the constraints are linear, and dependent on the binary variables. Following the same reasoning with regards to the Graph Coloring problem, we can conclude that the hybrid scheduling problem is of type NP-Hard. As the problem is also of type BLP, it can additionally be classified as NP-Complete [18]. Containing more variables and more constraints, this problem would take more time to solve than the previous one.

The complexities of the optimization problems, which can become prohibitive for an increased number of resources and UEs, motivates a heuristic approach. In the following section, we provide heuristic algorithms with the same objectives as the optimization problem, albeit bearing less complexity.

6 Heuristic algorithms

6.1 Our proposals

Seeking scheduling solutions with less complexity, we present heuristic algorithms corresponding to our optimal propositions. First, we introduce a heuristic full-duplex Max-SINR algorithm [19, 20]. This algorithm seeks to couple between two half-duplex UEs, one on the uplink and one on the downlink, on the same RBs. The traffic is non-full buffer. As such, a UE that has depleted its queue is excluded from the next resource allocation within the same TTI. For each RB k of the set $\mathcal{K}$, the algorithm calculates the SINR for each possible pair between an uplink UE and a downlink UE. The algorithm computes the SINR as indicated in Eqs. (1) and (2), and allocates the currently selected RB to the pair of UEs which has the highest value of the sum: $S_j^u(i,k) + S_i^d(j,k)$, where i belongs to the set of uplink UEs and j to the set of downlink UEs. This algorithm is iterative. In contrast with the globality of the optimization problem, which makes the allocation decision for all the resources at the same time, the decision here is made for each RB in turn. Moreover, in case it is impossible to pair between UEs due to one of the uplink or downlink sets being empty, the scheduler allocates the RB to a single UE. In such a case, the SINR is computed as in typical half-duplex networks.

If all the UEs empty their queues before the resources are depleted, the remaining RBs are marked as free. The function *UpdateQueue*(x), in Algorithm 1, is responsible for updating the queue status (of UE x) and the UE sets after resource allocation. The number of transmitted bits is calculated for each UE allocated an RB depending on the MCS and decremented from its corresponding queue. The pseudo-code for full-duplex Max-SINR is shown in Algorithm 2, when the utility function is equal to the UE SINR.

Algorithm 1 Queue Update Function

```
function UPDATEQUEUE(UE x)
if x ∈ 𝒰 then
    Q^u_x ← Q^u_x − T^u_{xjk}
    if Q^u_x == 0 then
        𝒰 ← 𝒰 − {x}
    end
end
if x ∈ 𝒟 then
    Q^d_x ← Q^d_x − T^d_{ixk}
    if Q^d_x == 0 then
        𝒟 ← 𝒟 − {x}
    end
end
end function
```

Algorithm 2 Heuristic Scheduling

```
for k=1,...,K do
    if 𝒰 ≠ ϕ and 𝒟 ≠ ϕ then
        (i*, j*) = argmax_{i∈𝒰, j∈𝒟} (F^u_j(i,k) + F^d_i(j,k))
        Allocate RB k to couple (i*, j*)
        UpdateQueue(i*), UpdateQueue(j*)
    else
        Select the best performing half-duplex UE e* such that
        e* = argmax_{e∈𝒰∪𝒟} (F(e,k))
        Allocate RB k to user e*
        UpdateQueue(e*)
    end
end
```

Similarly, we propose a heuristic version of our full-duplex Proportional Fair algorithm. For every RB, the UE pair with the highest sum of priorities is chosen. The corresponding pseudo-code is shown in Algorithm 2, when the objective function is equal to the priority of the UEs.

We further propose a heuristic implementation of our hybrid Max-SINR algorithm. The scheduling decision for this algorithm is done based on the following criteria. For every RB, pair allocation is used if the following condition is met:

$$S_j^u(i^*,k) + S_i^d(j^*,k) > r(e^*,k), \quad (14)$$

where $r(e^*,k)$ is the highest SINR value for a half-duplex UE and (i^*,j^*) is the UE pair with the highest sum of SINR values. Under this condition, we assume that we have sufficient SIC and/or acceptable radio conditions to support full-duplex communications. Otherwise, the scheduler allocates the RB in half-duplex to UE e^* which has the highest SINR (uplink or downlink). The pseudo-code for the algorithm is illustrated in Algorithm 3 when the objective function is equal to the UE SINR.

Algorithm 3 Hybrid Heuristic Scheduling

```
for k=1,...,K do
    (i*, j*) = argmax_{i∈U, j∈D} (F_j^u(i,k) + F_i^d(j,k))
    e* = argmax_{e∈U∪D} (F(e,k))
    if F_{j*}^u(i*,k) + F_{i*}^d(j*,k) > F(e*,k) then
        Allocate RB k to couple (i*, j*)
        UpdateQueue(i*), UpdateQueue(j*)
    else
        Allocate RB k to UE e*
        UpdateQueue(e*)
    end
end
```

Similarly, we propose a heuristic hybrid Proportional Fair algorithm. The scheduling decision for this algorithm is done based on the following criteria. For every RB, pair allocation is used if the sum of priorities of any UE pair is greater than the highest priority value of a single UE:

$$\rho_j^u(i^*,k) + \rho_i^d(j^*,k) > \rho(e^*,k), \quad (15)$$

where $\rho(e^*,k)$ is the highest priority value for a half-duplex UE, and (i^*, j^*) is the UE pair with the highest sum of priorities. We assume that we have sufficient SIC and/or acceptable radio conditions to support full-duplex communications. Otherwise, the scheduler allocates the RB in half-duplex to the UE with the highest priority (uplink or downlink). The pseudo-code for the algorithm is illustrated in Algorithm 3, when the utility function is set to be equal to the priority of the UEs.

