Queue-Aware Priority Based Scheduling and Power Allocation in Full-Duplex OFDMA Cellular Networks

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***Abstract*— While helping better utilize the system's resources, full-duplex technologies have the ability to double the efficiency of wireless networks. However, these networks would suffer from added types of interferences, namely self-interference and intra-cell co-channel interference. As such, efficiently addressing scheduling and power allocation in full-duplex networks is vital. In this article, we formulate a queue-aware, fair scheduling and power allocation problem for full duplex orthogonal frequency division multiple access networks. Due to its intractability, we decompose this problem into two: a scheduling problem and a power allocation problem. We compare our proposal to the state-of-the-art, and show that it improves fairness among the user equipment at no cost in the system's performance. Simulation results show a significant increase in throughput values for full-duplex users in comparison with their half-duplex counterparts, and that power allocation saves on expenditure while improving user performance.**

I. Introduction

Already exceeding a staggering 7.2 exabytes per month, mobile data traffic is expected to grow seven folds by the year 2021 [1]. Currently implemented half-duplex (HD) wireless communication systems could soon fail to meet this catapulting demand. These systems allocate a radio resource exclusively to one user equipment (UE) either for transmission or reception. This renders the network bandwidth inefficiently used. However, the development of self-interference cancellation (SIC) technologies have led to the introduction of full-duplex (FD) communications as a possible answer to an ever-growing mobile industry. We base our work on an FD orthogonal frequency division multiple access (FD-OFDMA) system which exhibits a full-duplex base station (BS) and half-duplex UEs. This reduces interference problems, and keeps most of the complexity of implementing FD at the base station. FD-OFDMA systems allocate the same resource block to two different UEs: one on the uplink and one on the downlink. The two UEs form a pair associated with the allocated resource block, on which the BS transmits and receives concurrently. This promises a doubling of the network's capacity, despite a hurdle of interference problems which threaten to diminish the gains.

The first of these interference problems is self-interference. Self-interference is the interference imposed by the transmitted signal from a full-duplex device, typically multiple times larger, on the received signal. This phenomenon leads to the masking of the received signal at the base station, and consequently, to a degradation in performance of uplink UEs. The introduction of self-interference cancellation techniques in recent years altered the vision on FD communications which were once perceived impossible. SIC is done via a set of advanced analog and digital processes as described in [2]. Our work builds on the presence of these technologies, as the efficiency of an FD system is tied closely to the potency of the SIC technology in place.

Secondly, FD-OFDMA systems suffer from intra-cell co-channel interference. The signal from an uplink UE, transmitting with relatively high power, will interfere on the signal being received by a downlink UE. This causes degradation in the performance of these UEs. As a result, scheduling in the uplink and the downlink can no longer be done independently as in half-duplex networks. 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 our work, we formulate a queue-aware scheduling problem that allocates resources to pairs of uplink-downlink UEs, in a manner that maximizes UE SINR and enforces fairness. Due to the intractability of optimally addressing scheduling and power allocation jointly, we decompose the problem and tackle them separately.

We prove that our proposed power allocation proposal can be transformed into a convex problem. Afterwards, we demonstrate the ability of our algorithm to save on power consumption and improve UE performance.

The rest of the paper is structured as follows. Section II discusses the related works and our contributions. Section III presents the system model. Section IV details our optimal problem for scheduling and power allocation in FD-OFDMA networks. A framework for solving this problem is presented in section V. Simulation results are presented and discussed in section VI. Finally, section VII concludes the paper.

