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Impact of Transport Control Protocol on Full Duplex Performance in 5G Networks

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***Abstract*—Full duplex (FD) communication has attracted the attention of the industry and the academia as an important feature in the design of the future 5th generation (5G) wireless communication system. Such technology allows a device to simultaneously transmit and receive in the same frequency band, with the potential of providing higher throughput and lower latency compared to traditional half duplex (HD) systems. In this paper, the interaction between Transport Control Protocol (TCP) and FD in 5G ultra-dense small cell networks is studied. TCP is a well-known transport layer protocol for providing reliability, which comes at the price of increased delay and reduced system throughput. FD is expected to accelerate the TCP congestion control mechanism and hence mitigate such consequences. System level results show that FD can outperform HD and alleviate the TCP drawbacks when the inter-cell interference is not the main limiting factor. On the other hand, under strong inter-cell interference, results show that the capabilities of the system to cope with such interference dictates the gain that FD may provide over HD.**

I. INTRODUCTION

Full duplex (FD) technology allows a device to transmit and receive simultaneously in the same frequency band, ideally doubling the throughput over conventional half duplex (HD) systems. However, building an operational FD node requires a high level of self-interference cancellation (SIC), i.e., a high attenuation of the transmitted signal at the own receive antenna. Current achievable levels of SIC are in the order of 100 dB [1], thus making feasible the implementation of a FD device. For this reason, FD is considered as a potential candidate for a future 5th generation (5G) radio access technology (RAT). Besides residual self-interference (SI), other limitations such as inter-cell interference (ICI) and traffic constraints [2] may also reduce the theoretical 100% throughput gain.

The design of the 5G RAT is still under discussion by the industry and the academia. We presented our vision in [3]. The system was originally designed as a HD time division duplexing (TDD) system but it can easily accommodate FD technology. 5G is targeting a massive and uncoordinated deployment of small cells, where all nodes are equipped with multiple-input multiple-output (MIMO) antenna technology and receivers with interference rejection capabilities.

A detailed study of the techniques for SIC is presented in [1]. The authors evaluated SI suppression using a testbed, showing $\sim$100 dB of cancellation. They conclude that in dense deployment of small cells, where transmit powers are low and distances among nodes are short, such level of SIC is enough to consider that ICI becomes a major limitation to achieve the promised FD gain. Moreover, they remark that large asymmetric traffic ratios between downlink (DL) and uplink (UL) data may compromise the usage of FD and hence its gain. These challenges are also described in [4]. Authors in [5] evaluate a FD network considering asymmetric traffic, showing that FD always outperforms HD. However, the authors assume a strong isolation between the cells, which may mitigate the ICI impact. Malik et al. propose a solution based on power control to accommodate asymmetric traffic [6]. The proposed scheme shows an improvement in DL at the expenses of lowering the UL rate. However, the analysis is carried on a single cell scenario. Finally, the authors in [2] study the impact of symmetric and asymmetric traffic in a multi-cell scenario. Throughput results show that the FD gain reduces with the perceived ICI and the traffic ratio. It is important to notice that the mentioned work disregards the usage of features such as link adaptation or recovery and congestion control mechanisms.

As previously stated, traffic constraints have an impact on the FD performance. According to [7], most of the Internet traffic is carried over Transport Control Protocol (TCP) flows, with a small percentage of User Data Protocol (UDP) flows. TCP [8] is used to provide a reliable communication and reduce packet losses as much as possible. The congestion control mechanism provided by TCP limits the amount data that can be pushed into the network, based on the reception of positive acknowledgments (ACKs) [9]. This procedure causes an increase in the delay and a reduction of the system throughput. Such drawbacks may be mitigated by FD since it may allow to accelerate the TCP congestion control mechanism, given the possibility of transmitting and receiving simultaneously.

This paper focus on the analysis of FD performance in 5G ultra-dense small cell networks with TCP traffic, considering the congestion control and recovery mechanisms defined by this protocol. To the best of the authors knowledge, this is the first work investigating the interaction between the TCP mechanism and the FD technology. This work extends our previous contribution [10] by considering multi-user cells and the TCP protocol. We study the case of bidirectional FD, where both access points (APs) and user equipments (UEs) are FD capable. Two types of traffic are considered: symmetric, when the ratio between the DL and the UL load is the same, and asymmetric, when the load in DL is larger than in UL. Results are extracted via system level simulations.

