A Queue-Aware Discrete Scheduling Simulator For Full-Duplex OFDMA Wireless Networks

Hassan Fawaz*, Samer Lahoud*, Melhem El Helou*
*Ecole Supérieure d'Ingénieurs de Beyrouth, Saint Joseph University of Beirut, Beirut, Lebanon

***Abstract*— With the promise of doubling a wireless network's capacity, researchers on full-duplex wireless networks need to address multiple issues such as user equipment pairing, power control, and the availability of channel state information. In this paper, we propose a discrete simulator for scheduling and power allocation proposals in full-duplex orthogonal frequency division multiple access networks. Our simulator is queue-aware and adaptable to different scheduling objectives. It enables varying the path-loss model, user distribution, noise conditions, and throughput demands. Additionally, it permits the calculation of packet level performance metrics such as the waiting delay.**

I. Introduction

Current half-duplex (HD) wireless systems are struggling to meet the ever growing demand for increased user equipment (UE) throughput [1]. These networks allocate resources to one UE either for transmission or reception. The bandwidth of the network is thus not optimally utilized. In a full-duplex (FD) orthogonal frequency division multiple access (OFDMA) wireless network, a pair of half-duplex user equipment (UE) share a radio resource on which one transmits, and the other receives. The base station, being the full duplex component of such a network, concurrently transmits and receives on the same resource. In theory, this doubles the bandwidth available to the UEs.

Nonetheless, FD networks need to deal with two added types of interferences which threaten their practicality: self-interference, and intra-cell co-channel interference. Self-interference is the interference at an FD device imposed by the transmitted signal, typically multiple times stronger, on the received signal. In an FD-OFDMA network, self-interference at the base station degrades the performance of uplink UEs. The recent development of self-interference cancellation (SIC) technologies, a set of digital and analog cancellation techniques [2], helped battle self-interference problems, ultimately making FD wireless communications feasible.

Traditionally an inter-cell problem, FD networks suffer from intra-cell co-channel interference between the UEs. In FD-OFDMA networks, an uplink UE would interfere on the signal received by its paired downlink UE, using the same resource block. This degrades the performance of the latter. UE pairing in FD-OFDMA networks should take these interferences into account and allocate resources in a manner that minimizes them.

FD networks could immensely increase bandwidth efficiency for wireless communications as long as the interference problems are contained. As such, it is vital to asses, through simulations, different UE pairing algorithms, radio conditions, and UE distributions, among other factors which could decide whether or not FD communications are profitable.

In this paper, we present a discrete scheduling simulator for FD-OFDMA wireless networks. This simulator is class based and makes use of object oriented programming (OOP). Built and compiled in MATLAB [3], the simulator code is easy to understand, manage, and modify. Our simulator is queue-aware. It takes dynamic arrivals into account, unlike the majority of the algorithms simulated in the state-of-the-art [4]–[9]. Furthermore, the simulator is adaptive to different scheduling objectives, and is capable of solving them both heuristically and optimally. We have made the source code for this simulator available online [10]. It is, to the best of our knowledge, the only open source simulator for such systems. This enables other researchers in the domain to build on our work, and focus more on evolving concepts rather than putting effort on developing a simulator.

This paper is structured as follows. Section II presents a general overview of the simulator. Section III presents the network model. This section highlights the traffic and channel models we used. Section IV details the UE class created in the simulator. The simulator's main uses and a simulation example are illustrated in section V. Section VI concludes the paper, and states our future work.

II. Simulator Overview

In this section, we give a general overview of the simulator. Figure 1 depicts a schematic block diagram of our proposal. The simulator conveys two main tasks: (i) Scheduling and (ii) Power Allocation. Depending on the simulation scenarios, power allocation on the RBs might not be necessary. As such, the simulator can output the results of the scheduling with constant powers, without going through the task of power allocation.

The scheduling task consists of forming the uplink-downlink UE pairs, and allocating the available resource blocks to these pairs. In addition to information on the radio channels, UE distribution in the cell, and the UEs' traffic model, a scheduling strategy is needed to indicate how the resources will be distributed on the UE pairs.

This strategy could be greedy *i.e.*, allocating the resources to the UEs with the best radio conditions, or fair *i.e.*, allocating the resources with the purpose of achieving equity between the UEs.