II. Related Work

In this section, we examine the main state-of-the-art publications in the domain. The authors of article [3] propose a joint subcarrier and power allocation algorithm which seeks to maximize the sum-rate in FD-OFDMA networks. They implement an iterative water filling power allocation algorithm. The scheduling problem is formulated as a combinatorial problem of high-complexity with the objective of maximizing the sum-rate. The authors thus introduce a heuristic solution with lower complexity. In [4], a joint UE selection and rate allocation algorithm is proposed. It is formulated as a nonlinear non-convex problem with mixed discrete and continuous optimization. Because of the complexity of this problem, a suboptimal method is introduced. The authors in [5] propose an optimization problem with the purpose of allocating resources in what is described as a three-node system. The scenario implemented exhibits a full-duplex BS and half-duplex UEs. They devise a distributed auction algorithm with the purpose of increasing the system's spectral efficiency. In [6], a problem for resource and power allocation in FD-OFDMA networks is formulated. The goal is to maximize the sum-rate. The problem is non-convex with exponential complexity. As such, the authors propose a heuristic alternative. Finally, in [7], the authors seek to jointly distribute resources and allocate power to UE pairs in a manner that maximizes the sum-rate. They formulate the problem as a non-convex optimization problem, and proceed to introduce a user-pairing and subchannel allocation suboptimal heuristic algorithm.

In this paper, we seek to optimally schedule resources and allocate power on the resource blocks, in a manner that maximizes UE SINR, and at the same time enforces fairness. Our scheduling is queue-aware and the arrivals are dynamic. These objectives give prevalence to multiple questions: *How can we optimally account for queue-awareness? How can we jointly maximize UE SINR whilst ensuring fairness? Two seemingly contradicting goals.* Our formulation answers these questions and puts us apart from the majority of the state-of-the-art [3]–[7], which address neither. Furthermore, our power allocation problem is tractable, as we demonstrate later on. It bears significantly less complexity than the non-convex optimization algorithms in the articles mentioned above. As non full-buffer traffic, like streaming and video, would make up to 78 % of the global mobile traffic by the year 2021 [1], our queue-aware approach is significantly more realistic than the full-buffer traffic models considered in the state-of-the-art.

III. System Model

A. Radio Model

We consider a single-cell FD-OFDMA system. This system exhibits 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 scheduler will pair between uplink and downlink UEs on the resource blocks *k* of the set *K*. This system is illustrated in Fig. 1.

In our work, we assume that the physical layer is operated using an OFDMA structure. The radio resource is divided into time-frequency resource blocks. In the time domain, a resource block (RB) 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 [8].

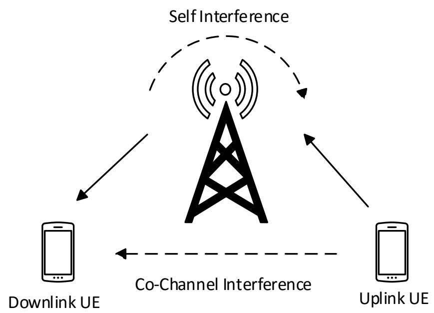

Figure 1. System model and interferences

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

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

For a downlink UE,

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

where $S^u_j(i,k)$ is the SINR of UE i on resource block k, while using the same resources as UE j. Similarly, $S^d_i(j,k)$ is the SINR of UE j on resource block k, while being paired with UE i.

B. Traffic Model

Our scheduling is queue-aware (Fig.2). Each UE has a predefined throughput demand which determines the rate

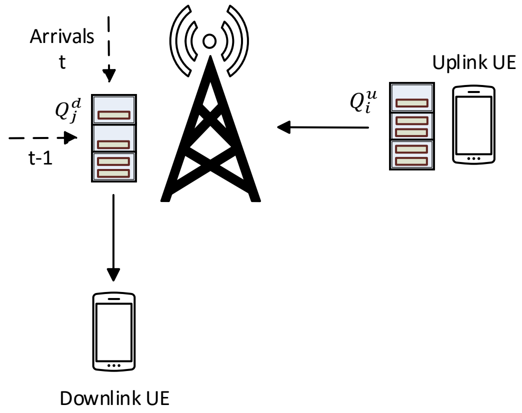

Figure 2. Traffic model and UE queues

at which the UE will transmit or receive. A downlink UE has a queue at the BS, denoted Q_j^d. 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 BS 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. In our work, the BS has complete information on the radio channels, and can thus estimate the number of bits a UE can transmit, or receive, depending on its SINR.

