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Full Duplex Communications in 5G Small Cells

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***Abstract*—Full duplex communication promises system performance improvement over conventional half duplex communication by allowing simultaneous transmission and reception. However, such concurrent communication results in strong self interference and an increase in the overall network interference, and can only be exploited when traffic is available in both directions. The potential throughput gains of full duplex communication over conventional half duplex transmission in a small cell network with asymmetric traffic conditions is investigated in this contribution. The throughput performance gains are analysed using tools from stochastic geometry, and further confirmed through extensive system level simulations. Our findings explicitly quantify how the gains from full duplex communication depend on the traffic profile and the inter-cell interference coupling. The demonstrated throughput gains and delay reduction make full duplex communication an attractive potential technology component for the fifth generation dense small cell cellular system.**

***Index Terms*—Full duplex communication, small cells, stochastic geometry, 5G.**

I. Introduction

CATERING to large-scale mobile data has been the main focus of wireless technologies up to and including the current fourth generation cellular network (4G). In contrast, a wide variety of new applications is expected to emerge by 2020, contributing to new use cases requiring different design foci for the upcoming fifth generation of cellular network (5G). Novel and disruptive techniques are therefore needed to meet the demanding 5G system design requirements.

Full duplex (FD) communication, i.e. simultaneous transmission and reception over the same frequency band, had generally been assumed infeasible in wireless communication due to the strong *loopback interference* from the transmission-end [1]. Recent advances in self-interference cancellation (SIC) in both analog and digital domain have made FD communication appealing in practical systems with viable cost [2]–[5], thus promising a throughput (TP) enhancement and latency reduction of up to 100% over conventional half duplex (HD) transmissions. In that respect, FD has been considered as a potential 5G technology component owning to such promising capabilities.

The TP performance of wireless networks with FD capable radios have been investigated in [6]–[8] among others. The authors in [6] show that FD capabilities can significantly increase the aggregate throughput of current cellular systems with FD enabled access points (AP) and HD user equipments (UE) under symmetric traffic conditions and relatively isolated cells. Reference [7] considers a large wireless network and analytically investigates the TP gain of FD communication using stochastic geometry tools. The role of FD communication in reducing the transmission latency in addition to boosting the network TP for a dense small cell scenario is studied in [8]. The impact of having symmetric and asymmetric finite buffer traffic is evaluated for FD communication when only the AP is FD capable, and when both the BS and the UE are FD capable.

This work presents an analytical framework to evaluate the network-wide TP gain of FD communication considering asymmetric DL/UL traffic pattern with varying ratios, complimented by detailed system level simulation study on the impact of inter-cell interference (ICI) and traffic constraints on full duplex performance in a 5G dense small cell systems. Such a detailed system level simulation exercise allows us to emulate higher layer protocols in details.

Similar to [7], stochastic geometry based tools are used in this study to model the wireless network. However, reference [7] models the wireless network as a Poisson point process (PPP), which better reflects an ad-hoc network with a large number of nodes [9]. In this contribution, the network is modelled as a binomial point process (BPP), which closely reflects a local area network with an arbitrary number of small cells [9]. Furthermore, we address asymmetric UL/DL traffic profiles which are typically disregarded in analytical studies.

Paper Contribution and Organization: The system model and an overview of the analytical performance evaluation framework are detailed in Section II, followed by preliminary numerical results based on the analytical findings in Section III. An analytical model allows us to obtain an overview of the network performance with FD communication. However a simplified system model has to be considered for analytical tractability. In order to evaluate the performance of a 'real-life system in further details, the analytical findings are complemented with extensive system level simulations from an equivalent small cell system as presented in Section IV. Transport and radio link layer protocols such as radio link control (RLC), Hybrid Automatic Repeat Request (HARQ) and link adaptation are implemented in the system-level simulator. System-level simulation results and related discussions are presented in Section V, and concluding remarks are drawn in Section VI.

II. Analytical Performance Evaluation: System Model and Overview

An analytical derivation of the TP gain of FD communication over HD transmissions considering variable isolation among cells and random transmission of devices, is presented as a short paper in [10]. For the sake of completeness, a brief outline of the derivation is presented in this section.