Finally, we introduce the last of our proposed algorithms, full-duplex Round Robin. The general idea is to make a list of random pairs, and then proceed to allocate the RBs to the pairs on this list in turn, regardless of any other factor. This might cause some UEs to be at a great disadvantage if the UEs of a pair are close to each other, or far away from the BS. Thus, we randomly re-pair the UEs at the beginning of every TTI. Note that if only one UE of a pair has emptied its queue, the other UE keeps getting the resource in its turn till the end of the TTI, albeit this time in half-duplex.

6.2 Complexity of the heuristic algorithms

Our heuristic algorithms have complexities of the same order. The wireless network has U uplink UEs, and D downlink UEs. This amounts to a total of $n = U.D$ possible UE pairs. In order to allocate the resources, the algorithm needs to find the UE pairs with the highest sum of SINR or priorities. The complexity of these heuristic algorithms is thus of the order $\mathcal{O}(n)$ [18].

We compare the simulation duration for each of the optimal and heuristic Max-SINR algorithms. The SIC value is set to 10^{11}. 10 UEs are simulated along with 20 RBs. We note the time taken by the simulator to allocate the resources during one TTI. A statistical interpretation of the results is given in Table 2. The criteria are measured in seconds. The machine used for the simulations has an INTEL(R) core i3-4170 CPU at 3.70 GHz processor. It runs on 8 GB of RAM.

For a limited number of RBs and UEs, the optimal algorithm can solve the resource allocation problem faster than the heuristic one. However, there are few exceptions as indicated by the higher mean value for the optimal algorithm.

7 Simulation and results

We are interested in verifying, via simulations, four major statements. First, we want to affirm the gains that full-duplex wireless networks bring, compared to half-duplex networks, and in different simulation scenarios. Second, we seek to justify the necessity for a hybrid algorithm, illustrating the cases where full-duplex alone would not be viable. Third, we want to validate our heuristic algorithms, and show that they achieve near optimal performances. Finally, we want to prove that our algorithms still produce gains, with respect to half-duplex wireless networks, in the case of incomplete channel state information. We simulate our algorithms using a class based simulator we developed in Matlab [21]. In order to solve the optimization problems, we use CVX [22], a Matlab software for disciplined convex programming.

Table 2 Heuristic versus optimal: simulation time

Criteria	Optimal (s)	Heuristic (s)
Mean	1.3125	0.1710
1st quartile	0.1563	0.1646
Median	0.1563	0.1692
3rd quartile	0.1836	0.1748

Table 3 Simulation parameters

Parameter	Value
Cell specifications	Single-cell, 120 m radius
Number of RBs	50
BS transmit power	24 dBm
Maximum UE transmit power	24 dBm
α_p	1
SIC value	10^{11}–10^{8}
Number of UEs	10 DL, 10 UL
UE distribution	Uniform
Demand throughput	2–4 Mbps
Fast fading	Exponential variable
Shadowing	Log-normal variable
Path loss model	Extended hata path loss model

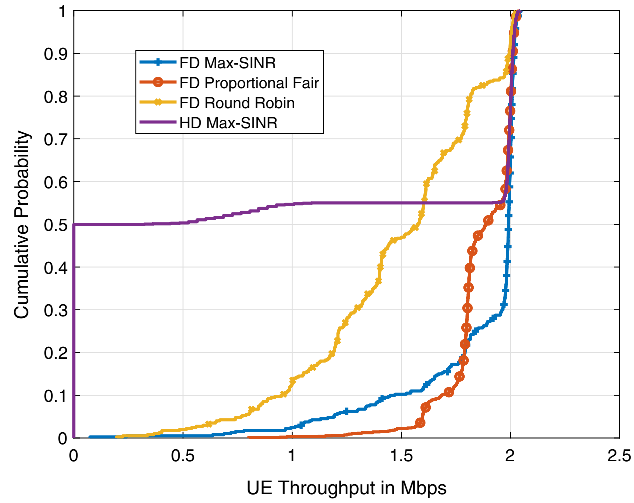

Fig. 3 Full-duplex algorithms performance in terms of UE throughput

Table 3 has our simulation parameters. The channel gain takes into account the path loss, the shadowing and the fast fading effects. The path loss is calculated using the extended Hata path loss model [23]. The shadowing is modeled by a log-normal random variable $A_s = 10^{(\frac{\xi}{10})}$, where ξ is a normal distributed random variable with zero mean and standard deviation equal to 10. The fast fading is modeled by an exponential random variable A_f with unit parameter. This model is used for urban zones, and it takes into account the effects of diffraction, reflection and scattering caused by city structures.

