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On the Potential of Full Duplex Communication in 5G Small Cell Networks

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***Abstract*—Full duplex communication promises a 100% throughput gain by doubling the number of simultaneous transmissions. In a multi-cell scenario, increasing the number of simultaneous transmissions correspondingly increases the number of interference streams observed at a particular receiver. As such, the potential throughput gain may not be 100% as promised. In this study, we evaluate the performance of full duplex communication in a dense small cell scenario as targeted by future 5th Generation (5G) radio access technology under the ideal assumptions of a full buffer, always active traffic model and perfect self interference cancellation. Advanced interference suppression/cancellation receivers are featured as well. Full duplex communication is found to provide about $30-40\%$ mean throughput gain over half duplex transmissions for indoor scenarios, which provides an indication of the maximum throughput gains that can be achieved with full duplex communication in indoor scenarios under such idealized assumptions.**

***Index Terms*—5G, full duplex communication, small cells.**

I. Introduction

Simultaneous transmission and reception of overlapping signals in the same frequency channel had generally been assumed impossible in wireless communication because of the resulting self interference [1]. Instead, radio access technologies traditionally relied on duplexing of the time and frequency resources for accommodating uplink (UL) and downlink (DL) transmissions.

Time Division Duplexing (TDD) mode has significant advantages in terms of reduced costs, and the flexibility to cope with the imbalance between UL and DL traffic. This is particularly advantageous for small cells which has a low level of traffic aggregation. TDD also allows exploiting unpaired frequency bands, and utilizing the reciprocity of the wireless channel in reducing the signalling burden. However, it is necessary to insert guard periods in the frame structure to accommodate the on/off power transition between transmission and reception in TDD mode. Furthermore, TDD mode may lead to poor coverage performance since a continuous transmission mode cannot be maintained.

Frequency Division Duplex (FDD), on the other hand, allows simultaneous transmission and reception over orthogonal frequency channels, which overcomes the coverage limitations of TDD. Nonetheless, operating over different bands obviously reduces the spectrum efficiency and the flexibility in resource allocation between UL and DL. Further, the hardware complexity is significantly higher since oscillators operating over different carriers are required.

Full-duplex communications (FDC), i.e. simultaneous transmission and reception over the same band, have recently gained significant attention owning to the promise of delivering FDD performance within a single unpaired TDD channel [2]–[4]. FDC has historically been considered unrealistic for practical implementation because of the loopback interference from the transmission-end [1]. The high power leakage of the transmit signal on the receiver chain may force its Automatic Gain Control to set a high operational point which may blank the desired receive signal due to the limited dynamic range of practical transceivers.

Recent advances in self-interference cancellation in both analog and digital domain allow overcoming the practical limitations of FDC with viable costs [2]. In that respect, FDC has the potential of becoming a significant breakthrough in the design of a novel 5G radio access technology. Nonetheless, the promise of a 100% throughput (TP) gain with respect to traditional half duplex transmission may be jeopardized by a number of factors. The residual self-interference may still negatively affect the dynamic range of the receiver and hence the possibility of recovering low power signals [3]. Furthermore, the presence of simultaneously active links between access points (APs) and user equipments (UEs) in neighbor cells also increases the interference footprint in the network, thus limiting the potential network TP gains.

The performance of FDC in a dense small cell network as targeted by the upcoming 5G radio access technology is evaluated in this paper through system level simulations involving 3GPP defined scenarios [5]. Advanced interference suppression receivers are also considered in this evaluation alongside the conventional interference unaware types. The main goal of this contribution is to obtain an insight on the potential TP gain with FDC in dense small cell networks.

The remainder of this paper is organized as follows: The envisioned 5G small cell concept is briefly introduced in Section II, followed by a presentation of the considered system and signal model in Section III. Details of the studied receiver types, and an outline the physical layer assumptions and simulation setup are discussed in Sections IV and V respectively. Finally, performance evaluation results are presented in Section VI, followed by concluding remarks in Section VII.

Notations: Throughout this paper, matrices and vectors are respectively denoted by the boldface symbols $\mathbf{H}$ (capital) and $\mathbf{h}$ (small letter). $\mathbf{I}$ denotes the identity matrix, while $diag(\mathbf{H})$ represents a diagonal matrix with the diagonal elements matching those of $\mathbf{H}$. $\mathbb{E}[\cdot]$ and $(\cdot)^H$ are respectively the expectation and the hermitian operator.