We consider a local area system with a number of small cells distributed in a circular area $\mathcal{R}$ of radius R in the two-dimensional plane $\mathbb{R}^2$. Each small cell consists of an AP and a single active UE. Our analysis focuses on the performance of a generic reference cell with the desired receiver located at the origin. K interfering cells are assumed to be distributed around the reference cell.

The considered random access protocol assumes that, at any given time slot, the AP and UE in cell k transmits data with independent access probabilities $\rho_{AP,k}$ and $\rho_{UE,k}$ respectively. The desired transmitter receiver separation distance is fixed at d meters. Assuming $R \gg d$, the UL and the DL transmissions in the reference cell can be considered to experience similar interference conditions.

Signal Model: The perceived interference power at the desired receiver from a random interferer k located r_k meters away is given by $\zeta_k = \eta g \beta(r_k)$, where $\eta = \eta_0 p \nu$ is a constant path loss factor accounting for the transmit power p, the interference isolation among neighbouring cells ν (commonly known as wall loss) and η_0 : the path loss at reference distance. The channel fast fade power g is assumed to be Gamma distributed as it can approximately represent a large number of fading models. We have adopted the distance dependent path loss with exponent $\alpha > 2$ given by $\beta(r) = (1+r)^{-\alpha}$ as it is found to be more appropriate for small cell scenarios [11].

A. Sum Interference Power from Multiple Interferers

Let $\Omega \in \{FD(AP), FD(UE), HD\}$ denote the index of set of interferers with the respective transmission mode. The sum interference power for the various transmission modes is modelled in this subsection.

Assuming each cell transmits independently with probability ρ_Ω;

1) Distribution of the Number of Interfering Cells: Due to the random transmission probabilities, the number of active interfering cells at any given time is a random variable (r.v.), represented by $\Lambda_\Omega(\rho_\Omega)$ with $\lambda \in \{0, 1, \ldots, K\}$ it realization. Here, Ω is the transmission mode with and ρ_Ω is the random transmission probability at each cell. By virtue of the assumed BPP network model, the probability mass function (PMF) of $\Lambda_\Omega(\rho_\Omega)$ is given as [12]

$$f_{\Lambda_\Omega(\rho_\Omega)}(\lambda; \rho_\Omega) = \binom{K}{\lambda} \rho_\Omega^\lambda (1-\rho_\Omega)^{K-\lambda}. \quad (1)$$

2) Sum Interference Power with HD Transmission: A particular cell can only transmit in either the UL or the DL direction in HD mode. Considering independent UL and DL traffic, the HD transmission probability of a particular cell is given by $\rho_{HD} = \rho_{AP} + \rho_{UE} - \rho_{AP}\rho_{UE}$ [1]. The sum interference power with HD transmission is then readily given by $\zeta_{HD} = \sum_{k \in \Lambda_{HD}(\rho_{HD})} \zeta_k$, where ζ_k is the interference from a single random interferer.

3) Sum Interference Power with FD Transmission: The AP and the UE can both transmit simultaneously as long as there are available packets to transmit in both directions in the FD mode. Hence, the APs and the UEs resemble two independent sets of interferers with the respective transmission probabilities ρ_{AP} and ρ_{UE}. The sum interference in FD mode is therefore the sum of the interference contributions from each of these sets, i.e. $\zeta_{FD} = \zeta_{FD(AP)} + \zeta_{FD(UE)}$, where $\zeta_{FD(AP)} = \sum_{k \in \Lambda_{FD(AP)}(\rho_{AP})} \zeta_k$ and $\zeta_{FD(UE)} = \sum_{k \in \Lambda_{FD(UE)}(\rho_{UE})} \zeta_k$.

B. Ergodic Throughput Calculation

The Shannon rate $R(\gamma) = \log_2(1+\gamma)$ is assumed as a measure of the instantaneous throughput in this work, where γ is the instantaneous signal to interference plus noise ratio (SINR). Let ϕ denote the signal power from the desired transmitter at the considered receiver. Considering the transmission mode $\Omega \in \{FD, HD\}$, the instantaneous SINR can be expressed as $\gamma_\Omega = \frac{\phi}{\zeta_\Omega + N_0}$, where N_0 is the additive white Gaussian noise power.