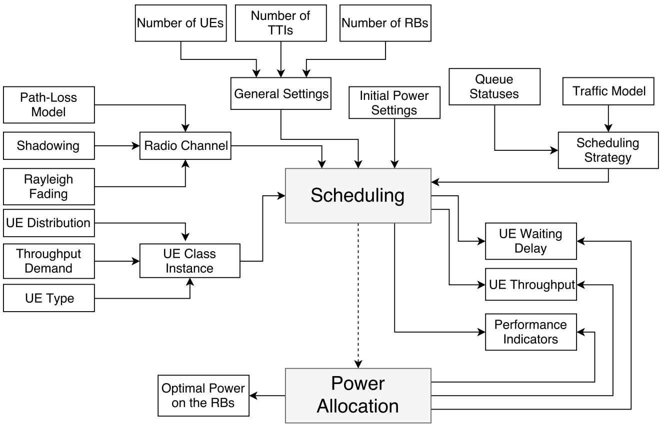

Figure 1. Schematic block diagram of the simulator

Allocating powers on the resource blocks can be done after the scheduling task has been performed for a certain TTI. Based on the power allocation objective, usually improving the UE SINR, the transmit powers on the resource blocks are updated.

Implementation wise, the simulator work is illustrated in the pseudo-code below. The scheduling decision is made, for all the available resources, each TTI. If desired, power allocation is performed post scheduling.

for *t=1....Number of TTIs* **do**
  for *k=1....K* **do**
    for *each UE* **do**
      Calculate UE SINR for all possible pairs.
    end
    Allocate k to pair i-j based on the scheduling objective.
  end
  Allocate power on the resource blocks.
  Calculate resulting UE throughputs.
end

In all cases, the resulting UE throughput values, among other metrics, are used to evaluate the performance of the network under the simulated scenarios. This permits exploring the gains and limitations of FD networks. The modularity of the simulator allows the permutation of the blocks shown in the schematic diagram changing thus specific functions and settings.

III. Network Model

A. Radio Model

We consider a single-cell FD-OFDMA system. This system 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 pair between uplink and downlink UEs on the resource blocks k of the set K. This system is illustrated in Fig. 2.

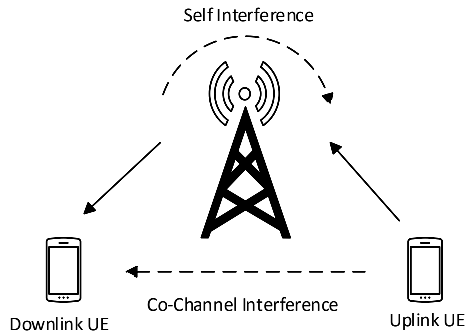

Figure 2. FD-OFDMA network and interferences

The signal-to-noise and interference (SINR) ratio is calculated differently in such a network, than in legacy HD networks. 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* on the kth resource block, respectively. We denote by $h^u_{i,k}$ and $h^d_{j,k}$ the channel gain from the *i*th uplink user to the BS and the channel gain from the BS to the *j*th downlink user on the kth resource block, respectively. Furthermore, $h_{ji,k}$ denotes the channel gain between the *i*th uplink user and *j*th downlink user on the kth resource block, and 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 kth 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 kth resource block, respectively. Equations (1) and (2) denote the formulas for SINR calculation for an uplink and downlink UEs respectively. For an uplink UE,

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

For a downlink UE,

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

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

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.

An FD-OFDMA network is concerned mainly with two types of channels: (i) BS-UE channels (ii) UE-UE channels. Currently implemented 3GPP protocols have mechanisms with which UEs can estimate BS-UE channels. UEs would periodically update the base station with this channel information. The need to estimate UE-UE channels is unique to FD networks. Knowing such channels enables a UE to distinguish the strongest interferers. This information is vital for optimal pair selection. In our work, we statistically model the radio channels 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. This model allows us to tune the factors affecting the different radio channels to encompass different environments such as rural or urban cells.