II. The 5G Optimized Frame Structure

The performance evaluation of FDC presented in this paper is carried out in the context of the 5G centimeter wave small cell concept envisioned in [6]. Though originally designed for the half duplex TDD mode, the proposed 5G small cell concept is flexible enough to be readily translated to a FDC scenario. Advanced interference rejection combining (IRC) receivers, which is a key component of the envisioned 5G system concept, are notably featured in this investigation. The 5G frame structure for half duplex TDD mode with built-in support for advanced receivers as proposed in [6] is briefly discussed in this Section for completeness of presentation.

Uplink and DL transmissions have symmetric frame format with all nodes being time synchronized at the frame level. Each frame features a control part time separated by a data part as presented in Fig. 1. In the case of half duplex TDD mode, the data part of the frame is entirely allocated to either UL or DL, but not both; while both links are simultaneously active for the entire frame duration for FDC 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 interfering channels from neighbouring cells, provided orthogonal reference sequences (e.g., in the code domain) are used. Note that, since the same frame format is used in both UL and DL, cross-link channels (e.g., AP-to-AP, or UE-to-UE) can also be estimated.

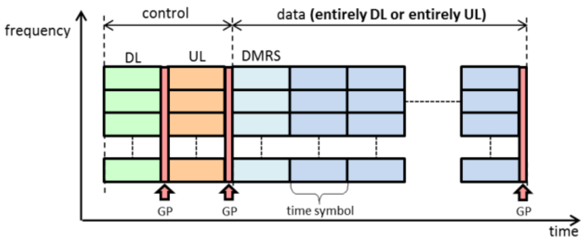

Fig. 1. The 5G Frame Structure proposed in [6] for half duplex TDD mode with support for accurate interference covariance matrix estimation.

III. Signal Model

The received signal model at a generic receiver as depicted in Fig. 2 is presented in this section. Let us consider a small cell local area network having L active cells sharing a given time-frequency slot, each having a single active UE. The AP and the active UE in cell l is assumed to have N_l and M_l antennas respectively. The transmitter-receiver pair in cell l communicates by transmitting d_l streams, with $1 \leq d_l \leq \min(M_l, N_l)$ through a d_l-column linear unitary precoding matrix $\mathbf{U}_l$. The set of all active cells is denoted by $\mathcal{L} = \{1, 2, \ldots, L\}$. Note that, the AP and the UE transmit powers are the same due to the considered small cell scenario.

Let us define $\Pi = \{AP, UE\}$ as the set of the node types (i.e., the AP or the UE). Assuming a generic multicarrier system, e.g., Orthogonal Frequency Division Multiplexing (OFDM), the received signal at node $\pi \in \Pi$ of cell l in a generic frequency subcarrier can be expressed as[1]

$$\mathbf{y}_l^{\pi} = \underbrace{\sqrt{\rho_l}\mathbf{H}_{ll}\mathbf{U}_l^{\Pi\backslash\pi}\mathbf{x}_l^{\Pi\backslash\pi}}_{\text{desired signal}} + \underbrace{\sum_{k\in\Phi}\sqrt{\zeta_{lk}}\mathbf{F}_{lk}\mathbf{U}_k^{AP}\mathbf{x}_k^{AP}}_{\text{sum DL interference}} + \underbrace{\sum_{k\in\Psi}\sqrt{\xi_{lk}}\mathbf{G}_{lk}\mathbf{U}_k^{UE}\mathbf{x}_k^{UE}}_{\text{sum UL interference}} + \underbrace{\mathbf{z}_{self}}_{\text{Self Interference}} + \mathbf{z}_l^{\pi}, \quad (1)$$

where $\Pi\backslash\pi$ indicates the AP if π denotes the UE, and vice versa. The path loss and the fading channel matrix between the desired transmitter and the receiver in cell l are respectively given by ρ_l and $\mathbf{H}_{ll}$, while $\mathbf{x}_l$ denotes the d_l-dimensional desired transmitted symbol. The set of all interfering APs are denoted by Φ, with ζ_{lk} and $\mathbf{F}_{lk}$ respectively representing the path loss and the fading channel matrix at the intended receiver from an interfering AP in cell k. Similarly, Ψ is the set of all interfering UEs, while ξ_{lk} and $\mathbf{G}_{lk}$ respectively represent the path loss and the fading channel matrix at the intended receiver from an interfering UE in cell k. The path losses are normalized by the noise power, and are calculated using the Winner II path loss model for indoor office scenario as defined in [5].