In order to derive the ergodic TP, we can average the instantaneous TP over the distribution of the SINR as follows

$$R_\Omega = \mathbb{E}_{\gamma_\Omega}\left[\log_2(1+\gamma_\Omega)\right],$$

where the expectation operator over the distribution of the r.v. X is denoted by $\mathbb{E}_X[\cdot]$. This expectation requires a two-fold integration over the distributions of ϕ and ζ_Ω, and is not easy to evaluate directly. Using the moment generating functions (MGF) of the ϕ and ζ_Ω, a simpler expression for the ergodic TP involving a single integration can instead be obtained as follows [13]

$$R_\Omega = \frac{1}{\ln(2)} \int_0^\infty \frac{\mathcal{M}_{\zeta_\Omega}(s/N_0)\,(1-\mathcal{M}_\phi(s/N_0))}{s\exp(s)}\,\mathrm{d}s, \quad (2)$$

where $\mathcal{M}_{\zeta_\Omega}(s)$ and $\mathcal{M}_\phi(s)$ are the MGFs of ζ_Ω and ϕ respectively. Considering Gamma distributed fading with parameter m, the MGF of ϕ readily evaluates to $\mathcal{M}_\phi(s) = \left(1 + \frac{s\eta_0 p_0 \beta(d)}{m}\right)^{-m}$ [14]. The MGFs $\mathcal{M}_{\zeta_\Omega}(s)$ for $\Omega \in \{FD, HD\}$ have been derived in [10].

Throughput Gain of Full Duplex over Half Duplex

Finally, the TP gain of FD over HD transmission is given as

$$\xi = \frac{TP_{FD} - TP_{HD}}{TP_{HD}}, \quad (3)$$

where $TP_{HD} = \rho_{HD} R_{HD}$ and $TP_{FD} = (\rho_{AP} + \rho_{UE}) R_{FD}$ are the average TP at the reference cell with HD and FD transmission mode, respectively.

[1]Henceforth, we assume $\rho_{AP,k} = \rho_{AP}$ and $\rho_{UE,k} = \rho_{UE}\ \forall k$.

III. Preliminary Numerical Findings

Matlab® based Monte Carlo simulation results validating the analytical findings derived in Section II are presented in this Section. At least $100,000$ independent snapshots of each scenario are simulated to ensure statistical reliability. The following general simulation parameters are assumed: path loss exponent $\alpha = 3$, cell radius $R = 100$, transmit power $p_0 = 13$ dBm, reference path loss $\eta_0 = -38$ dB, gamma fading parameter $m = 2$ and desired AP-UE distance $d = 10$ m.

A. Impact of Traffic Asymmetry in FD System

In this section, we investigate the FD TP gain in a network setting with multiple interferers and with variable transmission probabilities ρ_{AP} and ρ_{UE}. The TP gain of FD over HD vs. ρ_{UE} with $K = 10$ potential interferers for different values of ρ_{AP} are presented in Figure 1. The numerical results are found to closely follow the derived analytical TP gains. FD transmission with practical wall loss values (around $0.5 - 10$ dB) results in an increase in the network ICI, leading to a drop in the TP gains with FD communication. For example, the maximum TP gain is more than halved with a 5 dB wall loss figure, compared to that of 20 dB - representing a relatively isolated cells. Hence, the promised TP gains with FD communication is found to be adversely affected by the impact of the increased network interference due to FD transmissions.

An interesting paradox is observed for the $\rho_{AP} = \rho_{UE}$ scenario. The ICI is reduced at low transmission probabilities (i.e. low ρ_{AP}). However, opportunities to exploit FD communication, which is enabled by overlapping channel access at both ends is also reduced; thereby resulting in the observed low TP gain. Our study further reveals that the TP gain of FD also reduces with increasing the network size K and decreasing the parameters R and α, though the corresponding results are not presented for the sake of brevity.

