Max-SINR Scheduling in Full-Duplex OFDMA Cellular Networks with Dynamic Arrivals

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***Abstract*— In Half-Duplex (HD) systems, at a given time instant, a radio resource is exclusively assigned to one User Equipment (UE) either for transmission or for reception. Full-Duplex (FD) networks promise to increase the system's capacity by allocating resources simultaneously to two UEs: one uplink UE and one downlink UE. In order to enhance the network's spectral efficiency, the system needs to deal with two major types of interference: self-interference and co-channel interference. This is one of the main challenges of scheduling in FD systems. In this article, we propose two algorithms for scheduling in FD Orthogonal Frequency Division Multiple Access Systems (FD-OFDMA). First, we propose an FD Maximum Signal-to-Interference-plus-Noise ratio (FD Max-SINR) algorithm, which allocates resources in FD depending on the SINR values of the UEs. Second, we propose a Hybrid Max-SINR scheduling algorithm. This hybrid algorithm chooses astutely between allocating the resources either in HD or FD, in a manner that maximizes the SINR. We evaluate these algorithms and compare them to HD Max-SINR in terms of UE throughput and average waiting delay. According to the simulation results, FD Max-SINR provides, in comparison with its HD counterpart, increased throughput for uplink UEs. It also almost doubles the throughput for the downlink ones. FD Max-SINR reduces the waiting delay that UEs undergo. Furthermore, for relatively low values of Self-Interference Cancellation (SIC), our Hybrid Max-SINR algorithm can still provide higher network throughput compared to HD Max-SINR.**

I. INTRODUCTION

Today, the need for higher data rates is bigger than ever. According to Cisco's Visual Networking Index data traffic update, global mobile data traffic grew 63 percent in 2016 [1]. Current wireless communication systems work in Half-Duplex (HD). At any given time instant, a radio resource is exclusively assigned to one User Equipment (UE) either for transmission or reception. The bandwidth of the system is thus underutilized. Typically, scheduling techniques such as Max-SINR [2] select the UE with the highest SINR and allocate the radio resources accordingly.

Recently, Full-Duplex (FD) was introduced as a solution to cope with the increasing mobile data traffic. An FD Orthogonal Frequency Division Multiple Access (FD-OFDMA) system exhibits an FD Base Station (BS) and HD UEs. In such systems a resource block is allocated to two different UEs: one uplink UE and one downlink UE. The two UEs are said to be paired. The BS transmits and receives to this pair on the same resource block. Theoretically, this means doubling the capacity. However, FD mode introduces new challenges mainly due to the interferences this system produces. On the one hand, the transmitted signal from the BS, around 50-110 dB larger, would leak over the received signal masking it. This is known as self-interference, a consequence of implementing FD. In this perspective, Self-Interference Cancellation (SIC) defines the ability to mitigate self-interference. SIC is done via a set of advanced analog and digital processes as described in [3]. Recent developments in SIC technologies have made FD possible and our work builds on the presence of these technologies that render FD more efficient. The higher the SIC is, the more we gain from FD systems.

On the other hand, FD-OFDMA systems suffer from co-channel interference resulting from pairs of UEs using the same resource block. This is a new challenge for scheduling techniques. Consequently, scheduling in the uplink and the downlink can no longer be done independently as in HD mode. 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. Our work, though based on classical HD scheduling techniques as Max-SINR, has the originality to deal with co-channel interference as part of the resource allocation process.

The main challenge in our work is to tackle the issue of UE pairing. We need to find the UE pair that maximizes the resource utilization efficiency. We do this via a Max-SINR based scheduler. Particularly, we propose two algorithms for scheduling in FD-OFDMA systems. First, our FD Max-SINR algorithm couples the UE pair that has the highest sum of SINR. This maximizes the efficiency and ensures the selected UEs do not suffer from bad radio conditions due to co-channel interference. Second, our Hybrid Max-SINR algorithm, allows the scheduler to choose between allocating the resource blocks to one UE or to a pair of UEs depending on which leads to a higher SINR value.

This paper is structured as follows. Section II discusses related work in the FD domain. Section III presents the system model. Section IV and Section V detail our proposed algorithms for scheduling in FD wireless cellular networks. Section VI examines the complexity of our FD Max-SINR algorithm. Simulation results are presented and discussed in Section VII. Section VIII concludes the paper and states our future work.