1) Full Duplex Transmission: In a full duplex scenario involving simultaneous transmissions by both the AP and the UE, interference is perceived from all other APs as well as all other UEs in the case of a fully loaded network. Thereby, the sets Φ and Ψ contain all possible interferers in $\mathcal{L}$, i.e. $\Phi = \Psi = \mathcal{L}\backslash l$. Furthermore, the simultaneous transmission and reception of FDC introduces an additional (self) interference source labelled as $\mathbf{z}_{self}$ in Eq. (1), which results from the loopback interference of the outgoing transmission. Typically the transmitted signal is in the range of 100 dB stronger than the desired received signal, which is an indication of the level of isolation required between the two simultaneous communication directions [2].

2) Half Duplex Transmission: In the case of the baseline half duplex transmission, each cell independently decides its transmission direction at each frame [6]. The interference source from cell k at a particular transmission slot is either the AP or the UE, but not both of them simultaneously. Thus, the interferer sets Φ and Ψ for the half duplex scenario are mutually exclusive sets (i.e. $\Phi \cap \Psi = \varnothing$) such that $\Phi \cup \Psi = \mathcal{L}\backslash l$. Note that, $\mathbf{z}_{self} = 0$ for this case.

The resulting network has in total $K = \sum_l d_l$ simultaneously transmitted information streams. The desired information stream j at a particular receiver l can be generically represented by conveniently reorganizing Eq. (1) as

$$\mathbf{y}_{j,l} = \underbrace{\mathbf{h}_D x_D}_{\text{desired signal}} + \underbrace{\mathbf{H}_{\chi}\mathbf{x}_{\chi} + \mathbf{z}}_{\text{total interference plus noise (incl. potential self interf.)}}, \quad (2)$$

[1]Note, the subcarrier index is omitted for the ease of presentation.

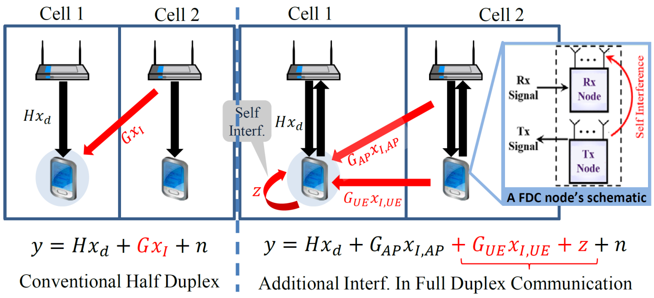

Fig. 2. Schematic diagram of the considered Full Duplex System Model.

where $\mathbf{h}_D$ and x_D are the equivalent channel for the desired stream and the desired transmitted symbol respectively. $\mathbf{H}_\chi$ is a $(K-1)$ column concatenated interference signal which includes the inter-stream interference (ISI) (i.e. the interference generated from other streams of the desired transmitter) as well as the inter-cell interference (ICI) signal, while $\mathbf{x}_\chi$. is the corresponding interference symbol vector.

IV. Receiver Model

Recent results have shown that the use of IRC, and IRC with successive interference cancellation (IRC-SIC) receivers can significantly boost the network throughput (TP) performance in dense small cell scenarios, and are foreseen to be a key feature of the future 5G system [7], [8]. Therefore, advanced receivers are considered alongside the conventional interference-unaware Maximal Ratio Combining (MRC) receiver in this performance evaluation study. The considered receiver models are briefly revised in this Section.

A. Maximal Ratio Combining receiver

The MRC receiver aligns the received signal at each antenna element such that the desired signal strength is maximized. The MRC receiver has a simpler architecture compared to the IRC or the IRC-SIC receiver and does not require estimating the exact interference signature $\mathbf{H}_\chi$ [9]. The resultant signal to interference plus noise ratio (SINR) for the desired stream j of receiver l can be expressed as

$$\gamma_{j,l|MRC} = \mathbf{h}_D^H \left(\mathbf{R}_{\chi|MRC} + \mathbf{I}\right)^{-1} \mathbf{h}_D, \tag{3}$$

where $\mathbf{R}_{\chi|MRC} = diag\left(\mathbf{H}_\chi \mathbf{H}_\chi^H\right)$ contains the interference plus noise power per receive antenna as the diagonal elements. It is reasonably assumed that the interference plus noise power per receive antenna can be accurately estimated.

