Full and Half Duplex-Switching Policy for Cellular Networks under Uplink Degradation Constraint

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***Abstract*—Full-duplex (FD) is a principle in which a transceiver can receive and transmit on the same time-frequency radio resource. Assuming perfect self-interference cancellation (self-IC), FD can potentially double the spectral efficiency (SE) of a given point-to-point communication. However in cellular networks, we may be far from this upper bound due to base stations (BSs) and users interference. In particular, even if the overall SE is improved, the uplink (UL) performance is degraded compared to a traditional half-duplex (HD) system. In this paper, we propose and evaluate a new duplex-switching (DS) policy in which BSs can adopt FD- or HD-mode according to the position of their scheduled users. This system is analyzed using stochastic geometry in terms of average SE (ASE) and signal-to-interference-plus-noise ratio (SINR). The proposed scheme allows to trade-off the downlink (DL) for the UL performance when comparing to a FD scenario. In terms of cell performance (UL+DL), our DS policy even outperform both HD and FD systems when the parameters are optimized.**

***Index Terms*—5G; Duplex-Switching; Full-Duplex; Stochastic Geometry; User Pairing**

I. Introduction

Designing, deploying and managing next-generation wireless networks is a highly constrained problem due to the existence of a limited and scarce available frequency-domain spectrum. The latter is a great issue, firstly, because there is a continuously increasing number of devices entering mobile networks and, secondly, due to a growing demand for greater data rates. Currently, new physical layer techniques allow to improve the spectral efficiency (SE). Some main examples are massive multiple-input multiple-output (MIMO), 3D beamforming and full-duplex (FD). But, these also raise new questions in terms of radio resource management.

Regarding FD, this principle arises after being long-held as impractical, as it was considered generally not possible for radios to simultaneously receive and transmit on the same frequency band because of the self-interference that results [1]. But recent studies prove that self-interference cancellation (self-IC) techniques are actually getting to that point of enabling true in-band FD systems to become practical in real world environments [2]–[4]. FD implementation may be considered as a huge problem solver, as it could theoretically double the average SE (ASE) of a certain transmission link.

However, in a cellular context, transmissions are interfered by co-channel interference coming from either base stations (BSs) or users equipment (UEs) employing the same radio resource. As a consequence, even if the overall network performance is improved with FD, uplink (UL) SE is degraded. In this paper, we propose a new duplex-switching (DS) policy, in which BSs can adopt FD- or HD-mode as a function of the position of their scheduled users.

A. Related Works

Recently, several papers have studied the performance of FD cellular networks using the tools of stochastic geometry. For example, authors in [5], consider a model in which BSs work under FD, whereas users under HD. Stochastic geometry is used to derive analytic expressions for the average data rates. Additionally a sub-optimal resource allocation algorithm based on proportional fairness is proposed. In [6] the impact of self-interference on the downlink (DL) performance in small-cell deployments is analyzed. Here, users and BSs operate under FD. Results show that the ASE critically depends on self-IC values. However the UL degradation problem is not highlighted in these papers.

A set of papers considers hybrid wireless networks in which FD and HD coexist, either to account for heterogeneous equipment capabilities or as a means to mitigate interference. Authors of [7] consider a multi-tier cellular network, in which access points are either FD or HD capable. There is however no DS policy and only DL performance is studied. Reference [8] studies an heterogeneous duplexing ad-hoc network (radios have both HD and FD capabilities) and uses the idea of selecting FD- or HD-mode based on the distance to the receiver and the self-IC performance. In [9], users in an heterogeneous network decide the duplex-mode based on the received power from their serving BSs. The SINR and SE are analyzed for both DL and UL by using inhomogeneous Poisson point process (PPP) tools. It is shown that the network sum data rate can be improved with respect to both FD- and HD-systems by adopting a hybrid network scheme. Inspired by the idea of choosing the duplex-mode regarding the received power from serving BSs, we build upon this work a novel DS policy based on two thresholds that aim to improve the UL performance, without degrading too much the DL when compared to a standard FD system. Reference [10] proposes a joint UL and DL power control scheme and the notion of FD reuse factor to mitigate interference. However, only the UL is studied and the model neglects the interference created by users. Finally, authors in [11] propose to partly overlap UL and DL bandwidths by using adapted pulse-shaping and matched filtering. Only a specific value of the overlap factor allows an UL improvement. However, the performance is very sensitive to this optimal value and a slight deviation leads to significant performance losses on the UL.