The simulator enables implementing different path-loss models. One implemented example is the Cost Hata Path-Loss model [11]. The path-loss (in dB), for the BS-UE channel for example, is calculated as follows. For simulating urban environments:

$$L_p|_{dB} = 46.3 + 33.9 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(h_{BS}) - a + (44.9 - 6.55 \cdot \log_{10}(h_{BS})) \cdot \log_{10}(d_{UE-BS}) + C_m, \tag{4}$$

where

$$a = (1.1 \cdot \log_{10}(f) - 0.7) \cdot h_{UE} - (1.56 \cdot \log_{10}(f) - 0.8).$$

f is the transmission frequency in *MHz*. h_{BS} is the base station antenna effective height in m. h_{UE} is the UE antenna effective height in m. d_{UE-BS} is the link distance in km. Finally, C_m is a constant equal to 3 dB for metropolitan centers, and 0 dB for medium-sized city and suburban areas. For simulating rural environments:

$$L_p|_{dB} = 69.55 + 26.16 \cdot \log_{10}(f) - 13.82 \cdot \log_{10}(h_{BS}) + (44.9 - 6.55 \cdot \log_{10}(h_{BS})) \cdot \log_{10}(d_{UE-BS}) - 4.78 \cdot (\log_{10}(f))^2 + 18.33 \cdot \log_{10}(f) - 40.94 \tag{5}$$

Other path-loss models can also be incorporated. The log-distance path-loss model is used for calculating indoor attenuations:

$$L_p|_{dB} = L_p^0|_{dB} + 10\gamma \log_{10} \frac{d_{UE-BS}}{d_0}, \tag{6}$$

where d_0 is a reference distance (usually 1 *km*), and L_p^0 is the path-loss at that distance. γ is the path-loss exponent, dependent on the type of the structures.

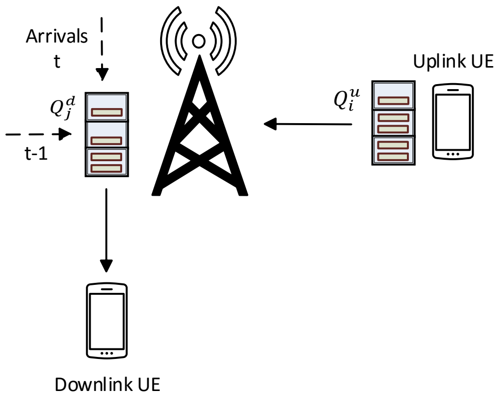

Figure 3. Traffic model: UE pair i-j

C. Traffic Model

The simulator incorporates both full buffers for the UEs, as well as queue-awareness (Fig. 3). In the case of queue-awareness and dynamic arrivals, 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 according to a Poisson 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.

D. Performance Model

The mapping between a UE's SINR and the number of bits it can transmit/receive is done following a modulation and coding scheme (MCS). Using LTE-like configurations, we set 15 CQI values. These values use coding error rates between 1/8 and 4/5 combined with 4-QAM, 16-QAM and 64-QAM modulations. Figure 4 maps between the UE SINR and the assigned CQI value.

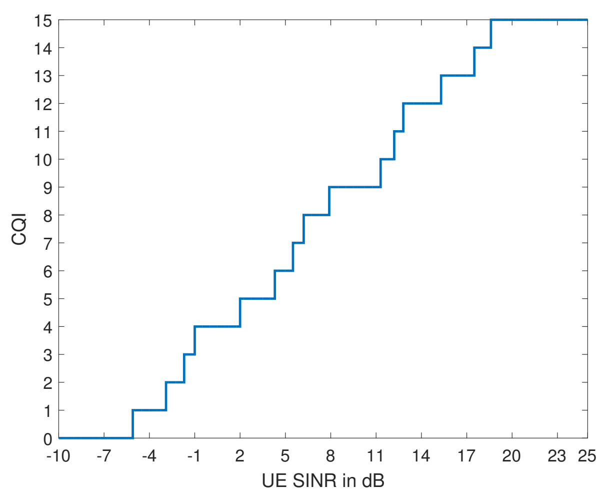

Figure 4. CQI as a function of UE SINR

Table I shows the relationship between the CQI level and the modulation and coding schemes used. Based on the MCS used, the number of bits each UE can transmit or receive on the resources allocated to it is recorded. At the end of the simulation the UE throughput is calculated as the number of bits the UE has transmitted, divided by the simulation duration. The average delay is calculated using Little's formula as the average queue length divided by the packet arrival rate.

