Queue-Aware Scheduling in Full Duplex OFDMA Wireless Networks with Imperfect Channel State Information

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Abstract— **Scheduling in full-duplex networks is essential for efficiently managing resources, and for mitigating interference problems. However, this task is hindered by the lack of complete channel state information. Full duplex networks need information on the radio channel in between the user equipment that current wireless networks do not provide. In this paper, we propose two queue-aware optimal algorithms, one greedy and one fair, for scheduling in full duplex orthogonal frequency division multiple access networks. We propose heuristic alternatives for these algorithms, and show that they provide near optimal performance. With two different scheduling objectives at hand, we study the impact of imperfect channel state information on scheduling in full duplex networks.**

I. Introduction

Current half-duplex (HD) wireless cellular systems could soon fail to meet the demand for increased network capacity and higher user equipment (UE) throughput. Cisco's Visual Networking Index [1] estimates that global mobile data, already exceeding 7.2 billion gigabytes a month, would grow seven folds by the year 2021. HD systems allocate a radio resource exclusively to one UE either in the uplink, or in the downlink. This renders the network bandwidth inefficiently used. Recent 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.

In this paper, we base our work on an FD orthogonal frequency division multiple access (FD-OFDMA) network. Such a network exhibits a full-duplex base station (BS) and half-duplex UEs. This reduces interference problems, and keeps most of the FD complexity at the base station. FD-OFDMA networks 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. Theoretically, this approach could double the network's capacity. Practically, interference problems could minimize the possible gains.

FD-OFDMA networks suffer from two major sources of interferences. The first of which is self interference. Self-interference is the interference imposed by the transmitted signal from an FD device, typically multiple times larger, on the received signal. This phenomenon leads to the masking of the received signal, thus degrading the performance of uplink UEs. The second, intra-cell co-channel interference, results from two UEs using the same frequency within the same cell. 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 the latter. While combating self-interference is done via a set of advanced analog and digital cancellation techniques [2], it is up to the scheduling algorithm to ensure that the co-channel interference between the UEs of a selected pair does not hinder their performance. Consequently, scheduling in the uplink and the downlink can no longer be done independently, as in HD systems.

In this paper, we study the effect of having imperfect channel state information on scheduling in FD-OFDMA networks. Specifically, we assume that the information the BS has on the channel in between the UEs is incomplete. Methods to determine, or estimate, the channel between the UEs and the BS exist in current Third Generation Partnership Project (3GPP) protocols.

To this end, we propose and simulate two scheduling algorithms for FD-OFDMA networks in multiple scenarios of imperfect channel state information. The first algorithm, FD Max-SINR, is opportunistic and greedy. It seeks to allocate the resource blocks to the UEs with the highest SINR values. The second, FD Proportional Fair, is a fairness oriented scheduler that allocates resources to UEs based on their priorities. The priority of a UE is selected as a function of its current and historic radio conditions.

Furthermore, we highlight the importance of queue-awareness in simulating resource allocation techniques, and study the effect of varying the SIC value on the performance of an FD network.

This paper is structured as follows. Section II discusses the related works. Section III presents the system model. Section IV details the first of our proposed scheduling algorithms, FD Max-SINR. Our second algorithm, FD Proportional Fair, is highlighted in section V. We discuss the complexity of our proposed algorithms in section VI. We propose a heuristic solution for our optimization problems in section VII. Simulation results are presented and discussed in section VIII. Section IX concludes the paper, and states our future work.

II. Related Works and Contributions

In this section, we discuss the state-of-the-art related to our work, and highlight our main contributions. The authors in [3]–[5] work on tracking the possible gains, as well as limitations, of FD wireless networks. They discuss, and simulate, different FD system scenarios and modules, and highlight the possible gains in capacity that these systems could provide. The authors in the articles [6]–[10] propose subcarrier allocation algorithms which seek to maximize the sum-rate in FD-OFDMA networks. In these articles, the scheduling problem is formulated as a combinatorial problem of high-complexity with the objective of maximizing the sum-rate. The authors thus introduce heuristic solutions with lower complexity, and verify that they achieve near optimal results. The most relevant to our work in the state-of-the-art is the article in [11]. The authors in this article address resource allocation in FD-OFDMA cellular networks with partial channel state information. They model the channel between the UEs as Gaussian, and consider that they know this channel with an error offset.