B. Contributions

Our contributions in this paper are the following:

- We propose a novel DS policy for cellular networks, where BSs can adopt either FD- or HD-mode. The choice is based on the position of the UL and DL scheduled users. If the distance between the UL user and its serving BS is less than some threshold and the distance between the UL and the DL user is greater than some other threshold, FD is activated at the BS. Otherwise HD is adopted. The goal is to allow FD only in good radio propagation conditions and low intra-cell interference.
- We model this stystem using the theory of stochastic geometry and we derive analytical expressions for the signal-to-interference-plus-noise ratio (SINR) distribution and the ASE. The scenarios where all BSs adopt either FD or HD are special cases and are denoted as "reference FD" and "reference HD" models for comparisons.
- We study the performance of our DS policy and the impact of the two introduced thresholds. We show that it is possible to trade-off the DL performance for an UL improvement. Parameters can be set in order to meet a maximum UL degradation constraint. In some special cases, we show that both UL and DL can be improved over the reference HD system. If a high UL degradation is acceptable, the DL performance can be enhanced with respect to the reference FD system.

The paper is organized as follows. In Section II the DS system is introduced. The analytical performance of the model is found in Section III. In Section IV numerical results are compared to the analytical expressions. Finally, Section V concludes the paper.

II. Duplex-switching System

A. System Model

We consider a cellular network composed of HD users and BSs that can choose whether to work under HD- or FD-mode. Thus, a UE can only receive or send information in each resource-block (RB). When a BS adopts the HD-mode it will simultaneously serve two of its users in an orthogonal manner, where the DL will take place in a RB and the UL in another without interfering between each other. On the other hand, when a BS adopts the FD-mode, in each time instant it can simultaneously serve one DL and one UL transmission in the same RB. Let us define $\daleth$ as the set of all RBs over the whole system bandwidth, W, during one radio frame. Then, for HD BSs $\daleth$ is partitioned in two subsets, such that $\daleth = \daleth_{\text{UL}} \cup \daleth_{\text{DL}}$, where UL and DL communications take place, respectively. While in a FD scenario, there is no need to differentiate between the latter subsets, as a RB can be used simultaneously for UL and DL.

BSs are placed following an homogeneous PPP Φ_b of spatial density λ_b, and the location of users follows an independent homogeneous PPP, Φ_u, of density λ_u. Round robin scheduling is considered and we assume that a UE is connected to its closest BS. Additionally, we assume full-buffer for every network element and that all users and BSs transmit at their maximum power capabilities. Furthermore, we consider small-scale Rayleigh fading with unit power between all the elements of the network and a path-loss exponent $\alpha > 2$.

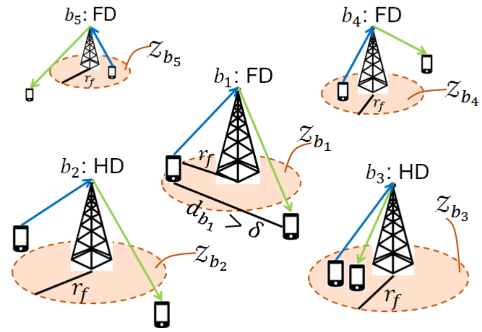

Fig. 1. Representation of cellular system based on the proposed DS policy.

For a given RB τ the configuration of the network can be characterized by the marked PPP $\Phi = \{x_{b_k}, m_{b_k}^{\text{DL}}, m_{b_k}^{\text{UL}}, s(m_{b_k}^{\text{DL}}, m_{b_k}^{\text{UL}})\} \in \mathbb{R}^2 \times \mathbb{R}^2 \cup \{\emptyset\} \times \mathbb{R}^2 \cup \{\emptyset\} \times \{0,1\}$, where $\emptyset$ is the empty set, i.e. no user is scheduled on this link. The set $\{x_{b_k}\}$ represents the locations of the BSs (Φ_b) and, $m_{b_k}^{\text{DL}}$ and $m_{b_k}^{\text{UL}}$ are independent marks depicting the position of the scheduled DL and UL users inside the area covered by BS $b_k \in \Phi_b$. Furthermore, $s(\cdot)$ is the DS function which is equal to 0 when BS b_k is operating in HD-mode and equal to 1 if it works in FD-mode.