7.1 Simulation scenario 1: performance of the full-duplex algorithms

The global optimal problem is NP-complete, and as we demonstrate later on, our heuristic algorithms produce near-optimal results. As such, we are going to consider multiple scheduling scenarios in order to better study the performances of the heuristic algorithms specifically, as well as the performance of full-duplex wireless networks in general.

Following the parameters indicated in Table 3, we simulate our full-duplex Max-SINR, Round Robin, and Proportional Fair algorithms. As a half-duplex reference, we simulate a traditional half-duplex Max-SINR algorithm. Figure 3 is a cumulative distribution function (CDF) plot of the throughput values attained by the UEs across the simulations. The trends which are set by the scheduling techniques are clear. Max-SINR, whether in half-duplex implementation, or in our full-duplex algorithm, seeks to serve the UEs with the best radio conditions. Nonetheless, around 70% of the full-duplex Max-SINR UEs attained a throughput equal to the demand, significantly more than that of its half-duplex counterpart at 45%.

On the other hand, Proportional Fair scheduling seeks equity between the UEs. The percentage of full-duplex Proportional Fair UEs which have attained a throughput equal to the demand sits at around 45%, less than that of full-duplex Max-SINR. However, the least attained UE throughput for full-duplex Proportional Fair is about 0.75 Mbps, compared to 0 Mbps (by 50% of the UEs simulated) for half-duplex Max-SINR and around 0.1 Mbps, the lowest for a full-duplex Max-SINR UE. Full-duplex Proportional Fair will degrade the performance of UEs with excellent radio conditions in order to provide resources to UEs with poor radio conditions.

Finally, our full-duplex Round Robin algorithm shows that even with random allocation, full-duplex can provide significant improvement with respect to half-duplex communications. Whilst half-duplex Max-SINR produces more UEs with throughput equal to the demand, our Round Robin algorithm gave better throughput values for about 55% of the UEs. The median UE throughput value for full-duplex Round Robin is about 1.6 Mbps.

We compute the fairness index, for each of the four algorithms, for the current simulation scenario. We use Jain's fairness index [24] to determine whether the resources are getting allocated fairly under our proposed scheduling algorithms. This index is computed according to the Raj-Jain equation as follows:

$$\mathcal{J}(x_1, x_2, \ldots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n.\sum_{i=1}^{n} x_i^2}. \qquad (16)$$

$\mathcal{J}$ represents the fairness of a scheduling algorithm, for n UEs, of x_i throughput each. The result for an algorithm is between $\frac{1}{n}$ and 1. It is maximum when all the UEs receive the same allocation. Full-duplex Proportional Fair allocates resources more fairly than the others, with a Jain index value equal to 0.97. Full-duplex Max-SINR sits near 0.80, and half-duplex Max-SINR with the lowest value close to 0.5. Max-SINR is opportunistic and greedy, it would not allocate resource fairly. This is shown clearly in the case of half-duplex Max-SINR, but rather concealed with full-duplex Max-SINR. The reason for that is that with this full-duplex scenario, UEs have practically double the resources at their disposal, sharply decreasing the unfair nature of Max-SINR scheduling.

Furthermore, we compare between these algorithms in terms of the average waiting delay for the UEs. The average waiting delay is calculated using Little's formula as the average queue length divided by the packet arrival rate. Figure 4 has box plots of the average waiting delay for the UEs, per simulation run, across the four algorithms we simulated in this section. Our full-duplex Proportional Fair and Max-SINR algorithms heavily outperform the rest in terms of maximum delay, with full-duplex Max-SINR edging out full-duplex Proportional Fair when it comes to UEs with bad radio conditions. Moreover, it is noticeable that all the full-duplex algorithms outperform half-duplex ones in terms of waiting delay. Naturally, with good SIC, full-duplex UEs will on average be getting double the resources, and thus experiencing half the delay. Full-duplex Round Robin UEs experience on average 1 ms less delay than half-duplex UEs. Full-duplex Proportional Fair and Max-SINR UEs experience on average more than 2 ms less delay.

7.2 Simulation scenario 2: heterogeneous traffic

We repeat the same simulations, but with heterogeneous traffic for the UEs. With equal probability, the throughput demand for the UEs is set to either 2 or 4 Mbps. All other parameters remain unchanged from the previous section. Figure 5 shows the throughput attained by the UEs, while scheduling using each of our proposed full-duplex heuristic algorithms.

The trends by the algorithms we observed in the previous section remain pertinent. Full-duplex Max-SINR allocates resources to the UEs with the best radio conditions. The Max-SINR algorithm thus has the highest percentage of UEs attaining a throughput equal to their demand, be it 2 or 4 Mbps. The tendency for full-duplex Proportional Fair to allocate resource more fairly is also visible. No full-duplex Proportional Fair UE attained a throughput less than 0.75 Mbps. All other algorithms have UEs which have been totally denied resources. The Jain fairness index reflects this, with full-duplex Proportional Fair having an index value of 0.95, compared to 0.73 for full-duplex Max-SINR.