In this paper, we seek to study the effects of imperfect channel state information on scheduling in FD-OFDMA networks. Our approach to scheduling addresses fairness among the UEs, unlike the vast majority of the related works [6]–[11]. Additionally, we formulate the scheduling task as an Integer Linear Problem (ILP). It bears significantly less complexity than the non-convex optimization algorithms in the articles mentioned above. In contrast to the article in [11], in our work we consider that elements of the channel in between the UEs are completely missing, rather than partially offset. This further tests the validity of FD in such scenarios, and supersedes the simulations implemented in that article. Finally, our work has the originality of using a dynamic traffic model $i.e.$, the scheduling is queue-aware. Queue-awareness allows us to compute packet level metrics such as the waiting delay. Additionally, it is a more realistic approach compared to the full buffer traffic assumed in the majority of the state-of-the-art, as in [6]–[11]. Non full-buffer traffic, like streaming and video, would make up to 78 % of the global mobile traffic by the year 2021 [1], and misrepresenting the queue statuses could severely implicate the scheduling process as we later demonstrate. As such, we deal with dynamic traffic arrivals by placing additional constraints on the optimization problems.

III. System Model

A. Radio Model

We consider a single-cell FD-OFDMA 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 *k* of the set *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 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). 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 LTE like specifications, with a resource block being composed of 12 subcarriers and 7 OFDM symbols [12].

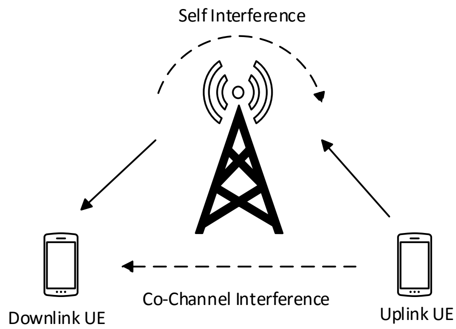

Figure 1. Network model and interferences

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 $P^u_{i,k}$ denote the transmit power of the *i*th uplink user, on the *k*th resource block. Similarly, $P^d_{j,k}$ is the transmit power of the BS serving downlink user *j*, on the *k*th resource block. We denote by $h^u_{i,k}$ the channel gain from the *i*th uplink user to the BS on resource block *k*, and by and $h^d_{j,k}$ the channel gain from BS to the *j*th downlink user, on the *k*th 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. $P^u_{i,k}|h_{ji,k}|^2$ is thus the co-channel interference on downlink UE j caused by uplink UE i, using the same 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, on the *k*th resource block, respectively. Equations (1) and (2) denote the formulas for SINR calculation for uplink and downlink UEs. For an uplink UE,

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

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 using the same resources as UE i. Note that the inter-UE channel $h_{ji,k}$ is the focus of our simulation scenarios.

B. Channel State Information

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

Legacy HD networks would rely on feedback from the UEs to determine the current channel state. These networks are concerned mainly with the channel in between the base station and the UEs, and different techniques are used to determine how often, and on which frequency 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 CSI. In FD systems, additional information on the channel in between the UEs of a certain pair is required. Not only do current wireless systems 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 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 mean 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.

We aim to assess the vitality of the inter-UE channel state information to the functioning of an FD-OFDMA system. 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 system 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 need less periodical updates to convey such information to the BS. These three scenarios of CSI availability are simulated and compared to the optimal case, where the CSI is completely known at the BS.

C. Traffic Model

Our scheduling is queue-aware (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. 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.

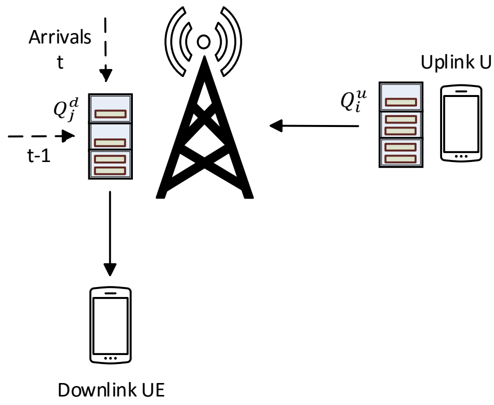

Figure 2. Traffic model: UE pair i-j

IV. Optimal FD Max-SINR Scheduling

In this section we present the first of our scheduling algorithms, FD Max-SINR. We previously discussed a heuristic approach to FD Max-SINR scheduling in [13]. The objective is to allocate the resource blocks to UE pairs with the highest sum of SINR values. This optimal algorithm is illustrated in (4).

