Queue-Aware Resource Allocation in Full-Duplex Multi-Cellular Wireless Networks

Hassan Fawaz*, Samer Lahoud†, Melhem El Helou‡, and Kinda Khawam §
*SAMOVAR, Télécom SudParis, Institut Polytechnique de Paris, 91120 Palaiseau, France
† University of Rennes, IRISA, Campus de Beaulieu, 35042 Rennes, France
‡Ecole Supérieure d'Ingénieurs de Beyrouth, Saint Joseph University of Beirut, Beirut, Lebanon
§ Université Paris-Saclay, UVSQ, 78000, Versailles, France

***Abstract*—In this paper, we aim to tackle challenges of resource block scheduling and power allocation in the context of multi-cell full-duplex wireless networks. This is a more realistic setting than the single cell scenario, and it better envisions how full-duplex wireless communications could eventually be implemented. We propose an optimal queue-aware joint scheduling and power allocation algorithm for full-duplex wireless networks in a multi-cell scenario. Because of its mathematical intractability, we decouple the problem and solve it for scheduling first, and for power allocation second. We consider both indoor and outdoor scenarios and show that the gains of multi-cell full-duplex wireless networks, with respect to their half-duplex counterparts, are not always prevalent. Furthermore, we highlight the importance of inter-cell cooperation when it comes to scheduling resources and show that depending on the scenario at hand, interference mitigation from inter-cell cooperation can improve the performance of user equipment in terms of throughput and waiting delay. Finally, we show that power allocation can improve user equipment throughput with its efficiency being tied to the deployment scenario at hand.**

I. Introduction

With an ever increasing global mobile data demand, already on the premises of one billion 5G subscriptions alone, and with five folds that amount expected by the end of they year 2028 [1], current half-duplex wireless communications will struggle to keep up with the bandwidth demand. Half-duplex wireless networks allocate a radio resource exclusively to one user equipment (UE) either for transmission or reception. They necessitate orthogonal time or radio channels for bidirectional transmissions. In a best case scenario, about half of the bandwidth potential is being met. However, full-duplex wireless networks are capable of exploiting the bandwidth in its entirety. In such networks, concurrent transmission and reception occurs on the same frequency band allowing, at least theoretically, the duplication of current wireless network capacity.

In our work, we consider a full-duplex orthogonal frequency division multiple access (FD-OFDMA) network. This network exhibits a full-duplex base station (BS) and half-duplex UEs. Limiting full-duplex implementation to the base station reduces interference problems, and keeps most of the complexities of implementing full-duplex away from the terminals. The BS, being the full-duplex device, transmits and receives simultaneously on the radio resources. The half-duplex UEs form uplink-downlink pairs which share the same radio resources with one UE transmitting, and the other receiving.

Full-duplex communications produce two added types of wireless interferences. The first, self-interference, is the interference imposed by the transmitted signal from a full-duplex device, typically multiple times larger, on the received signal. Self-interference degrades the quality of uplink signals in the network. The second, intra-cell co-channel interference or cross-link interference, results from uplink and downlink UEs using the same radio resources inside the same cell. The signal from an uplink UE, transmitting with relatively high power, will interfere on the signal being received by its paired downlink UE. Intra-cell co-channel interference degrades the performance of downlink UEs in an FD-OFDMA wireless network.

Most practical implementations of full-duplex wireless communications are bound to be in multi-cell scenarios. As such, the interference problems for full-duplex wireless networks will be multiple folds more significant. In comparison with traditional half-duplex wireless networks, UEs on the downlink would now also interfered upon by inter-cell UEs on the uplink, and UEs on the uplink would now also interfered upon by inter-cell BS transmissions on the downlink. The lucrative full-duplex gains simulated in single-cell wireless networks might not stand.

In this paper, we assess the feasibility, as well as profitability, of full-duplex wireless communications in a multi-cell setting. We propose an optimal scheduling and power allocation algorithm. The latter belongs to the category of mixed integer non-linear programming (MINLP), making the problem mathematically intractable. As a result, we divide the problem into two: a scheduling problem and a power allocation problem. Each cell in the network will allocate its radio resources independently and in a centralized manner. Afterwards, a power allocation algorithm will compute the power levels on the resource blocks (RBs). We propose both centralized and distributed approaches to power allocation. We show via simulations that the profitability of full-duplex communications, with respect to their half-duplex counterparts, is tied to the interference mitigation provided by the deployment scenario being considered. We highlight our main contributions as follows:

(a) We propose a resource block scheduling and power allocation algorithm for multi-cell full-duplex wireless networks. While there is a plethora of articles on scheduling and power allocation in full-duplex wireless networks in the state-of-the-art, very few tackle the challenges in the context of multi-cellular networks.

(b) We assume a non-full buffer traffic model. This is a more realistic approach that also enables us to compute packet level metrics, such as the waiting delay.

(c) We consider both indoor and outdoor deployment scenarios, and illustrate how the full-duplex gains are tied to the latter.

(d) We propose both centralized and distributed approaches to power allocation, and show that the distributed approach incurs no losses in performance.

The rest of this paper is structured as follows. Section II discusses the related works in the state-of-the-art. Section III has the network model of our work and includes the radio model, the traffic model and the channel model. The multi-cell deployment scenarios we consider in our work, both indoor and outdoor, can be seen in section IV. In section V, we present our scheduling algorithm and both our centralized and distributed approaches to power allocation in multi-cell full-duplex wireless networks. We discuss the complexity of our proposed algorithms in section VI. Different simulation scenarios and results are presented in section VII, wherein we assess the performance of our proposals with respect to half-duplex communications in terms of UE throughput and waiting delay. This paper is concluded by section VIII.

II. Related Works

In this section, we give a general overview of where the state-of-the-art is at for full-duplex wireless communications. We classify the latter into three categories. The first deals with the development and progress of self-interference cancellation (SIC) techniques. It was essential for these technologies to be well established before researchers went any further with their work on full-duplex technologies. The second category encompasses early works in the domain which sought either to suggest different possible full-duplex scenarios, or merely to validate that gains could be extracted from full-duplex communications. The third category in the state-of-the-art, to which our work practically belongs, builds on the previous two to propose and simulate scheduling and power allocation algorithms for full-duplex wireless networks.

It was important for SIC technologies to be well developed and tested before any other work was done on full-duplex wireless. After all, the development of these technologies is what made full-duplex wireless communications feasible in the first place.

The authors in [2] were among the first to discuss the direct impacts of developed SIC techniques on full-duplex communications. They state that these technologies invalidate long-held assumptions regarding wireless network design, and they overview what would be required of interference cancellation techniques in order to propel full-duplex wireless communications into reality. In one of the earliest works on in-band full-duplex for wireless networks, the authors in [3] survey a range of SIC techniques and touch on the main challenges facing full-duplex wireless networks. The articles in [4] and [5] aimed to evaluate the performance of self-interference in the context of full-duplex wireless communications. The authors in [4] conclude that the SIC performance increases as the signal bandwidth decreases, while those in [5] focus on the impact of amplitude and phase errors on the efficiency of interference cancellation technologies. Finally, authors in [6] demonstrate that 110 dB of self-interference can be canceled at a transmitter of 25 dBm power. We consider this to be a benchmark for our work.