II. Related Work

In [3] a study of SIC techniques is presented, and its methods are explained. SIC is a set of promising digital and analog techniques that allow full-duplex communications to exist. The benefit of FD increases with the efficiency of these technologies.

The article in [4] discusses recent developments in wireless communications which enabled the introduction of full-duplex mode. It mentions four main FD systems, FD-MIMO systems, FD-OFDMA systems, FD-Relay systems and FD Heterogeneous Networks (HetNets). In addition, the authors of the article propose two schemes for resource allocation in FD-MIMO systems and FD-OFDMA systems. Their algorithms focus on maximizing the sum-rate. Furthermore, the authors describe their algorithms to be advantageous in terms of reducing the complexity of the centralized approach and not performance wise.

Directly related to our work, the authors of article [5] present a hybrid FD-OFDMA scheduler based on a greedy subcarrier allocation method and an Iterative Water Filling (IWF) power allocation algorithm. The algorithm seeks to maximize the sum-rate, choosing the pair of UEs which has the highest sum of instantaneous rates. The scheduling problem is formulated as an optimization problem (combinatorial problem) of high-complexity. An exhaustive search is needed to find the optimal solution. Thus, the authors introduce a subcarrier and power allocation algorithm with lower complexity. Furthermore, they made their algorithm hybrid by allocating certain time slots from each frame in FD and others in HD for either downlink or uplink UEs.

In [6], 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. The authors note that finding a global optimum through an exhaustive search method is computationally difficult, thus a suboptimal method is considered. The article concludes that FD systems have the potential to significantly increase the capacity of small cells under the presence of efficient self-interference cancellation.

In our paper we focus on scheduling in FD cellular networks. We propose algorithms for scheduling in cells that adopt FD-OFDMA. We use a non full-buffer traffic for the UEs. This is a more realistic approach than in the articles mentioned above [4]–[6]. This takes into account dynamic arrivals and allows us to compute packet-level performance metrics such as waiting delay. Furthermore, we avoid the complexity of modeling the objective as a non-linear optimization problem as in [5] and [6], basing our algorithm on relatively simple Max-SINR scheduling. This simplicity makes our algorithm more efficient and easier to implement in practical wireless networks. Moreover, our hybrid algorithm can make the decision to either allocate a certain resource block to one or multiple UEs (FD) depending on what yields a higher SINR. This is a more granular approach than the TDD-like method suggested in [5].

III. System Model

A. Radio Model

The FD scenario used in our work is based on a single-cell FD-OFDMA system. Our system exhibits an FD BS and HD UEs. This keeps the cost and complexity of implementing FD at the base station. In our work, the UEs are virtually divided into two sets: an uplink UE set, denoted by $\mathcal{U}$ and a downlink UE set, denoted by $\mathcal{D}$. We seek, via our scheduling algorithms, to pair between uplink and downlink UEs on the resource blocks. Each resource block is used by an uplink UE to transmit to the BS, a downlink UE to receive from the BS, with the BS itself transmitting and receiving on the same resource block. This system is illustrated in Fig. 1 [4][5].

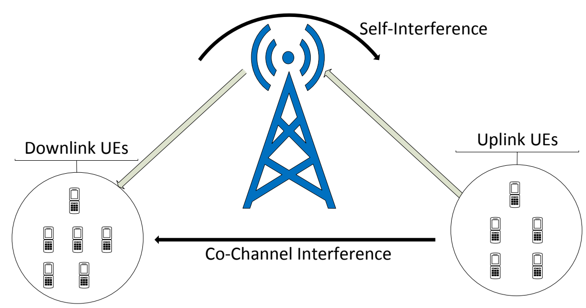

Figure 1. System Model

SINR calculation in this system differs from HD systems. We calculate the SINR, on each resource block, for each possible pair between an uplink UE and a downlink UE. An adapted formula is used to calculate the SINR which takes into consideration the resulting co-channel interference and the self-interference cancellation performed by the BS. Let $P_{i,k}^{UL}$ and $P_{j,k}^{DL}$ denote the transmit power of the *i*th uplink user and the transmit power of the BS serving downlink user *j* on the *k*th resource block, respectively. We denote by $h_{i,k}^{UL}$ and $h_{j,k}^{DL}$ the channel gain from the *i*th uplink user to the BS and the channel gain from BS to the *j*th downlink user on the *k*th resource block, respectively. 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, and thus $P_{i,k}^{UL}|h_{ji,k}|^2$ 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, $\frac{P_{j,k}^{DL}}{C_{SI}}$ represents the residual self-interference power at the BS on the *k*th resource block or what remains of the self-interference after the cancellation process. 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 an uplink and downlink UE respectively [3].