(P_1^t):

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

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

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

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

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

The UE pair-resource assignment 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. $S_j^u(i,k)$ and $S_i^d(j,k)$ are the UE pair SINR values.

T_{ijk}^u is the number of bits UE i can transmit on resource block k while paired with 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 is the demand of UE i *i.e.*, the number of bits in its queue. Likewise, D_j is the demand of UE j. α_p represents the minimum percentage resource utilization. This means that the UE will transmit or receive at least α_p of the bits it can on the resources allocated to it.

Equation (4a) is the objective of our problem, to select the pairs which have the highest sum of SINR values. According to (4b), each resource block should be allocated to either one or no pair. Equations (4c) and (4d) dictate the efficiency of the resource allocation process. When α_p = 1, a UE is allocated a number of resource blocks if the number of bits in its queue is greater than or equal to the number of bits it can transmit on these resources. Since the UE queues are finite, these constraints insure that the resources are distributed efficiently, and not allocated to UEs that do not need them.

V. Optimal FD Proportional Fair Scheduling

We aim to allocate the resource blocks in a manner that maximizes the system's throughput, while at the same time insures a certain level of fairness. To this end we propose an FD Proportional Fair algorithm, which allocates resource blocks to the pairs of UEs with the highest sum of priorities. The priority of a UE is a function of its current radio conditions, represented by the number of bits a UE can transmit, or receive, on the current resource block, and its historic radio conditions, represented by the number of bits it has already transmitted. The priority for an uplink UE i, paired with a downlink UE j on resource block k, for example, is defined as:

$$\rho_j(i,k) = \frac{T^u_{ijk}}{T_i}, \tag{5}$$

where T_i is the number of bits UE i has transmitted over a certain time window. The optimization problem for FD Proportional Fair is presented in (6), where the objective function is to maximize the sum of priorities $i.e.$, select the pairs with the highest priorities. The constraints and assumptions from the previous problem remain the same. (P^t_2):

$$\text{Maximize} \quad \sum_{k\in K}\sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk}(\rho_j(i,k)+\rho_i(j,k)), \tag{6a}$$

$$\text{subject to} \quad \sum_{i\in\mathcal{U}}\sum_{j\in\mathcal{D}} z_{ijk} \le 1, \ \forall k \in K, \tag{6b}$$

$$\alpha_p \sum_{k\in K}\sum_{j\in\mathcal{D}} z_{ijk}T^u_{ijk} \le D_i, \ \forall i \in \mathcal{U}, \tag{6c}$$

$$\alpha_p \sum_{k\in K}\sum_{i\in\mathcal{U}} z_{ijk}T^d_{ijk} \le D_j, \ \forall j \in \mathcal{D}, \tag{6d}$$

$$z_{ijk} \in \{0,1\}, \ \forall i \in \mathcal{U}, \forall j \in \mathcal{D}, \forall k \in K. \tag{6e}$$

VI. Complexity of the Optimization Problems

The variables in these problems are all integers. The objective function and the constraints, which depend on the binary value of z_{ijk}, are linear. The optimization problem is thus an integer linear program (ILP). This problem is NP hard [14]. The number of constraints and variables are important factors when estimating if this problem is tractable. Generally, ILP problems are solved using a linear-programming based branch-and-bound approach. These problems could become prohibitive for very large numbers of UEs and resource blocks.