Table I
MODULATION AND CODING SCHEME

CQI	Modulation	Coding Rate
0	-	-
1	QPSK	1/8
2	QPSK	1/5
3	QPSK	1/4
4	QPSK	1/3
5	QPSK	1/2
6	QPSK	2/3
7	QPSK	3/4
8	QPSK	4/5
9	16-QAM	1/2
10	16-QAM	2/3
11	16-QAM	3/4
12	16-QAM	4/5
13	64-QAM	2/3
14	64-QAM	3/4
15	64-QAM	4/5

IV. UE CLASS

The base station is located at the center of the simulated cell with (0,0) coordinates. The UEs are created as class instances with multiple property tags as shown in fig. 5.

```
classdef UE
    properties
        ID;  %Mobile ID
        type;  %Uplink or downlink
        throughput;  %Throughput demand in (bits/s)
        coordinates;  %UE coordinates in a plane
        arrivals;  %Number of bits arriving during the current TTI
        d_BS;  %Distance between the UE and the base station
        q_k;  %Max number of bitsto tx/rx on resource block k
        sinr;  %Stores the last calculated UE SINR value
        uplinkqueue;  %Number of bits waiting for transmission
        downlinkqueue;  %Number of bits waiting for reception
        transmitted_bits;  %Number of bits already transmitted
        tx_bits;  %Number of bits transmitted in current TTI
        delay;  %Waiting delay at the beggining of the current TTI
    end
```

Figure 5. Class UE

The UEs are given an ID, and for a certain simulation assigned a type: uplink or downlink. The UEs are also initialized with the throughput demand. Afterwards, a UE distribution function is called upon to determine the position of a UE inside the cell. This function enables simulating different UE distribution scenarios, with the possibility of forming UE clusters within the cell.

The remainder of the UE properties are related to the functionality of the simulator. The distance between the UE and the BS is subsequently calculated and stored. When making scheduling decisions, the simulator needs to calculate the UE SINR and the number of bits it can transmit on the resource block being allocated. These property values are as such update accordingly. After the scheduling is performed, the UE queues, also stored as properties of the class, are deducted following the resources allocated. Finally, because the simulator is queue-aware, it can compute and store performance metrics such as the waiting delay.

V. USES AND SIMULATION EXAMPLE

The primary use of the simulator, presented in this paper, is to test the validity of different scheduling and power allocation proposals for FD-OFDMA wireless networks, under multiple simulation scenarios. The simulator allows us to asses the impact of dynamic traffic arrivals, and consequently enables studying the effect of heterogeneous traffic on UE performance. The flexibility of the channel model allows taking different path-loss environments into account. Since the simulator is queue-aware, packet level metrics such as the waiting delay can be calculated. Finally, the availability of this code online [10] allows it to be cross-checked, and the results be validated. The code is easy to manage and can be modified to include more simulation scenarios such as multi-cell networks.

We used this simulator in previous publications to simulate an FD Max-SINR algorithm [12]-[13]. Another prominent scheduling objective in wireless networks is to allocate resource blocks to the UEs which can put forth the highest rates. Following this objective, the FD scheduler will allocate the resources to the uplink-downlink UE pair i-j which has the highest value of sum-rates:

$$\log_2(1 + S_j^u(i,k)) + \log_2(1 + S_i^d(j,k)) \tag{7}$$

We use this objective and run our simulator using the settings presented in Table II. Note that under these simulation parameters, a traditional HD network is considered to be under a heavy load.

Table II
SIMULATION SETTINGS

Parameter	Value
Cell Specifications	Single-Cell, 200 m Radius
Number of RBs	50
BS Transmit Power	24 dBm
Maximum UE Transmit Power	24 dBm
SIC Value	10^{11}
Number of UEs	10DL, 10UL
UE Distribution	Uniform
Demand Throughput	2 Mbps
Path Loss Model	Urban

A. Gain in Throughput

We simulate the FD algorithm vs. its HD counterpart. Figure 6 has a cumulative distribution frequency (CDF) plot of the resulting UE throughput values. Almost 60% of the FD UEs attain a throughput value equal to the demand of 2 Mbps, compared to only 22% for the HD UEs. Around 30% of the HD UEs attained a throughput value equal to

0 Mbps, whilst none of the FD UEs were denied throughput. On average a FD UE will attain a throughput 1 Mbps higher than its HD counterpart.