IV. Formulation of the Optimal Scheduling and Power Allocation Problem

We propose a queue-aware scheduling and power allocation optimal problem for FD-OFDMA networks. Our aim is to maximize the UE SINR values, while at the same time enforcing fairness among the UEs. Solving such a problem requires information on the UE radio conditions, their queue statuses, as well as an innate definition of fairness. As such, we define a UE pair priority and formulate the problem with the objective of maximizing the sum of these priorities.

The priority of a UE pair is defined as a function of its current radio conditions, represented by the sum of the log of the pair's UE SINR values, and its historic radio conditions, represented by the number of bits these UEs have already transmitted. The priority for an uplink-downlink UE pair i-j, on resource block k, is defined as:

$$\rho_{ijk} = \frac{\log(S_j^u(i,k)) + \log(S_i^d(j,k))}{T_i + T_j}, \tag{3}$$

where T_i is the number of bits UE i has transmitted in a certain time window. Consequently, the fairness is relative to the UE SINR. The priority of a certain pair, and with it the priority of the UEs which have transmitted for a prolonged period of time will drop. The sum of logarithmic functions of the SINR enforces fairness as illustrated in [9]. It dictates that no UE will attain an SINR equal to zero. Furthermore, the UE queue is finite, and the UE priorities are dependent on the transmitted bits, as such, they are periodically reset. This guarantees that no UE priority will be zero, as long as it can, and has, bits to transmit. The UE pair-resource scheduling variable z_{ijk}, is defined $\forall\ k \in K$, $\forall\ i \in \mathcal{U}$, $\forall\ j \in \mathcal{D}$, and is equal to one if uplink UE i is paired with downlink UE j on resource block k. It is equal to zero otherwise. In this optimization problem, the variables are the UE pair-resource block scheduling variables, and the uplink and downlink powers. We formulate the problem for TTI t as follows:
$(\mathcal{P}^t)$:

$$\underset{z_{ijk}, P_{j,k}^d, P_{i,k}^u}{\text{Maximize}} \quad \sum_{k\in K}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}.\rho_{ijk}. \tag{4a}$$

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

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

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

$$\sum_{k\in K}\sum_{j\in\mathcal{D}} P_{j,k}^d \le P_{max}^d, \tag{4e}$$

$$\sum_{k\in K} P_{i,k}^u \le P_{max}^u,\ \forall i \in \mathcal{U}, \tag{4f}$$

$$P_{i,k}^u \ge P_{min}^u,\ \forall i \in \mathcal{U}, \tag{4g}$$

$$P_{j,k}^d \ge P_{min}^d,\ \forall k \in \mathcal{D}, \tag{4h}$$

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

T_{ijk}^u is the number of bits uplink UE i can transmit on resource block k, while paired with downlink UE j. Similarly, T_{ijk}^d is the number of bits UE j can receive on resource block 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) is the objective of our problem, to select the pairs which have the highest priorities. According to (4b), each resource block should be allocated to either one or no pair. Equations (4c) and (4d) help incorporate queue-awareness. By estimating the number of bits a UE can transmit (T_{ijk}^u) or receive (T_{ijk}^d) on a resource block, these constraints ensure that a UE will get a certain number of resources, if and only if, it is going to use them in their entirety.

Equation (4e) indicates the power budget at the base station. Equation (4f) limits the transmit power of a UE to a maximum value. Due to the necessity of giving minimum power values on the resource blocks, we add the constraints (4g) and (4h). P_{min}^u and P_{min}^d are constants and equal to 0.001 W and 0.005 W, respectively.