VII. Heuristic Scheduling

In this section, we present heuristic alternatives for our optimal scheduling problems. Let F be the UE utility function. The utility for an uplink UE i when paired with downlink UE j is then $F^u_j(i,k)$. Similarly, the utility for downlink UE j while being paired with uplink UE i is $F^d_i(j,k)$. F is equal to the UE SINR in the case of FD Max-SINR in (P^t_1), and is equal to the UE priority in the case of FD Proportional Fair in (P^t_2).

for *k=1....K* **do**
  if $\mathcal{U} \neq \phi$ *and* $\mathcal{D} \neq \phi$ **then**
    (i^*, j^*) = $\underset{i\in\mathcal{U},j\in\mathcal{D}}{\text{argmax}}(F^u_j(i,k)+F^d_i(j,k))$
    Allocate resource block k to couple (i^*, j^*)
    Update UE Queues
  else
    e^*= $\max_{e\in\mathcal{U}\cup\mathcal{D}}(F(e,k))$
    Allocate resource block k to user e^*
    Update UE Queue
  end
end

Algorithm 1: Heuristic Scheduling

The algorithm works as follows. Each TTI, and for every resource block, the scheduler will allocate the selected resource block to the UE pair i-j with the highest sum of utility functions. If allocation in FD is not feasible because one of the uplink or downlink sets is empty, the scheduler will allocate the resource block in HD to the UE with the highest HD utility $F(e,k)$. In such a case, the UE SINR is calculated as in typical HD networks.

VIII. Simulation and Results

A. Simulation Parameters

The simulation parameters, used to run our algorithms in MATLAB, are presented in the table I.

Table I
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}
Number of UEs	10DL, 10UL
UE Distribution	Uniform
Demand Throughput	2 Mbps
Fast Fading	Exponential variable
Shadowing	Log-normal variable
Path Loss Model	Extended Hata Path Loss Model
Simulation runs	500

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 [15]. 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.

B. Optimal Solution vs. Heuristic Approach

We seek to both validate our heuristic approaches, and compare between our two proposals. Figure 3 has the cumulative distribution function (CDF) plot of the UE throughput values for both our algorithms, solved optimally and heuristically, under complete channel state information. For the FD Max-SINR algorithms, the UE throughput results are near identical, with the optimal algorithm producing slightly better values for the UEs with bad radio conditions. The lowest recorded value for the heuristic FD Max-SINR algorithm is 300 kbps compared to around 400 kbps for the optimal. Similarly, the heuristic FD Proportional Fair algorithm produces near optimal results, with a limited number of UEs achieving slightly higher throughput values under the optimal algorithm. The gain for the heuristic approaches comes in reduced computation time as the number of UEs and resource blocks increase.

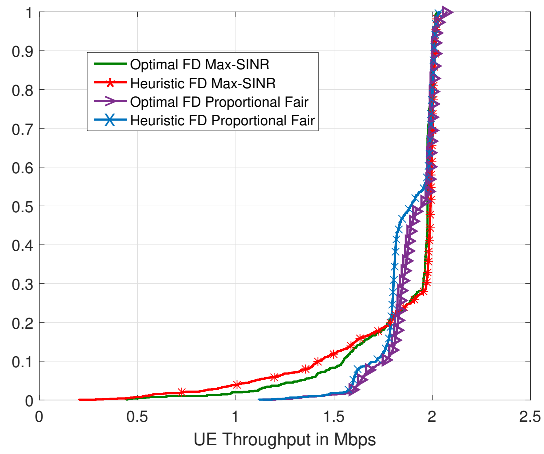

Figure 3. FD Max-SINR vs. FD Proportional Fair

Furthermore, we asses the performance of our FD Proportional Fair proposal in comparison with its greedy counterpart, FD Max-SINR. Under complete channel state information, the lowest attained throughput by an FD Proportional Fair UE is around 1.1 Mbps, compared to 300 kbps for FD Max-SINR. This improvement comes at the expense of the UEs with the best radio conditions. FD Max-SINR has 70% of the UEs attaining a throughput equal to the demand of 2 Mbps, compared to 46% for FD Proportional Fair. In this simulation, our FD Proportional Fair has a 0.98 Jain [16] fairness index value, compared to 0.8 for FD Max-SINR.

C. Effect Of Imperfect CSI on Greedy Allocation

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 resource blocks and 20 UEs, the system is considered to be under heavy load conditions.

The channel in between a pair of UEs is the focus of our work. We simulate multiple scenarios of channel state information availability for our FD Max-SINR algorithm as detailed in section III-B.

