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FULL DUPLEX RADIOS FOR FUTURE MOBILE COMMUNICATION SYSTEMS

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Abstract

This work presents a detailed description of the full-duplex technology, the technological advances which propitiate this new technology and its importance for the future of the mobile communications. The main advantages and problems related to the implementation of this technology are discussed with the presentation of some mechanisms to solve them. A complete discussion of the project developed in cooperation with TIM, an event driven system simulator based on the ITU-R M.2135 channel model and on the abstraction of the 4G layer, the theoretical and analytical work carried out in the project with the employed formulas are presented to later analyze the results of the simulations. Finally, some conclusions are presented with an analysis of next possible steps.

1 Introduction

Cellular networks have entered in a period of unprecedented changes and ever increasing importance for the economy and society (Fig. 1), it's predicted that the worldwide mobile traffic by 2020 will reach a 33 times increase compared with the figures in 2010 [5, 4].

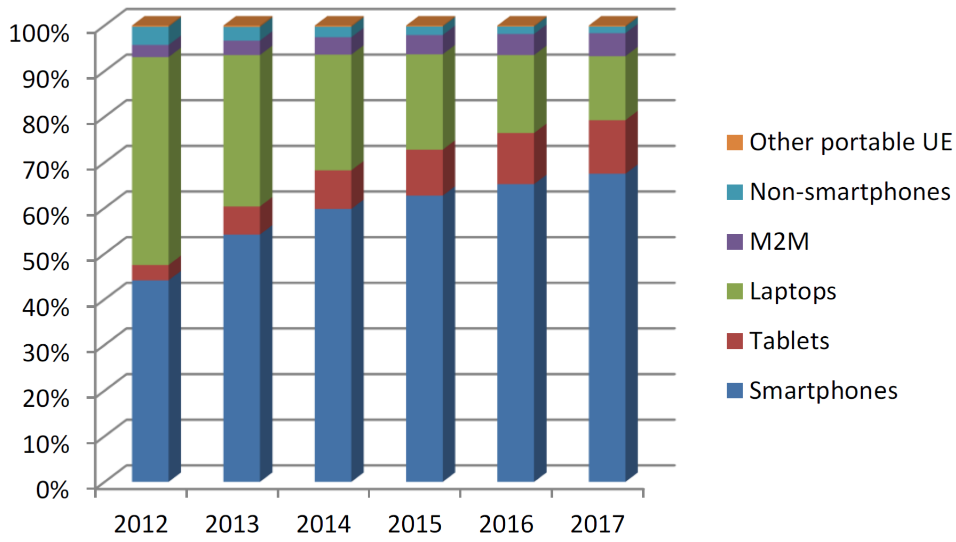

Figure 1: Relative distribution of the global mobile data traffic over different portable users [9].

To support the exploding demand for video and other high-rate data services, such networks have begun a major shift from being voice-centric, circuit-switched, and centrally optimized for coverage toward being data-centric, packet switched, and organically deployed for maximum capacity. Meanwhile, internet access will become dominated by wireless devices such as smart-phones, tablets, machines, sensors and so on. This unprecedented growth in wireless devices and mobile data traffic has motivated the research and

development of next generation wireless networks with higher data rates, spectrum efficiency, and energy efficiency, as well as lower latency [5, 10].

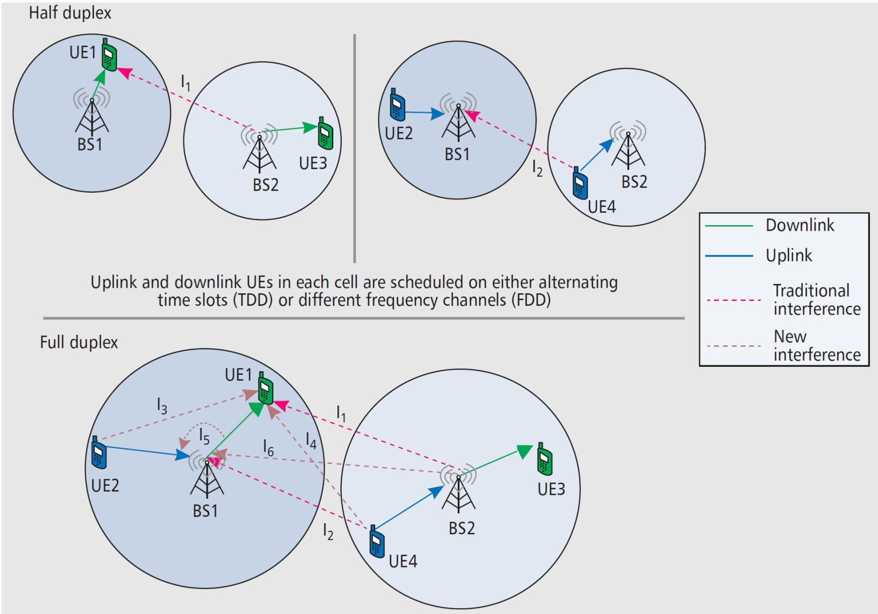

Figure 2: Half-duplex and Full-duplex multi-scenarios [5].

Among the emerging technologies for next-generation wireless networks, in-band full-duplex (IBFD) wireless has become a hot research topic. In the past was thought that "It is generally not possible for radios to receive and transmit on the same frequency band at the same time because doing so will result in strong self-interference[1] ", this assumption has been held for long time in wireless system design since the transmission creates a massive amount

[1] If a radio operates in in-band full-duplex mode, the receive antennas will hear the interference signal (i.e., self-interference) from its own transmit antennas while receiving the desired signals from another radio. Moreover, because of the short distance between the transmit and receive antennas at the radio (rather than the distance between two radios), the self-interference can be even billions of times stronger than the desired receive signal [7]. Taking small-cell cellular systems as an example, the self-interference can be up to 99 dB stronger than the desired signal [9].

of interference at the receiver, preventing it from detecting the desired signal coming from the other end of the wireless link. For this reason, also in 4G Networks like in previous technologies the uplink transmission from the User Equipment (UE) to the network infrastructure (eNode B) and the downlink transmission (from the eNode B to the UE) are separated in time using a Time Division Duplex (TDD) or in frequency using a Frequency Division Duplex (FDD) [1]. At the upper part of Fig. 2 could be seen the half-duplex case with its respective interference, clearly in this case only the traditional and well known interferences are present.

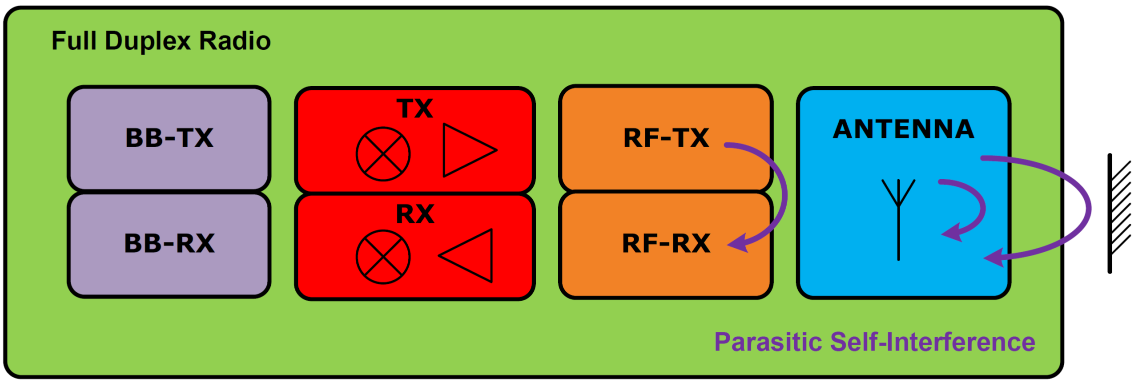

Figure 3: Self interference problem in full-duplex [9].

As a promising technology for next-generation wireless networks, the full-duplex communication principle (i.e., the same carrier frequency is simultaneously used both for transmission and reception at the wireless transceiver) opens new possibilities for improving wireless communication system performance, but also sets challenging requirements for wireless transceiver implementation. At the lower part of the Fig. 2 the full-duplex scenario with its new interferences generated between users and base stations is reported.

As expected transmission at same frequency and time for UL and DL cause now users interferes each other as well as base stations too. Moreover, the self-interference (Fig. 3) and the interference between bases is also present. In-band full-duplex wireless system not only has the potential to double the spectrum efficiency in physical layer, but also can help to solve some important problems in existing wireless networks, such as hidden terminals[2], loss of throughput due to congestion[3], and large end-to-end delays [10, 9].

Beyond spectral efficiency, full-duplex concepts can also be advantageously used beyond the physical layer, such as at the access layer. From the access-layer point of view, enabling frame level in-band full-duplex, where a terminal is able to reliably receive an incoming frame while simultaneously transmitting an outgoing frame, could provide terminals with new capabilities. For example, terminals could detect collisions while transmitting in a contention-based network or receive instantaneous feedback from other terminals.

[2]The classic hidden terminal problem in ad-hoc networks occurs when one node is unable to hear another node's transmissions to the access point and starts sending data to the access point at the same time, thus causing a collision at the access point [2].

[3]In a general star topology ad-hoc network with 2n+1 nodes and nodes N1 to Nn trying to route data to nodes Nn+1 to N2n respectively via node N0, the aggregate network throughput is 1/n. Hence, node N0 becomes a congested node and this results in loss of throughput [2].

2 Full-duplex importance for 5G

Enabling wireless terminals to operate in full- duplex transmission mode offers the potential to double their spectral efficiency, i.e. the numbers of transmitted bits per second per Hz. In band Full Duplex (IBFD) operation can also provide more flexibility in spectrum usage. The same frequency resources can be used for one directional or bi-directional transmission. IBFD operation can complement legacy systems based on TDD or FDD. Beyond spectral efficiency and physical layer, full-duplex concepts can be advantageously utilized in higher layers, such as at the access layer. IBFD operation can reduce air interface delay due to simultaneous reception of feedback information (control channels, signaling related to error correction protocol, etc.) while transmitting data. IBFD capable terminals could detect collisions while transmitting data and also resolves the 'hidden node' problem, both typical issues for contention-based networks. Thus, IBFD operation promises to enable various 5G mobile network targets [3].

The basic advantages offered by the features of IBFD transmission can be summarized as follows:

- **Can double ergodic capacity:** Full utilization of time and frequency resources make it theoretically possible for IBFD transmission to double the link capacity compared to Half Duplex (HD) transmission [8].

- **Can reduce feedback delay:** Reception of feedback signaling (such as control information, Channel State Information (CSI) feedback, acknowledge/nacknowledge (ACK/NACK) signals, resource allocation information, etc. during data signal transmission enables shorter air interface latency in feedback information [8].

- **Can reduce end-to-end delay:** In relay systems, relay nodes with IBFD transmission can reduce end-to-end delay because the relay node simultaneously receives data from a source node and transmits data to a destination node [8].

- **Can improve network security:** The use of simultaneous transmission at two nodes means that eavesdroppers receive mixed signals that are hard for the eavesdropper to decode due to interference signals [8].

- **Can improve the efficiency of ad hoc network protocols:** Because all nodes are transmitting, IBFD transmission can solve the 'hidden node' problem in ad hoc networks. Furthermore, the fact that simultaneous listening and sensing is being performed on a frequency band while the signals are being transmitted means that each node can decide whether or not the other nodes are transmitting signaling and thus prevent collisions [8].

- **Can increase spectrum usage flexibility:** By retaining the option to use one frequency band (IBFD transmission) or two different frequency bands (HD transmission) for uplink and downlink, each transceiver can select either the IBFD or the HD transmission mode [8].

3 Main problems and challenges of Full Duplex Systems

Full-duplex, in theory, should be simple to accomplish. After all, we know the signal we are transmitting, and we are only designing circuits and algorithms to subtract it from the received signal. The intuition follows from the conventional abstraction that the analog radio (also known as the RF front-end) is a black-box that takes the digital baseband signal, converts it to analog, up-converts it to the carrier frequency, scales it to the right power and sends it. In other words, the assumption has been that the radio preserves the original baseband signal except for power scaling and frequency shifting. In practice this abstraction turns out to be incorrect. Radios in fact significantly distort the signal being transmitted, relative to the digital baseband representation [1].