The scheduling problem presented is combinatorial in nature. Addressing it together with power allocation in an optimal manner is challenging, especially as the combined problem is of type mixed integer non-linear programming (MINLP). It will become intractable as the number of UEs and resource blocks increase. As such, we solve this problem according to the framework presented in the following section.

V. Problem Solving Framework

The optimal problem is decomposed and solved according to the following framework (fig. 3). Knowing the UE radio conditions and their queue statuses, we obtain an optimal resource allocation matrix z^*_{ijk} with fixed uplink and downlink power values. Afterwards, the power allocation problem takes this matrix as input, and computes the powers on the uplink and the downlink. The UE SINR values are recomputed using the optimal power values, and the number of bits each UE can transmit, or receive, is calculated. The UE queues Q^u_i and Q^d_j are then appropriately deducted depending on the resources each UE was allocated. At the beginning of the next TTI, new arrivals are added to the UE queues, and the UE demands D^u_i and D^d_j are updated.

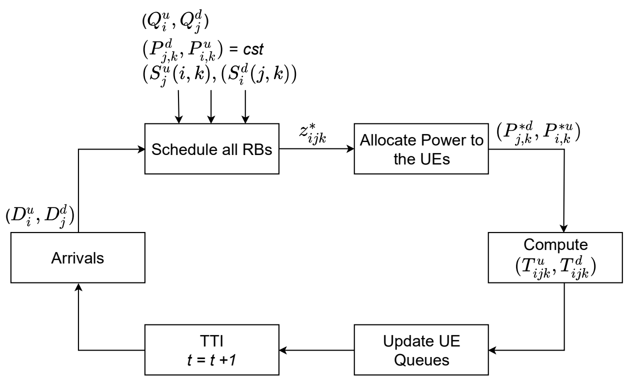

Figure 3. Scheduling and power allocation framework

A. Scheduling Problem

According to the proposed framework, and with fixed powers on the resource blocks, the optimization variables are now the values of z_{ijk}. The scheduling problem is written as follows:
$(\mathcal{P}^t)_S$:

$$\underset{z_{ijk}}{\text{Maximize}} \sum_{k \in K} \sum_{i \in \mathcal{U}} \sum_{j \in \mathcal{D}} z_{ijk} . \rho_{ijk}. \tag{5}$$

Subject to (4b) to (4d)

The values of z_{ijk} are binary. The constraints are linear. This problem is as such of type integer linear programming. The number of constraints and variables are important factors when estimating if a problem is tractable. Generally, ILP problems are solved using a linear-programming based branch-and-bound approach. The idea of this approach to look for an integer solution by branching and bounding on the decision variables provided by the LP relaxations. Thus, the number of integer variables determines the size of the search tree and influences the running time of the algorithm.

B. Power Allocation Problem and Convex Transformation

Power allocation is performed after the resources are scheduled. The optimization variables are now the power levels on the resource blocks $P^d_{j,k}$ and $P^u_{i,k}$. The power allocation problem is written as follows:
$(\mathcal{P}^t)_{PA}$:

$$\underset{P^d_{j,k}, P^u_{i,k}}{\text{Maximize}} \sum_{k \in K} \sum_{i \in \mathcal{U}} \sum_{j \in \mathcal{D}} \frac{z^*_{ijk}}{T_i + T_j}.$$

$$(\log(\frac{P^u_{i,k}|h^u_{i,k}|^2}{N_{0,k} + \frac{P^d_{j,k}}{C_{SI}}}) + \log(\frac{P^d_{j,k}|h^d_{j,k}|^2}{N_{j,k} + P^u_{i,k}|h_{ji,k}|^2})), \tag{6}$$

Subject to (4e) to (4h)