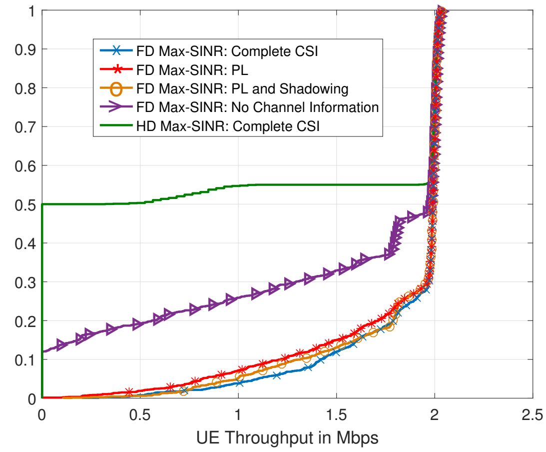

Figure 4. Effect of imperfect CSI on FD Max-SINR

Figure 4 is a CDF plot of the throughput attained by the UEs across the different simulation scenarios. For reference, a traditional HD Max-SINR algorithm is simulated under complete CSI. The throughput attained by FD 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 11% 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 base station. When the path loss information is available, FD Max-SINR UEs show substantial improvement in performance, where almost half of the UEs got an 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 200 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, FD Max-SINR outperforms HD Max-SINR regardless of the channel estimation errors. Under these simulation parameters, almost 50% of the HD UEs were denied throughput, compared to 11% the worst case scenario for FD. In addition, for any UE simulated, the throughput attained by an FD UE is higher than that attained by an HD UE. To conclude, it is evident that scheduling without complete information on the channel between the UEs degrades the performance of FD networks, but this performance remains much better than that of traditional HD Max-SINR scheduling.

D. Effect Of Imperfect CSI on Fair Allocation

In this section we study the effect of imperfect channel state information on fair scheduling techniques. Figure 5 is a box plot of the resulting UE throughputs for our FD Proportional Fair algorithm under different scenarios of CSI availability. An HD Proportional Fair algorithm is also simulated under complete CSI.

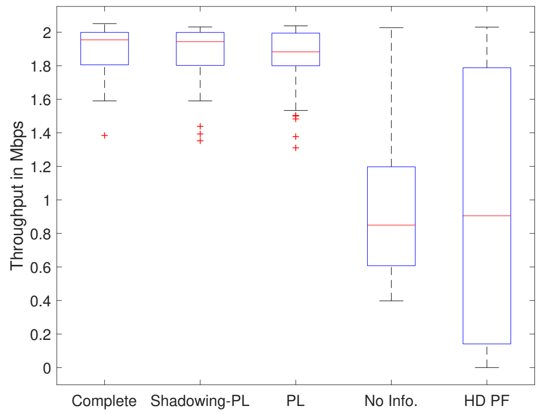

Figure 5. Effect of imperfect CSI on FD Proportional Fair

Similar to the case of FD 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 dropped 1 Mbps, and the gains with respect to HD Proportional Fair become questionable. Although the FD 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 (Eq.5). This incurs that a previously erroneous decision will be carried on and even magnified.

E. Effect of Imperfect CSI on the Waiting Delay

Because of our queue-aware scheduling model, we are able to compare the average UE waiting delay for the different simulation scenarios of our FD Max-SINR algorithm. For reference, we also compute the average waiting delay for the HD Max-SINR algorithm we simulated. The average delay is calculated using Little's formula as the average queue length divided by the packet arrival rate. Figure 6 is a box plot of the average UE waiting delay per simulation run, for every considered scenario.

The box plots show that the presence of inter-UE channel information decreases the waiting delay. In case of complete channel state information, the median value for the average waiting delay is 1.7 ms, with lowest value being 1.5 ms and the highest about 1.9 ms. For the worst case scenario, where the channel is totally unknown, the median average waiting delay rises to 2.3 ms, with the highest value around 2.6 ms. Nonetheless, as in the case for the UE throughput, FD Max-SINR UEs will always outperform their HD counterparts. The average waiting delay for HD Max-SINR UEs, under complete CSI, is between 3.2 and 3.4 ms, significantly higher than the worst case scenario for FD Max-SINR.