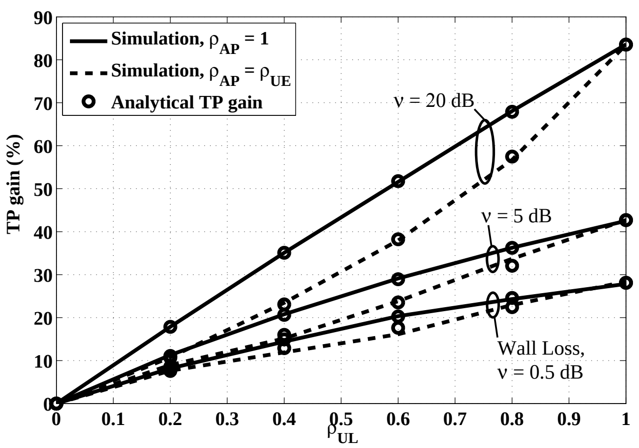

Fig. 1. Throughput gain of FD over HD communication in a system level setting with 10 potential interferers with various transmission probabilities ρ_{AP} and different wall loss values ν.

B. Impact of the Inter-cell Isolation (Wall Loss)

In this final study, the TP gain of FD over HD is presented as a function of the wall loss and the DL/UL ratio (i.e. $^{\rho_{AP}}/_{\rho_{UE}}$) in Figure 2. A full buffer traffic model is assumed at the AP ($\rho_{AP} = 1$). It is interesting to note that the TP gains in the range of the ideal '100%' gain is only observed with extremely high wall loss values. The TP gain trend is found to increase logarithmically with increasing wall loss, whereas it falls exponentially with the increasing asymmetry between the DL and UL traffic.

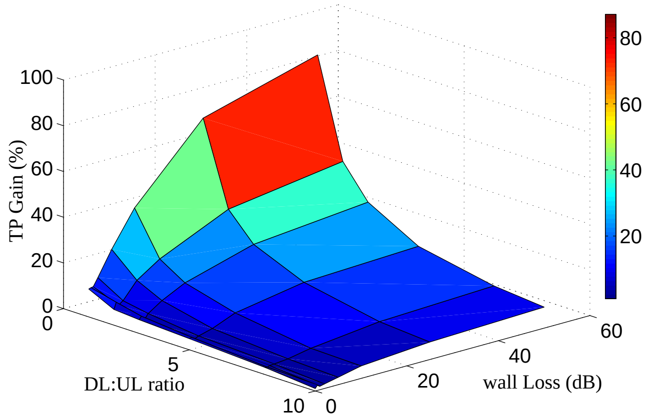

Fig. 2. TP gain of FD over HD vs. wall loss (dB) and DL/UL ratio for $\rho_{AP} = 1$.

IV. System-level Simulations

The system level performance evaluation of FD communication presented in this paper is carried out in the context of the 5G centimeter wave small cell concept as envisioned in [15] using 3GPP defined scenarios. Though originally designed for the HD TDD mode, the proposed 5G small cell concept is flexible enough to be readily translated to a FD scenario. The 5G frame structure for HD TDD mode as proposed in [15] is first briefly introduced for completeness of presentation.

A. The 5G Optimized Frame Structure

The 5G Optimized Frame Structure comprises of UL and DL transmissions having symmetric frame format with all nodes being time synchronized at the frame level. Each frame features a control part separated by a data part as presented in Figure 3. In the case of HD TDD mode, the data part of the frame is entirely allocated to either UL or DL, but not both; whereas both links are simultaneously active for the entire frame duration for FD mode. The first symbol of the data part is dedicated to the Demodulation Reference Sequences (DMRS) for enabling channel estimation at the receiver. This allows the possibility of estimating the interference covariance matrix (ICM), provided orthogonal reference sequences are used in neighbouring cells. Since the same frame format is used in both UL and DL, cross-link interference (e.g., AP-to-AP, or UE-to-UE) resulting from FD communication can also be efficiently estimated.

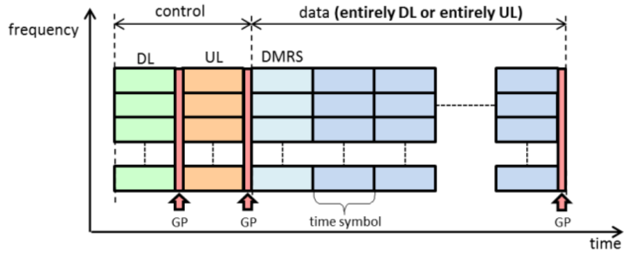

Fig. 3. The 5G Frame Structure proposed in [15] for HD TDD mode with support for accurate interference covariance matrix estimation.