The expression of the SINR has the following form:

$$\log(\frac{ax}{b + cy}), \tag{7}$$

where a, b, and c are constants. x and y are the optimization variables that represent the powers. Maximizing a concave function, subject to linear and convex constraints, leads to a convex problem. We perform a logarithmic change to the variables and the constants such that $\hat{x} = \log x$. This changes equation (7) into

$$\log(e^{\hat{x}+\hat{a}}) - \log(e^{\hat{b}} + e^{\hat{y}+\hat{c}}) = \hat{x} + \hat{a} - \log(e^{\hat{b}} + e^{\hat{y}+\hat{c}}), \tag{8}$$

$\hat{x} + \hat{a}$ is a linear function, therefore it is a concave function [10]. The function $\log \sum e^x$ is convex, therefore $-\log \sum e^x$ is concave. Thus, the expression in (8) is concave. As the objective function is concave, we still need to proof that the constraints are convex. These constraints can be written in the form of:

$$\sum x \leq d. \tag{9}$$

With the change of variables we did, it becomes:

$$\sum e^{\hat{x}} - d \leq 0. \tag{10}$$

$\sum e^x$ is a convex function and d is a constant, this means that (10) is convex. In conclusion, the power allocation problem can be transformed into a non-linear convex problem, and can be solved efficiently by standard convex program solvers such as CVX [11]

VI. Simulation and Results

A. Simulation Parameters

The simulation parameters we used are presented in table I. The channel gain takes into account the path loss, the shadowing, and fast fading.

Table I
Simulation Parameters

Parameter	Value
Cell Specifications	Single-Cell, 120 m Radius
Number of RBs	20
BS Transmit Power	24 dbm
Maximum UE Transmit Power	24 dbm
SIC Value	10^{11} or 10^8
Number of UEs	5DL, 5UL
UE Distribution	Uniform
Demand Throughput	2 Mbps
Fast Fading	Rayleigh. σ=1
Shadowing	Normal law. μ=0 σ^2=10
Path Loss Model	Extended Hata Path Loss Model
Simulation runs	500, 10 TTI each

B. Gain In Throughput and Fairness

We seek to validate the possible gain achievable from FD. The self-interference cancellation value is set at the relatively high value of 10^{11}. We plot the cumulative distribution function (CDF) for the throughput attained by the UEs for our FD priority based algorithm, and for HD scheduling. Additionally, we augment and adapt the sum-rate maximization algorithm proposed in [3] to our queue-aware model, and compare it to our proposal.

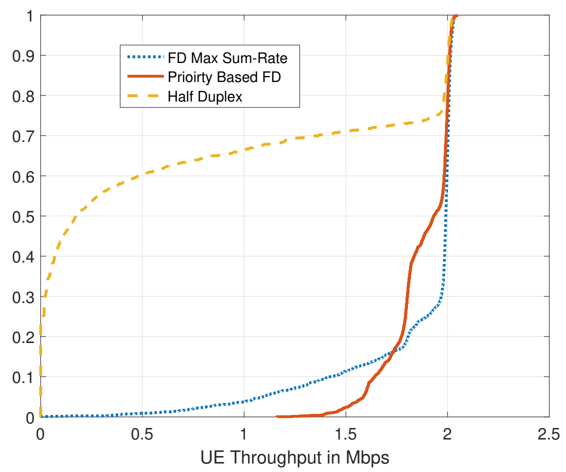

Figure 4. UE Throughput: Priority Based FD, HD, and Max Sum-Rate

The graph in Fig. 4 shows massive improvement in performance for FD UEs. The minimum attained throughput by an HD UE is 0 Mbps, compared to 1.2 Mbps by our FD algorithm. On average FD Priority Based UEs attained 1 Mbps more throughput than their HD counterparts. The gain is almost double. In comparison to the sum-rate maximization algorithm we simulated, our FD algorithm has less UEs attaining the maximum throughput value of 2 Mbps. However, it has no UEs attaining values lower than 1.2 Mbps, whilst the lowest throughput for the sum-rate algorithm is 0 Mbps. Our algorithm focuses more on the aspect of UE fairness, giving more resources to UEs which have transmitted less often than others. We use Jain's fairness index [12] to evaluate the equity among the UEs. Our proposed algorithm has a Jain index value equal to 0.9803. The greedy algorithm, proposed in [3], has a fairness index value equal to 0.75. The fairness of the latter will decrease exponentially as the load increases.