Furthermore, we compare the values of the network throughput attained by both schedulers, across different simulation iterations. Figure 7 shows boxplots of the results. With 20 UEs being simulated, and the throughput demand per UE being 2 Mbps, the highest achievable network throughput is 40 Mbps. The simulated FD scheduler nearly achieves that value with a median (red line) of around 37 Mbps. The lowest recorded FD network throughput, seen in an outlier (red cross) is close to 33 Mbps. On the other hand, the median HD network throughput is around 14 Mbps. The highest attained, also seen in an outlier, is about 19 Mbps, much lower than the lowest FD value. FD networks more than doubled the gain in total network throughput.

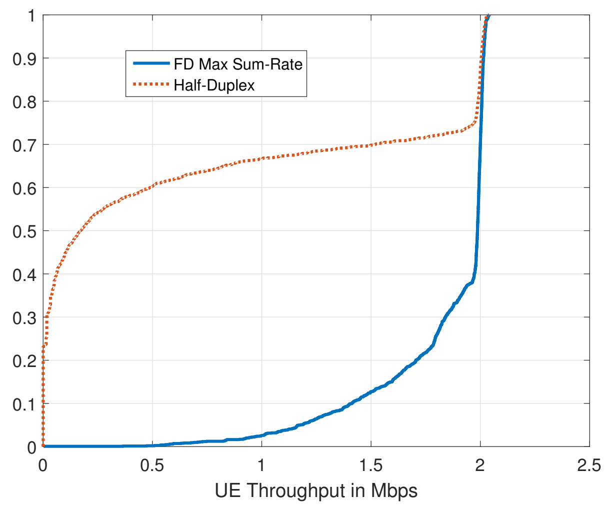

Figure 6. FD gain in UE throughput

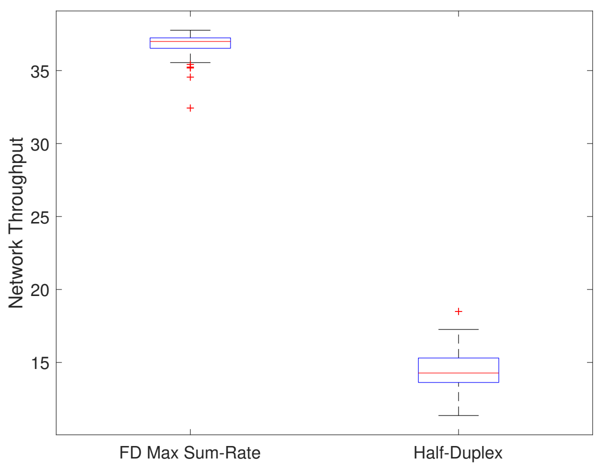

Figure 7. FD gain in network throughput

B. Gain in Waiting Delay

We compare the simulated FD scheduler vs. its HD counterpart in terms average waiting delay per UE. Figure 8 is a plot of the average UE waiting delay for a sample of 80 iterations. The FD gains, seen in terms of throughput, are also evident in terms of average UE waiting delay. The maximum average delay for UEs in an FD network is close to 2 ms compared to 4.3 ms for its HD counterpart. The delay is on average cut in half.

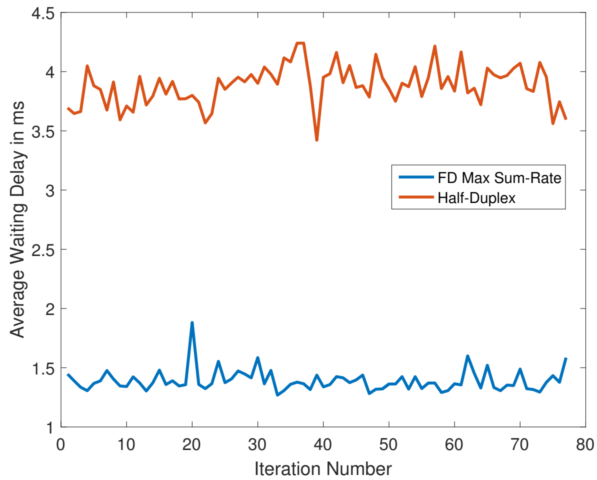

Figure 8. FD gain in average waiting delay

C. Simulator Efficiency

Finally, we are interested in evaluating the efficiency of the simulator in terms of computation speed. For the scheduling objective proposed above, and for the same simulation parameters, we record the time needed for a single scheduling iteration to be completed, both for optimal and heuristic implementations. The machine used for the simulations has an INTEL core i3-4170 CPU and runs on 8GB of RAM.