7.3 Simulation scenario 3: UE clustering

In this subsection, we study the effects of UE clustering on the performance of our algorithms. The cell has 20 UEs, 10 uplink (UL), and 10 downlink (DL), with the throughput demand set to 2 Mbps. The SIC value is 10^{11}. All other parameters remain as in Table 3. We form a cluster containing all 20 UEs. The circular cluster's center is 50 m away from the BS, and has a radius of 10 m. The clustering of UEs means bringing them closer to each other. As such, the intra-cell co-channel interference would spike. This affects the SINR of downlink UEs in a full-duplex network (Eq. 2). Therefore, we plot the uplink and downlink UE throughput values separately.

Figure 6 has box plots of the UE throughput values for this simulation scenario. For all of our full-duplex

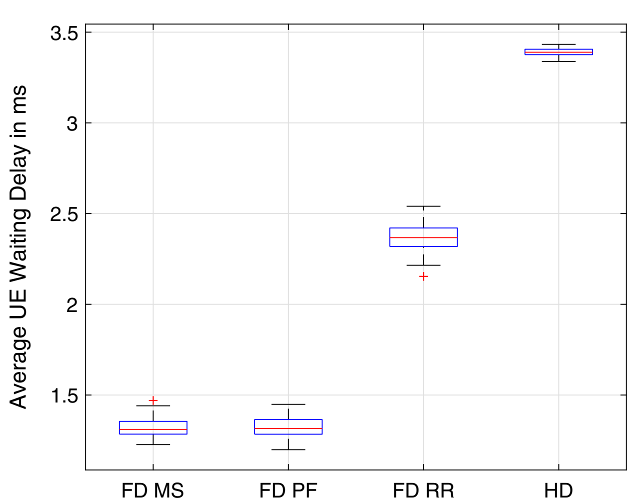

Fig. 4 Full-duplex algorithms performance in terms of average UE waiting delay

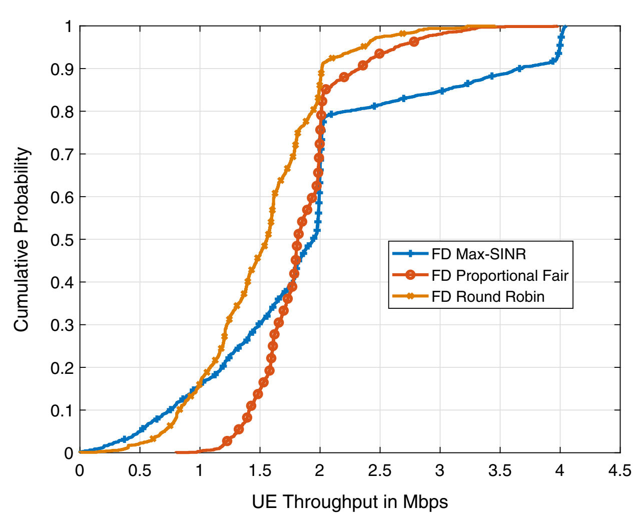

Fig. 5 Full-duplex algorithms performance in the case of heterogeneous traffic

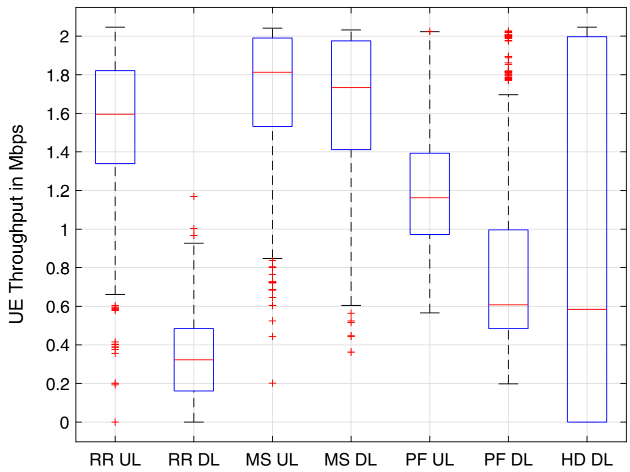

Fig. 6 Effect of UE clustering on UE throughput

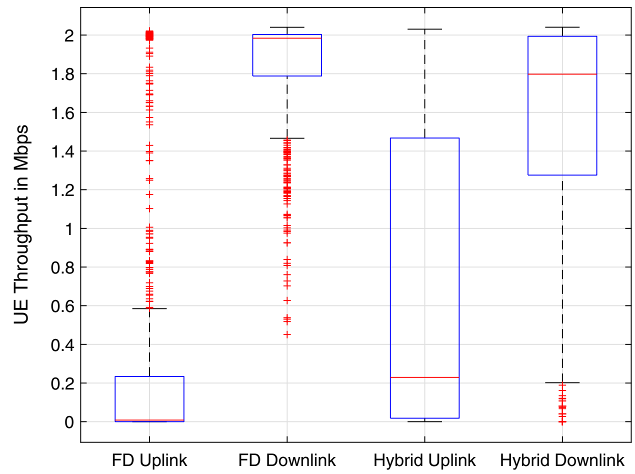

Fig. 7 Effect of low SIC on UE throughput

algorithms, a degradation in performance of downlink UEs is seen. The full-duplex Round Robin algorithm UEs suffer the most. Since no specific method is implemented in this case to avoid scheduling pairs with bad radio conditions, the chance of selecting downlink UEs with bad radio conditions increases. Downlink UEs scheduled with the full-duplex Proportional Fair algorithm also have their throughput values decreased, although to a lesser extent. Nonetheless, because of the small cell size, and the greedy nature of the algorithm, full-duplex Max-SINR downlink UEs are effected the least by the clustering. Following these results, we can argue the need for a hybrid algorithm that could switch scheduling to half-duplex when a certain threshold, below which full-duplex is no longer profitable, is reached.

7.4 Necessity of hybrid algorithms

The effect of UE clustering on the performance of downlink UEs, shown in the previous section, is just a part of the argument for hybridity. We examine the performance of our heuristic full-duplex Max-SINR algorithm, in comparison to that of our hybrid Max-SINR algorithm in the presence of insufficient self-interference cancellation. The SIC factor is set at the relatively low value of 10^8. The box plots in Fig. 7 show the UE throughput per simulation for both downlink and uplink UEs.