Furthermore, we seek to study the effect this added fairness has on the overall network performance. Figure 5 has the boxplots for network throughputs attained by our algorithm, and by the sum-rate maximization algorithm throughout the simulations.

The highest network throughput attained by the sum-rate algorithm is around 38 Mbps, compared to 38.4 Mbps for our algorithm. The latter has 36.2 Mbps as the lowest attained network throughput, compared to around 35.6 Mbps for the sum-rate algorithm. In general, our algorithm slightly improves the overall network throughput, and the added fairness comes at no cost in the overall system performance. This is mainly due to the effects of multi-user diversity and dynamic traffic. With UEs having finite queues and limited bits to transmit, UEs with

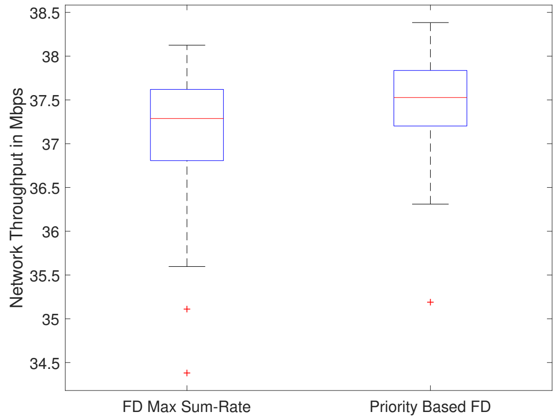

Figure 5. Network throughput: Max-Sum Rate and Priority Based FD

high SINR values will not hog the resources and transmit indefinitely. If the UEs were to have full buffer traffic, the sum-rate algorithm would always produce higher network throughput. Nonetheless, this is not the case neither in our model, nor in real wireless networks.

C. Power Expenditure

In this subsection, we seek to compare the difference in power expenditure by our algorithm, in the presence and absence of power allocation. The SIC value is 10^{11}. For the case where the powers are not optimally allocated, the transmit power of a UE on a resource block is equal to the maximum transmit power, divided by the number of resource blocks it was allocated during that TTI.

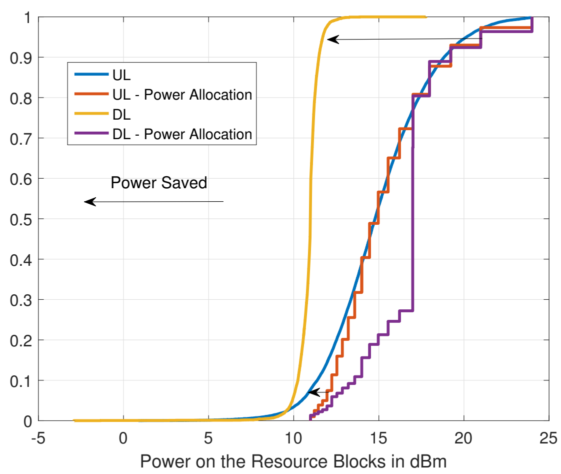

Figure 6. Power expenditure per resource block, with and without power allocation

Figure 6 shows the CDF plot for the transmit power, per resource block, of both uplink and downlink FD Priority Based scheduled UEs, with and without power allocation. The CDF shows significantly lower power expenditure on the downlink for the algorithm, when power allocation is performed. None the uplink UEs with power allocation transmitted on powers higher than 18 dBm per RB, compared to 18% of their counterparts crossing that mark. As for uplink UEs, the advantage is also there for the UEs with power allocation, albeit with less significance.

As resource allocation on the uplink and downlink in FD-OFDMA networks is intricate and correlated, there will always be a trade off between the gains on the uplink and on the downlink.