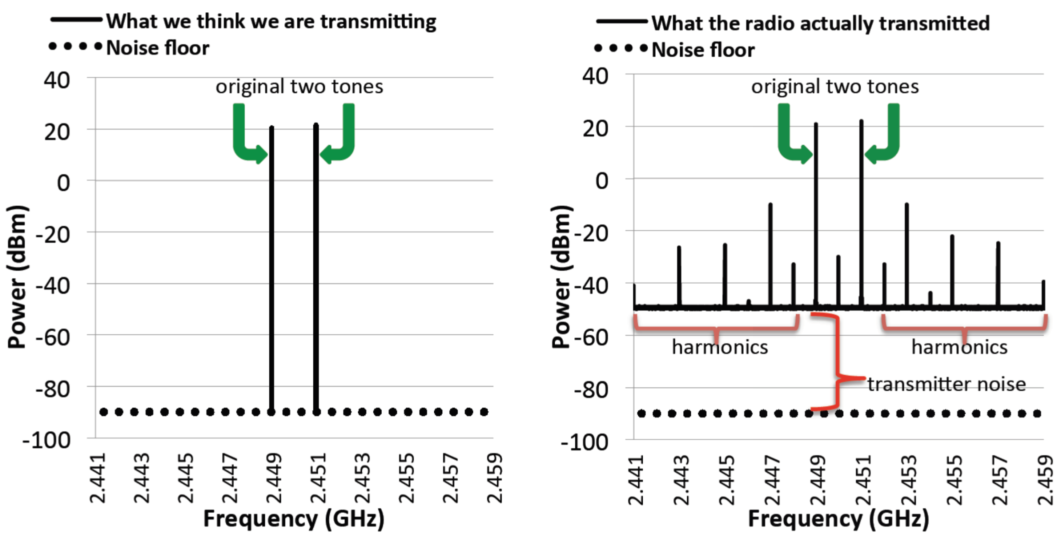

Figure 4: Transmitted signal (left) and real transmitted signal (right) [1].

To demonstrate the distortions, could be followed the experiment done in [1], where they take a software radio transceiver and send the following signals: two tones at 2.449GHz and 2.451GHz. In other words, they are sending an extremely simple signal, two sine waves with frequencies 1MHz away from the carrier frequency of 2.45GHz. This is done by creating a digital baseband signal with samples of the sine waves at -1MHz and 1MHz which the radio then up-converts to 2.45GHz and amplifies to 20dBm average transmit power (the power used by WiFi radios). Then they compare the signal output of the antenna to what we would ideally expect if the radio did not introduce any distortions. This experiment serves as some sort of lower bound on the quality of radios. If radios cannot transmit even this simplest of signals without distortion, then more complex signals such as WiFi are likely to be significantly distorted. Fig. 4 plots the ideal and actual transmitted signals spectra that resulted from the experimental set-up (they ensured a clean environment from other interferences at the time when the experiment was done).

Ideally, it is expected to see only two tones at 2.451GHz and 2.449GHz as shown on the left side of Fig. 4. However, in the transmitted signal, whose spectrum is plotted on the right side, can be easily seen that there are several other distortions present in addition to the two main tones that were transmitted. The main components in self-interference can be classified into three major categories:

1. **Linear Components:** This corresponds to the two main tones themselves which are attenuated and could consist of reflections from the environment. These are linear components because the received distortion can be written as a linear com-

bination of different delayed copies of the original two tones [1].

2. **Non-Linear Components:** These components are created because radio circuits can take in an input signal x and create outputs that contain non-linear cubic and higher order terms such as x3; x5, etc... These higher order signal terms have significant frequency content at frequencies close to the transmitted frequencies, which directly correspond to all the other harmonics we see on the right side of Fig. 4. Harmonics, as the name suggests, are signal distortions which occur at equally spaced frequency intervals from the transmitted frequencies. As the right side of Fig. 4 shows, we see spikes at frequencies 2.447GHz and 2.453GHz, that are spaced 2MHz apart from the two transmitted tones 2.451GHz and 2.449GHz, on either side [1].

3. **Transmitter Noise:** The general increase we see in the base signal level which we can clearly see on the sides of the two main tones is noise from the radio transmitter. A radio will of course always have noise, which works out to a noise power level of -90dBm as shown in Fig. 4. But as we can see, the power at the side-bands is significantly higher, on the level of -50dBm, or 40dB higher than the receiver noise floor. This extra noise is being generated from high power components in the radio transmitter such as power amplifiers. In the radio literature this is referred to as broadband noise. Further radios have phase noise generated by local oscillators (LO), which is typically of level of -40dBm, or 50dB above (not seen in the Fig. 4 because its hidden under the main signal component) [1].

To remove completely the noise introduced in the transmission process, different kinds of cancellation techniques have been developed, each of them

focusing on specific parts of the transmission chain and having effect only on the specific domain. Let's see some techniques to cancel the self-interference in detail.

3.1 Self-interference and cancellation techniques

3.1.1 Propagation-Domain self-interference suppression

Since the power of self-interference in full-duplex terminal is very high in general, it has the potential to overwhelm the desired signal at the receiver and also to exceed the dynamic range of the receiver circuitry (e.g., ADC). To avoid these problems, it's indispensable for full-duplex terminals to use propagation-domain self-interference suppression technologies as the first line of defense against self-interference. For full-duplex systems with shared-antenna deployment, the propagation domain isolation is also usually accomplished using a duplexer (e.g. a circulator plus a filter).Through carefully designing the position for a duplexer or optimizing the weight for the antennas, they aim to mitigate the self-interference electromagnetically before it manifests in the receiver circuitry. In this way, the receiver circuitry can hear a much weaker self-interference. Moreover, propagation-domain self-interference suppression is very important and contributes to a large portion of self-interference cancellation in existing full-duplex designs [10].

For full-duplex systems with separate-antenna deployment, the earliest known propagation-domain self-interference suppression technologies leverage the path loss between transmit and receive antennas. For example, traditional on-frequency repeaters, suppress the self-interference by increasing the physical distance between transmit and receive antennas, or exploiting the surrounding obstacles (e.g. buildings, tunnels, and shielding plates) to block the direct-paths. Due to their simplicity, the path loss-based techniques are also used in the several recent testbeds [10].

Meanwhile, cross-polarization serves as another approach that electromagnetically increases the isolation between the transmit and receive antennas. For instance, the transmit signal of a full-duplex terminal can be horizontally polarized while it can only receive vertically polarized signals with the goal of avoiding interference between them [10].

Although the above propagation-domain self-interference suppression techniques are effective to passively combat the direct paths of self-interference, they are sensitive to device size and antenna placement. It has been shown that environmental reflections limit the amount of passive suppression achieved, since they are unaware of the channel characteristics of the reflected self-interference [10].

3.1.2 Analog-Circuit-Domain self-interference cancellation

As the second line of defense, analog-circuit-domain self-interference cancellation technologies try to cancel the self-interference in the analog receive-chain circuitry by subtracting a copy of the predicted self-interference from the received signal before it is digitized. According to whether they can response to the changing environmental effects, the analog-circuit-domain self-

interference cancellation technologies can be either non-adaptive or adaptive. The non-adaptive ones are unaware of the changes in environment and use fixed parameters (e.g. gain, phase, and delay) to form the predicted self-interference when the system is designed or calibrated. Hence, they might be sensitive to the reflected paths of self-interference [10].

However, the noise cancellation circuit requires manually setting the amplitude and phase for interference cancellation. By contrast, the adaptive ones dynamically adjust the parameters according to the reflection channel and hence they can mitigate both the direct and reflected self-interference effectively [10].

Generally, there are several ways to form a copy of the predicted self-interference. One can tap the transmit signal at the transmit antenna feed and electronically processes it to form the predicted self-interference in the analog-circuit domain. In this way, the non idealities like oscillator phase-noise and high power amplifier (HPA) distortion can be better captured. However, doing so requires analog-domain signal processing, which becomes difficult in the case of wideband reflected self-interference. Besides, one can also generate the predicted self-interference by tapping the transmit signal in digital domain, properly adjusting the gain/phase/delay digitally and then converting it to analog signal for self-interference cancellation. In this way, we can take the advantage of digital signal processing techniques to cancel the reflected path self-interference. Nevertheless, the effectiveness of self-interference cancellation is affected by the downstream analog circuit non-idealities [10].

3.1.3 Digital-Domain self-interference mitigation

With the self-interference mitigation technologies in propagation and analog-circuit domain, the self-interference in full duplex terminals can be partially suppressed, which might be enough for amplify-and-forward full duplex relaying (AF FDR) since they don't need to decode the received signals. However, those suppression is not enough in some cases, e.g. Decode-and-Forward full duplex relaying (DF FDR). Hence, digital-domain self-interference mitigation technologies can be adopted after the ADC as the last line of defense against the self-interference. The advantage of working in the digital-domain is that sophisticated processing becomes relatively easy by taking the advantages of advanced digital signal processing techniques. Generally, digital-domain self-interference mitigation technologies include digital self-interference canceller and receive beamforming. Digital self-interference canceller first estimates the residual self-interference after the propagation and analog circuit domain suppression, and then this prediction is subtracted from the received base-band samples in digital-domain [10].

On the other hand, receive beamforming is widely used in MIMO full-duplex systems, in which the per-antenna received signals are weighted by separate adaptative complex-valued gains before being summed together. In this way, the self-interference can be suppressed by adaptively adjusting per-antenna weight according to the self-interference channel condition [10]. Although this technique could be implemented in the analog-domain, it's more common the implementation in the digital-domain because in this way the circuit

complexity and the power consumption are reduced.

3.2 Physical layer enhancements

There are numerous important research opportunities for the advancement of IBFD physical-layer communications strategies, such as coding, modulation, power allocation, beamforming, channel estimation, equalization, digital interference cancellation, and decoding [11]. Let's see some more in detail.

As very first step in the design of any digital communication system is an accurate statistical characterization of the effective channel seen by the system, in the case of IBFD, the effective channel, seen in the digital domain, includes the analog circuitry and antennas as well as the propagation environment, taking into account in the analysis all of the non-idealities as well as the combined effects of any propagation domain and all the suppression strategies employed, as well as external noise and external interference [11].

Another line of research is the optimal resource allocation, and in particular the optimal allocation of limited transmit power over space, IBFD transmitters should be designed not just to suppress self-interference but rather to optimize the balance between self-interference suppression and desired-signal radiation [11].

3.3 Link and Medium Access Control (MAC) layer enhancements

Apart from the aforementioned physical-layer solutions, FD research opportunities have also been explored in the context of efficient MAC protocols for addressing the challenges of long end-to-end delays of network congestion and the hidden terminal problems. For instance, in [12], a new MAC protocol referred to as FD-MAC was developed and implemented for infrastructure based WiFi-like networks to provide opportunities for all the accessed nodes while trying to maximize the overall network throughput and maintaining fairness to all users simultaneously. In order to satisfy the above-mentioned requirements, three mechanisms, shared random back-off (SRB), snooping, and virtual contention resolution can be employed. FD-MAC is capable of guaranteeing seamless wireless access while maximizing the FD gains. Experimental results showed that FD-MAC achieves a throughput gain of up to 70 percent over its comparable HD counterpart [13].

3.4 Network layer enhancements

A typical wireless terminal of today is but one drop of a sea of networked terminals. Different networks often have to share the same radio spectrum. To fully exploit the potentials of IBFD, careful engineering in medium-access control and higher-layer protocols is as important as that in the physical layer. Research results on the networking aspects of IBFD are emerging and there are abundant research opportunities in this direction. Perhaps the biggest research challenge lies in developing a foundation for network design where all or some of the terminals are capable of IBFD operation. IBFD has the potential to significantly increase the overall throughput of a wireless network, beyond simply doubling the spectral efficiency of a point-to-point link. This is because IBFD removes a major scheduling constraint due to self-collision, so that a terminal may transmit to a second or a group of terminals and simultaneously receive from a third or another group of terminals [11].