For an uplink UE,

$$S_j^u(i,k) = \frac{P_{i,k}^{UL}|h_{i,k}^{UL}|^2}{N_{0,k} + \frac{P_{j,k}^{DL}}{C_{SI}}},\ \ i \in \mathcal{U},\ \ j \in \mathcal{D}. \tag{1}$$

For a downlink UE,

$$S_j^d(j,k) = \frac{P_{j,k}^{DL}|h_{j,k}^{DL}|^2}{N_{j,k} + P_{i,k}^{UL}|h_{ji,k}|^2},\ \ i \in \mathcal{U},\ \ j \in \mathcal{D}, \tag{2}$$

where $S_j^u(i,k)$ is the SINR of UE i on resource block k while using the same resources as UE j. Similarly, $S_i^d(j,k)$ is the SINR of UE j on resource block k while using the same resources as UE i.

The SINR calculation is done for every possible uplink-downlink UE pair independently on every resource block for each Transmission Time Interval (TTI). In our work, the channel model takes into consideration fast fading which follows a Rayleigh distribution with zero mean and unit variance. This imposes that the SINR is not only different per UE pair, but also for the same pair on a different resource block as well as for the same pair on the same resource block in a different TTI. Furthermore, the Modulation and Coding Scheme (MCS) a UE uses differs depending on its SINR [7]. The higher the SINR value for a UE on a resource block, the higher the modulation order used, therefore the more bits the UE can transmit or receive on this resource block.

B. Traffic Model

We consider a non full-buffer traffic model. Queues are filled according to a random process with a number of bits equal, on average, to the UE throughput demand. An uplink UE is characterized by an uplink queue, denoted $UpQueue$. Similarly, a downlink UE is characterized by a downlink queue, denoted $DownQueue$. The queue length of the UEs is examined each TTI. If a resource block is allocated to a UE, its queue status is then decremented by a number of bits following the MCS used. In our work, the scheduler knows the queue status of the UEs, be it for a downlink or uplink UE, ahead of the resource allocation process. The scheduler knows how many bits a UE has in its designated queue, can estimate the number of bits it can send depending on its SINR, and can thus recalculate the queue status after the resource blocks are assigned.

IV. Full-Duplex Max-SINR

In this section we introduce our FD Max-SINR algorithm (Algorithm 2). The idea of our algorithm is to iteratively allocate resource blocks to the couple of UEs that has the highest sum of SINR. Our algorithm works as follows. Considering the two sets $\mathcal{U}$ and $\mathcal{D}$, a UE belongs to a set if its corresponding queue is not empty. Each TTI, the UE queues are filled following a random process. This makes the traffic non-full-buffer. As such, a UE that has depleted its queue is excluded from the resource allocation within the same TTI. For each resource block k of the set K, the algorithm calculates the SINR for each possible pair between an uplink UE and a downlink UE. We compute the SINR as indicated in equations (1) and (2), and allocate the currently selected resource block to the pair of UEs which has the highest value of the sum: $S_j^u(i,k) + S_i^d(j,k)$, where i belongs to the set of uplink UEs and j to the set of downlink UEs. Moreover, in case it is impossible to pair between UEs due to one of uplink or downlink sets being empty, the scheduler allocates the resource block to a single UE. In such case, the SINR is computed as in typical half-duplex systems and is given by equations (3) and (4). For an uplink UE,