After a consensus was reached on the viability of SIC techniques and on the role that these technologies could play in making full-duplex communications feasible, research in the domain pivoted towards exploring what full-duplex wireless networks would look like, and whether impediments other than self-interference would hinder extracting gains from full-duplex wireless communications. In [7], the authors showed that full-duplex communications can more than double the capacity of half-duplex networks. The works in [8], [9], [10], [11] revolve around assessing the possible gains of full-duplex wireless networks. Their authors study different implementations of full-duplex systems alongside the limitations and obstacles facing them. From proposing a full-duplex module as in [8] to introducing realistic compact models as in [11], authors in the state-of-the-art show the technology for implementing full-duplex transmission and reception is existent and well tested. Our work builds on this to propose scheduling and power allocation algorithms for full-duplex wireless networks.

With SIC technologies now well established in the state-of-the-art, and with full-duplex technologies now well motivated, it was only a matter of time before researchers in the wireless domain moved towards devising scheduling and power allocation algorithms for full-duplex wireless networks. Radio resource management has always been the pillar for any transmission technology. For full-duplex wireless networks specifically, there was more at stake. Scheduling and power allocation in this context is not only about better management of the radio resources, but also about mitigating full-duplex interferences. As attested to by our simulations, without proper scheduling–capable of fighting off the effects on intra-cell co-channel interference–full-duplex communications would not be viable.

Table I summarizes the majority of the state-of-the-art concerned with scheduling and power allocation in full-duplex wireless networks. It highlights the full-duplex network scenarios used, and states whether the referenced articles have power allocation algorithms alongside the scheduling proposals. The table also indicates whether these approaches to power allocation are distributed or centralized. Additional information on cell scenario and size, traffic type and the state of the SIC considered are included. Table cells marked ”-” are for when the stated information is not given in the papers, or cannot be directly inferred from them.

Table I
STATE-OF-THE-ART FOR SCHEDULING AND POWER ALLOCATION IN FULL-DUPLEX WIRELESS NETWORKS

Publication	Network Type	Scheduling		Power Allocation		Cell Specifications		
		Objective	Q-Aware	Centralized	Distributed	Multi-Cell	Size (R)	SIC
A. Saeidi *et al.*[12]	BS FD	Max SR	×	✓	-	×	100 m	RSI Model
Shahsavari *et al.*[13]	MC FD	Max SR	×	-	-	×	50 m	80-110 dB
Song *et al.*[9]	BS/UEs FD	Max SR	×	×	×	×	-	-
Zheng *et al.* [14]	BS FD	Max TP	×	-	-	-	2 m	30 dB
Gao *et al.* [15]	MIMO Relay	Max TP	×	×	×	×	-	-
Zhang *et al.* [16]	OFDMA	Max-Min	-	✓	×	×	100 m	110 dB
Tehrani *et al.*[17]	OFDMA	Max SR	×	✓	×	×	20-1000 m	130 dB
Di *et al.*[18]	OFDMA	Max SR	×	✓	×	×	-	100 dB
Nam *et al.* [19]	OFDMA	Max SR	×	✓	×	×	1 km	Ideal
Sun *et al.* [20]	MC-NOMA	Max SR	×	✓	×	×	600 m	110 dB
Goyal *et al.* [21]	BS FD	Max $\log(R)$	×	✓	✓	✓	Small	RSI Model
Marasevic *et al.* [10]	BS/UEs FD	Max SR	×	-	-	×	×	RSI Model
Hakimi *et al.* [22]	FD MIMO	Max SR	×	-	-	×	-	120 dB
Liu *et al.* [23]	OFDMA	Max $\log(R)$	×	-	-	×	500 m	Near Ideal
Park *et al.* [24]	BS FD	Max SE	×	✓	×	×	100 m	RSI Model
Al-Imari *et al.* [25]	OFDMA	Max SR	×	✓	×	×	200 m	85 dB
Tran *et al.* [26]	OFDMA	Max SR	×	✓	×	×	250 m	120 dB
Wu *et al.* [27]	BS FD	Max SR	×	✓	×	×	150 m	RSI Model
Shaikh *et al.* [28]	Hybrid BS	-	×	✓	×	×	Small	Ideal
Our Proposal	BS FD	Max $\log(S)$	✓	✓	✓	✓	Small	110 dB

The vast majority of the papers in the state-of-the-art introduce a full-duplex scenario similar to the one we used in our work. The BS is assumed to be the full-duplex node and the UEs remain half-duplex. This scenario is the one implemented in all the FD-OFDMA [17], [18], [19] models referenced as well. Other models in the related works focus on relay [15], MIMO [29], and even heterogeneous networks [28]. Though the latter three are not of direct connection to our work, we studied them due to the existence of a common problematic when it comes to dealing with full-duplex problems and interference issues.

As for scheduling, almost all of the works in the state-of-the-art implement greedy approaches focusing on the maximization of the sum-rate [13] (Max SR), the logarithm of the rates (Max $\log(R)$) [21] , or the throughput [14] (Max TP). Other variations in the related works include maximizing the minimum rates [16], maximizing the network's spectral efficiency (Max SE) [30], and maximizing the sum-rates [22], or the weighted sum-rates [12]. In this work, we utilize maximizing the logarithmic value of the SINR as a scheduling objective (Max $\log(R)$) Furthermore, a variance of power allocation algorithms are utilized with a good number of them being based on some form of optimization. Approaches such as successive convex approximation [31], [32], and fractional power control [28] were used in some of the approaches. In previous works, we discussed scheduling in full-duplex networks without complete channel information, producing a reinforcement learning approach to scheduling [33].

Multi-cell scenarios are scarcely implemented in the state-of-the-art. This is mainly due to the exponential increase in complexity that both studying and simulating such scenarios would incur. Additionally, the existence of inter-cell interference further complicates proving the feasibility and gains of full-duplex wireless communications. As we show later on in our work, not every multi-cell scenario produces gains with respect to half-duplex communications. Some papers in the state-of-the-art implement a simplistic model, as in [8], wherein unrealistic ideal inter-cell interference cancellation assumptions are made. To the best of our knowledge, the paper in [21] has the most thorough multi-cell model in the related works. The authors consider both indoor and outdoor cell scenarios and pair their sum-rate maximization scheduling with an optimal power allocation problem. They consider single-cell scheduling and coordinated power allocation.

Self-interference cancellation technologies are a corner stone for full-duplex communications. Some articles in the state-of-the-art assume ideal conditions [19] *i.e.,* the technologies available are capable of canceling all of the self-interference. As we discussed before, this is not completely realistic. Other models assume near-ideal interference cancellation conditions, where a small residual self-interference (RSI) factor is added to the SINR calculation as noise. Another approach to modeling the effect of self-interference is via using an RSI model [10], wherein the RSI follows a probabilistic function such as a Gaussian law. Similar to our work, the majority of the papers reviewed use a set of interference cancellation factors to determine the RSI. Within the upper limits of 120 to 130 dB, these assumptions remain permissible.