A preliminary study in [6] indicates that the throughput gain over random access schemes (such as ALOHA) increases without bound as the number of neighbors increases. Fundamentally, with simultaneous transmissions, each receiver experiences an ergodic multi access channel (hence the sum energy is collected), whereas, with intermittent transmissions following a random-access protocol, each receiver experiences a nonergodic channel at the frame level, where some transmissions are lost and energy is wasted due to collisions [11].

From the network perspective, IBFD also allows more concurrent transmissions to be packed in a given area. IBFD may have implications on network layer protocols such as routing, as the routing algorithm may not need to try to avoid intersecting routes, which may reduce the length of the route and the overall interference. In addition, the system throughput may benefit by letting terminals route jointly process bidirectional flows, perhaps also by leveraging network coding techniques [11].

4 Project Description

The aim of the project was the upgrade of the event simulator for 4G OFDMA cellular systems developed by TIM to make it capable to simulate a full-duplex scenario. Then, being able to simulate the full-duplex case show how certain parameters, like the inter-site distance and the type of scheduler, influence the performance of the total system in terms of SINR, user throughput and cell throughput.

As first step an exhaustive investigation was carried out to find in the literature how to model the new interferences produced by this new type of configuration. As soon as the first step was analyzed and studied the work continued with the introduction of the changes to get active users in uplink and downlink at the same time. Clearly under this situation and because of the aforementioned reasons the formulation of the SINR was changed. At the end, a new type of scheduler was created with the aim to:

- Increase the number of users.
- Increase user and and cell throughput.
- Assign the resources in order to minimize the DL/UL interference.

Finally an analysis of the overall system performance varying the distance between the users was made in order to validate the new scheduler.

In the next session a detailed description of the simulator will be given, with the results and analysis obtained from the simulations.

5 Simulator and system analysis

The simulator used is an event driven system simulator based on the ITU-R M.2135 Channel Model and on an abstraction of 4G layer technology performance realized by the phy function described in the figure below (Figure 6). The supported ITU Channel model is a geometry-based stochastic model also known as Spatial Channel Model (SCM). It doesn't explicitly specify the locations of the scatters, but rather the direction of the rays.

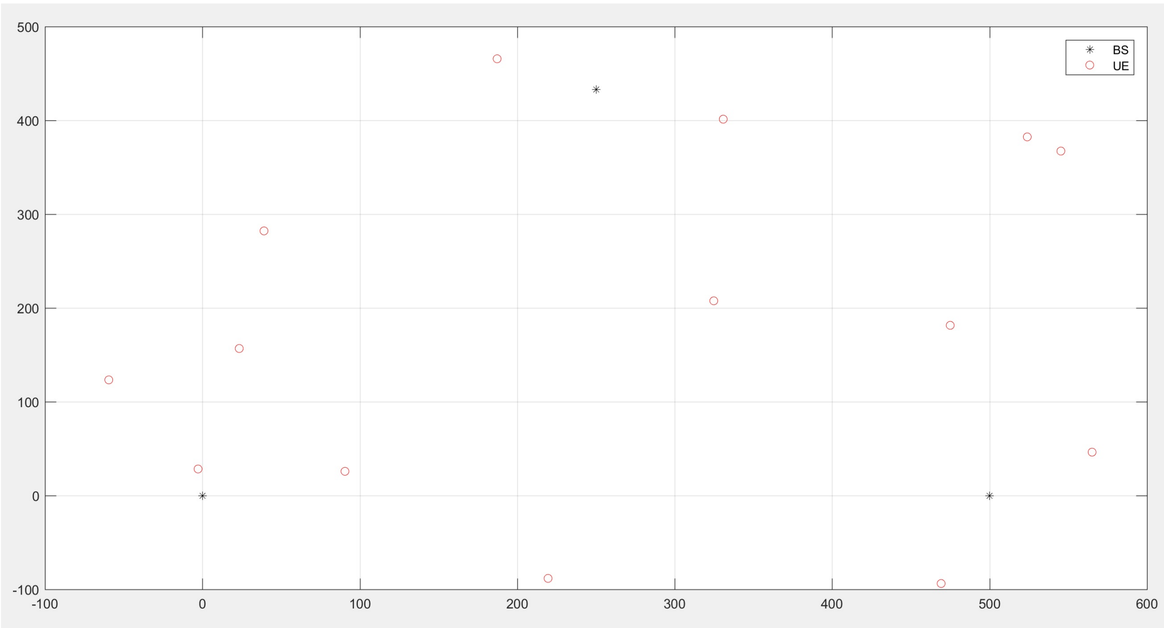

Figure 5: Simulated scenario.

As initial conditions the simulator consist of 15 users and 3 base stations, the transmission consist of 50 physical resource blocks (PRB) of 180KHz each one, the disposition of the users is randomly generated while the base stations are placed in a triangular configuration (Fig. 5), the radiated power by the users is 46dBm with a delta of 20dBm between users and base stations.

Other blocks implemented in the system simulator is shown in the block diagram below:

- **Traffic Generator Block:** Generates the data to transmit in DL/UL, simultaneously takes into account the correct reception of the packets in order to update the buffer information.

- **Channel Measurement:** Is used to obtain the user feedback information about channel quality (e.g. Rank Indicator and Channel Quality Indicator) and the SINR experimented by each user.

- **Scheduler Block:** Select users that need to transmit taking into account the buffer status hold in the traffic information and the quality of the channel contained in the user feedback information.

- **Phy:** Is a module that contains an abstraction of link layer performance, exploiting SINR information and scheduling information (as band allocation and transport format). It's able to compute if the transmission is correct or an error have occurred.

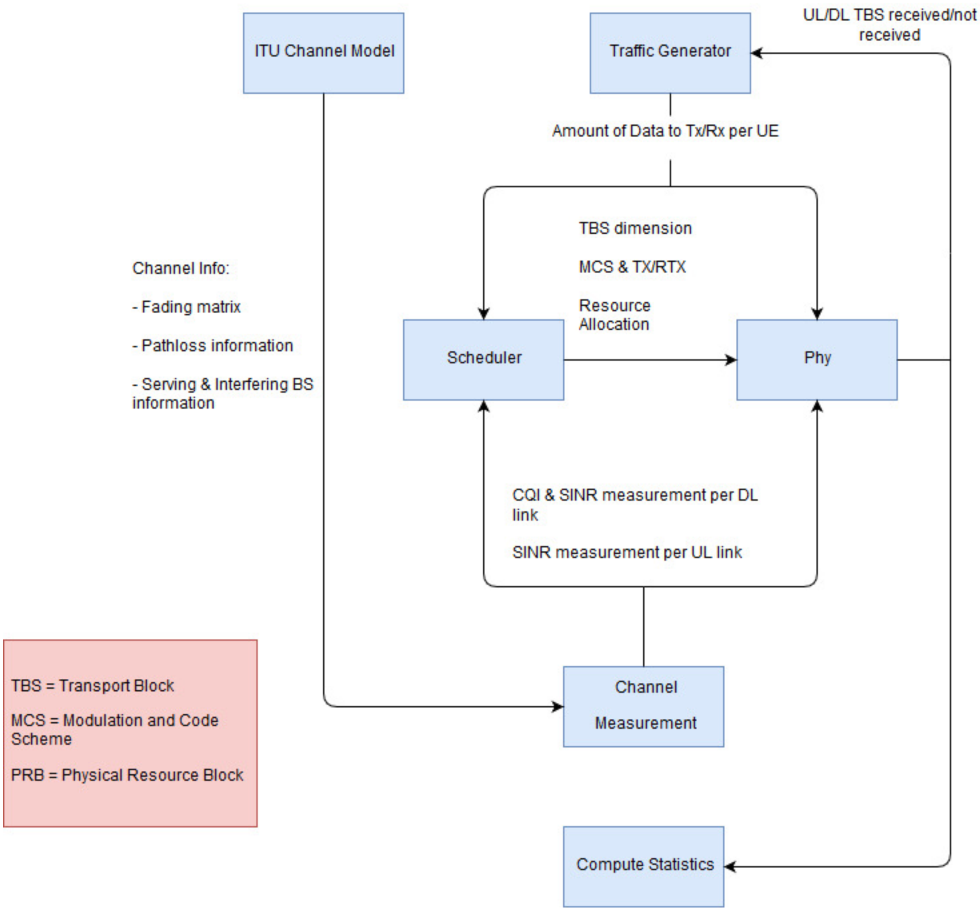

Figure 6: Block diagram of the simulator.

The types of schedulers used were:

- **Full-Duplex Round-Robin:**

  As it name suggest, this scheduler performs the assignment of the user in a Round-robin process, i.e. starting from the first element and going element by element successive till the end, clearly this way of schedule the users for transmit in a given time is fair and doesn't take into account important parameters as the interference or other factors that could affect the communication.

To be more specific, the following pseudocode is given:

Given the total number of users, the total number of cells and all the variables related to the transmission are initialized (e.g. total number of PRBs, MCS used, TBS dimension, etc.):

1. The best base station and the best CQI are computed per each UE each time to serving computation.
2. Select the best base station as the nearest useful BS for the best CQI for each user.
3. Users that share the best base station are grouped in cells.
4. In the first transmission time interval (TTI), for each cell the UE to serve in DL is selected as the first user in the list, clearly as it a Round-robin scheduler election is fairly and cyclic.
5. Then, in UL the UE to serve is selected as the first element of the cell, if it's the same UE transmitting in DL, the scheduler selects the next one.
6. The process is repeated for the total number of snapshots.

- **Full-Duplex Downlink first (DL first):**

Having understood the first scheduler, it's introduced a small variation on it. As it's mentioned, using Round-robin scheduling the process is fair and doesn't consider relevant parameters for a communication system. Therefore, a possible way to improve the performance of the simulator could be reducing the interference between users.

Going deeper in the scheduler, firstly, the distance between the users are computed and the users belonging to the same cell are arranged in arrays in order of distance. Then it's proceed with the normal DL process using Round-robin, however in UL the user is taken from the array of distance, being the most distant the selected one, in this way the interference between users is reduced and at the same time the throughput of the cell is increased.

To be more specific, the following pseudocode is given:

Given the total number of users, the total number of cells and all the variables related to the transmission are initialized (e.g. total number of PRBs, MCS used, TBS dimension, etc.):

1. The best base station and the best CQI are computed per each UE each time to serving computation.
2. Select the best base station as the nearest useful BS for the best CQI for each user.
3. Users that share the best base station are grouped in cells.
4. Users within the same cell are listed by order of distance from the nearest to the farthest.
5. According by the distance are formed couples of users, is two or more users share the same couple, the scheduler forms the couple with the next user according by the distance.

6. In the first transmission time interval (TTI), for each cell the UE to serve in DL is selected as the first user in the list.

7. Then, in UL the UE to serve is the couple of the user transmitting in DL.

8. When all the couples are served the process starts again by the first user.

9. The process is repeated for the total number of snapshots.

- **Full-Duplex sub-frame optimization:**

  Finally, a further variation was introduced with the aim to reduce even more the interference between the users and improve the performance of the simulator, using the previous scheduler and every 10 TTI, the last two intervals are assigned to perform only UL transmission and the selected users are the ones which yields maximum throughput to the system, in this way these links are not affected by the interference generated by other users and higher cell and user throughput in UL is achieved.