$$r(i,k) = \frac{P_{i,k}^{UL}|h_{i,k}^{UL}|^2}{N_{0,k}}. \tag{3}$$

For a downlink UE,

$$r(j,k) = \frac{P_{j,k}^{DL}|h_{j,k}^{DL}|^2}{N_{j,k}}, \tag{4}$$

where $r(i,k)$ is the SINR for uplink UE i on resource block k if it were to be allocated the resource block solely. Similarly, $r(j,k)$ is the SINR for downlink UE j on resource block k if it were to be allocated the resource block solely. The scheduler then assigns the selected resource block to UE e with the highest SINR (uplink or downlink) denoted $r(e,k)$. If all the UEs empty their queues before the resources are depleted, the remaining resource blocks are marked as free. The function $UpdateQueue(x)$, in Algorithm 1, is responsible for updating the queue status and the UE sets after resource allocation. The number of transmitted bits, denoted $TxBits$, is calculated for each UE allocated a resource block depending on the MCS and decremented from its corresponding queue.

```
function S(x)
if x ∈ U then
    UpQueue(x) ← UpQueue(x) − TxBits
    if UpQueue(x)=0 then
        U ← U − {x}
    end
end
if x ∈ D then
    DownQueue(x) ← DownQueue(x) − TxBits
    if DownQueue(x)=0 then
        D ← D − {x}
    end
end
end function
```

Algorithm 1: Queue Update Function

V. Hybrid Max-SINR Algorithm

In this section we introduce our second contribution, a Hybrid Max-SINR algorithm. We seek to incorporate the ability of the algorithm to efficiently choose between allocating a resource block to a single UE (HD) or to allocate it to a pair of UEs (FD). In certain cases FD might not be preferable. For instance, if the SIC is not high enough,

for *k=1....K* **do**
  if $\mathcal{U} \neq \phi$ *and* $\mathcal{D} \neq \phi$ **then**
    (i^*, j^*) = $\underset{i \in \mathcal{U}, j \in \mathcal{D}}{\text{argmax}}(S_j^u(i,k) + S_i^d(j,k))$
    Allocate resource block k to couple (i^*, j^*)
    $UpdateQueue(i^*)$, $UpdateQueue(j^*)$
  else
    e^*=$\underset{e \in \mathcal{U} \cup \mathcal{D}}{\text{argmax}}(r(e,k))$
    Allocate resource block k to user e^*
    $UpdateQueue(e^*)$
  end
end

Algorithm 2: Max-SINR Full-Duplex Algorithm

uplink UEs would be denied access, thus rendering FD Max-SINR scheduling ineffective. Another factor could be the varying radio conditions due to calculating the SINR for one UE or for a pair of UEs.

As such, making the algorithm hybrid guarantees the system is always working in the transmission mode that maximizes the SINR. This scheduling decision is done based on the following criteria. Pair allocation is used if the sum of SINR of the UE pair is greater than the highest SINR value of a single UE: $S_j^u(i^*,k) + S_i^d(j^*,k) > r(e^*,k)$, where $r(e^*,k)$ is the highest SINR value for a HD UE. We assume that if this statement is correct then we have sufficient SIC and/or acceptable radio conditions to support FD mode. If not, the UE pair is no longer formed and the scheduler allocates the resource block in HD mode to the UE with the highest SINR (uplink or downlink). The pseudo-code for the algorithm is illustrated in Algorithm 3.

for *k=1....K* **do**
  (i^*, j^*) = $\underset{i \in \mathcal{U}, j \in \mathcal{D}}{\text{argmax}}(S_j^u(i,k) + S_i^d(j,k))$
  e^*=$\underset{e \in \mathcal{U} \cup \mathcal{D}}{\text{argmax}}(r(e,k))$
  if $S_{j^*}^u(i^*,k) + S_{i^*}^d(j^*,k) > r(e^*,k)$ **then**
    Allocate resource block k to couple (i^*, j^*)
    $UpdateQueue(i^*)$, $UpdateQueue(j^*)$
  else
    Allocate resource block k to user e^*
    $UpdateQueue(e^*)$
  end
end

Algorithm 3: Hybrid Max-SINR Algorithm

VI. Algorithm Complexity

In our FD Max-SINR algorithm, we seek to find the best possible pair for each resource block. For U uplink UEs and D downlink UEs, we have $n = U.D$ possible pairs. The algorithm needs to find the maximum for n values thus the complexity of this process and generally the algorithm is $\mathcal{O}(n)$.

VII. Simulation and Results

A. Simulation parameters

The simulation parameters, used to run our algorithms in MATLAB, are presented in this section. We consider a single-cell scenario. We implement certain physical layer specifications of the Long Term Evolution (LTE) standard such as the LTE resource block. A resource block is made up of 12 subcarriers over seven OFDM symbols. The cell is circular and of 1 km radius. The operating bandwidth is 10 MHz, where 50 resource blocks are available. The duration of a TTI is 1 ms and the simulation duration is 10 ms. The BS transmission power per resource block is assumed constant and equal to 0.1 W. The transmission power per UE, also considered constant, is 0.02 W. The SIC value is 10^{14} unless specified otherwise. The data arrival follows a Poisson law. The channel gain takes into account the path loss, log-normal shadowing and fast fading. The path-loss and the shadowing are calculated using the extended Hata path-loss model [8]. The fast fading follows a Rayleigh distribution with zero mean and unit variance. This model is used for urban zones and it takes into account the effects of diffraction, reflection and scattering caused by city structures. Numerical results are obtained for 500 runs of each algorithm.