Figure 7 shows a median on the verge of 0 Mbps throughput for full-duplex Max-SINR UEs in the uplink. These UEs are completely denied any resources. Self-interference degrades the performance of uplink UEs, as shown in the SINR equations, where the decrease in the SIC factor decreases the uplink UEs' SINR. Downlink UEs do not suffer under low SIC values, however, their good performance in this case is not of importance, as we would not operate a wireless network in which there can be little to no transmission on the uplink. On the other hand, the hybrid Max-SINR algorithm does far better. Almost none of the hybrid algorithm UEs got denied throughput, and the median on the uplink is greater than 200 kbps. Therefore, the availability of a hybrid algorithm improves the performance of the network, especially when UE radio conditions go below that certain threshold where half-duplex communications becomes more profitable than their full-duplex counterparts.

Finally, we compare our hybrid algorithm to traditional half-duplex Max-SINR scheduling. In the worst case scenario, the hybrid algorithm would choose to allocate all the resource in half-duplex, and would thus match half-duplex Max-SINR's performance. We verify this by showing, in Fig. 8, the box plots for the network throughput of 500 simulations runs, for both half-duplex Max-SINR and our hybrid Max-SINR algorithm. The parameters remain unchanged as above for this simulation, with the SIC value still at the relatively low value of 10^8. Figure 8 shows that

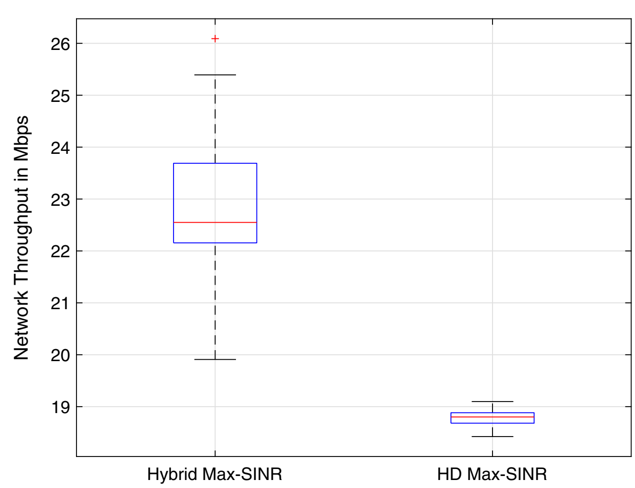

Fig. 8 Half-duplex versus hybrid Max-SINR, SIC = 10^8

for all the simulations, the hybrid algorithm would attain a higher network throughput than its half-duplex counterpart. Moreover, the median hybrid network throughput is close to 22.5 Mbps, significantly higher than that of half-duplex Max-SINR at about 19 Mbps. In conclusion, not only do we show that is it necessary to have a hybrid option, we also prove that we can still outperform half-duplex operation with only a partial implementation of full-duplex.

7.5 Validity of the heuristic algorithms

We seek to verify that our heuristic algorithms produce near optimal performances. To this end, we first simulate our optimal full-duplex Max-SINR and Proportional Fair algorithms versus their heuristic counterparts. In this simulation, the cell has 10 UEs, and the SIC value is set to 10^{11}. The number of RBs available is 20, and the throughput demand is 2 Mbps. The remainder of the parameters are as shown in Table 3. Figure 9 has the box plots for the UE throughput values achieved by each of these four algorithms.