  To be more specific, the following pseudocode is given:

  Given the total number of users, the total number of cells and all the variables related to the transmission are initialized (e.g. total number of PRBs, MCS used, TBS dimension, etc.):

  1. The total number of TTI are divided in packets of 10.

  2. The best base station and the best CQI are computed per each UE each time to serving computation.

3. Select the best base station as the nearest useful BS for the best CQI for each user.
4. Users that share the best base station are grouped in cells.
5. Users within the same cell are listed by order of distance from the nearest to the farthest.
6. According by the distance are formed couples of users, is two or more users share the same couple, the scheduler forms the couple with the next user according by the distance.
7. In the first transmission time interval (TTI), for each cell the UE to serve in DL is selected as the first user in the list.
8. Then, in UL the UE to serve is the couple of the user transmitting in DL.
9. At the 9 and 10 TTI the transmission in DL is turned off and just take place transmission in UL, where the selected users are the 3 that gives higher throughput.
10. After the 10 TTI the process star again.
11. The process is repeated for the total number of snapshots.

5.1 Theoretical and analytical work

In downlink the formula used to calculate the SINR was:

$$SINR = \frac{BTS\_TX\_Power * PL}{Noise + \sum_{i=1}^{N}(BTS\_TX\_Power * PL_i) + \sum_{u=1}^{M}(MS\_RX\_Power * PL_u)} \quad (1)$$

Where:

- BTS_TX_Power is the power at which the base station is transmitting.

- PL is the pathloss, shadowing and fading of the serving link.
- Noise is the noise level fixed for the simulation.
- PL_i is a factor determined by the pathloss, shadowing and fading of the N interfering BS link.
- MS_RX_Power is the power at which the user is transmitting.
- PL_u is defined as the user-to-user pathloss, shadowing and fading of u-th interfering user (these M users are transmitting simultaneously with the DL reception of the selected user).

Similarly, in uplink the formula used to calculate the SINR was:

$$SINR = \frac{MS\_TX\_Power * PL}{Noise + \sum_{i=1}^{N}(BTS\_RX\_Power * PL_i) + \sum_{u=1}^{M}(MS\_RX\_Power * PL_u)} \quad (2)$$

In this case N base stations are transmitting (DL) simultaneously with the UL transmission of the selected user.

5.2 Simulation Results

The following results were obtained during the simulations, 40 snapshots with a duration of 1000 transmission time intervals, for more clarity the results will be described in three parts corresponding with 33%, 66% and 100% of the total users:

5.2.1 SINR in Downlink

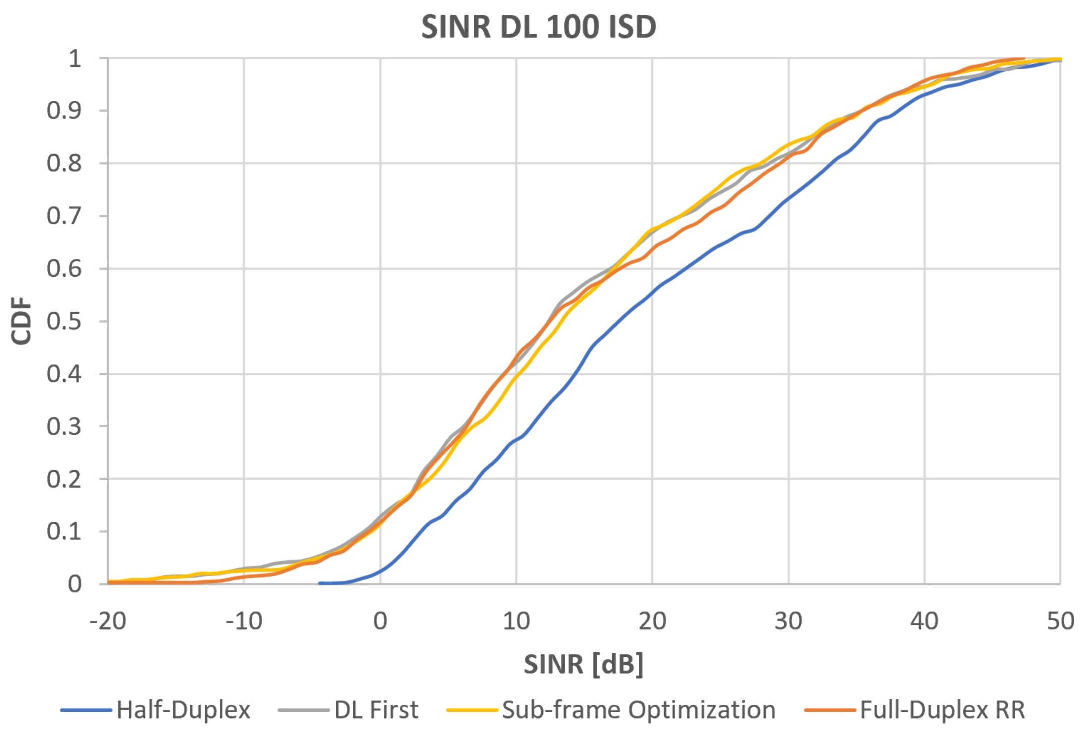

Figure 7: Comparison of the Signal-to-Interference plus Noise ratio in downlink given by the different schedulers at a inter-site distance of 100 mts.

The results obtained by the three schedulers in full-duplex were very similar, there are not considerable difference among the three schedulers.

- 33% of the users have a SINR of 12.5 dB or lower in half-duplex while in full-duplex the result was 8.5 dB or lower.

- 66% of the users have a SINR of 26.5 dB or lower in half-duplex while in full-duplex the result was 22 dB or lower.

- 100% of the users have a SINR of 52 dB or lower in half-duplex while in full-duplex the result was around 55 dB or lower.

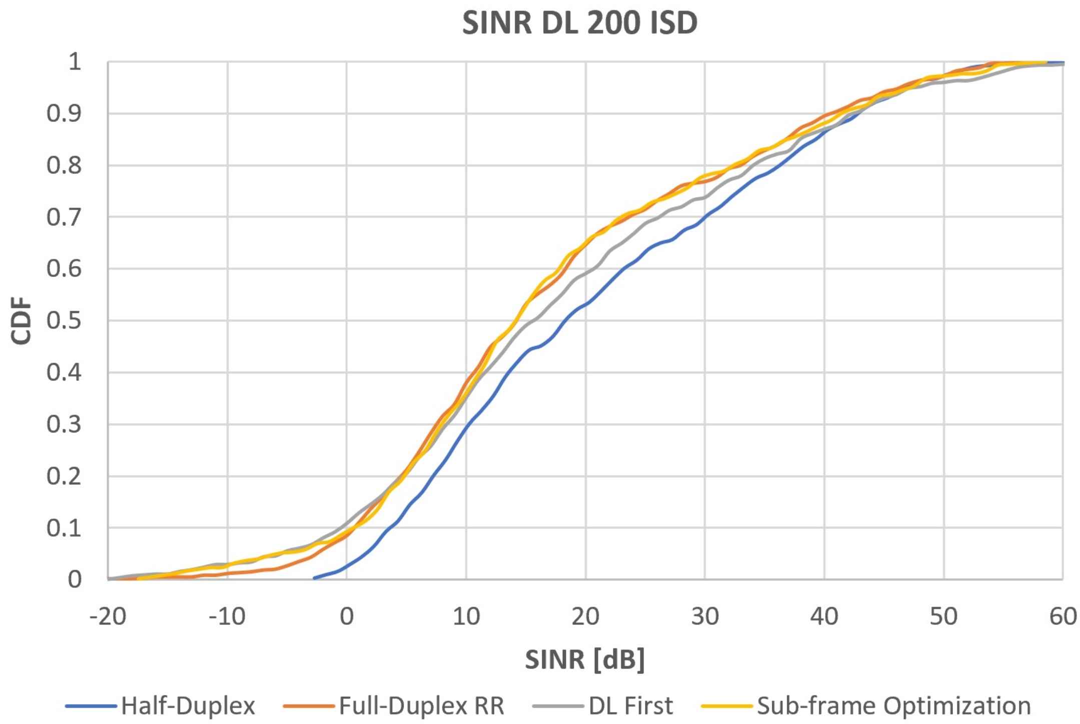

Figure 8: Comparison of the Signal-to-Interference plus Noise ratio in downlink given by the different schedulers at a inter-site distance of 200 mts.

The results in full-duplex were similar, there are not considerable difference between the schedulers.

- 33% of the users have a SINR of 12 dB or lower in half-duplex while in full-duplex the result was around 9.5 dB or lower.

- 66% of the users have a SINR of 28 dB or lower in half-duplex while in full-duplex the result was 25 dB or lower.

- 100% of the users have a SINR of 64 dB or lower in half-duplex while in full-duplex the best result was around 69 dB or lower given by DL first.

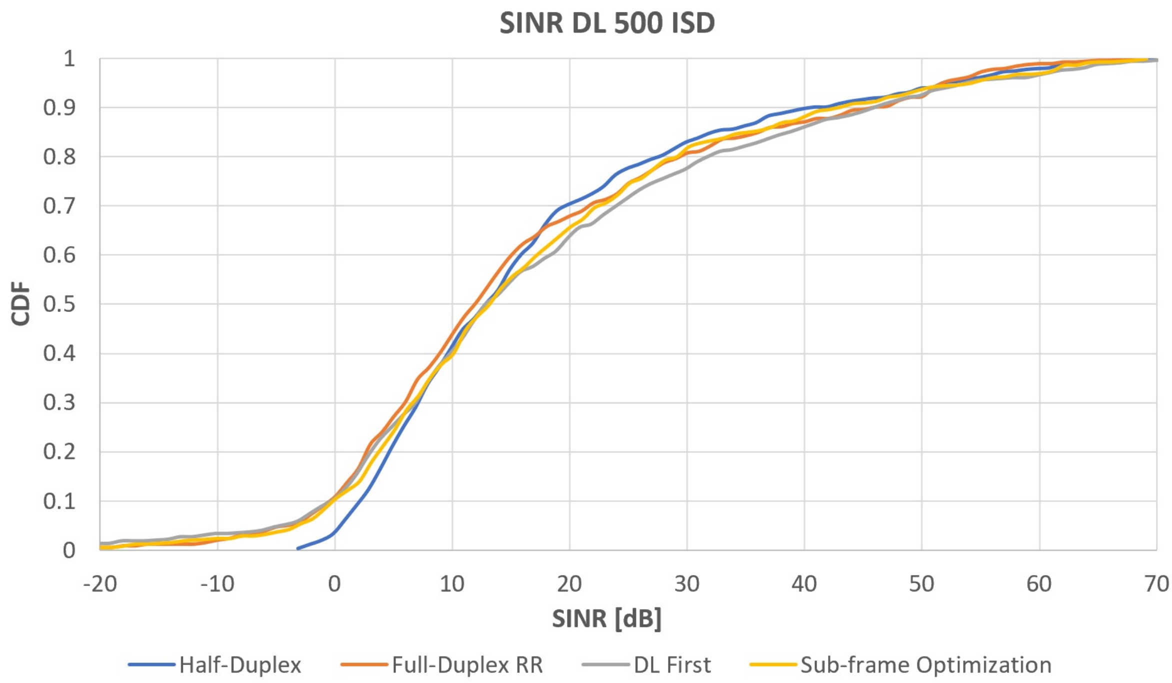

Figure 9: Comparison of the Signal-to-Interference plus Noise ratio in downlink given by the different schedulers at a inter-site distance of 500 mts.

The results in full-duplex are similar, all of the schedulers give almost the same results.

- 33% of the users have a SINR of 8 dB or lower in half duplex while in full-duplex the result was around 8 dB or lower.
- 66% of the users have a SINR of 18 dB or lower in half duplex while in full-duplex the result was 21 dB or lower.
- 100% of the users have a SINR of 76 dB or lower in half duplex while in full-duplex the best result was around 73 dB or lower given by DL first.