Finally, a recapitulation of the buffer models used in the related works highlights the uniqueness of our approach to queue-awareness. Almost all the articles we reviewed in the state-of-the-art, as show in Table I, used full buffer traffic models. Some authors [21] used a simple non-full buffer model, as for downloading a file, without incorporating queue-awareness into the traffic model. The traffic model being queue-aware in our work allows to better emulate real-life networks and enables us to compute packet level metrics such as the waiting delay.

III. NETWORK MODEL

We consider a multi-cell FD-OFDMA wireless network containing B BSs b, where b belongs to the set of BSs

$\mathcal{B}$. Each cell exhibits a full-duplex BS and half-duplex UEs. The UEs across the multi-cell network are virtually divided into two sets: an uplink UE set, denoted by $\mathcal{U}$ and a downlink UE set, denoted by $\mathcal{D}$. The scheduler will pair between uplink and downlink UEs on any RB k of the set $\mathcal{K}$. The presence of multi-cells greatly magnifies the interference impact in a full-duplex wireless network. Consider the scenario illustrated in Fig. 1 below, where we have two adjacent cells following our network model. Each BS will schedule pairs of uplink-downlink UEs on the available RBs.

As a result, each uplink UE in the first cell will experience interference from three sources:

1) I1: Self-interference at the BS due to its transmission towards a downlink UE on the same RB.
2) I2: Co-channel interference resulting from uplink UEs in neighboring cells using the same RB.
3) I3: Inter-cell interference from neighboring cell BSs transmitting on the same RB.

A downlink UE in the first cell also experience interference from three different sources:

1) I4: Intra-cell co-channel interference from its paired uplink UE using the same RB.
2) I5: Co-channel interference resulting from uplink UEs in neighboring cells using the same RB.
3) I6: Inter-cell interference from neighboring cell BSs transmitting on the same RB.

A. Notations

Let $S^u(i,j,k,b)$ be the SINR of uplink UE i on RB k in the pair (i,j) associated with BS b. Similarly, $S^d(i,j,k,b)$ denotes the SINR of downlink UE j on RB k in the pair (i,j) associated with BS b. P^u_{ik} is the transmit power of uplink UE i on RB k, and P^d_{bk} denotes the transmit power of BS b on RB k. The channel between uplink UE i and BS b on RB k is represented by h^u_{ibk}, and the channel between two BSs b' and b on RB k is denoted by $h^s_{b'bk}$. h_{ijk} is the inter-UE channels between a pair of uplink-downlink UEs (i,j). SIC represents the self-interference cancellation capability at the BS, equivalently how much of the self-interference can each BS cancel. Finally, N^u_{bk} and N^d_{jk} represent the noise power at BS b on RB k and the noise power at downlink UE j on RB k, respectively.

Table II
NOTATION SUMMARY

Notation	Definition
$S^u(i,j,k,b)$	SINR of uplink UE i on RB k
$S^d(i,j,k,b)$	SINR of downlink UE j on RB k
P^u_{ik}	Transmit power of uplink UE i on RB k
P^d_{bk}	Transmit power of BS b on RB k
h^u_{ibk}	Channel between i and BS b on RB k
$h^s_{b'bk}$	Channel between BSs b' and b on RB k
h_{ijk}	Inter-UE channel i-j on RB k
h^d_{bjk}	Channel between b and downlink UE j on RB k
SIC	Self-interference cancellation factor
N^u_{bk}	Noise power at BS b on RB k
N^d_{jk}	Noise power at j on RB k

B. Interference Calculation

The full-duplex interference on a UE transmitting or receiving on an RB k are calculated as follows.

- The residual self-interference (RSI) experienced by every uplink UE, on RB k, at its corresponding BS is written as:
$$I_1 = \frac{P^d_{bk}}{\mathsf{SIC}}. \tag{1}$$
- The interference on a particular uplink UE i from all uplink UEs $i' \neq i$ using the same RB k:
$$I_2 = \sum_{i' \in \mathcal{U} \backslash i} P^u_{i'k} |h^u_{i'bk}|^2 \tag{2}$$
- The interference on a particular uplink UE i from all BSs transmitting on the downlink using the same RB k:
$$I_3 = \sum_{b' \in \mathcal{B} \backslash b} P^d_{b'k} |h^s_{b'bk}|^2 \tag{3}$$
- The interference on a downlink UE from all uplink UEs i' using the same RB k:
$$I_4 + I_5 = \sum_{i' \in \mathcal{U}} P^u_{i'k} |h_{i'jk}|^2 \tag{4}$$
- The interference on a downlink UE from all BSs transmitting on the same RB k:
$$I_6 = \sum_{b' \in \mathcal{B} \backslash b} P^d_{b'k} |h^d_{b'jk}|^2 \tag{5}$$

C. Radio Model and SINR Calculation

In our work, we assume that the physical layer is operated using an OFDMA structure. The radio resources are divided into time-frequency resource blocks. In the time domain, a resource block contains an integer number of OFDM symbols. In the frequency domain, a resource block contains adjacent narrow-band subcarriers and experiences flat fading. Scheduling decisions for downlink and uplink transmissions are made in every transmission time interval (TTI) t. At the beginning of each TTI, K resource blocks 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 resource block to another, but remain constant over a TTI. The modulation and coding scheme (MCS), that can be assigned to a UE on a resource block, depends on its radio conditions. For performance evaluation, we consider in what follows LTE-like specifications, with a resource block being composed of 12 subcarriers and 7 OFDM symbols [34].

As a result, the SINR for an uplink UE i, paired with a downlink UE j on RB k and associated with BS b *i.e.,* the quality of the received signal from UE i measured at BS b, is written as:

$$S^u(i,j,k,b) = \frac{P^u_{ik}|h^u_{ibk}|^2}{N^u_{bk} + \frac{P^d_{bk}}{\mathsf{SIC}} + \sum\limits_{b' \in \mathcal{B} \backslash b} P^d_{b'k}|h^s_{b'bk}|^2 + \sum\limits_{i' \in \mathcal{U} \backslash i}(P^u_{i'k}|h^u_{i'bk}|^2)}, \tag{6}$$

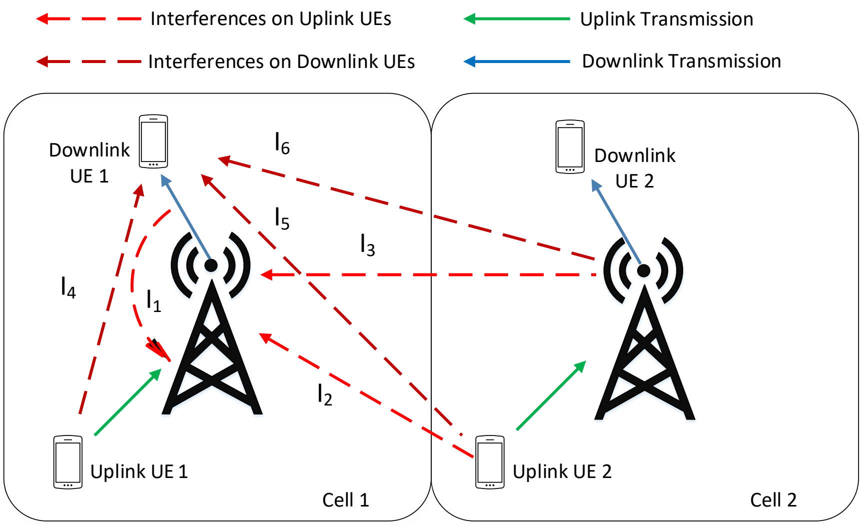

Figure 1. Inter-cell interference in a multi-cell scenario

For a downlink UE j paired with an uplink UE i on RB k and associated with BS b, the SINR becomes:

$$S^d(i,j,k,b) = \frac{P^d_{bk}|h^d_{bjk}|^2}{N^d_{jk} + \sum_{i' \in \mathcal{U}} (P^u_{i'k}|h_{i'jk}|^2) + \sum_{b' \in \mathcal{B} \setminus b} P^d_{b'k}|h^d_{b'jk}|^2}. \quad (7)$$