D. Effect of Low Self-Interference Cancellation

We want to study the performance of our algorithm in case of relatively low SIC. The SIC value is lowered to 10^8. Following the uplink UE SINR equation in (1), the value of the SIC affects the performance of uplink UEs. We use bag plots [13] to asses the SINR values attained by uplink UEs as a function of their transmission power on the resource blocks. Figures 7 and 8 show the results, with and without power allocation, respectively.

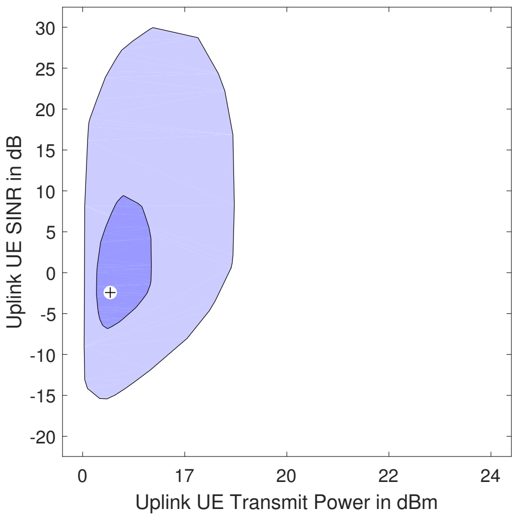

Figure 7. UE SINR as a function of transmit power per resource block, in the presence of power allocation and under the effect of low SIC

The inner bag (dark blue) in fig. 7 is thinner than that corresponding to the algorithm runs without power allocation (fig. 8). This implies that the power spread is smaller in the case of power allocation. Furthermore, the SINR spread favors the case of the latter as well. Power allocation helped increase the SINR values of the worst performing UEs. The lowest UE SINR value in the case of power allocation is -15 dB compared to -20 dB for the case without. Finally, the bag in fig. 7 slopes upwards. This means that the SINR increases as the power expenditure increases. This is not true for the case without power allocation, where sometimes the expenditure of uplink power does not necessarily translate into better SINR.

VII. Conclusion

In this article, we present our optimal FD Priority Based algorithm for scheduling and power allocation in FD-OFDMA networks. We seek to fairly schedule the resources while appropriately allocating power to the UEs. Our algorithm is queue-aware and takes dynamic traffic arrivals into account. Simulation results show almost double the values for throughput in FD systems, compared to HD. Additionally, our algorithm enforces fairness among the UEs without cost to the system performance. Finally, optimally allocating power on the resource blocks decreased expenditure, and helped improve radio conditions for the worst fairing UEs.

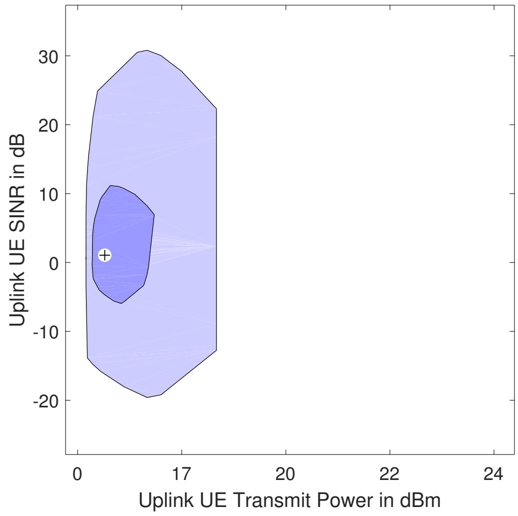

Figure 8. UE SINR as a function of transmit power per resource block, in the absence of power allocation and under the effect of low SIC

VIII. Acknowledgment

This work was supported by the Lebanese National Council for Scientific Research (CNRS-L), and by the research council at Saint Joseph University of Beirut, under the CNRS-USJ doctoral fellowship program.

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