5.2.2 SINR in Uplink

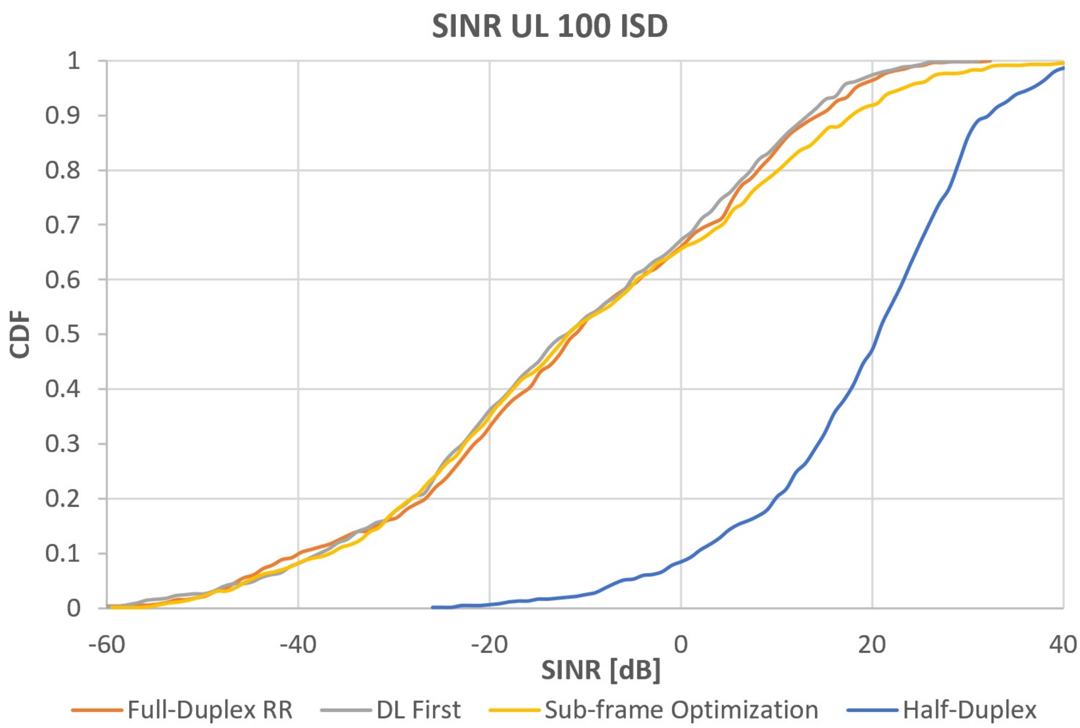

Figure 10: Comparison of the Signal-to-Interference plus Noise ratio in uplink given by the different schedulers at a inter-site distance of 100 mts.

The obtained results in full-duplex are very similar, however the sub-frame optimization technique gives the best performance for the last users.

- 33% of the users have a SINR of 15 dB or lower in half-duplex while in full-duplex the result was around -19.5 dB or lower.
- 66% of the users have a SINR of 25 dB or lower in half-duplex while in full-duplex the result was 2.5 dB or lower.
- 100% of the users have a SINR of 46 dB or lower in half-duplex while in full-duplex the best result was around 41 dB or lower given by the sub-frame optimization.

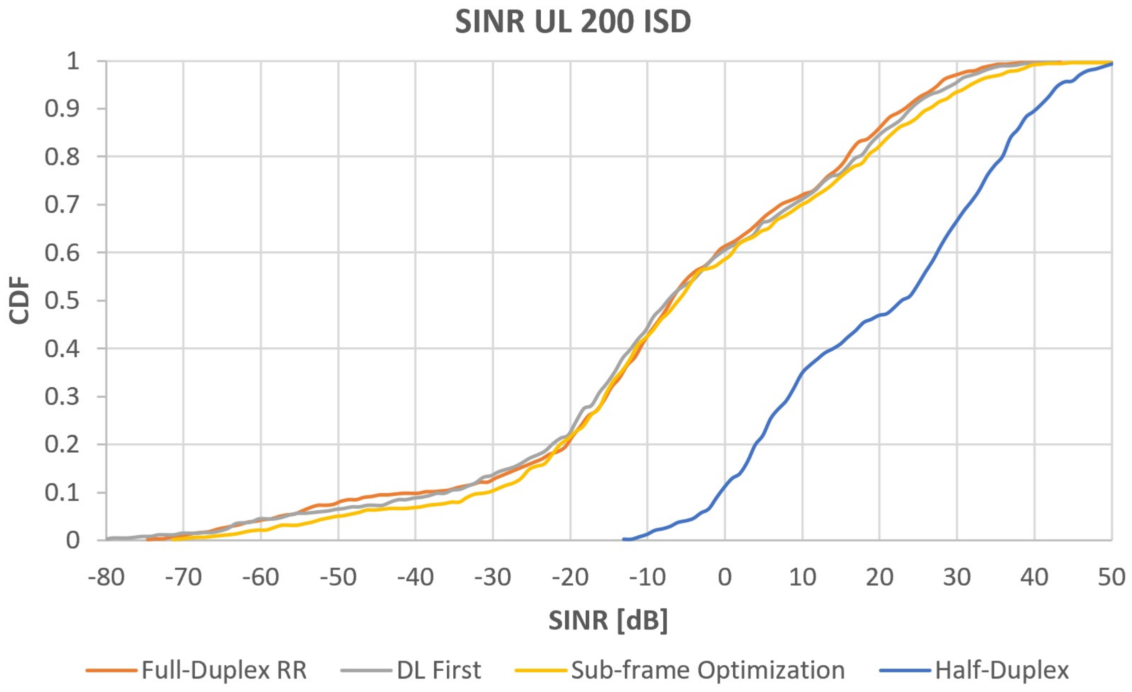

Figure 11: Comparison of the Signal-to-Interference plus Noise ratio in uplink given by the different schedulers at a inter-site distance of 200 mts.

The results given by the three schedulers in full-duplex are very similar, there are no considerable difference among the curves.

- 33% of the users have a SINR of 9 dB or lower in half-duplex while in full-duplex the result was -14 dB or lower.
- 66% of the users have a SINR of 30 dB or lower in half-duplex while in full-duplex the result was 6 dB or lower.
- 100% of the users have a SINR of 54 dB or lower in half-duplex while in full-duplex the best result was 52 dB or lower given by sub-frame optimization.

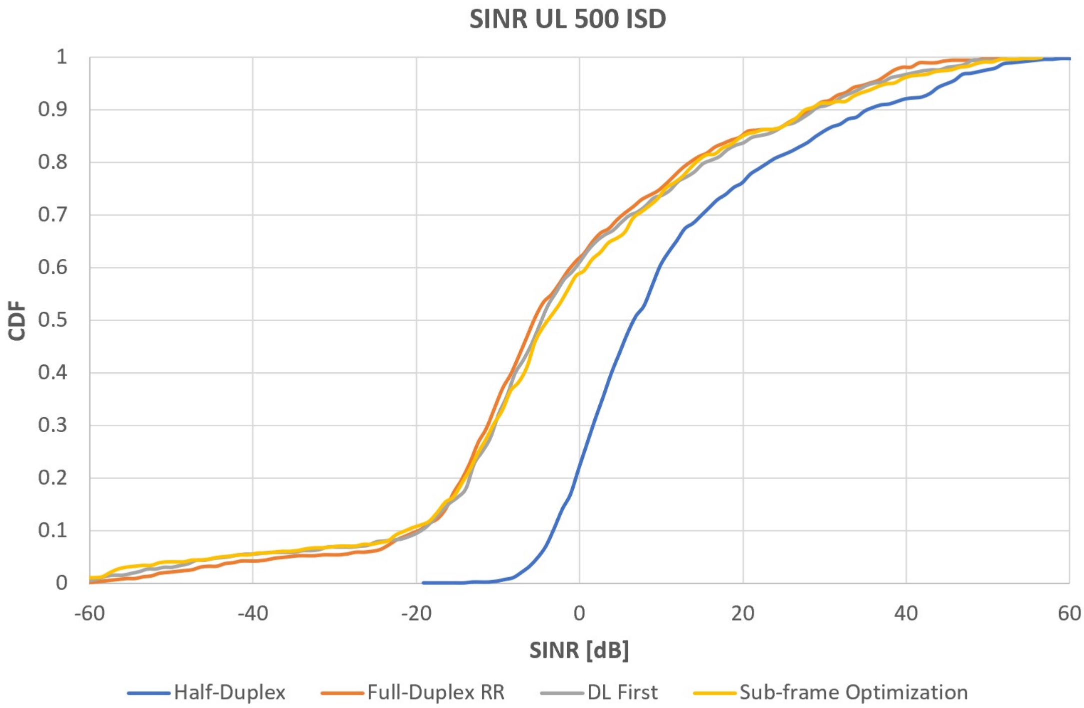

Figure 12: Comparison of the Signal-to-Interference plus Noise ratio in uplink given by the different schedulers at a inter-site distance of 500 mts.

The results in full-duplex were similar, there are not considerable difference between the schedulers.

- 33% of the users have a SINR of 3 dB or lower in half duplex while in full-duplex the result was around -8.5 dB or lower.
- 66% of the users have a SINR of 12 dB or lower in half duplex while in full-duplex the result was 5.5 dB or lower.
- 100% of the users have a SINR of 63 dB or lower in half duplex while in full-duplex the best result was 56 dB or lower given by sub-frame optimization.

5.2.3 User Throughput Downlink

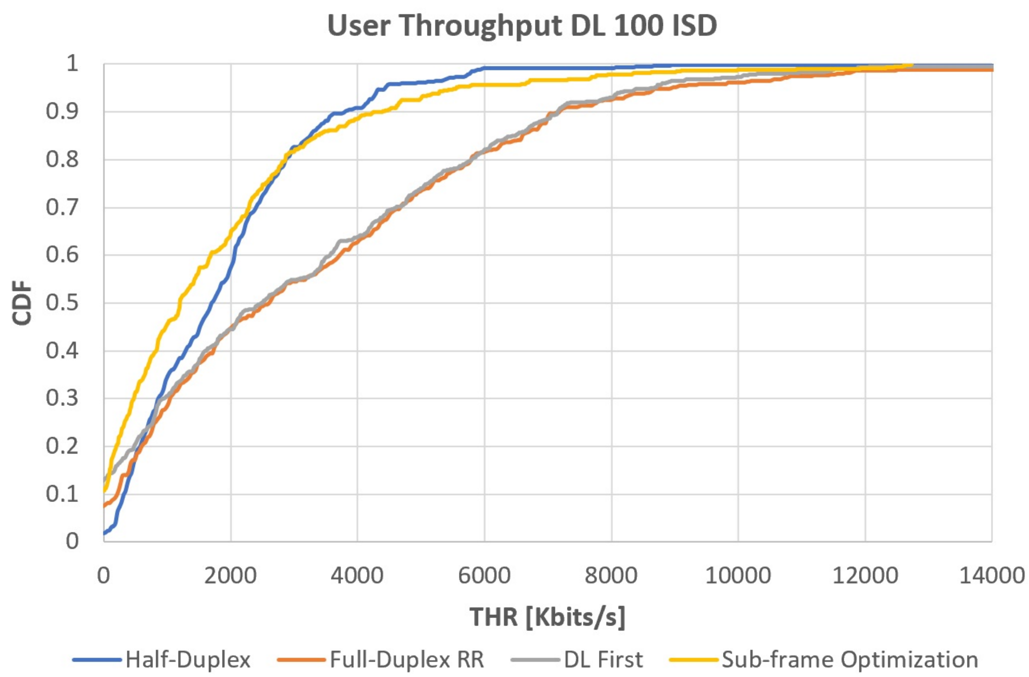

Figure 13: Comparison of the user throughput in downlink given by the different schedulers at a inter-site distance of 100 mts.

In general the best result is given by the round-robin scheduler and performing DL first.

- 33% of the user have a throughput of 1000 Kbits/s or lower in half duplex while in full-duplex the highest throughput was 1250 Kbits/s achieved in round-robin and DL first.
- 66% of the user have a throughput of 2250 Kbits/s or lower in half duplex while in full-duplex the highest throughput was around 4360 Kbits/s, again given by round-robin and DL first.
- 100% of the users have a throughput of 15750 Kbits/s or lower in half duplex while

in full-duplex the highest throughput was obtained in round-robin, the value was around 33000 Kbits/s.