B. HD vs. FD Max-SINR

In the present and the subsequent simulations, we consider 10 UEs in the cell, distributed uniformly. Half of the UEs are downlink UEs and the other half are uplink. In Fig. 2 we plot the Cumulative Distribution Function (CDF) of the individual throughput per UE in the downlink and the uplink for both HD Max-SINR and FD Max-SINR for a throughput demand of 2 Mbps.

If we observe the curves corresponding to FD Max-SINR UEs, we notice that more than 90 % of the UEs attained a value around the demand of 2 Mbps. However, for HD Max-SINR UEs, we notice that only approximately half the UEs attained a throughput equal to the demand. In addition, the CDF plot also shows that more HD Max-SINR UEs suffered from low throughput. The lowest attained throughput by a HD Max-SINR UE is 0.3 Mbps compared to 1.9 Mbps, the lowest recorded for a FD Max-SINR UE. More than 35 % of the HD UEs attained a thorughput lower than 1.9 Mbps. We can conclude that FD Max-SINR provides higher throughput for UEs in both the uplink and the downlink. Our FD Max-SINR algorithm uses the resources more efficiently.

We increase the throughput demand to 4 Mbps and repeat the simulations. Fig. 3 shows the CDF plot for the throughput attained per UE in the downlink and the uplink for both HD and FD Max-SINR. The median of the CDF plot shows that more than 60 % of the FD Max-SINR UEs have attained a throughput around the demand of 4 Mbps. In comparison, the median for the HD Max-SINR UE throughput is approximately 1.6 Mbps. Upon increasing the average to demand to 4 Mbps we can further elaborate the advantage our FD Max-SINR presents with respect to

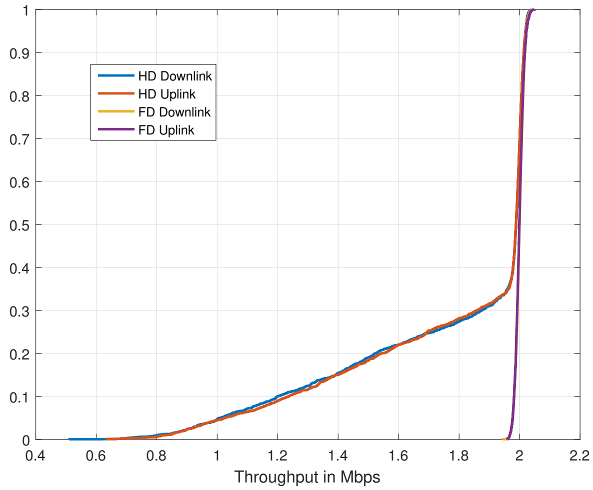

Figure 2. Throughput CDF Plot, HD vs. FD Max-SINR, Demand=2 Mbps

HD Max-SINR. The plot shows, that under tough condition in terms of bandwidth availability, the advantage FD Max-SINR brings in terms of UE throughput is further increased. This is explained by the fact that the simulation for 2 Mbps throughput demand, showed up to 20 % remaining free resource blocks for our FD Max-SINR algorithm whilst the HD Max-SINR algorithm used up all the available resources.

Furthermore, we plot (in Fig. 4) the average waiting delay experienced by UEs for both algorithms during the simulations for a throughput demand of 2 Mbps. The average delay is calculated using Little's formula as the average queue length divided by the packet arrival rate. The median waiting delay for HD Max-SINR UEs is about 1.6 ms. This value is significantly improved in the case of FD Max-SINR UEs which experience a waiting delay equal on average close to 1 ms. In terms of waiting delay, our FD Max-SINR algorithm also outperforms HD Max-SINR. This reduction in waiting delay is also due to the resources being used more efficiently by our FD Max-SINR algorithm.