B. Simulation Setup

The dual stripe scenario outlined by 3GPP for the study of local area small cells as detailed in [16] forms the basis of this investigation. 20 cells organized in a 10×2 dual stripe formulation are simulated with one active UE and one AP randomly placed in each 10 m $\times 10$ m cell. A Closed Subscriber Group (CSG) access mode is assumed.

Results are extracted from an event-based system level simulator. It includes a detailed modelling of the RLC and transport control protocol (TCP) layers, and a vertical radio resource management (RRM) layer that collects information from the physical (PHY), medium access control (MAC) and RLC layers to provide the scheduling parameters. Finally, the application layer generates File Transfer Protocol (FTP) traffic. The Internet Protocol (IP) layer is modelled as an overhead. The PHY and MAC layers also implement the HARQ retransmission mechanism and link and rank adaptation schemes.

The RLC mode is set to unacknowledged mode (UM). Furthermore, user datagram protocol (UDP) is used, which acts as a transparent layer. Two FTP traffic cases are studied: symmetric with equal offered load in DL and UL, and asymmetric where the amount of DL traffic is six times higher than that in UL. For each case, three levels of load are considered: low, medium and high, corresponding approximately to $25\%, 50\%$ and 75% channel occupation. 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). Each session is characterized by the packet size and the traffic arrival parameter, which is negative exponentially distributed.

We also study the packet delay, which is defined as the time, including buffering, between the generation of a packet and its successful reception at the application layer. Note that, packet delays cannot be readily captured from the analytical results presented in Section II, and usually require extensive system level evaluation to encompass the impact of the upper layer protocols.

The wall loss figure is a measure of the interference isolation among cells. Two different wall loss values, namely 5 dB corresponding to an indoor office scenario, and 25 dB corresponding to almost an isolated cell are considered. A block Rayleigh fading model is used as the fading channel model, whereas the path loss is given by the Winner II indoor office model. The details of the simulation scenarios/assumptions are outlined in Table I.

TABLE I
SIMULATION ASSUMPTIONS

Physical Layer Assumptions	
Sub Carrier Bandwidth	10 MHz
Carrier Frequency	3.5 GHz
Transmission Power	10 dBm
Receiver Noise Power	-155 dBm/Hz
MIMO Scheme	4×4 with fixed rank 2
System Assumptions	
System Bandwidth	200 MHz
Cell size	10×10 (m)
Nr. of Cells	20 (10×2)
Deployment Ratio	100%
Access Mode	Close Subscriber Group (CSG)
Data Generation	File Transfer Protocol
Path Loss Model	Winner II Indoor Office (A1)

V. SYSTEM LEVEL PERFORMANCE EVALUATION

Extensive 5G system level simulation results are presented in this Section. The TP performance of the FD communication is compared against a baseline HD scenario. Such a baseline provides an optimum performance in case of HD. It accommodates the traffic according to the UL and DL buffer size and the previous time slot allocation. For further information about the HD baseline, please refer to [8]. There are 100 simulation drops, with at least $1,000$ independent snapshots of each drop simulated to ensure statistical reliability. The path loss, shadowing and the location of devices remain constant at each snapshot, but change independently from one snapshot to another.

The detailed system level simulations exhibit some full duplex performance trends that are otherwise not captured in the analytical study. More specifically, in the analytical evaluations we assume the Shannon TP can be achieved at every resource slot, which implies that the achievable TP is virtually unbounded and a small but non zero TP can be achieved even at low SINR values. In practice, the maximum achievable TP is determined by the highest modulation and coding scheme (MCS) order, which is set to 256 QAM with $9/10$ coding rate. Alongside, a HARQ retransmission is triggered when the SINR target is not met, resulting in a zero TP for that specific time slot. The SINR target is defined according to a block error rate (BLER) target of 10%. Moreover, the Chase Combining model [17] is used.

A. *Performance in an Isolated Cell Scenario*

The cumulative density function (CDF) of the average TP per cell in each link direction (UL or DL) for different traffic load with symmetric traffic and a 25dB wall loss, corresponding to an almost completely interference isolated cell, are presented in Figure 4. The corresponding TP and delay gains of FD over HD transmission are further tabulated in Table II.