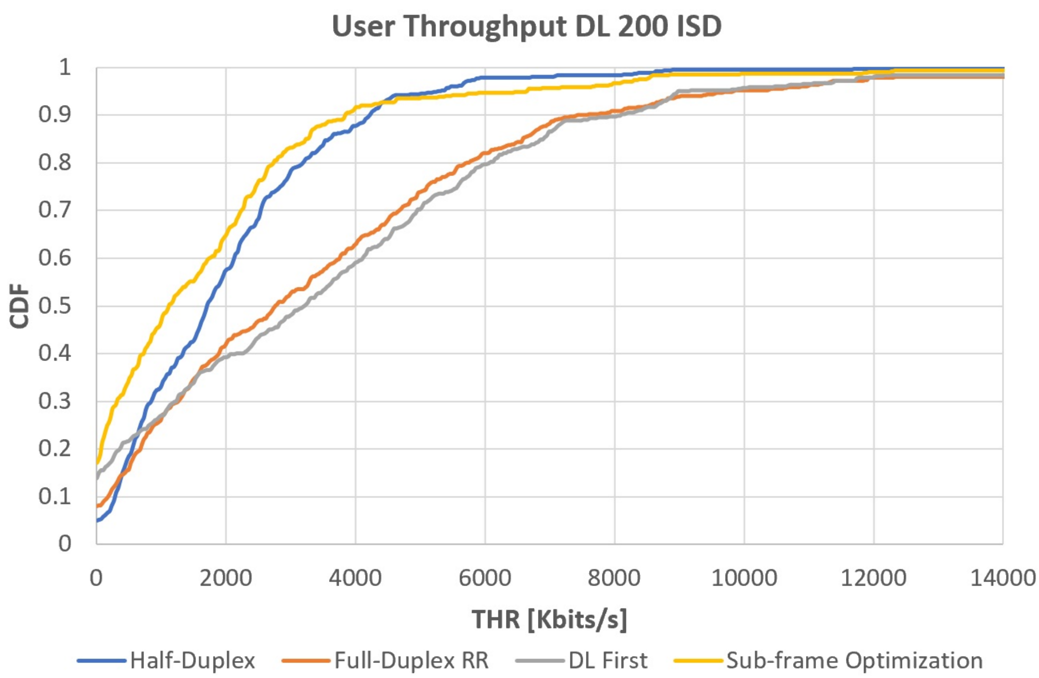

Figure 14: Comparison of the user throughput in downlink given by the different schedulers at a inter-site distance of 200 mts.

In general, the best result is given performing DL first.

- 33% of the user have a throughput of 1000 Kbits/s or lower in half-duplex while in full-duplex the best result was 1500 Kbits/s or lower in DL first and round-robin.

- 66% of the users have a throughput of 2400 Kbits/s or lower in half-duplex while in full-duplex the best result was 4800 Kbits/s or lower in DL first.

- 100% of the users have a throughput of 16500 Kbits/s or lower in half-duplex while un full-duplex the best result was 33250 Kbits/s given by DL first.

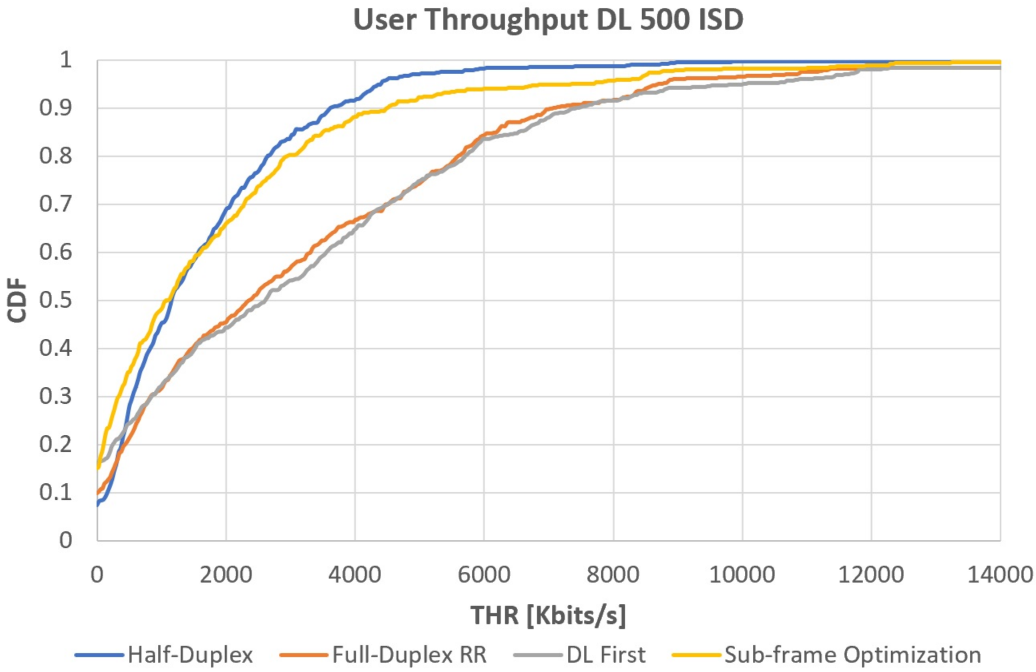

Figure 15: Comparison of the user throughput in downlink given by the different schedulers at a inter-site distance of 500 mts.

The best results were obtained by DL first and round-robin schedulers.

- 33% of the users have a throughput of 650 Kbits/s or lower in half duplex while in full-duplex the best result was 1100 Kbits/s or lower given by DL first and round-robin.
- 66% of the users have a throughput of 1900 Kbits/s or lower in half duplex while in full-duplex the best result was around 4200 Kbits/s given by DL first and round-robin.
- 100% of the users have a throughput of 16750 Kbits or lower in half duplex while in full-duplex the best result was 33200 Kbits/s obtained by DL first.

5.2.4 User Throughput Uplink

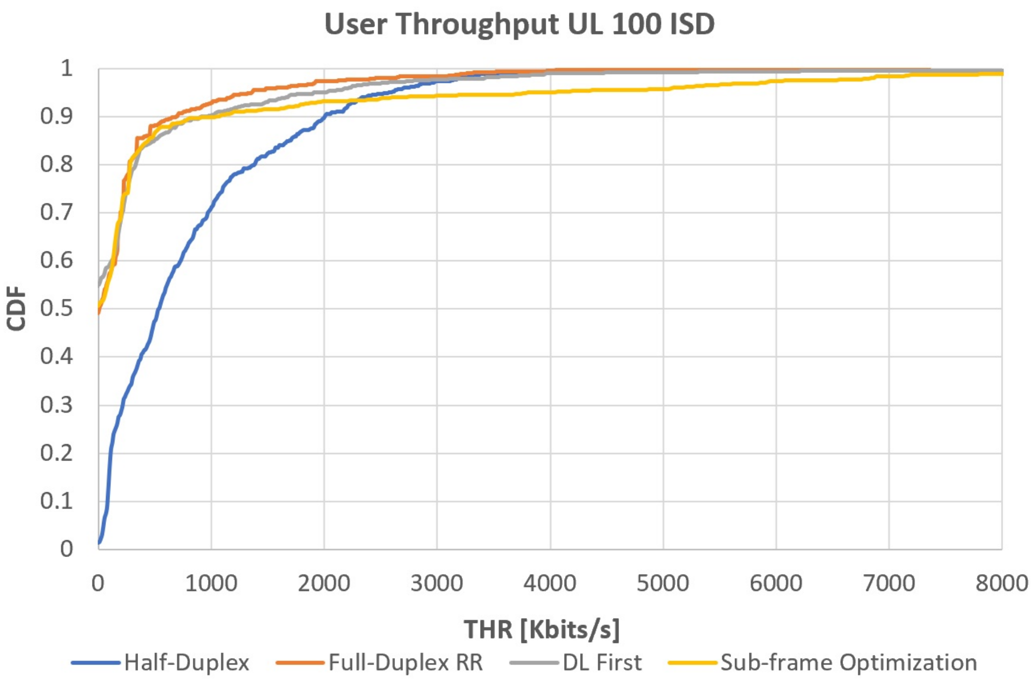

Figure 16: Comparison of the user throughput in uplink given by the different schedulers at a inter-site distance of 100 mts.

The results in full-duplex were similar, however the sub-frame optimization technique performs slightly better for the last users.

- 33% of the users have a throughput of 250 Kbits/s or lower in half duplex while in full-duplex as a consequence of the interference the data couldn't be computed.
- 66% of the users have a throughput of 850 Kbits/s or lower in half duplex while in full-duplex the result was 190 Kbits/s or lower.
- 100% of the users have a throughput of 5650 Kbits/s or lower in half duplex while in full-duplex the best result was 21850 Kbits/s using sub-frame optimization.

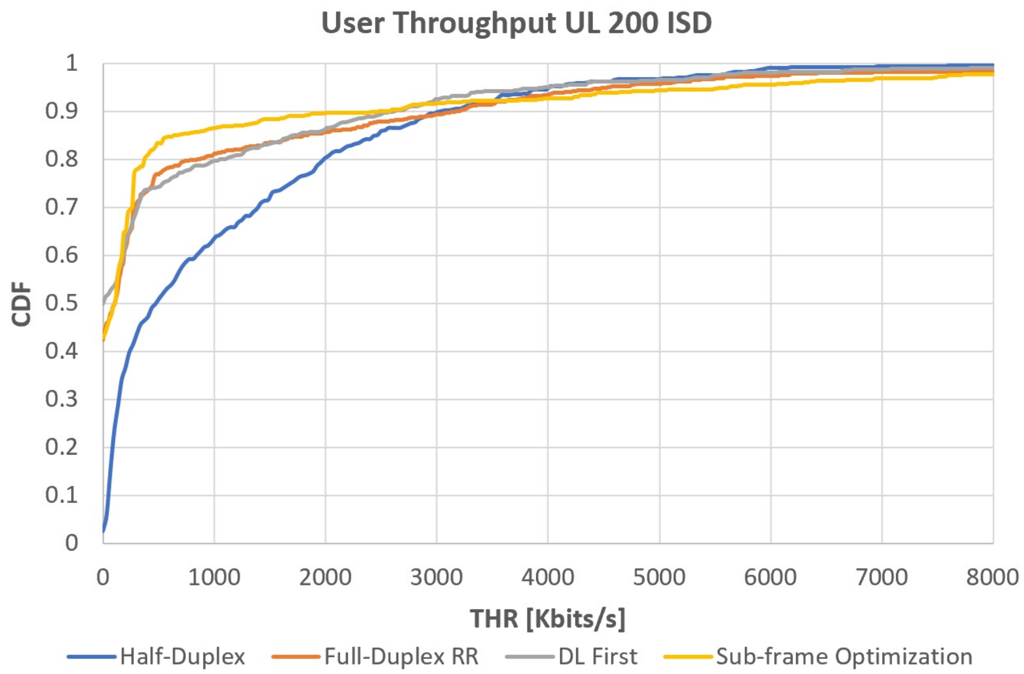

Figure 17: Comparison of the user throughput in uplink given by the different schedulers at a inter-site distance of 200 mts.

In general the behavior in full-duplex is very similar.

- 33% of the users have a throughput of 250 Kbits/s or lower in half-duplex while in full-duplex as a consequence of the interference the data couldn't be computed.
- 66% of the users have a throughput of 1200 Kbits/s or lower in half-duplex while in full-duplex the result was 250 Kbits/s or lower.
- 100% of the users have a throughput of 17000 Kbits/s or lower in half-duplex while in full-duplex the best result was 24500 Kbits/s using sub-frame optimization.