The paper is structured as follows. Section II presents the envisioned 5G system. Section III describes the interaction between TCP and FD. Section IV defines the simulation environment. System level results are discussed in Section V. Section VI concludes the paper and states the future work.

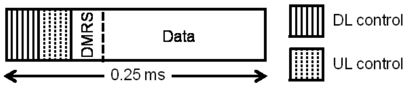

Fig. 1: Envisioned 5G frame structure

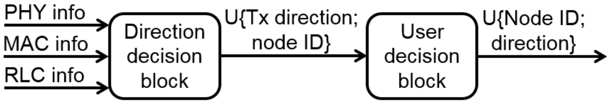

Fig. 2: Module in charge of deciding transmission mode and scheduled node(s)

II. FULL DUPLEX IN 5G SMALL CELLS

In [3], we presented the design of our envisioned 5G system. It was originally designed as a HD TDD system, targeting a massive and uncoordinated deployment of small cells. Nodes are assumed to be synchronized in time and frequency. The system uses a novel frame structure of duration 0.25 ms, defined as the Transmission Time Interval (TTI) and shown in Figure 1. A scheduling grant containing transmission parameters such as the link direction, the modulation and coding scheme (MCS) or the number of transmission streams (i.e., transmission *rank*) is sent within the DL control symbol. UE specific information is sent within the UL control symbol, including channel and buffer state information and Hybrid Automatic Repeat Request (HARQ) feedback. The data part carries UL or DL data in case of HD, and both UL and DL data in FD. Note that the transmission direction may change every 0.25ms. Thus, a TTI may be DL HD, UL HD or FD, independently of the decisions from previous TTIs. All nodes are equipped with 4×4 MIMO antenna configuration and advanced receivers, such as Interference Rejection Combining (IRC) [11]. These receivers use the degrees of freedom from the antenna domain to suppress incoming interference.

This work focuses on the performance of bidirectional FD, which refers to the case where both APs and UEs can simultaneously transmit and receive. In this case, a node may perceive SI and ICI, since FD is always exploited between the same pair AP-UE, thus avoiding intra-cell interference. Figure 2 shows the structure of the module that decides the transmission mode (HD or FD) and the scheduled node(s). This module is located in the Radio Resource Management (RRM) layer and it is divided into two blocks, *direction decision block* and *user decision block*, in order to separate functionalities and thus reduce complexity. In the first step, the optimal transmission direction per node is extracted, based on information from the physical (PHY), medium access control (MAC) and radio link control (RLC) layers. The output from the *direction decision block*, which corresponds to the union of pairs {*optimal transmission direction, node identifier*}, is transferred to the *user decision block*, where the transmission mode and the scheduled node(s) are then decided. A FD transmission has always priority over a HD one. In case there are more than one pair of nodes that are able to use FD, different time scheduling algorithms may be applied to decide which node to schedule. The output of the FD module is then the pair {*scheduled node, direction*}.

The procedure to extract the optimal transmission direction is different for HD and FD:

- **HD**: the optimal transmission direction is decided based on the amount of data which is currently in the buffers (UL and DL), and previous decisions. For example, in case of asymmetric traffic, where the DL traffic load is six times higher than in UL, a node will decide *DL* six times more than *UL* in average. The information regarding previous slot allocations is used to avoid the starvation of the lightly loaded link, i.e., at least one slot should be allocated to such link with a certain periodicity. The optimal direction can be *DL* or *UL* if there is data in at least one of the buffers, or *MUTE* if there is not data in either of them.
- **FD**: since we want to exploit FD as much as possible, the link decision is based only on the buffer size. This means that the optimal transmission direction will be *DL+UL* if there is data in both buffers, *DL* (*UL*) if the *UL* (*DL*) buffer is empty, or *MUTE* if both buffers are empty.