In general, we observe a performance trend similar to that presented in Section III, wherein the TP gains are improved with increasing traffic. For example, Figure 1 shows TP gains of approximately $15\%, 30\%$ and 55% corresponding to $25\%, 50\%$ and 75% offered load with symmetric traffic ($\rho_{AP} = \rho_{UE}$ and $\nu = 20$ dB curve), which is similar to the respective TP gains presented in Table II. The CDF curves in Figure 4 are mostly steep, indicating a low variation in the achieved TP. This is because the high interference isolation among the cells result in stable SINR conditions.

Detailed performance behaviour can be observed through the system level simulation results, which are otherwise obscured in the abstracted model used for analytical evaluation. For example, the gain in transmission time (or reduction in transmission delay) can be easily extracted from such a simulation campaign. Besides improving the TP, FD communication is also found to provide an improvement in the transmission time and thus reduce the transmission latency. As such, FD has the potential to be a key technology component of 5G systems which aims at significantly improving the latency over existing communication standards.

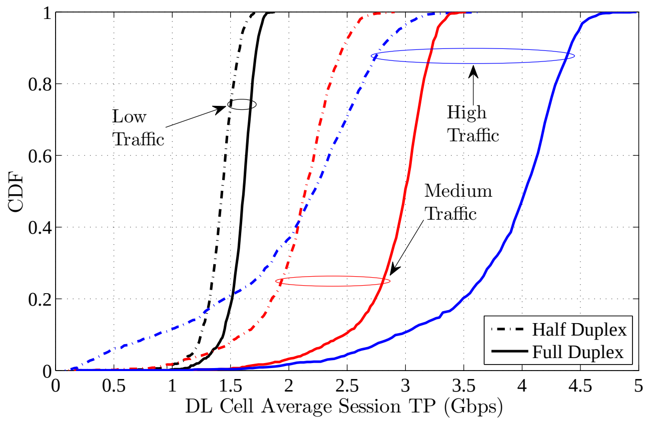

Fig. 4. CDF of the achievable TP with 5 dB wall loss for different traffic profile.

TABLE II
TP GAIN AND DELAY REDUCTION OF FD OVER HD COMMUNICATION IN ISOLATED CELL SCENARIO.

Traffic	TP gains			Delay Reductions		
	Sym.	Asymmetric		Sym.	Asymmetric	
		UL	DL		UL	DL
Low	12%	21%	3%	15%	20%	6%
Med	29%	51%	9%	32%	43%	17%
High	73%	111%	22%	63%	68%	34%

B. *Performance in an Indoor Office Scenario*

The average TP and transmission delay CDF for different traffic load with symmetric traffic are shown in Figure 5 and Figure 6 respectively. A wall loss value of 5dB is considered emulating the indoor office scenario, which is the default wall loss value in the Winner II indoor office A1 channel model. The average TP gains and reduction in transmission time of FD over HD transmission are further presented in Table III.

The differences in assumptions between the analytical studies and the system level investigation are well reflected in the findings presented in Figure 5. In fact, we observe that the tips of the CDF curves (i.e., maximum achieved TP) are almost the same with FD and HD communication, whereas they are expected to be close to double in theory. This is a consequence of the maximum MCS order capping the maximum achievable TP.

With low traffic, both FD and HD performance trends are expectedly similar. The low probability of overlapping transmission opportunities in the UL and DL directions results in a similarly low TP gain with FD transmissions; with the TP gain being lower than that in the isolated cell scenario due to the increased ICI in the indoor office setting.

Some interesting findings are observed with medium and high traffic scenarios, where approximately 50% and 75% of the time slots carry traffic respectively. The time-variation in traffic, and the relatively low wall loss value of 5dB results in a wide fluctuation in the received SINR from each time slot to the next. We may recall here that our considered link adaptation scheme chooses the transmission MCS based on the log-average of the previous five SINR values. Due to the high SINR fluctuation, this tend to induce an aggressive MCS selection in the case of HD transmissions. On the other hand, FD communication generates around 15% (for medium traffic) and 35% (for high traffic) more transmissions in the network, resulting in an overall increase in the ICI. Interestingly, such an increase in the ICI has a self-healing effect as it causes the nodes to be more conservative in selecting the MCS order, which subsequently translates more successful transmissions and hence less HARQ retransmissions. Such an impact is reflected in the larger-than-expected TP gain and delay reduction with FD over conventional HD communication. It also explains the shape of the CDF with HD communication, which indicates a very high variation in the achieved TP.