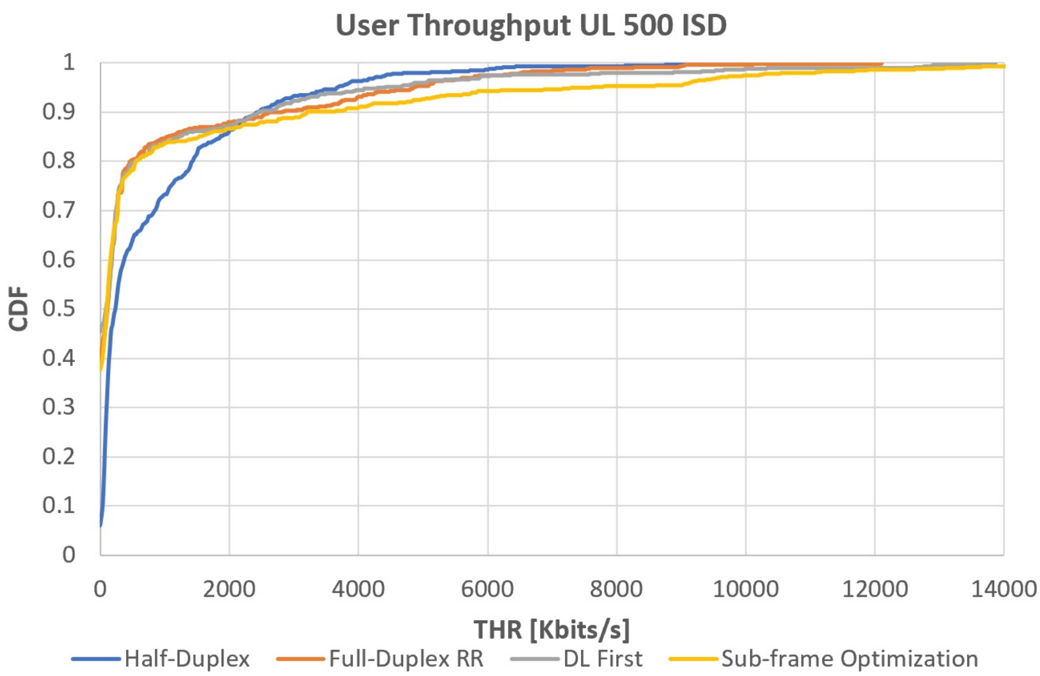

Figure 18: Comparison of the user throughput in uplink given by the different schedulers at a inter-site distance of 500 mts.

In general the results in full-duplex are similar, with a slightly part were sub-frame optimization performs better.

- 33% of the users have a throughput of 100 Kbits/s or lower in half-duplex while in full-duplex as a consequence of the interference the data couldn't be computed.
- 66% of the users have a throughput of 650 Kbits/s or lower in half-duplex while in full-duplex the result was 250 Kbits/s or lower.
- 100% of the users have a throughput of 10750 Kbits/s or lower in half-duplex while in full-duplex the best result was 32150 Kbits/s or lower given sub-frame optimization.

5.2.5 Cell Throughput Downlink

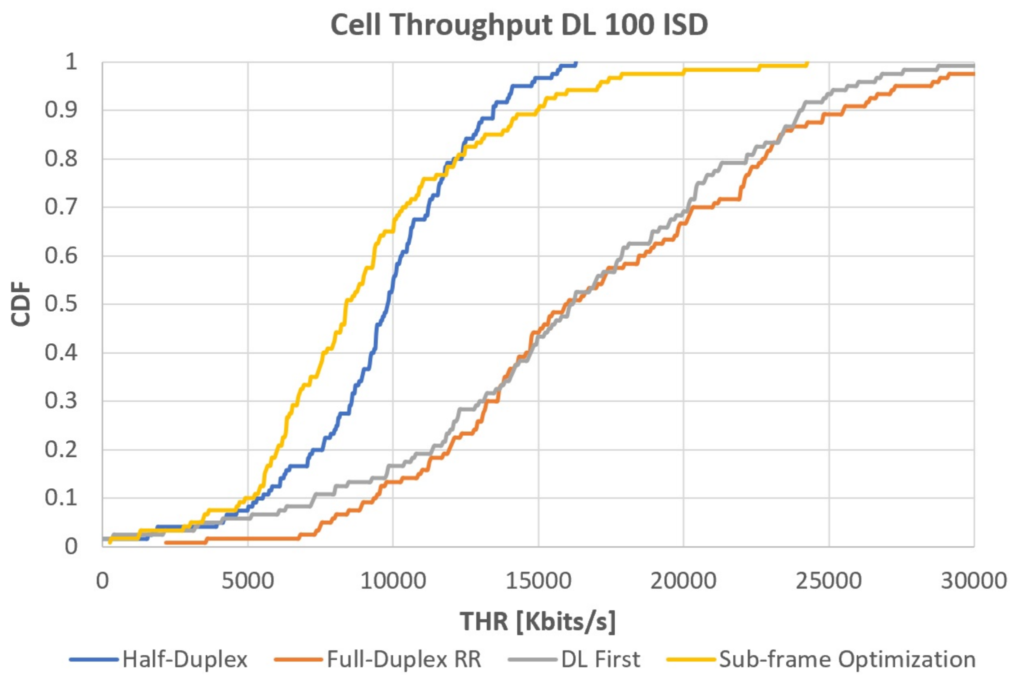

Figure 19: Comparison of the cell throughput in downlink given by the different schedulers at a inter-site distance of 100 mts.

In general the best result is given by the two new proposed schedulers.

- 33% of the users have a throughput of 8800 Kbits/s or lower in half-duplex while in full-duplex the best result was around 13700 Kbits/s or lower using round-robin and DL first.
- 66% of the users have a throughput of 10700 Kbits/s or lower in half-duplex while in full-duplex the best result was around 20000 Kbits/s or lower given by round-robin and DL first.
- 100% of the users have a throughput of 16300 Kbits/s or lower in half-duplex while in full-duplex the best result was 33000 Kbits/s or lower given by round-robin and DL first.

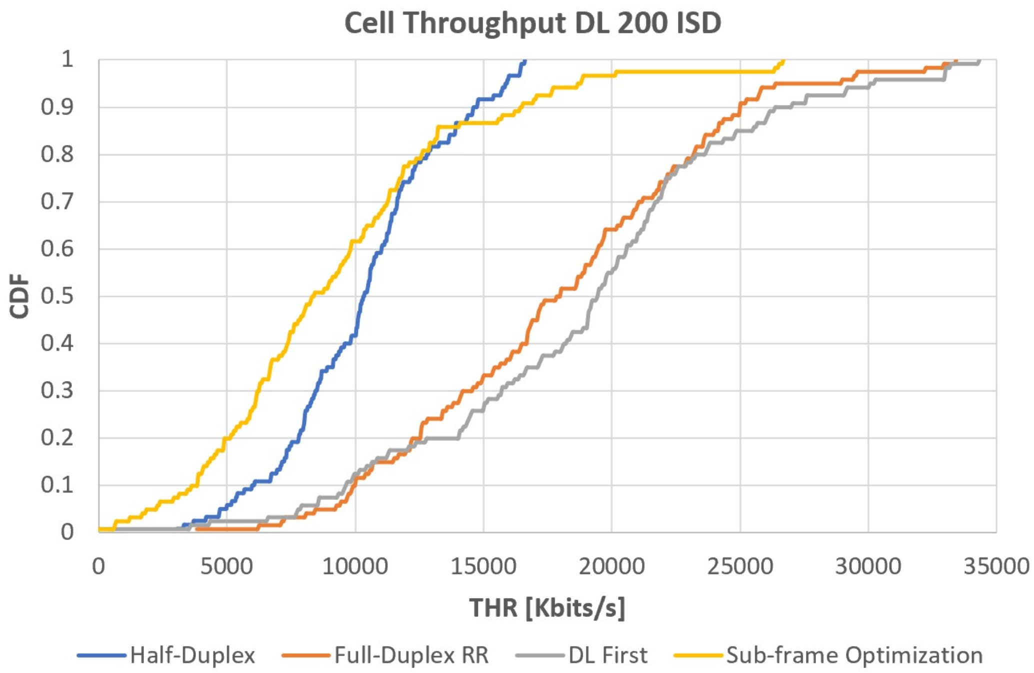

Figure 20: Comparison of the cell throughput in downlink given by the different schedulers at a inter-site distance of 200 mts.

In general the best results in full-duplex are given by DL first and round-robin.

- 33% of the users have a throughput of 8700 Kbits/s or lower in half-duplex while in full-duplex the best result was 16500 Kbits/s or lower using DL first.
- 66% of the users have a throughput of 11400 Kbits/s or lower in half-duplex while in full-duplex the best result was 21350 Kbits/s or lower given by DL first.
- 100% of the users have a throughput of 16600 or lower in half-duplex while in full-duplex the best result was 34300 Kbits/s or lower given by DL first and round-robin.

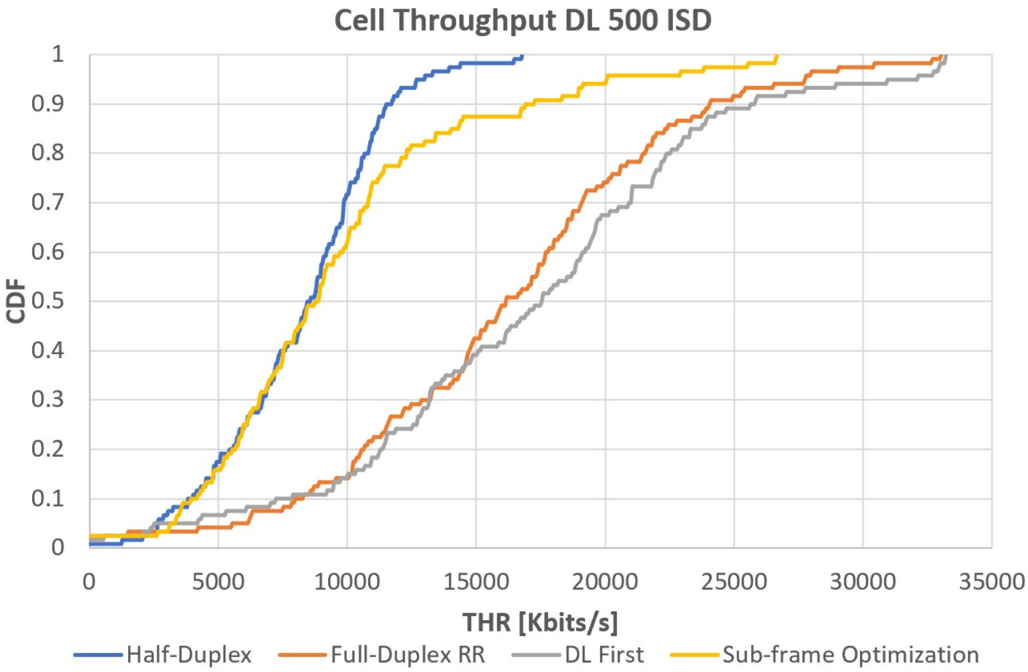

Figure 21: Comparison of the cell throughput in downlink given by the different schedulers at a inter-site distance of 500 mts.

In general the best result was given in full-duplex by DL first and round-robin.

- 33% of the users have a throughput of 7050 Kbits/s or lower in half duplex while in full-duplex the best result was around 13600 Kbits/s or lower given by DL first and round-robin.
- 66% of the users have a throughput of 9800 Kbits/s or lower in half duplex while in full-duplex the best result was around 19800 Kbits/s or lower given DL first.
- 100% of the users have a throughput of 16800 Kbits/s or lower in half duplex while in full-duplex the best result was around 33200 Kbits/s given by round-robin and DL first.