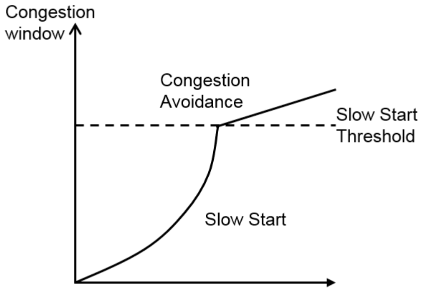

Fig. 3: TCP congestion window

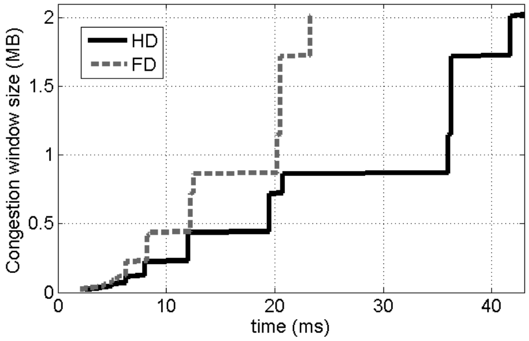

Fig. 4: Congestion window growth

III. INTERACTION BETWEEN FULL DUPLEX AND TCP

TCP [8] is a protocol that provides reliability by using a congestion control mechanism [9]. TCP limits the amount of data that can be sent through the channel based on the reception of positive ACKs. The congestion window, shown in Figure 3, controls such limitation. During the *Slow Start* stage, the congestion window grows exponentially according to the received TCP ACKs. When the *Congestion Avoidance* phase is reached, the growth of the congestion window is linear, following the same principle on the TCP ACKs as the *Slow Start* phase. Nevertheless, TCP has an inherent impact on the system throughput and delay, since the amount of transmitted data is limited by the reception of positive feedback and consequently it will increase only if the channel conditions are favorable.

We believe that FD may help at mitigating the TCP drawbacks since simultaneous transmission and reception might increase the congestion window faster and help at reaching the

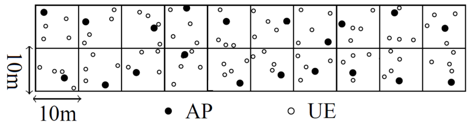

Fig. 5: Simulated scenario

TABLE I: Used parameters to run the simulations

Parameter	Value/State/Type
System parameters	BW = 200MHz; f_c = 3.5GHz
Frequency reuse	1 (whole band)
Propagation model	WINNER II A1 w/fast fading [12]
Antenna configuration	4x4
Receiver type	IRC
Transmission power	10 dBm (BS and UE)
Self-interference cancellation	Ideal
Link adaptation filter	Log average of 5 samples
Rank adaptation	Taxation-based [13]
HARQ max retransmissions	4
RLC mode	Acknowledged
Transport protocol	UDP and TCP
TCP timer for ACK	100 ms
TCP initial retransmission timeout	1 ms
Segment size threshold	10 MB
Traffic type	Symmetric and asymmetric (6:1) finite buffer
Simulation time per drop	15-40 seconds
Number of drops	50

Congestion Avoidance phase sooner, where a larger amount of data is transmitted within a single TTI. For clarification, a simple example is shown in Figure 4. This figure shows the growth of the congestion window for HD and FD in a single cell scenario with one AP and one UE, where both nodes have a 2 megabytes file to transmit and the probability of exploiting FD is 100%. Shadowing and fast fading have been disabled to provide a fair comparison between both cases, and the general simulation parameters are listed in Table I and they will be further discussed in the next section. We can observe that FD is able to transmit the file faster than HD since its congestion window grows faster. The transmission time is reduced by approximately 45% in this case. It is important to remark that in dense networks, ICI may slow down the growth of the congestion window. The performance of FD with TCP traffic in such networks is discussed in section V.

IV. SIMULATION ENVIRONMENT

Results are extracted from an event-based system level simulator. It implements the 5G MAC and PHY design described in Section II. Furthermore, it includes a detailed modeling of the RLC and TCP layers, and a vertical RRM layer that collects information from the PHY, MAC and RLC layers to provide the scheduling parameters. Finally, the application layer generates File Transfer Protocol (FTP) traffic [14] and the Internet Protocol (IP) layer is modeled as overhead.