As such, the residual self-interference impacting an uplink UE scales with the transmit power of the BS on the downlink, on the same resource block. The self-interference cancellation capability of each BS (SIC) is the same across all the resource blocks and is set at a maximum of 110 dB, well within the limits established in the state-of-the-art.

D. Traffic Model

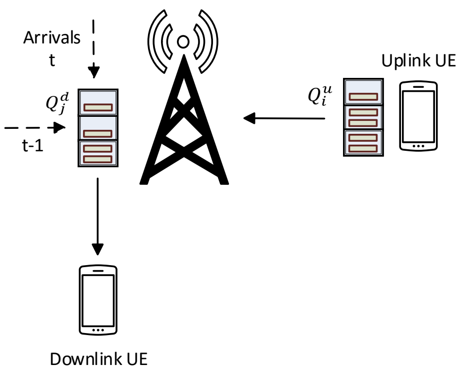

Figure 2. Traffic model and UE queues

We introduced our traffic model in our previous work in [35] (Fig. 2). It encompasses a non-full buffer model. Each UE has a predefined throughput demand which determines the rate at which the UE will transmit or receive. A downlink UE j has a queue at the BS, denoted Q^d_j, that it wants to receive. An uplink UE i has a queue of bits it wants to transmit to the BS, denoted Q^u_i. UE queues are updated each TTI. They are filled according to a Poisson process with an arrival rate λ equal to the throughput demand. It is one of the most widely used and established traffic models [36]. Once the scheduling is done for a certain TTI, the number of bits each UE can transmit or receive is calculated, and the UE queues are deducted accordingly. The traffic is packeted into small units known as transport blocks. Based on the MCS used and the number of resource blocks allocated for a UE, its transport block size is determined for the TTI. Any bits remaining in a UE queue at the end of a TTI are carried on to the next one. Our main concern in this paper is that the arrivals are dynamic and that the traffic is non-full buffer, emulating thus real life traffic scenarios. This allows us to compute performance metrics such as the waiting delay and also allows for UEs to exit and rejoin the scheduling process. The latter signifies that the resources are not all being allocated to a limited set of UEs, and that the performances of our proposals and the network are being properly assessed.

E. Channel State Information

The state of a wireless channel is determined by the combined effect of several factors, the most pertinent being the path loss, the shadowing, and the fast fading. Knowledge of the channel on a wireless link permits adapting the transmission to the communication channel. This is essential for achieving reliable communications, and for making efficient resource allocation decisions.

Legacy half-duplex networks rely on feedback from the UEs to determine the current channel state [37]. These networks are concerned mainly with the channel in between the BS and the UEs, and different techniques are used to determine how often, and on which resource blocks, would this feedback information be required. 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 systems, additional information on the channel between the UEs of a pair is required. Not only do current wireless systems not account for such information, there is also no implemented method for which a UE can estimate the state of such UE-UE channels. Additionally, it is perceivable that continuously updating such information by the UEs would cause an excessive overhead.

We statistically model the inter-UE channel as follows:

$$h_{ji,k} = G_t G_r L_p A_s A_f \quad (8)$$

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

In our previous work in [38], we detailed the intricacies of scheduling without complete CSI, and the major losses that it would incur on full-duplex gains. In the context of this paper, we assume that complete CSI is available at the BSs and to the scheduler. With the assumption of independent single-cell scheduling, and considering the limited number of UEs per cell, it is logical to assume that the relaying of inter-UE channels to the BS remains feasible.

IV. Multi-Cell Deployment Scenarios

In our work, we consider both indoor and outdoor cell scenarios. In what follows, we highlight the specifics of these scenarios [21].

1) Indoor Scenario: We consider the indoor cell scenario illustrated in Fig. 3 below. Seven indoor cells are present in this network. The distance from the central cell BS to all other BSs is constant. Each cell has 10 distributed UEs, with their coordinates being generated uniform randomly.

The parameters used for this scenario are stated in Table III below. The path loss model used is based on 3GPP simulation recommendations for a remote radio head (RRH) cell environment [39]. Additionally, a penetration loss of 20 dB between cells due to walls is assumed. The path loss model used for BS-to-BS channels is the same one used for UE-to-UE channels with the justification that the BSs have no significant height advantages in the case of indoor cells. The probability of line of sight is given by (d is the distance in m):

$$P_{LOS} = \begin{cases} 1, & \text{if d} \leq 18 \\ \exp(-(d-18)/27), & \text{if } 18 < \text{d} < 37 \\ 0.5, & \text{if d} \geq 37 \end{cases} \quad (9)$$

2) Outdoor Scenario: The outdoor scenario we consider in this paper is illustrated in Fig. 4 below.
There are no physical barriers between the cells in the outdoor scenarios. 10 UEs are randomly dropped in each cell. The random distribution of the UEs is done within the borders of their corresponding BS. This is similar to Pico cell deployment scenarios. The path loss model used for this scenario, as given by 3GPP simulation standards [40], can be seen in Table IV. The probability of line of sight in this case is given by (d is the distance in km):

$$P_{LOS} = 0.5 - \min(0.5, 5\exp(-0.156/d)) + \min(0.5, 5\exp(-d/0.03)). \quad (10)$$