Table III
SIMULATION TIME

Criteria	Optimal (s)	Heuristic (s)
Mean	12.04	2.934
1^{st} Quartile	10.52	2.85
Median	11.57	2.91
3^{rd} Quartile	14.31	3.012

Naturally, as the number of variables increases, solving the optimization problem will take significantly more time. For a high number of resources blocks and UEs, heuristic approaches become the most feasible.

VI. CONCLUSION

In this article, we presented our simulator for scheduling and power allocation in FD-OFDMA wireless networks. As FD networks continue to evolve, this simulator permits the testing and evaluation of different scheduling and power allocation proposals. This is essential for assessing the practicality and gains of FD networks. The simulator incorporates dynamic arrivals making the simulated network model more realistic. Finally, the class based simulator code is open source, making it easier to modify, adapt, and improve the simulator.

VII. 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.

References

[1] C. V. Mobile, "Cisco visual networking index: global mobile data traffic forecast update, 2016–2021 white paper," 2017.

[2] S. Hong, J. Brand, J. I. Choi, M. Jain, J. Mehlman, S. Katti, and P. Levis, "Applications of self-interference cancellation in 5g and beyond," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 114–121, 2014.

[3] *MATLAB version 8.5.0.197613 (R2015b)*, The Mathworks, Inc., Natick, Massachusetts, 2015.

[4] A. C. Cirik, K. Rikkinen, and M. Latva-aho, "Joint subcarrier and power allocation for sum-rate maximization in ofdma full-duplex systems," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*. IEEE, 2015, pp. 1–5.

[5] S. Goyal, P. Liu, S. S. Panwar, R. A. DiFazio, R. Yang, and E. Bala, "Full duplex cellular systems: will doubling interference prevent doubling capacity?" *IEEE Communications Magazine*, vol. 53, no. 5, pp. 121–127, 2015.

[6] J. M. B. da Silva, Y. Xu, G. Fodor, and C. Fischione, "Distributed spectral efficiency maximization in full-duplex cellular networks," in *Communications Workshops (ICC), 2016 IEEE International Conference on*. IEEE, 2016, pp. 80–86.

[7] C. Nam, C. Joo, and S. Bahk, "Joint subcarrier assignment and power allocation in full-duplex ofdma networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3108–3119, 2015.

[8] B. Di, S. Bayat, L. Song, Y. Li, and Z. Han, "Joint user pairing, subchannel, and power allocation in full-duplex multi-user ofdma networks," *IEEE Transactions on Wireless Communications*, vol. 15, no. 12, pp. 8260–8272, 2016.

[9] A. C. Cirik, K. Rikkinen, R. Wang, and Y. Hua, "Resource allocation in full-duplex ofdma systems with partial channel state information," in *Signal and Information Processing (ChinaSIP), 2015 IEEE China Summit and International Conference on*. IEEE, 2015, pp. 711–715.

[10] H. Fawaz, S. Lahoud, and M. El Helou, "Simulation code: A queue-aware discrete scheduling simulator for full-duplex ofdma wireless networks." [Online]. Available: https://github.com/Hassan-Fawaz/FDOFDMA-Simulator

[11] P. E. Mogensen and J. Wigard, "Cost action 231: Digital mobile radio towards future generation system, final report," in *Section 5.2: on Antenna and Frequency Diversity in Gsm. Section 5.3: Capacity Study of Frequency Hopping Gsm Network*, 1999.

[12] H. Fawaz, S. Lahoud, M. El Helou, and M. Ibrahim, "Max-sinr scheduling in fd-ofdma cellular networks with dynamic arrivals," *IEEE ISCC*, 2017.

[13] ——, "Optimal max-sinr scheduling in fd-ofdma cellular networks with dynamic arrivals," *Wireless Days*, 2018.