B. Interference Rejection Combining receiver

The IRC receiver is based on the minimum mean square error criterion, and requires estimating the interference covariance matrix (ICM) of the interference signal $\mathbf{H}_\chi$. The provision for DMRS symbol in the envisioned 5G frame format is specifically designed to facilitate an accurate estimation of the interfering channels $\mathbf{H}_\chi$. The ICM of $\mathbf{H}_\chi$, defined as $\mathbf{R}_{\chi|IRC} = \mathbb{E}\left[\mathbf{H}_\chi \mathbf{H}_\chi^H\right]$, can then be readily approximated as $\mathbf{R}_{\chi|IRC} \approx \mathbf{H}_\chi \mathbf{H}_\chi^H$ [7]. The post-IRC SINR at the j^{th} stream of the l^{th} cell is thereby given as [9]

$$\gamma_{j,l|IRC} = \mathbf{h}_D^H \left(\mathbf{R}_{\chi|IRC} + \mathbf{I}\right)^{-1} \mathbf{h}_D. \tag{4}$$

C. IRC with Inter-Stream Interference Cancellation

Interference cancellation (IC) is the ability of a receiver to decode an interference signal, subtract it from the received signal, and extract the desired signal from the residue. In practice, decoding the interference signals require signalling the necessary control information of the interfering cells to the interfered receiver [8]. Such control information is readily available for the ISI signals, but not so for the ICI signals due to the increased complexity and overhead associated with the latter. Therefore, to incorporate practical interference decoding and cancellation constraints, we limit the IC paradigm to the ISI signals only, where the IRC receiver is used to decode each successive stage of IC process (termed as IRC-SIC).

Due to the considered inter-stream IC paradigm, the desired signal for the j^{th} stream does not experience any interference generated by the streams $1, 2, \ldots, (j-1)$ from its own transmitter, but the ICI signals remain. The expression for the resulting post IRC-SIC SINR at the j^{th} stream of the l^{th} cell is similar to that given by Eq. (4), where $\mathbf{H}_\chi$ now represents a $(K-j)$-column matrix consisting of the ICI and the *yet-to-be decoded* $(d_l - j)$ ISI signals.

V. Simulation Setup

This paper investigates the potential of FDC in an envisioned 5G small cell system with an extensive system level evaluation using 3GPP defined scenario. The simulation setup and the physical layer assumptions are detailed in this section.

A. Simulation Setup

The dual stripe scenario outlined by 3GPP for the study of local area small cells as detailed in [5] is used in this study. For simplicity, only one floor is simulated with one active UE and one AP randomly placed in each 10 m $\times$10 m office. A Closed Subscriber Group (CSG) access mode is assumed, i.e. the UE can only connect to the AP in the same office, but not to any of the neighbour's APs. A total of 20 cells organized in a 10×2 dual stripe formulation is simulated.

The wall loss figure is a reflection of the interference isolation among cells. Different wall loss values, including the standard 0.5 and 5 dB corresponding to an open hall and an indoor office scenario [5], are considered in this study, In order to investigate the TP gain with FDC for different level of interference isolation among the cells, different wall loss values are considered in this study. These include the standard wall loss figures of 0.5 and 5 dB corresponding to an open hall and an indoor office scenario [5].

B. Physical Layer Assumptions

We assume ideal estimation of the desired and the interfering channel based on the aforementioned reference DMRS. A fixed rank is considered for all the cells, i.e. $d_l = d \, \forall l \in \mathcal{L}$. A full buffer traffic model where all cells are always active is assumed to provide the most favorable conditions for FDC. An uniform linear antenna arrays with four elements separated by half a wavelength spacing at all the nodes, i.e. $M_l = N_l = 4 \forall l$ is considered. For the sake of uniformity between the different scenarios and the receiver types, we assume a power normalized identity precoder matrix in this work, i.e. the j^{th} stream is transmitted through the j^{th} antenna element. A block Rayleigh fading model is used as the fading channel model, while the path loss in given by the Winner II indoor office model [5]. The details of the simulation scenarios/assumptions are outlined in Table I.

Throughput Calculation: The Shannon rate is assumed achievable at all SINRs in any resource slot; and the interference experienced at a particular receiver is considered to be Gaussian. The message intended for different streams at a given receiver are assumed to be uncorrelated, and decoded independently. Correspondingly, the achievable physical layer TP at cell l is given by $R_l = \sum_{j=1}^{d_j} \log_2(1 + \gamma_{j,l})$. Note, the TP per cell for FDC is the sum of the UL and the DL TP.