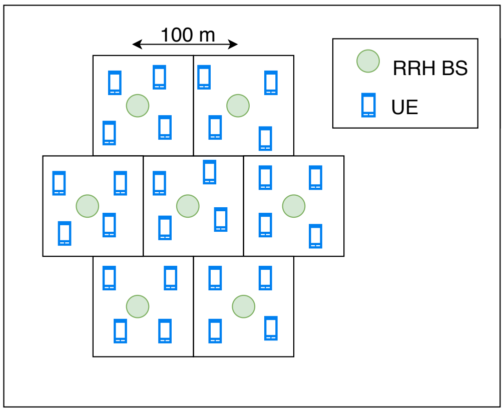

Figure 3. Indoor deployment scenario

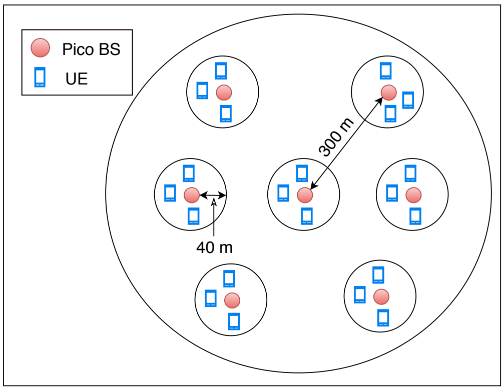

Figure 4. Outdoor deployment scenario

V. Optimal Approach to Scheduling and Power Allocation in a Multi-Cell Setting

We propose an optimal algorithm for scheduling and power allocation in a multi-cellular full-duplex wireless network. Our objective is to maximize the logarithmic sum of the signal-to-interference-plus-noise-ratios (SINR) of the scheduled pairs of user equipment (UEs). This is a fairness oriented allocation as proclaimed in [41], [42]. We define the UE pair-RB-base station (BS) allocation variable z_{ijkb}, $\forall i \in \mathcal{U}, \forall j \in \mathcal{D}, \forall k \in \mathcal{K}, \forall b \in \mathcal{B}$. It is equal to one if uplink UE i is paired with downlink UE j on RB k, whilst associated with BS b. It is equal to zero otherwise. Each BS has its unique set of UEs i and j and subsequently, unique possible UE pairings. Reuse-1 is assumed for the radio resource allocation process. As such, each BS has access to all the RBs. The scheduling and power allocation problem problem can be thereafter formulated as follows:
$(\mathcal{P}^t_{mc})$

$$\underset{z_{ijkb}, P^d_{bk}, P^u_{ik}}{\text{Maximize}} \sum_{b\in\mathcal{B}} \sum_{k\in\mathcal{K}} \sum_{i\in\mathcal{U}} \sum_{j\in\mathcal{D}} z_{ijkb} \Big(\log(S^u(i,j,k,b)) + \log(S^d(i,j,k,b)) \Big) \quad (11a)$$

Subject to

$$\sum_{i\in\mathcal{U}} \sum_{j\in\mathcal{D}} z_{ijkb} \leq 1, \ \forall k \in \mathcal{K}, \ \forall b \in \mathcal{B}, \quad (11b)$$

Table III
PATH LOSS MODEL FOR THE INDOOR CELLS

Parameter (d in m, f_c in GHz)	**Value**
Shadowing	Log-normal with σ = 3 dB if LOS, 4 dB otherwise
Fast Fading	Exponential with unit parameter
LOS path loss within a cell in dB	32.8 + 20$\log_{10}(f_c)$ + 16.9$\log_{10}$(d)
NLOS path loss within a cell in dB	11.5 + 20$\log_{10}(f_c)$ + 43.3$\log_{10}$(d)
Path loss between two cells in dB	11.5 + 20$\log_{10}(f_c)$ + 43.3 $\log_{10}$(d)
Penetration loss	Due to boundary: 20 dB, within a cell: 0 dB

Table IV
PATH LOSS MODEL FOR THE OUTDOOR CELLS

Parameter (d in km)	**Value**
Shadowing inside the cell	Log-normal with σ = 3 dB if LOS, 4 dB otherwise
Shadowing between the cells	Log-normal with σ = 6 dB
Fast Fading	Exponential with unit parameter
BS-to-BS LOS path loss	if d $<$ 2/3 km then 98.4 + 20$\log_{10}(d)$, else 101.9 + 40$\log_{10}(d)$
BS-to-BS NLOS path loss	169.36 + 40$\log_{10}(d)$
BS-to-UE LOS path loss	103.8 + 20.9$\log_{10}(d)$
BS-to-UE NLOS path loss	145.4 + 37.5$\log_{10}(d)$
UE-to-UE path loss	if d $<$ 50 m then 98.45 + 20$\log_{10}(d)$, else 175.78 + 40$\log_{10}(d)$
Penetration loss	0 dB

$$\sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} z_{ijkb}T^u_{ijk} \le D^u_i,\ \forall i\in\mathcal{U},\forall b\in\mathcal{B}, \tag{11c}$$

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} z_{ijkb}T^d_{ijk} \le D^d_j,\ \forall j\in\mathcal{D},\forall b\in\mathcal{B}, \tag{11d}$$

$$\sum_{k\in\mathcal{K}} P^d_{bk} \le p^{max}_0,\ \forall b\in\mathcal{B}, \tag{11e}$$

$$\sum_{k\in\mathcal{K}} P^u_{ik} \le p^{max}_i,\ \forall i\in\mathcal{U}, \tag{11f}$$

$$P^u_{ik} \ge p^{min}_i,\ \forall i\in\mathcal{U},\forall k\in\mathcal{K}, \tag{11g}$$

$$P^d_{bk} \ge p^{min}_0,\ \forall k\in\mathcal{K},\ \forall b\in\mathcal{B}, \tag{11h}$$

$$z_{ijkb}\in\{0,1\},\ \forall i\in\mathcal{U},\forall j\in\mathcal{D},\forall k\in\mathcal{K},\forall b\in\mathcal{B} \tag{11i}$$

The objective of the problem as seen in (11a) is to allocate the resource blocks to the pairs of uplink-downlink UEs which maximize the logarithmic sum of SINR values. The constraint in (11b) ensures that every resource block is allocated to only one UE pair per cell. T^u_{ijk} is the number of bits UE i can transmit on RB k while paired with UE j. Similarly, T^d_{ijk} is the number of bits UE j can receive on RB k while paired with UE i. T^u_{ijk} and T^d_{ijk} depend mainly on the radio conditions of the UEs. In addition, D^u_i is the demand of uplink UE i *i.e.*, the number of bits in its queue. Likewise, D^d_j is the demand of downlink UE j. As such, the constraints in (11c) and (11d) ensure that a UE is not allocated a resource block that it does not need. The equations in (11e) and (11f) are the maximum power constraints of the problem. The former indicates the maximum BS transmit power and the latter the maximum UE transmit power. Similarly, the constraints in (11g) and (11h) indicate the minimum power on each allocated RB for the BS on the downlink and the UEs on the uplink, respectively.

This problem in its current form belongs to the category of mixed integer non-linear programming (MINLP). Because of the high number of variables, it is already intractable and can become significantly more so as the number of UEs, RBs, and BSs increases. As such, the problem is divided into two: (a) a scheduling problem, followed by (b) a power allocation problem. Each of these problems is solved optimally on its own. While this is not equivalent to solving the original problem optimally, we show that our proposal produces efficient results. Furthermore, This decoupling of the problem does not impact global optimality since scheduling scheme selection, optimized for power allocation, will always be re-selected when consecutive passes are made on the decoupled algorithm.

A. Single Cell Scheduling

In each time slot, every BS schedules its radio resources independently. With the exception of the central cell, the cells are oblivious of their surroundings and do not account for inter-cell interferences. As such, these interferences are not included in the SINR calculations made in order to allocate the RBs. Though the cells are oblivious of them, these interferences still exist and are taken into account when calculating the performance of the network. The SINR of uplink UE i observed on RB k, whilst paired with downlink UE j, is expressed as:

$$S^u(i,j,k) = \frac{P_{ik}\left|h^u_{ik}\right|^2}{N_{0k} + \frac{P_{0k}}{\mathsf{SIC}}}, \tag{12}$$

where on RB k, P_{ik} is the power emitted by UE i, $\left|h^u_{ik}\right|^2$ is the channel gain between uplink UE i and the BS, and P_{0k} is the power emitted on the downlink by the BS. SIC denotes the self-interference cancellation performed by the BS, and thus $\frac{P_{0k}}{\mathsf{SIC}}$ is the residual self-interference. Finally, N_{0k} is the noise power at the BS on RB k.