In addition to the procedures described in Section II, the PHY and MAC layers also implement the HARQ retransmission mechanism and link and rank adaptation schemes. The link adaptation algorithm keeps track of the last five channel measurements to extract an accurate MCS. The rank adaptation (RA) algorithm is taxation-based [13]. It decides, according to the incoming interference, which is the most appropriate rank to reduce the overall network interference, i.e., how many MIMO antennas will be used for transmission and how many of them for IRC interference suppression [11]. The reader can refer to [13] for further details on the rank adaptation algorithm. Finally, the selected scheme for the *user decision block* is time domain round robin, i.e. frequency multiplexing is not considered.

In terms of deployment, a small cell is located in a 10×10 m^2 room, containing one AP and four UEs randomly deployed, with the UEs affiliated to the AP in the same cell (closed subscriber group). The multi-cell scenario refers to a 10×2 grid of small cells, as shown in Figure 5. SIC is considered ideal, according to [1], given the current SIC capabilities, the short distances among nodes and the low transmit power, which is set to 10 dBm for all the nodes. The RLC mode is set to Acknowledged (AM) [15]. We assume that the RLC ACK is sent within the control channel, i.e., it does not generate additional overhead. The TCP implementation in the simulator is New Reno [16], which includes the recovery and congestion control mechanisms, whereas handshake procedures are not considered since they are not relevant for our studies. TCP parametrization and the remaining simulation parameters are listed in Table I.

The generated results compare HD and FD performance with TCP, whereas UDP [17] is considered for the sake of comparison. Notice that UDP acts as a transparent layer, sending everything that it receives to the upper layers, without performing error checking or congestion control. For both cases, RLC AM and HARQ are enabled. Two FTP traffic cases are studied: symmetric, where the offered load in DL and UL is the same (1DL:1UL ratio), and asymmetric, where the amount of DL data is six times higher than in UL (6DL:1UL ratio). For each case, three levels of load are considered: low, medium and high, corresponding approximately to 25%, 50% and 75% resource utilization (RU). The RU is defined as the percentage of time the medium is used. Results are presented in terms of average session throughput, defined as the average of the individual session throughputs per link (UL or DL) or per cell (UL+DL), where the session throughput corresponds to the amount of time required to successfully transmit a session. Such a session is characterized by the packet size and the $t_{arrival}$ parameters, which are negatively exponential distributed [14]. The average packet size is 2 megabytes, and the average $t_{arrival}$ is set according to obtain the loads described above. The second key performance indicator (KPI) is the packet delay, defined as the time between the generation of a packet and its successful reception, including the buffering time. Finally, percentages indicate the gain of FD over HD. In throughput, a plus (+) indicates that FD outperforms HD, and a minus (-) the opposite case. In delay, (-) indicates better performance of and vice versa for (+).

V. PERFORMANCE EVALUATION

Results are divided according to the deployment, in order to isolate the ICI impact, since it may be the limiting factor in the achievable FD gain [1].

A. Single cell scenario: avoiding inter-cell interference

Since this scenario is not affected by ICI, retransmissions rarely occur and the FD gain is only affected by the traffic constraints. Figure 6 depicts the average cell throughput with symmetric traffic. This result shows that FD always outperforms HD, independent of the transport protocol, and the FD gain is higher when the load increases. However, notice that the FD gain obtained with TCP is higher than with UDP. This

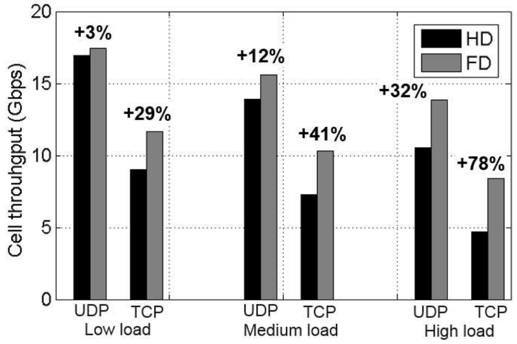

Fig. 6: Single cell throughput with symmetric traffic

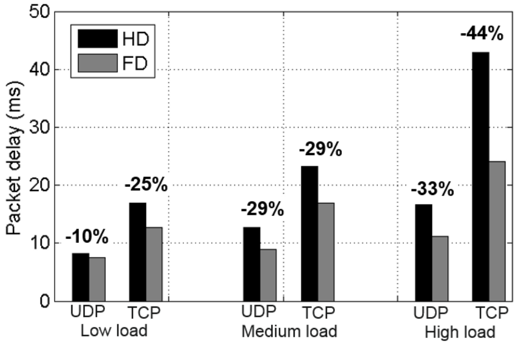

Fig. 7: Single cell delay with symmetric traffic

TABLE II: TP gain and delay reduction of FD over HD with asymmetric traffic in single cell scenario