For both full-duplex Max-SINR and Proportional Fair, the optimal and heuristic box plots are very similar. For full-duplex Max-SINR, both the optimal and heuristic algorithms show a maximum of 2 Mbps and a minimum of about 0 Mbps. The median is around 1.8 Mbps. Nonetheless, the box plot for the optimal Max-SINR algorithm is slightly shifted upwards, indicating that the optimal algorithm does in fact still produce better throughput values for some UEs. The same goes for full-duplex Proportional Fair. The slightly upwards shifted box plot for the optimal algorithm shows that some optimal UEs are doing better than their heuristic counterparts, but the vast majority are still performing almost identically. The box plots also highlight the greedy nature of the full-duplex Max-SINR algorithms and the fairness orientation of the Proportional Fair algorithms. The rectangular boxes for the Proportional Fair algorithms are small, indicating that the UE throughput values are close to each other. It's the opposite for Max-SINR, where the long boxes show a big span of UE throughput values, albeit with a gain in throughput for the UEs with good radio conditions. The respective box plots show that more than quarter of the Max-SINR UEs have attained a throughput equal or close to the demand.

We repeat the same simulation but for hybrid Max-SINR. Figure 10 shows a box plot of the ratio between the objective value (sum of SINR values) of the heuristic algorithm to that of the optimal algorithm. Except for a few outliers, the heuristic algorithm matches the optimal one with a minimum of 85% of the value outside of some outliers. In the vast majority of the cases, it matches it with an efficiency higher than 90%.

7.6 Impact of imperfect CSI on greedy allocation

We aim to assess the vitality of accurately estimating inter-UE channels. To this end, we examine the components of the statistical CSI of the inter-UE channel, jointly and independently. We simulate our proposed algorithms for multiple scenarios of CSI availability. First, we assume that the channel information is completely unavailable. Second, we consider that the path loss component of the CSI is available to the scheduler at the BS. Since the path loss is related to the distance between the UEs, we assume that the presence of a geographical positioning network helps estimate it. Finally, we assume that the shadowing information is also available. This would form an additional level of complexity that we consider is possible to model, if knowledge of the terrain is present. Additionally, the path loss and the shadowing vary less often than other factors, such as the fast fading. It would require less periodical updates to convey such information to the BS. These three

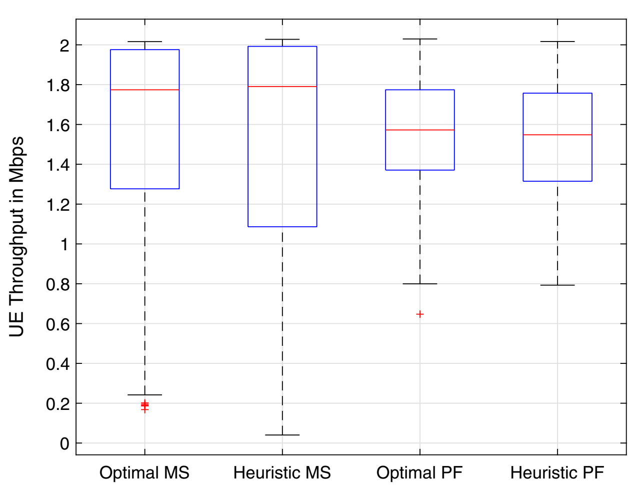

Fig. 9 Optimal versus heuristic full-duplex algorithms

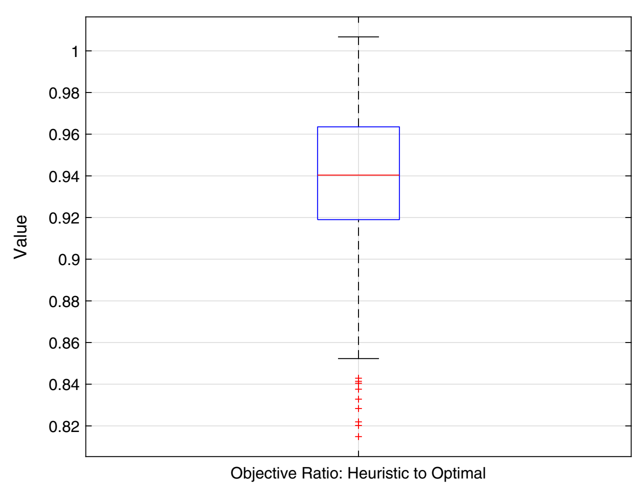

Fig. 10 Optimal versus heuristic hybrid Max-SINR

scenarios of CSI availability are simulated and compared to the optimal case, where the CSI is completely known at the BS.

In this section, we study the effect of imperfect CSI on UE throughput in the case of greedy resource allocation. Note that under our simulation parameters of 50 RBs and 20 UEs, the network is considered to be under heavy load conditions.