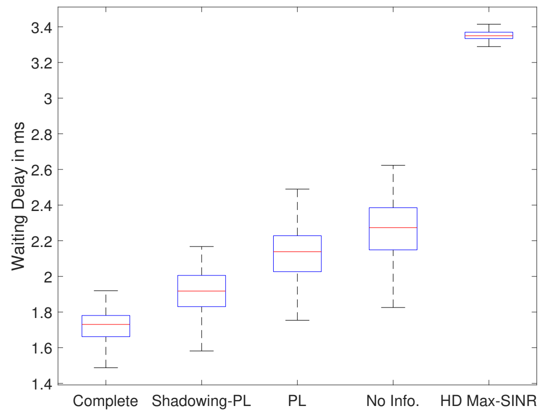

Figure 6. Effect of imperfect CSI on UE waiting delay

F. Significance of Queue-Awareness

UEs in mobile networks do not have infinite buffers, and do not always have data to transmit. While assuming full buffer traffic is more convenient for simulated scenarios, it could also lead to unrealistic results. We simulate the sum-rate maximization algorithm presented in [6], albeit with dynamic arrivals. The arrivals are finite, but the algorithm from the state-of-the-art does not count for that. Figure 7 is a CDF plot of the achieved UE throughput. The performance of the max sum-rate algorithm is severely degraded in comparison to our proposal. Almost 30% of the UEs attained zero throughput. The number of UEs attaining maximum throughput is less than half in comparison with our FD Max-SINR algorithm, and the average UE throughput value is cut in two. Queue-awareness helps assess the performance of scheduling algorithms more realistically.

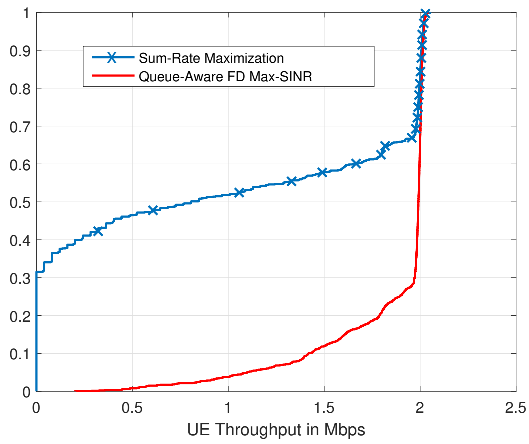

Figure 7. Importance of queue-awareness

G. Effect of Varying the SIC Value

We simulate our FD Max-SINR algorithm for a range of self-interference cancellation values, and compare the mean throughput results with that of a traditional HD Max-SINR algorithm. Figure 8 is a plot of the results. With relatively good values of SIC, FD Max-SINR provides a mean UE throughput value of 1.82 Mbps, double that of HD Max-SINR. As the value of SIC decreases, the gain from FD diminishes. For a

SIC value of 10^6, FD communications are no longer profitable in comparison with HD scheduling. Current self-interference cancellation techniques can easily surpass the value of 10^8, making full duplex technologies immensely profitable, at least for small cells.

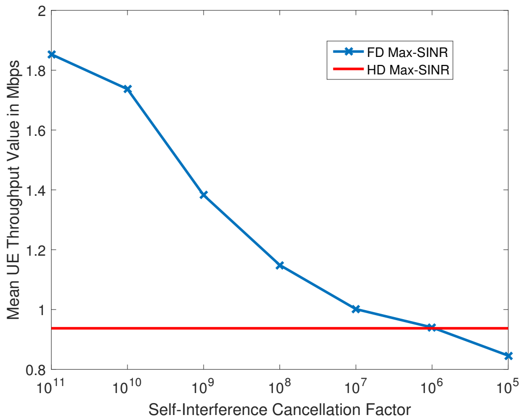

Figure 8. Effect of self-interference cancellation on UE throughput

IX. Conclusion

In this article, we presented two algorithms for scheduling in FD OFDMA cellular networks. The first, FD Max-SINR, is greedy oriented and seeks to allocate resources to the UEs with best radio conditions. The second, FD Proportional Fair, is fairness oriented. It aims to achieve a certain level of equity among the UEs. We simulate our algorithms in the absence of complete channel state information, and ultimately verify that they would still outperform HD scheduling. Furthermore, we test the importance of self-interference cancellation on the operation of FD networks, and establish a threshold below which FD communications are no longer profitable.

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