Furthermore, the SINR observed by downlink UE j alloted RB k, and paired with uplink UE i, is expressed as:

$$S^d(i,j,k) = \frac{P_{0k}\left|h^d_{jk}\right|^2}{N^d_k + P_{ik}\left|h_{ji,k}\right|^2}, \tag{13}$$

where $\left|h_{jk}^{d}\right|^2$ is the channel gain between downlink UE j attributed RB k and the BS, and $\left|h_{ji,k}\right|^2$ is the channel gain between downlink UE j attributed RB k and interfering UE i, matched on that same RB. As such, $P_{ik}\left|h_{ji,k}\right|^2$ is the co-channel interference affecting downlink UE j. Finally, N_k^d is the noise power at downlink UE j allocated RB k.

The central cell allocates its resources based on feedback from the surrounding cells on how they each distributed their own resources. The assumption of single scheduling is essential to obtain a tractable problem as well. If each of the seven cells (as discussed in our deployment scenarios) has 10 UEs, a total of $(25)^7$ or more than 6×10^9 possible scenarios exist for the allocation of each RB. This makes the problem hard to solve in a centralized manner. The problem in its current form–as single cell scheduling–is a simple ILP problem and can be solved efficiently using disciplined convex programming and solvers such as CVX [43]. For the purpose of scheduling, constant power levels within the feasible constraints are assumed. In addition, the BS is assumed to have complete channel state information (CSI) including all the UE-to-UE channels. The single cell scheduling problem can thereafter be written as follows:

$$\underset{z_{ijk}}{\text{Maximize}} \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}\Big(\log(S^u(i,j,k)) + \log(S^d(i,j,k))\Big) \quad (14a)$$

Subject to

$$\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk} \le 1,\ \forall k \in \mathcal{K}, \quad (14b)$$

$$\sum_{k\in\mathcal{K}}\sum_{j\in\mathcal{D}} z_{ijk}T_{ijk}^{u} \le D_i^u,\ \forall i \in \mathcal{U}, \quad (14c)$$

$$\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}} z_{ijk}T_{ijk}^{d} \le D_j^d,\ \forall j \in \mathcal{D}, \quad (14d)$$

$$z_{ijk} \in \{0,1\},\ \forall i \in \mathcal{U}, \forall j \in \mathcal{D}, \forall k \in \mathcal{K}. \quad (14e)$$

With the exception of the central cell which allocates its resources according to what follows:

$$\underset{z_{ijk}}{\text{Maximize}} \quad \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}\Big(\log(S^u(i,j,k,1)) + \log(S^d(i,j,k,1))\Big) \quad (15)$$

Subject to (11b) to (11d)

B. Centralized Multi-Cell Power Allocation

The power is allocated on all the RBs for all the cells conjointly, by an assumed central unit, after the radio resources have been allocated by each cell independently. The power allocation problem can thereafter be written as follows:

$$\underset{P_{bk},P_{ik}}{\text{Maximize}} \quad \sum_{b\in\mathcal{B}}\sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijkb}^{*}\Big(\log(S^u(i,j,k,b)) + \log(S^d(i,j,k,b))\Big) \quad (16)$$

Subject to (11e) to (11i)

The aim is to use power allocation to minimize the interference generated from full-duplex operation and single cell scheduling. Whilst this problem is still of the MINLP category, it is now tractable and can be efficiently solved for each TTI using geometric programming [44].

C. Distributed Cooperative Multi-Cell Power Allocation

An alternative approach to power allocation includes a distributed method for power allocation. In each TTI, after each cell allocates its radio resources individually, the BSs coordinate power allocation in a way that maximizes the logarithmic sum of uplink-downlink UE SINR values (11a). In this case, each BS would allocate power on the RBs it has allotted given feedback from other BSs in the network on how they each allocated their resources. The power allocation problem $\forall\ b \in \mathcal{B}$ can be written as follows:

$$\underset{P_{bk}^{d},P_{ik}^{u}}{\text{Maximize}} \sum_{k\in\mathcal{K}}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijkb}^{*}\Big(\log(S^u(i,j,k,b)) + \log(S^d(i,j,k,b))\Big) \quad (17a)$$

Subject to

$$\sum_{k\in\mathcal{K}} P_{bk}^{d} \le p_0^{max},\ \forall b \in \mathcal{B}, \quad (17b)$$

$$\sum_{k\in\mathcal{K}} P_{ik}^{u} \le p_i^{max},\ \forall i \in \mathcal{U}, \quad (17c)$$

$$P_{ik}^{u} \ge p_i^{min},\ \forall i \in \mathcal{U},\ \forall k \in \mathcal{K}, \quad (17d)$$

$$P_{bk}^{d} \ge p_0^{min},\ \forall k \in \mathcal{K},\ \forall b \in \mathcal{B}. \quad (17e)$$

This problem is significantly less complex than its centralized counterpart, and can be solved quickly and efficiently using disciplined convex programming and optimization solvers such as CVX. The scheduling and distributed power allocation algorithm pseudo-code can be seen in Algorithm 1. The power allocation is repeated until the power allotted on all RBs (uplink/ downlink) varies by no more than a tiny value ϵ between two iterations.

Algorithm 1 Scheduling and Distributed Power Allocation Algorithm

```
Requires: Initial Power Settings
Input: Maximum Tolerance ϵ
Set: Number of Iterations n = 0
for TTI t=1,...,T
Scheduling
    Allocate RBs to pairs of uplink-downlink UEs
    following (14) and (15)
Power Allocation
    repeat:
        All BSs take turns allocating power to the
        scheduled pairs of UEs following (17)
        n ← n + 1
    until: Power level variations < ϵ
end for
```

VI. Complexity of the Algorithms

Each cell has U uplink UEs, and D downlink UEs. This amounts to a total of $n = U \cdot D$ possible UE pairs. In order to allocate the resources, the algorithm needs to find the UE pairs which maximizes the objective. The complexity of the scheduling algorithm is thus of the order $\mathcal{O}(n)$ [45].

We compare between the time needed to solve the scheduling optimal problem, and the power allocation optimal problem. The scheduling problem for one cell has 1310 variables and 60 equality constraints. The centralized power allocation problem has 17312 variables and 5504 equality constraints. The distributed power allocation problem, per BS, has 2486 variables and 794 constraints. A statistical interpretation of the results is given in Table V. The criteria are measured in seconds. The machine used for the simulations is basic and has an INTEL(R) core i3-4170 CPU at 3.70 GHz processor. It runs on 8 GB of RAM.

Even on a constrained machine, the time needed to solve the problems, specifically in the distributed case, is insignificant. This makes our proposals easy to implement in practical full-duplex wireless networks.