Load	Traffic	DL TP	UL TP	DL delay	UL delay
Low	**UDP** **TCP**	+1% +17%	+10% +39%	0 -13%	-16% -29%
Medium	**UDP** **TCP**	+6% +37%	+36% +77%	-5% -21%	-44% -43%
High	**UDP** **TCP**	+5% +61%	+69% +128%	-6% -36%	-61% -55%

TABLE III: TP gain and delay reduction of FD over HD with symmetric traffic in multi-cell scenario

Load	Traffic	Cell TP	Average delay
Low	**UDP** **TCP**	+2% +1%	-8% +22%
Medium	**UDP** **TCP**	+16% -50%	-27% +284%
High	**UDP** **TCP**	+41% -32%	-26% +52%

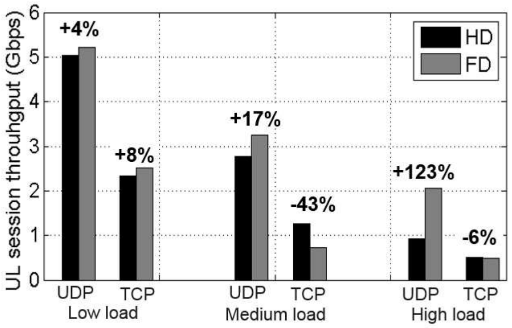

Fig. 8: Multi-cell UL throughput with asymmetric traffic

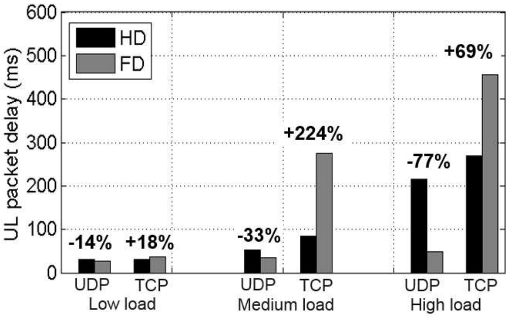

Fig. 9: Multi-cell UL delay with asymmetric traffic

difference is a consequence of the TCP congestion control mechanism. Packets accumulate in the buffer because data transmission is controlled by the TCP congestion window, thus increasing the probability of having simultaneously UL and DL data. In this case, the FD probability ranges from 67% to 83% for TCP, while it goes from 4% to 11% for UDP because this protocol acts as a transparent layer. Figure 7 shows the packet delay with symmetric traffic, which has a similar behavior as the throughput. We observe that FD also outperforms HD for all cases and the FD gain increases with the load.

For asymmetric traffic (see Table II), FD always outperforms HD in terms of throughput and delay, for both UDP and TCP. However, the UL gain is higher because in HD the UL gets less transmission opportunities since it is the lightly loaded link. Furthermore, in TCP, DL (UL) data needs to be acknowledged from the UL (DL) in order to increase the TCP congestion window and continue transmitting. In HD, DL suffers since UL has less transmission opportunities, hence delaying the UL TCP ACK transmission. In UL the impact is less significant because DL gets more transmission opportunities (highly loaded link) and the DL TCP ACK is transmitted with lower delay. This HD problem is solved with FD since the TCP ACK can be transmitted immediately in both UL and DL, allowing the congestion window to grow faster.

From this first analysis we can conclude that FD is able to improve TCP performance, providing better results than UDP. Such gains come from a faster growing of the TCP congestion window and the immediate transmission of the TCP ACK with FD. Moreover, without ICI, FD can always outperform HD, specially the lightly loaded link in case of asymmetric traffic.