Figure 11 is a CDF plot of the throughput values attained by the UEs across the different simulation scenarios. For reference, a traditional half-duplex Max-SINR algorithm is simulated under complete CSI. The throughput attained by full-duplex Max-SINR UEs when the channel state information is complete is the highest among those simulated. Around 70% of those UEs attained a throughput equal to the demand, with the lowest UE throughput recorded being around 300 kbps. The performance of UEs degrades depending on the channel estimation error. The lack of any information on the inter-UE channel incurs the most degradation in performance. In this case, almost 12% of the UEs attain zero throughput, with the rest of the UEs transmitting with a rate lower than the optimal case. The performance of the algorithm improves when parts of the channel become known at the BS. When the path loss information is available, full-duplex Max-SINR UEs show substantial improvement in performance, where almost half of the UEs got an average increase in throughput close to 1 Mbps. When the shadowing information is also available, the number of UEs which were denied throughput drops to zero, with 150 kbps being the lowest attained UE throughput. In both these cases however, the performance of the UEs is still degraded when compared with the case for complete CSI. Nonetheless, full-duplex Max-SINR outperforms half-duplex Max-SINR regardless of the channel estimation errors. Under these simulation parameters, almost 50% of the half-duplex UEs were denied throughput, compared to 12% the worst case scenario for full-duplex. In addition, for any UE simulated, the throughput attained by a full-duplex UE is higher than that attained by a half-duplex UE. To conclude, it is evident that scheduling without complete information on the channel between the UEs degrades the performance of full-duplex networks, but this performance remains much better than that of traditional half-duplex Max-SINR scheduling.

7.7 Impact of imperfect CSI on fair allocation

In this section we study the impact of imperfect channel state information on fair scheduling techniques. Figure 12 has box plots of the resulting UE throughput values for our full-duplex Proportional Fair algorithm under different scenarios of CSI availability. A half-duplex Proportional Fair algorithm is also simulated under complete CSI.

Similar to the case of full-duplex Max-SINR, the lack of CSI deteriorates the performance of the algorithm, and the presence of partial CSI is sufficient for near-optimal performance. Nonetheless, in the case where no information on the inter-UE channel is available, the median value for UE throughput drops more than 1 Mbps, and the gains with respect to half-duplex Proportional Fair become questionable. Although the full-duplex algorithm maintains higher UE throughput values for the majority of the UEs, the fairness of the algorithm is severely struck. This can be inferred from the size of the box corresponding to no CSI information, where it spans nearly all the possible values. This effect is due to the nature of the algorithm, where the scheduling decision at a certain instant is tied to the previous one in terms of transmitted bits. This incurs that a previously erroneous decision will be carried on and even magnified. We present a thorough study on the effects of

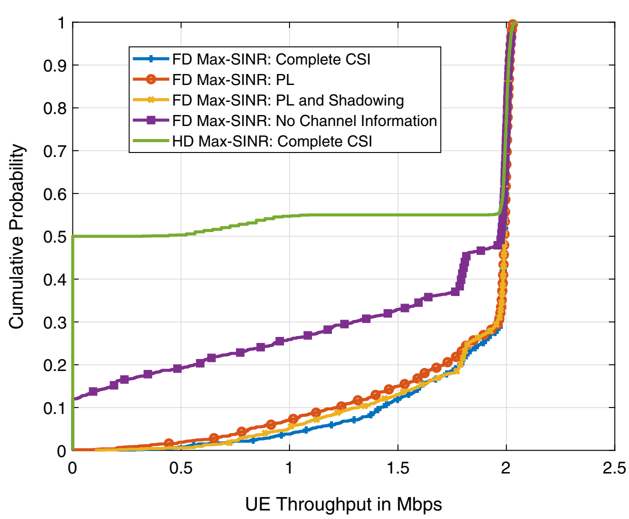

Fig. 11 Effect of imperfect CSI on full-duplex Max-SINR

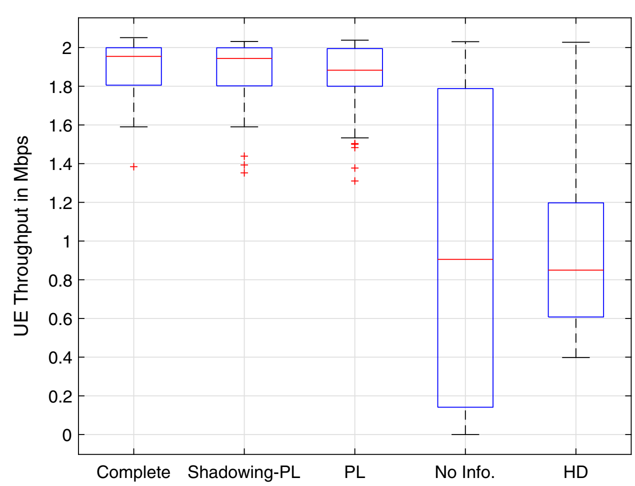

Fig. 12 Effect of imperfect CSI on fair scheduling

imperfect CSI on scheduling in full-duplex wireless networks in [25].

7.8 Comparison with the state-of-the-art

We first aim to assess the importance of our queue-aware approach. To this end, we simulate the "Queue-Oblivious" full-duplex Max Sum-Rate approach presented in [7] with our dynamic arrivals scenario. We compare the results with our full-duplex Max-SINR algorithm. This can be seen in the CDF plot of Fig. 13. We use the same simulation parameters seen in Table 3.

Figure 13 shows that about 30% of the Max Sum-Rate UEs attained a throughput equal to 0, with about 32% attaining a throughput equal to the demand of 2 Mbps. On the other hand, scheduling with our queue-aware proposal gives about 70% of the UEs throughput values equal to the demand, while none get denied RBs.