Table V
Scheduling and Power Allocation: Simulation Time (s)

Criteria	Scheduling	PA Centralized	PA Distributed
Mean	0.9506	50.2722	3.1830
1^{st} Quartile	0.8704	45.7656	3.0938
Median	0.9470	46.4375	3.1719
3^{rd} Quartile	1.0003	52.8125	3.2656

VII. Simulations and Results

In this section, we seek to evaluate the performance of our scheduling and power allocation algorithm for multi-cell full-duplex wireless networks. We do so via a set of simulations with the performance metrics being the achieved average UE throughput and average UE waiting delay for UEs in the central cell. The waiting delay is an important metric in contemporary telecommunications as applications become more and more time sensitive. We calculate it using Little's formula as the average queue length divided by the packet arrival rate. Our simulations are done in a class based simulator we developed in Matlab. We detailed our simulator for full-duplex wireless networks in [46]. Table VI has the simulation parameters we used.

We simulate four different cases in our work: Our full-duplex scheduling proposal alongside centralized power allocation, our full-duplex scheduling proposal alongside distributed power allocation, randomized full-duplex scheduling alongside centralized power allocation, and finally half-duplex scheduling alongside maximum power allocation. Except for the case of randomized scheduling, the scheduling objective remains to maximize the logarithmic sum of uplink-downlink UE pair SINR values. In the case of random scheduling, the UE pairs are generated in a random manner, and a round-robin scheduler allocates the resource blocks to these pairs in turn. The random coupling of uplink-downlink UE pairs is constantly redone in order to prevent a bad luck scenario wherein the worst possible pairings are generated. In all of the following simulations, we are studying the performance of central cell UEs only, as it is the cell which experiences the most interference. The value of the SIC is set to 110 dB a benchmark in the state-of-the-art [6].

Table VI
Simulation Parameters

Parameter	Value
Number of RBs	50
SIC Value	10^{11} or 110 dB
Number of UEs	10 UEs per cell: 5 UL, 5 DL
Demand Throughput	4 Mbps
Max UE Transmit Power	24 dBm
Max BS Transmit Power	24 dBm

A. UE Throughput in an Indoor Scenario

We first aim to assess the profitability of full-duplex wireless communications with respect to their half-duplex counterparts. For the considered indoor scenario, we simulate the proposed scheduling algorithm for both full-duplex and half-duplex resource allocation. The results can be seen in the cumulative distribution function (CDF) plot of Fig. 5.

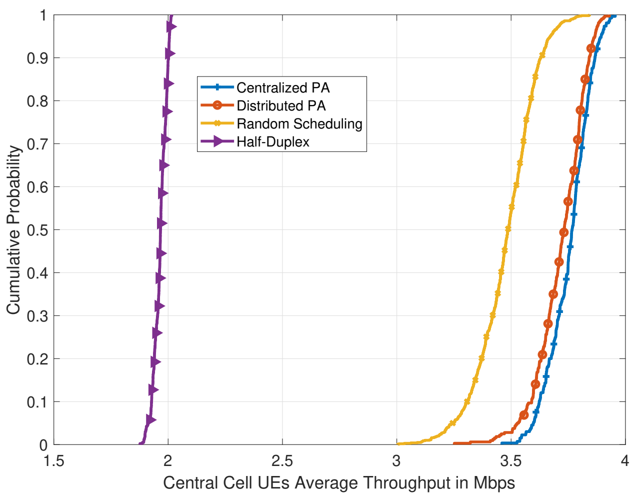

Figure 5. Central cell UE throughput values for the indoor scenario

The average UE throughput value for half-duplex UEs is almost always less than 2 Mbps. In comparison, the average UE throughput value for full-duplex UEs is between 3.3 and about 4 Mbps. The latter achieves almost double the throughput values. Furthermore, the distributed approach achieves average UE throughput values almost identical to that of the centralized one. Furthermore, random scheduling causes limited albeit visible degradation in UE performance, where the average UE throughput values drop by about 0.5 Mbps.

B. UE Throughput in an Outdoor Scenario

We consider the outdoor deployment scenario seen in Fig. 4. This scenario is similar to typical Pico cell deployments. The added distance between the BSs, and the close proximity of the UEs to their corresponding BSs, both help reduce inter-cell interference. Fig. 6 shows how the UEs perform in this scenario and under both half-duplex and full-duplex scheduling.

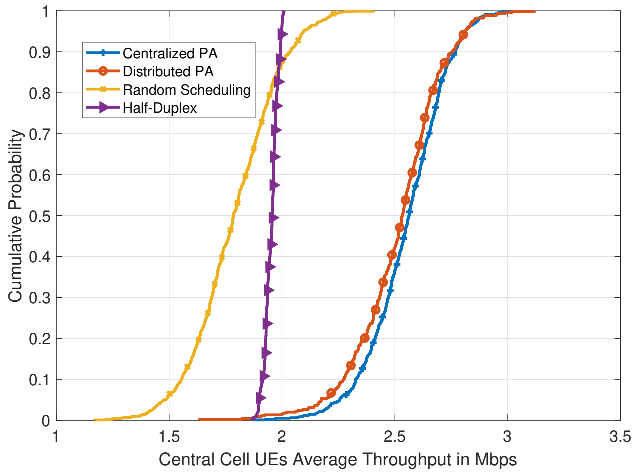

Figure 6. Central cell UE throughput values for the outdoor scenario

Fig. 6 shows average full-duplex UE throughput values between 1.6 and 3 Mbps, while the average half-duplex UE throughput value remains slightly less than 2 Mbps. There are three main takeaways from these results. First, the gains of full-duplex communications in outdoor high interference scenarios are limited although valid. Second, efficient scheduling is needed to extract gains from full-duplex communications as the random scheduling algorithm performed worse than traditional half-duplex scheduling. And third, our distributed approach to power allocation performs similarly to the centralized one albeit with less computational cost.

C. Average UE Waiting Delay

We are interested in computing the average UE waiting delay for our proposal and comparing how it fares with respect to half-duplex communications. In our work we compute the average UE waiting delay using Little's formula as the average queue length divided by the packet arrival rate [47]. Fig. 7 has box plots showing the average UE waiting delay for full-duplex scheduling with centralized power allocation and half-duplex scheduling with equal maximum power allocation, for both the indoor and outdoor deployment scenarios.

In both scenarios, full-duplex communications significantly reduce the average UE waiting delay. For the indoor scenario, the results show a median average delay of 1.2 ms for full-duplex UEs and 3.42 ms for half-duplex UEs. For the outdoor scenario, the results show a median average delay of 2.63 ms for full-duplex UEs and about 3.43 ms for their half-duplex counterparts.

D. Impact of Inter-Cell Cooperation

In our previous simulations, we assumed that the central cell is scheduling resources given information from the surrounding cells on how each allocated its own RBs. We start with the indoor scenario. For the same UE distributions, we simulate our scheduling and power allocation algorithm in two cases: one where the central cell has this relayed information, and one where it does not (*i.e.*, it schedules its resources as if no inter-cell interferers exist). We do this for both half-duplex and full-duplex scheduling and compute the ratio corresponding to the central cell throughput achieved in the absence of such information to that achieved in its presence. Fig. 8 has box plots with the results.