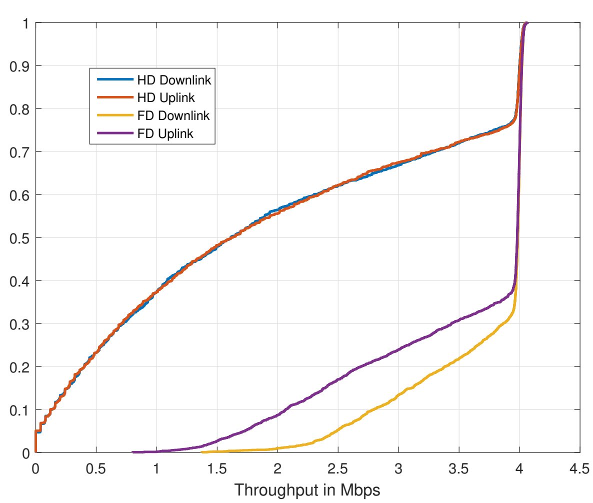

Figure 3. Throughput CDF Plot, HD vs. FD Max-SINR, Demand=4 Mbps

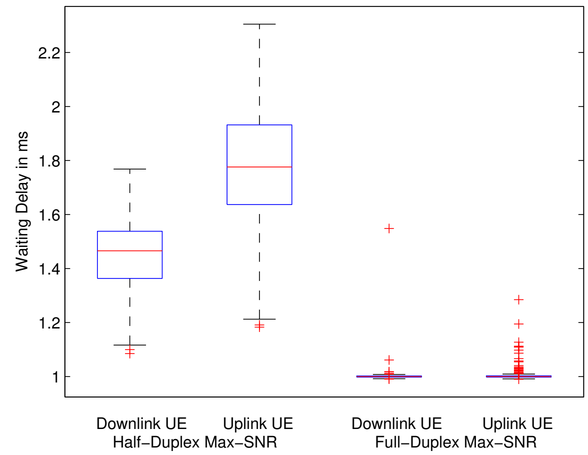

Figure 4. Average Waiting Delay, HD vs. FD Max-SINR, Demand=2 Mbps

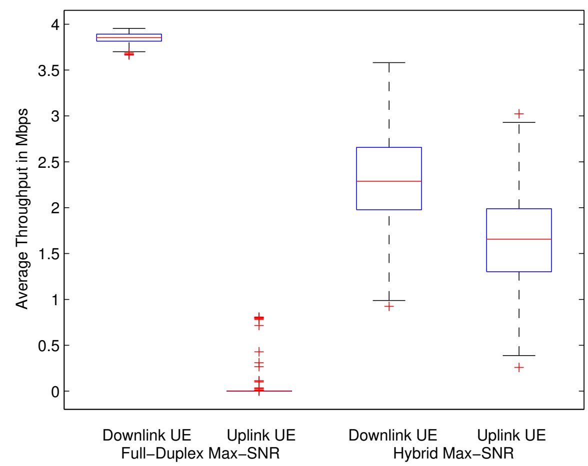

Figure 5. Average Throughput, FD Max-SINR vs. Hybrid Max-SINR, Demand= 4 Mbps, SIC=10^{10}

C. Hybrid Max-SINR

For relatively low values of SIC, FD mode becomes inapplicable because of the high levels of self-interference. This is illustrated in Fig. 5 where we plot the average UE throughput per simulation for both uplink and downlink users, for both FD and Hybrid Max-SINR with the SIC value lowered to 10^{10}. The average throughput for HD Max-SINR uplink UEs, for example, is calculated as the sum of their throughputs divided by their number. The throughput demand is 4 Mbps. Figure. 5 shows a median on the verge of 0 Mbps average throughput for FD Max-SINR UEs in the uplink. These UEs do not transmit at all. The good performance shown by FD Max-SINR downlink UEs is insignificant and thus FD Max-SINR is no longer viable. It is clear however, that our Hybrid Max-SINR algorithm can be an efficient alternative in this case. As such, we seek to compare how our hybrid algorithm fairs in comparison with HD mode for the same value of SIC (10^{10}).