As the greedy approach proposed by the authors in [7] does not count for dynamic arrivals, it cannot account for UEs emptying their queues which would result in them leaving the network. It cannot count for the same UEs rejoining the network when they have new arrivals either. This will lead to an inefficient resource allocation algorithm that would allocate RBs to UEs which cannot make use of them.

In order to compare our approaches to the state-of-the-art in terms of objectives, we adapt the same Max Sum-Rate scheduling algorithm to our queue-aware model. This enables us to compare between the two objectives: maximizing the sum-rate versus maximizing the SINR (our proposal). Figure 14 has the simulation results under the same parameters seen in Table 3.

Figure 14 shows a great similarity between the two greedy objectives, with our proposal being slightly greedier

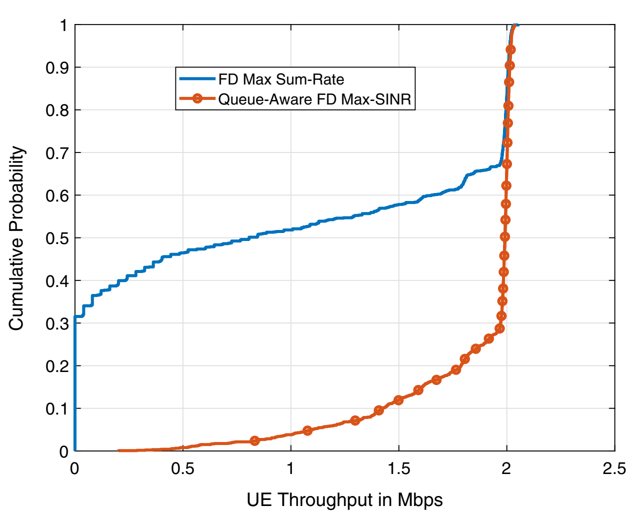

Fig. 13 Importance of queue-awareness

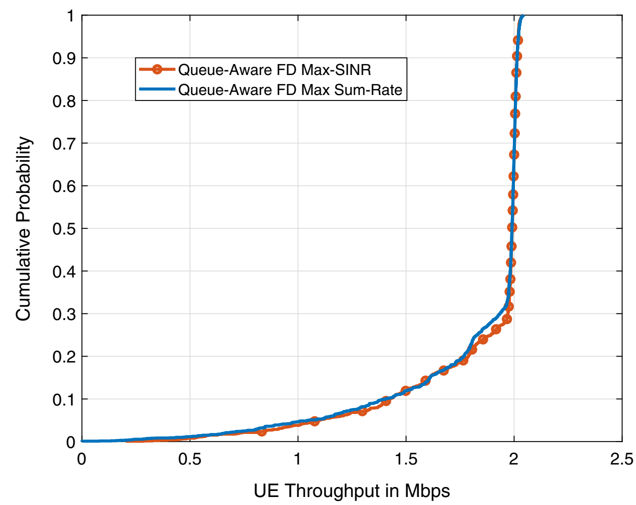

Fig. 14 Max-SINR versus Max Sum-Rate

(a few more UEs attain a throughput equal to the demand). This is because the log function inherently present in the Max Sum-Rate algorithm enforces a certain fairness aspect. This aspect still does not compare to our full-duplex Proportional Fair algorithm whose results can be seen in Fig. 4. Our full-duplex Proportional Fair algorithm serves as a fairness-oriented approach to scheduling unlike the vast majority of the state-of-the-art which proposes a variance of greedy approaches from Max Sum-Rate, to Max Throughput, Logarithmic Maximization of Throughput, and others.

8 Conclusion

In this paper, we presented optimal scheduling models for both full-duplex and hybrid OFDMA wireless networks. We applied these models with different scheduling objectives. With focus on UE SINR, we proposed an optimal full-duplex Max-SINR algorithm that allocates resources to UE pairs with the highest sum-SINR. We also proposed an optimal hybrid Max-SINR algorithm that chooses between allocating resources in half-duplex or full-duplex, depending on the SINR. With focus on fairness, we proposed an optimal full-duplex Proportional Fair algorithm that allocates resources to UE pairs that have the highest priority. Similarly, we proposed an optimal hybrid Proportional Fair algorithm that can choose to allocate the resources in half-duplex or full-duplex depending on the UE priorities. We then proposed heuristic versions of these four algorithms, and proved that their performance is near optimal. Under different simulation scenarios, we illustrated the gains full-duplex wireless networks provide in comparison with current half-duplex networks, and we verified that our hybrid algorithms provide a good alternative to full-duplex scheduling in the case of low SIC. We showed that with sufficient SIC, full-duplex communications can almost double the throughput for the UEs and can cut the waiting delay to half. We tested our algorithms in the case of imperfect CSI, and proved that even then, full-duplex communications are still profitable. Finally, we compared our proposals to the state-of-the-art stressing the importance of queue-awareness, as well as the significance of a fair approach to scheduling.

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