5.2.6 Cell Throughput Uplink

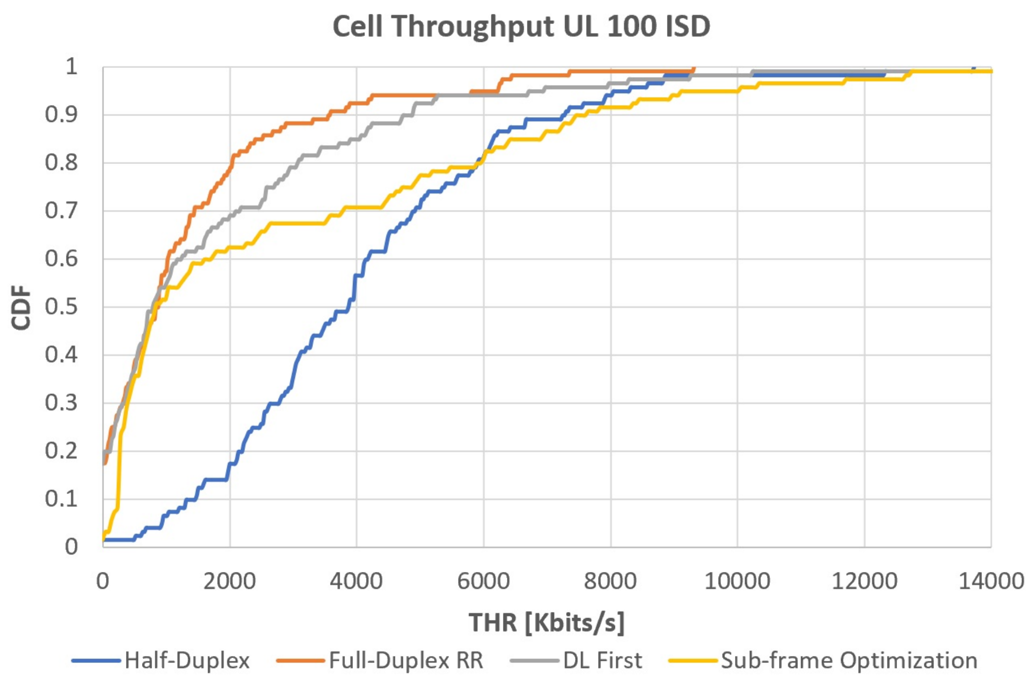

Figure 22: Comparison of the cell throughput in uplink given by the different schedulers at a inter-site distance of 100 mts.

In general the best result was obtained sub-frame optimization.

- 33% of the users have a throughput of 3000 Kbits/s or lower in half-duplex while in full-duplex the best result was 470 Kbits/s or lower.
- 66% of the users have a throughput of 6650 Kbits/s or lower in half-duplex while in full-duplex the best result was 2600 Kbits/s or lower given by sub-frame optimization.
- 100% of the users have a throughput of 13800 Kbits/s or lower in half duplex while in full-duplex the best result was 23600 Kbits/s or lower given by sub-frame optimization.

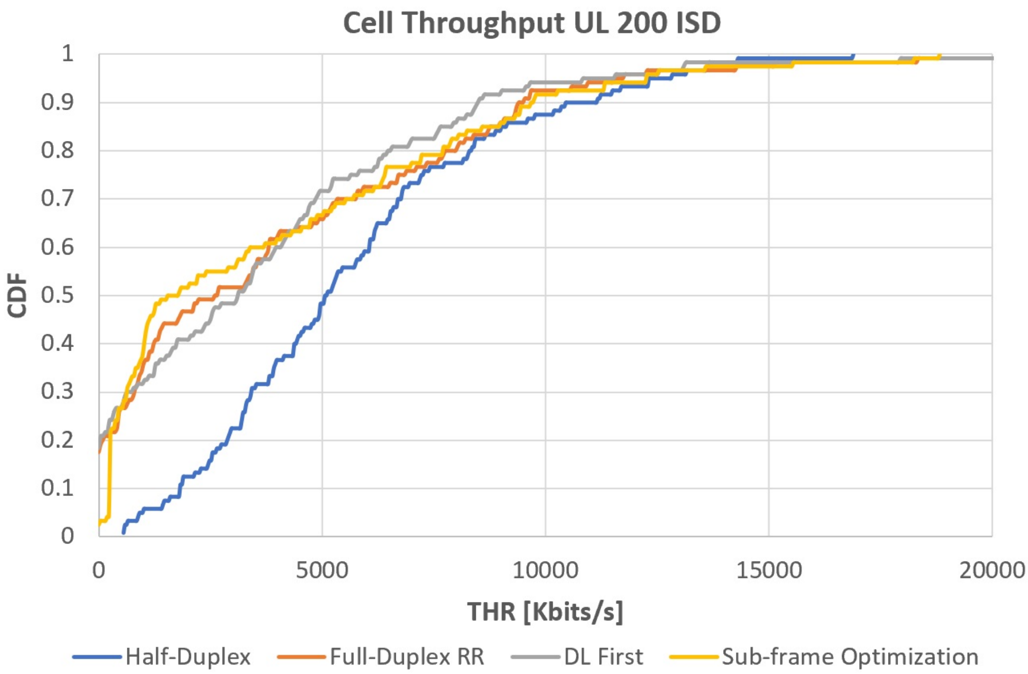

Figure 23: Comparison of the cell throughput in uplink given by the different schedulers at a inter-site distance of 200 mts.

In general the full-duplex behavior is very similar, there are not considerable difference between the schedulers.

- 33% of the users have a throughput of 3900 Kbits/s or lower in half-duplex while in full-duplex the result was 1250 Kbits/s or lower.
- 66% of the users have a throughput of 6500 Kbits/s or lower in half-duplex while in full-duplex the result was 4900 Kbits/s or lower.
- 100% of the users have a throughput of 16900 Kbits/s or lower in half-duplex while in full-duplex the result was 24500 Kbits/s or lower given by DL first.

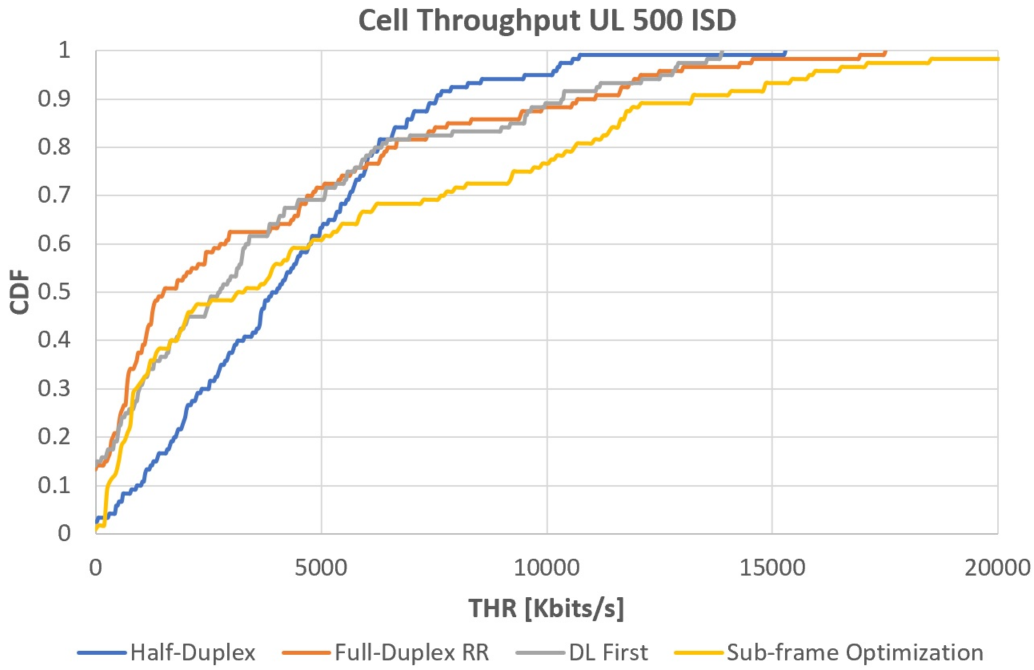

Figure 24: Comparison of the cell throughput in uplink given by the different schedulers at a inter-site distance of 500 mts.

In general the best result was obtained the sub-frame optimization technique.

- 33% of the users have a throughput of 2700 Kbits/s or lower in half-duplex while in full-duplex the best result was 1150 Kbits/s or lower given by DL first and sub-frame optimization.
- 66% of the users have a throughput of 5400 Kbits/s or lower in half-duplex while in full-duplex the best result was 6150 Kbits/s or lower given by sub-frame optimization.
- 100% of the users have a throughput of 15300 Kbits/s or lower in half-duplex while in full-duplex the best result was 32100 Kbits/s or lower given by sub-frame optimization.

6 Results analysis

After seeing the graphs and data obtained in the simulation the first thing that have to be remarked is that the results are coherent with the expectations ensuring the correctness of the employed model. This can be seen from the SINR graphs for all the possible cases: as the distance between users increases the level of interference decreases, or looking at the cell and user throughput, which become significantly higher in full-duplex than the counterpart in half-duplex as the distance increases either in uplink as in downlink.

Firstly, looking at the SINR graph in downlink, as the distance between users increments the SINR in full-duplex becomes closer and even higher to the SINR in half-duplex (for 500 ISD the SINR in the full-duplex case is higher), moreover the SINR for the total of users increases with the distance. Looking at the SINR graphs in uplink, clearly as the base stations power is very high with respect to the user power (about 20 dBm difference) the interference generated by the bases is higher than the interference generated by the users, in this way as could be seen the interference in full-duplex is always larger than the interference in half-duplex, however as the distance between users increases the SINR increases too.

Now let's take a look at the user throughput in downlink. Can be seen that independently from the distance the performance obtained in full-duplex is always better than in half-duplex, even doubling the half-duplex performance in some cases, the DL first scheduler and round-robin yields almost the same results, the sub-frame optimization performance was poor (worse than half-duplex in some cases). In uplink it's important to highlight that the curves for the full-duplex case begin nearly to 50%. This is due to the fact that this part of the curve correspond with the closest users within the cell, and this provides a large amount of interference, can be seen that the trending of the curves are independent of the distance and the advantages of the full-duplex could be seen just for the last portion of users, for which the throughput is the double compared with half-duplex.

Focusing on the cell throughput in downlink, where the maximum improvements can be seen, for all the distances the performance in full-duplex is much better than half-duplex and those are for the total number of users, the DL first and round-robin scheduler gives high performances and the advantages of full-duplex over half-duplex are clearly shown. The cell throughput in uplink shows that the sub-frame optimization gives the better performance in full-duplex, and its advantages increases with the distance, clearly the aim of this technique is to perform better in uplink therefore this is the expected behavior, for the DL first and round-robin scheduler the performances are coherent with all the parameters in uplink, clearly uplink is being affected heavily by the new interferences.

Finally, as can be seen in the previous graphs the advantages of full-duplex are more evident as the distance between users increases, clearly this is because the interference provided by the different users is being reduced, however the strongest interference is provided by the bases, affecting heavily the uplink, the DL scheduler and round-robin performs very well in downlink, yielding

high throughput and a SINR comparable with the half-duplex case. In uplink the benefits of the sub-frame optimization were shown, specially for highest separation between users.

7 Conclusions

With the pass of the years, the long-held assumption of the impossibility to transmit and receive on the same frequency and the same time is no longer true. Nowadays the astonishing advances reached in technology rises a wide spectrum of possibilities to enhance the performance of actual systems. Between them, full-duplex is an excellent option to evolve in the technology of the future.

At the same time, the global necessity for better, faster, and more secure devices render the creation of new technologies, that could be employed to continue the growth of economies and societies, an extremely important process, again, full-duplex and all its advantages could be the key for the future of the communications.

Inside the present work it has been analyzed the possibility to use the full duplex technology to increase the spectral efficiency of a radio communication system. The main pro and cons related to the full duplex scenarios have been investigated and two new scheduling algorithm have been proposed in order to minimize the interference inside the system maximizing the performance in terms of user and cell throughput.

The goals of the project have been reached: the performance of the simulator under the full-duplex condition was assessed in terms of three principal metrics and the obtained results make the study of this technology an important point to continue with this work.

8 Future works

- Until this point, all the improvements that full-duplex could represent for the actual communication systems have been given, also have been presented the challenges to make this feasible in the near future. Considering the next steps these could include: An updated version of the proposed simulator enabling MIMO transmission to make the model more realistic.

- An updated version of the proposed simulator with different traffic profiles available, not only full buffer as in the present work. These is important because more gain is expected in case of less challenging traffic profile compare to full buffer type.

- The design of a portable device that meets the specifications for full-duplex transmission.

- The design of an adaptative algorithm that enables the full-duplex communication over the network when detects an improvement using it instead of the classical half-duplex network [4].

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