We plot the CDF of the throughput per UE in both the uplink and downlink for both HD Max-SINR and Hybrid

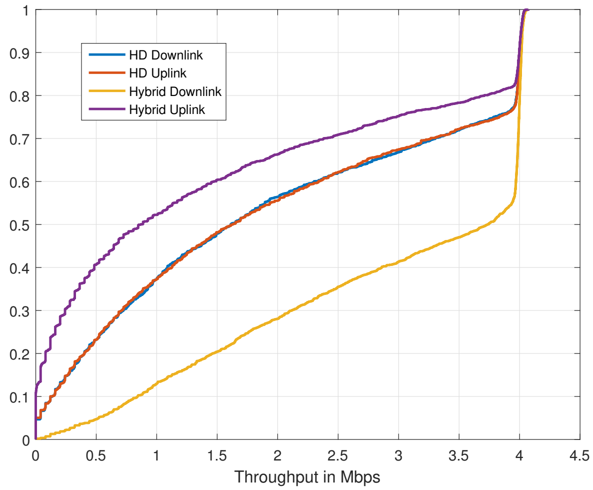

Figure 6. Throughput CDF Plot, HD Max-SINR vs. Hybrid Max-SINR, Demand= 4 Mbps, SIC=10^{10}

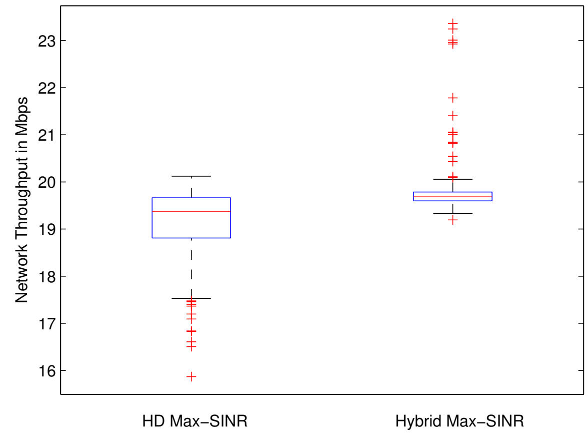

Figure 7. Network Throughput, Hybrid Max-SINR vs. HD Max-SINR, Demand=4 Mbps, SIC=10^{10}

Max-SINR with the throughput demand set to 4 Mbps (in Fig. 6). Around 40 % of the FD Max-SINR downlink UEs and 20 % of the uplink UEs have attained a throughput equal to the demand, more in total than the 25 % of the HD Max-SINR UEs. However, we notice that this advantage is not there for the UEs suffering from lower throughputs. More Hybrid Max-SINR uplink UEs suffer from low throughput. For instance, Fig. 6 shows that more than 50 % of the Hybrid Max-SINR uplink UEs attained a throughput less than 1 Mbps compared to 40 % of the HD Max-SINR uplink UEs. The reason for this is that our Hybrid Max-SINR algorithm choses between single or pair allocation depending on what leads to a higher SINR and thus a higher network throughput.

We illustrate this by plotting (in Fig. 7) the network throughput for HD Max-SINR and Hybrid Max-SINR for our 500 simulation runs. The throughput demand is 4 Mbps and the SIC value remains at 10^{10}. This boxplot shows that network throughput for our hybrid algorithm would most certainly be higher than HD Max-SINR. The network throughput median is around 19.5 Mbps for the HD Max-SINR simulation runs. The median for our Hybrid Max-SINR is just above that with a value of around 19.75 Mbps. Morever, the boxplot shows that at least 75 % of the FD simulation runs produced higher network throughput compared to HD Max-SINR. In conclusion, our Hybrid Max-SINR algorithm can still outperform HD Max-SINR in case of relatively low SIC values.

VIII. Conclusion

In this article we introduced two algorithms for scheduling in FD OFDMA systems. We proposed a FD Max-SINR algorithm, which seeks to allocate the resource blocks to pairs of UEs in a manner that maximizes the SINR. We also introduced a Hybrid Max-SINR algorithm. This algorithm allows the scheduler to allocate a resource block to one UE or to a pair of UEs depending on the SINR value. Our simulations showed that FD mode has the capability of increasing the throughput for wireless networks in both the uplink and the downlink. Our FD Max-SINR algorithm for scheduling in FD-OFDMA networks provides, for high values of SIC, almost double the throughput compared to HD Max-SINR. Furthermore, for relatively low values of SIC, our Hybrid Max-SINR algorithm can still outperform HD Max-SINR in terms of throughput attained by the UEs. Our future work will include broadening our scope to include other, fairer scheduling techniques, such as Proportional Fair. In addition, we will tackle the issue of power control and implement a multi-cell scenario.

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