The overheads resulting from the control part of the frame and the upper layer protocols are not accounted for in the TP calculation, while an ideal self interference cancellation is assumed for FDC mode, i.e. $\mathbf{z}_{self} = \mathbf{0}$. Such assumptions provide an indication of the maximum ideal TP gain. Moreover, such a simplifying abstraction allows us to single out the potential TP gain of FDC in interference limited scenarios.

TABLE I
SIMULATION ASSUMPTIONS

Physical Layer Assumptions	
Sub Carrier Bandwidth	10 MHz
Carrier Frequency	3.5 GHz
Transmission Power	13 dBm
Receiver Noise Power	-160 dBm/Hz
MIMO Scheme	4×4 with fixed rank 2
System Assumptions	
Cell size	10×10 (m)
Nr. of Cells	20 (10×2)
Deployment Ratio	100%
Access Mode	Close Subscriber Group (CSG)
Data Generation	Full Buffer Traffic
Path Loss Model	Winner II Indoor Office (A1)

VI. NUMERICAL RESULTS

Matlab® based system level simulation results are presented in this Section. The TP performance of the FDC is compared against a baseline half duplex scenario. At least 5000 independent snapshots of each scenario are 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. All the nodes are assumed to be perfectly synchronized in time.

A. Impact of the Receiver Type

The cumulative density function (CDF) of the achievable TP per cell with the different receiver types are presented in Figs. 3 and 4 for wall loss of 0.5 dB and 5 dB respectively. Alongside, the absolute TP performance of FDC and the gain over half duplex transmission for the outage (5%-ile), median and peak (95%-ile) TP performance are shown in Table II. In general, though the MRC receiver has the least TP performance among all three considered receiver types, it displays the highest TP gain with FDC. Full duplex is also found to boost the outage and the peak TP more than the median TP performance.

Advanced receivers have the potential to cancel/suppress some of the interfering signals. This is manifested in their significantly better TP performance over the interference unaware MRC receiver. However, the interference cancellation/suppression capabilities result in a non-linear behaviour of the post-processed SINR with respect to the number of interference streams [10], i.e. increasing the number of interference streams does not lead to a proportional decrease in the SINR unlike the MRC receiver. As a result, the impact of doubling the number of interference streams in FDC compared to a half duplex scenario is more pronounced for the advanced receivers compared to the MRC receiver, as demonstrated by the relatively lower TP gain for the former case.

The wall loss values of 0.5 and 5 dB correspond to an open hall (e.g., airport, shopping mall etc.) and an indoor office scenario respectively. Comparing Figs. 3 and 4, the TP gain is found to improve with increasing wall loss value irrespective of the receiver type. Intuitively, this indicates that a higher interference isolation among the cells is conducive for FDC. The impact of the wall loss figure on the TP gain with FDC is further investigated next.

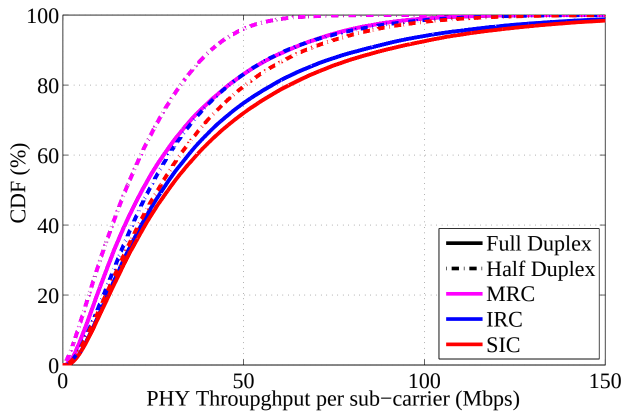

Fig. 3. CDF of the achievable TP per cell with 0.5 dB wall loss for different receiver types.