TABLE III
TP GAIN AND DELAY REDUCTION OF FD OVER HD COMMUNICATION IN INDOOR OFFICE SCENARIO.

Traffic	TP gains			Delay Reductions		
	Sym.	Asymmetric		Sym.	Asymmetric	
		UL	DL		UL	DL
Low	6%	10%	2%	12%	20%	4%
Med	40%	47%	19%	54%	65%	47%
High	103%	121%	43%	58%	75%	37%

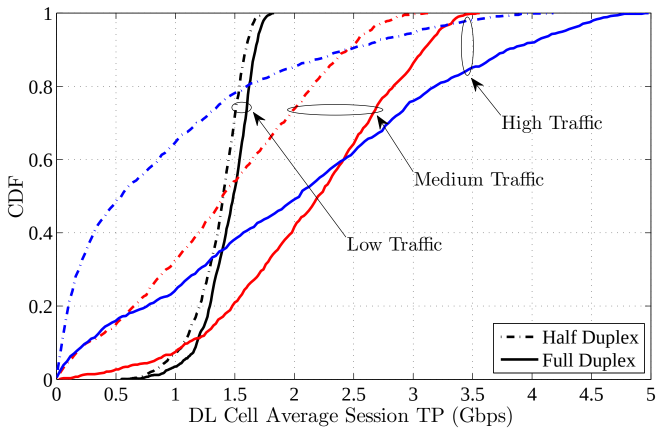

Fig. 5. CDF of the achievable TP with 5 dB wall loss for different traffic profile.

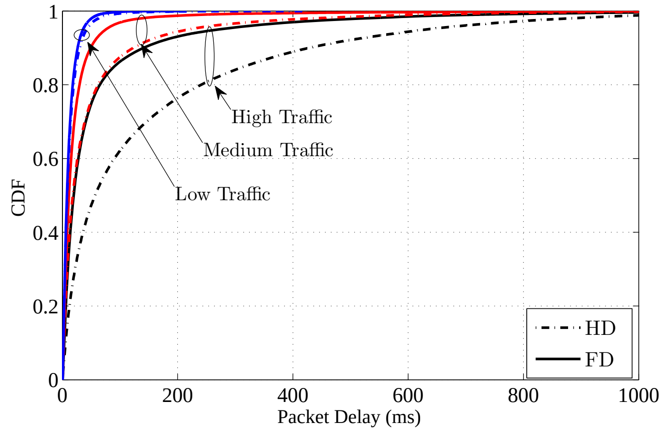

Fig. 6. CDF of the transmission delay with 5 dB wall loss for different traffic profiles.

VI. Conclusion

The potential TP gain of FD communication over conventional HD transmissions in a dense small cell scenario, as targeted by the upcoming 5G radio access technology is analytically derived, and cross validated through extensive Monte Carlo and system level simulations in this contribution. Ideal self interference cancellation is assumed in order to focus on the system-level performance. The derived analytical results provide with a rather simple model to evaluate the potential performance of FD communication in a system level setting without invoking lengthy system level simulations. On the other hand, insights into the performance gains with FD communications such as latency improvement figures are obtained only through the extensive system level simulations exercise.

The results reveal that the average TP of FD over HD is doubled only in the case of an isolated cell and full buffer traffic. The TP gains in a network setup depend on two critical factors; namely the interference coupling among the cells, and the availability of traffic at both ends in order to exploit the FD potential. The interference coupling among the cells is in turn a function of the wall loss, the path loss exponent, fading parameters and the user density. Contrary to the promised 100% gain, TP gains of around $40-50\%$ was observed considering realistic parameter values with a full buffer traffic model. In addition, the system level result reveals a delay reduction of around $50-60\%$. Thus, with careful network design, FD communication is found to exhibit the potential to be an important technology component for 5G dense small cell systems.

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