B. Multi-cell scenario: impact of inter-cell interference

In the multi-cell scenario (Figure 5), a node may perceive significant interference from its neighbors, meaning that FD will be affected by increased ICI compared to HD. Table III shows the FD gain with symmetric traffic. We can observe that, with UDP, FD always outperforms HD, both in terms of throughput and delay, and the FD gain increases with the load. Nevertheless, with TCP, the situation is the opposite and FD leads to worse throughput and delay performance than HD in all cases. Such performance is caused by the interference conditions as a consequence of the FD probability. Such probability ranges from 11% to 34% with UDP and from 67% to 89% with TCP. This indicates that, the higher is the FD probability, the larger is the ICI, since FD doubles the number of interfering streams. Notice that, according to the

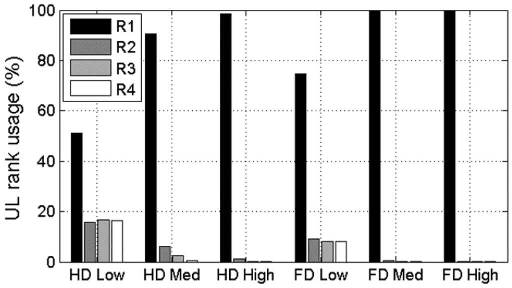

Fig. 10: Multi-cell UL rank with TCP asymmetric traffic

TABLE IV: TP gain and delay reduction of FD over HD with asymmetric traffic in multi-cell scenario

Load	Traffic	DL TP	UL TP	DL delay	UL delay
Low	**UDP**	+1%	+4%	-2%	-14%
	TCP	-9%	+8%	+45%	+18%
Medium	**UDP**	+3%	+17%	-5%	-33%
	TCP	-60%	-43%	+429%	+224%
High	**UDP**	+17%	+123%	-22%	-77%
	TCP	-51%	-6%	+123%	+69%

RA algorithm, HD would then use a higher rank than FD. Consequently, HD is able to transmit a larger amount of data, increase faster the TCP congestion window and get rid of the data sooner than FD. Then, HD occupies the medium for less time and hence reduces the interference generated to neighboring cells. Results shows that the worst case is at medium load, where the RU is 67% for HD and 92% for FD.

Figures 8 and 9 show the UL throughput and delay, respectively, which correspond to the performance of the lightly loaded link. We can observe that results show the same trends as the symmetric traffic case. With UDP, FD shows the best performance, specially at high load (123% throughput gain an 77% delay reduction) because FD mitigates the buffering effect, since UL get more transmission opportunities than in HD. Table IV shows that also the DL is always improved with FD. However, with TCP, not even the lightly loaded link, which may perceive six times more resources in FD than in HD, can be improved. The reasoning is the same as for the symmetric traffic case. The FD probability, which has an effect on the ICI and hence in the transmission rank, goes from 4% to 11% with UDP and from 85% to 91% with TCP. Figure 10 shows the UL transmission rank, where *R1* refers to rank one, *R2* to rank two, etc. From the figure, we observe that FD is already limited to rank one at medium and high load, while HD exploits MIMO spatial multiplexing at all loads (with very low probability at high load). Choosing a higher transmission rank allows the TCP congestion window to grow faster and reduce the ICI since the medium is freed before.

According to the presented results, we conclude that TCP leads to a higher FD probability, thus increasing the ICI and provoking a slower growth of the TCP congestion window. We showed that there is a trade-off between the MIMO antennas used for data transmission and the ones used for interference suppression to achieve the best system performance.

VI. CONCLUSIONS AND FUTURE WORK

In this paper we have investigated the performance of bidirectional FD in 5G ultra-dense small cell networks considering the impact of strong inter-cell interference, traffic constraints and TCP congestion control and recovery mechanisms. System level results show that, under ideal interference conditions, FD outperforms HD in terms of throughput and delay, and helps at reducing the increased latency inherent in the TCP mechanism. However, in case of significant inter-cell interference, HD provides better performance. Therefore, we conclude that there is a trade-off between HD MIMO spatial multiplexing and FD to obtain the optimal system performance. Such trade-off is strongly linked to the probability of exploiting FD and hence to the level of inter-cell interference. Finally, future work will focus on studying FD in contention based systems and discovery procedures in device-to-device communication.

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