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

In this final subsection, the TP gain of FDC over half duplex communication is presented as a function of the wall loss in Fig. 5. A higher wall loss indicates a higher interference isolation among the cells, and hence a higher expected TP gain with FDC. 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 figures of 25 dB or

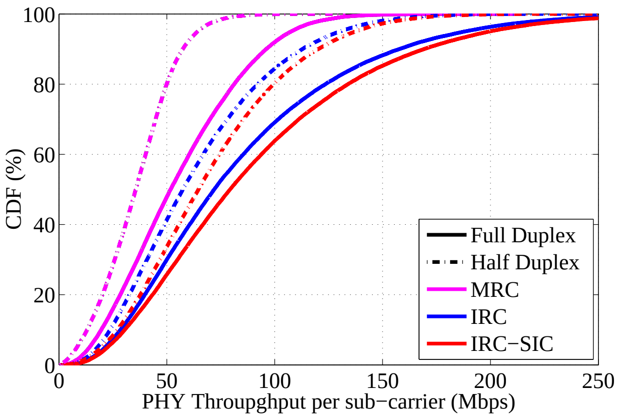

Fig. 4. CDF of the achievable TP per cell with 5 dB wall loss for different receiver types.

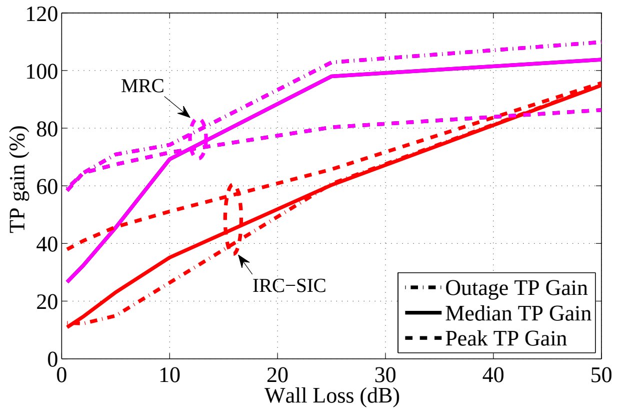

Fig. 5. Per cell TP gain of FDC over half duplex vs. wall loss (dB) for difference receiver types, rank = 2.

TABLE II
ABSOLUTE TP WITH FDC AND THE GAIN OVER HALF DUPLEX.

		0.5 dB Wall Loss		5 dB Wall Loss	
Receiver	Percentile	FDC TP	TP Gain	FDC TP	TP Gain
MRC	5%	4.0	59%	14.2	71%
	50%	22.0	26%	51.9	46%
	95%	76.2	59%	107.8	67%
IRC	5%	5.6	15%	21.4	22%
	50%	27.6	16%	72.2	26%
	95%	106.0	37%	188.6	45%
IRC-SIC	5%	5.7	14%	22.7	16%
	50%	29.2	11%	79.5	23%
	95%	114.1	38%	200.7	45%

more. The TP gain trend of IRC receivers is found to be similar to that of IRC-SIC receiver, and is therefore not shown in Fig. 5.

Advanced receivers are found to demonstrate a higher peak TP gain with FDC compared to the outage or the median TP gain, while generally the opposite trend is observed for the case of MRC receivers. Finally, the slightly more than 100% TP gain of MRC receivers for high wall loss figures is a ramification of diversity combining gain (more specifically the maximum ratio combining gain) accorded by the fact that the number of receive antennas is greater than the transmission rank [9]. Though not shown here, the TP gain is limited to 100% for a rank 4 transmission (with 4 receive antennas), which has a much reduced diversity combining gain.

Finally, it must be reiterated that the advanced receivers provide significantly better TP performance compared to MRC receiver for FDC as well as half duplex transmissions.

VII. CONCLUSION

The performance of full duplex communication in a dense network of small cells as targeted by the upcoming 5G radio access technology is evaluated and compared against the conventional half duplex transmission in this contribution. Both, interference unaware and interference suppression receivers are considered. The results have shown that FDC delivers a mean TP gain of around 30 – 40% over half duplex transmissions for indoor scenarios with full buffer traffic model, which is an indication of the maximum possible TP gain with FDC under such ideal assumptions. The 'promised 100% TP gain of FDC' is only observed when the cells are isolated by extremely high wall loss figures. Our investigations highlight that, the additional interference generated by doubling the number of transmitting nodes in a FDC scenario should not be readily neglected. In fact, it has a strong impact on the TP gain of FDC over half duplex communication. Moreover, the TP gain with advanced interference suppression/cancellation receivers, which are likely to be a key technology component in the future 5G system, is found to be different from that with conventional interference unaware receivers.

As part of the future work, we plan to extend our investigation of FDC in future 5G systems by considering realistic constraints such as asymmetric UL/DL traffic pattern, practical dynamic range of self interference cancellation and limited dynamic range of transceiver operations.

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