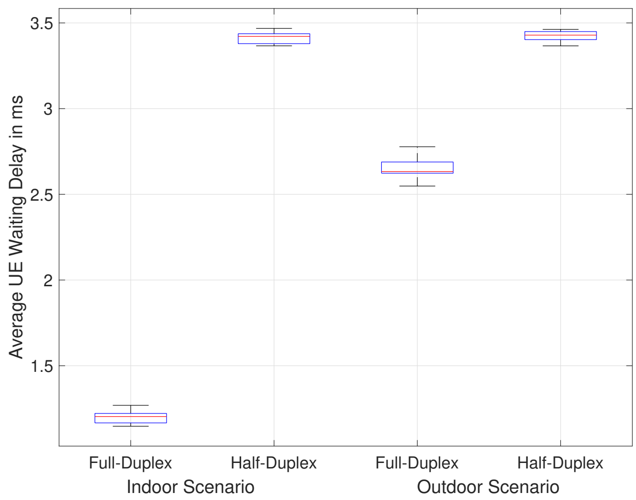

Figure 7. Average UE waiting delay

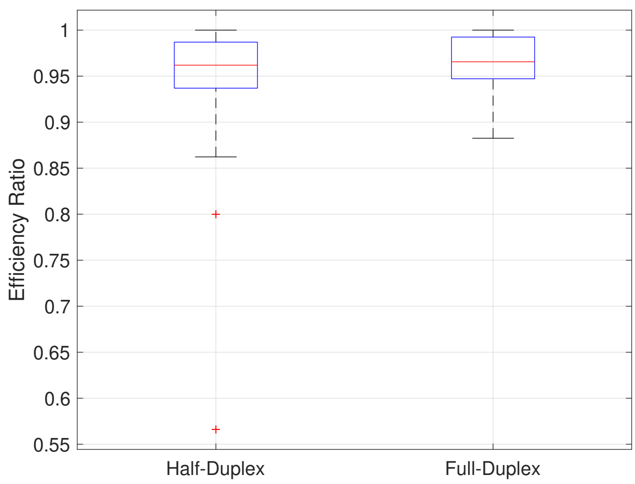

Figure 8. Impact of inter-cell cooperation: indoor scenario

Depending on how the UEs are dropped inside the cell, the lack of relayed information to the central cell could cost up to 12% in its throughput efficiency in the case of full-duplex communications. Half-duplex communications are also affected by the absence of cell cooperation. Except for a few outliers, the maximum loss in efficiency for half-duplex is about 14%. In the case of indoor cells, full-duplex communications would still perform significantly better than their half-duplex counterparts.

We repeat the same simulation for the outdoor scenario. Fig. 9 has box plots with the results. In the case of half-duplex communications, up to 10% of the central cell's throughput could be lost due to the lack of inter-cell cooperation. In the case of full-duplex communications, up to 25% of the central cell's throughput could be lost as a result, with a minimum efficiency loss of about 5%. Whilst

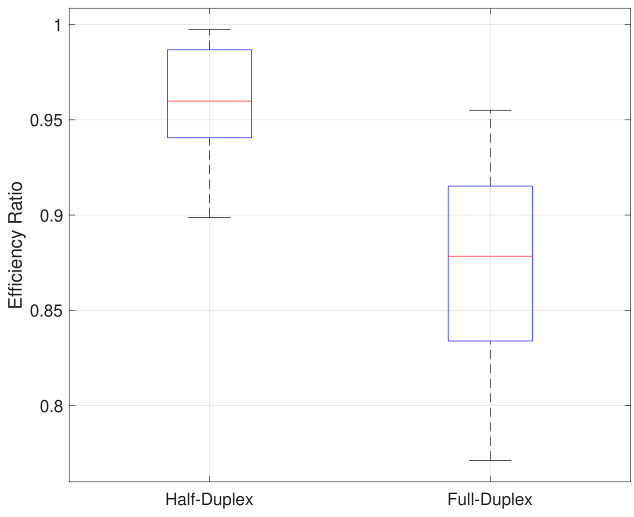

Figure 9. Impact of inter-cell cooperation: outdoor scenario

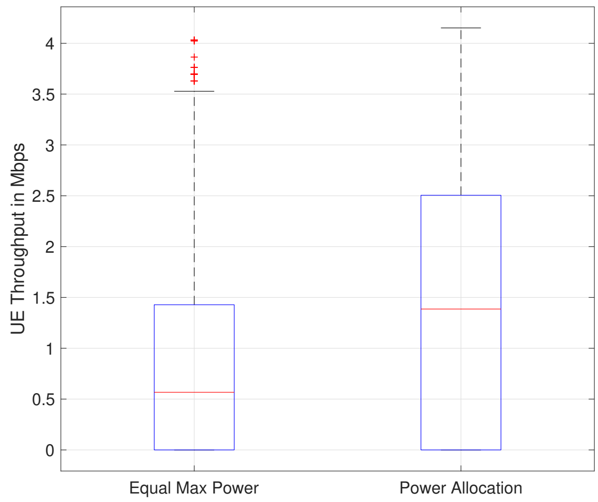

Figure 10. Effect of low SIC on uplink UE performances

full-duplex communications are likely to remain profitable with respect to their half-duplex counterparts regardless of such cooperation, this profit could be severely limited in this outdoor deployment scenario.

E. Impact of Low SIC

We repeat the simulations for the outdoor deployment scenario albeit with the self-interference cancellation (SIC) factor lowered to 80 dB. Following the SINR formulas, this will degrade the performance of uplink UEs in the network. Fig. 10 has box plots showing the performance of uplink UEs in the central cell for our proposed power allocation approach vs. the case of equal maximum power allocation *i.e.,* the UEs transmitting at maximum power equally divided amongst the utilized RBs. The same scheduling approach (our proposal) is used in both cases. Intelligent power allocation improves the performance of uplink UEs in the central cell. Without power allocation, these UEs achieve a median throughput of about 0.5 Mbps and a maximum of 3.5 Mbps (barring some outliers). Well over 75% of the uplink UEs would achieve a throughput less than 1.5 Mbps. On the other hand, uplink UEs allocated power by our approach achieve a median of about 1.4 Mbps with half of the UEs achieving a throughput above 1.5 Mbps. Power allocation better adapts the UEs to the challenges the network could experience.

VIII. Conclusion

In this paper, we presented a joint scheduling and power allocation algorithm for full-duplex wireless networks in a multi-cell setting. We proposed single cell scheduling alongside both centralized and distributed power allocation approaches. We assessed the performance of full-duplex wireless networks, in terms of UE throughput and waiting delay, with respect to their half-duplex counterparts, in both indoor and outdoor deployment scenarios. We showed that the gains of full-duplex communications are relevant to the interference mitigation provided by the cell deployment *i.e.,* isolation due to the presence of walls in indoor scenarios reduces inter-cell interference problems. Finally, we highlighted the importance of cell cooperation when it comes to extracting gains from multi-cell full-duplex wireless networks.

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