To avoid any confusion and to improve readability, we will refer to $b_k \in \Phi_b$ and $u_j \in \Phi_u$ as elements of set Φ_b and Φ_u, respectively, and not as particular locations in $\mathbb{R}^2$. So, we define $\varphi = \{m_{b_k}^{\text{UL}}\}_{b_k \in \Phi_b}$ as the set of all active UL users in the network. Let us recall that $\varphi \subset \Phi_u$ is not necessarily an homogeneous PPP, as the position of a certain $u_j \in \varphi$ depends on the scheduling decision and location of the BS to which it is connected. Additionally, let us define point processes Φ_F and Φ_H as the sets of BSs operating in FD- and HD-mode, respectively. And, φ_F and φ_H as the set of UL users linked to FD- and HD-enabled BSs, correspondingly. Note that φ_F and φ_H are not homogeneous PPPs and are dependent on the processes Φ_F and Φ_H. Finally, we define $\mathcal{B}(u_j) \in \Phi_b$ as the function that returns the BS associated to UE $u_j \in \Phi_u$.

B. Duplex-switching Policy

We propose the following DS policy. Each BS b_k has a "FD zone" $\mathcal{Z}_{b_k}$. For tractability reasons, we will assume in this paper that $\mathcal{Z}_{b_k}$ is a disk of fixed radius, r_{b_k}, centered on b_k, i.e. $r_{b_k} = r_f$, $\forall b_k$. Then, $s(\cdot)$ is defined as:

$$s(m_{b_k}^{\text{DL}}, m_{b_k}^{\text{UL}}) = \begin{cases} 1, & \text{if } m_{b_k}^{\text{UL}} \in \mathcal{Z}_{b_k} \text{ and } d_{b_k} > \delta, \\ 0, & \text{otherwise}, \end{cases} \quad (1)$$

where d_{b_k} is the distance between $m_{b_k}^{\text{DL}}$ and $m_{b_k}^{\text{UL}}$, and δ is a network parameter. A representation of this model is depicted in Fig. 1.

From (1), we can firstly notice that the proposed policy adopts FD only when the UL user is at most r_f meters apart from its BS. Hence, the received signal power coming from an active user towards its linked FD BS is increased and, consequently, the UL SINR as well. Secondly, the policy enables FD links only when the UL user is at least δ meters away from the DL user in its same cell, allowing the reduction of the intra-cell interference and thus, providing higher DL SINR values. In addition, it is important to see that for a fixed δ, the probability of having a FD-enabled BS increases with r_f, as $\mathcal{Z}_{b_k}$ gets bigger and so the chances of having the scheduled UL user inside the FD zone increases as well. So, the DL performance is expected to be enhanced for greater r_f values, whereas the UL performance is favored for smaller r_f.

III. Analytical Performance Analysis

A. Preliminaries

In order to conduct performance evaluation, we require few assumptions and results. First, note that in general $||m_{b_0}^{\text{DL}} - x_{b_k}|| \gg ||x_{b_k} - m_{b_k}^{\text{UL}}||$, $\forall b_k \in \Phi_b \backslash b_0$. So, $||m_{b_0}^{\text{DL}} - m_{b_k}^{\text{UL}}|| \approx ||m_{b_0}^{\text{DL}} - x_{b_k}||$. We can thus make the following assumption.

Assumption 1. *Let $u_0 \in \Phi_u \backslash \varphi$ be a DL UE and $u_j \in \varphi$ an UL interferer. UE u_j is served by $\mathcal{B}(u_j)$ and located at $m_{\mathcal{B}(u_j)}^{UL}$. Then, the distance between u_0 and u_j can be approximated by the distance between u_0 and $\mathcal{B}(u_j)$, i.e.:*

$$D_{u_j,u_0} \approx D_{\mathcal{B}(u_j),u_0}, \tag{2}$$

where $D_{i,j}$ denotes the distance between network elements i and j.

Notice that (2) implies that φ forms an independent homogeneous PPP of density λ_b. Analog representations of Assumption 1 can be found in several related works, e.g. [7], [10]–[12].

Lemma 1. *With Assumption 1 and the DS policy in (1), the probability for a BS to be in FD-mode is:*

$$p(r_f, \delta) = \exp(-\pi\lambda_b\delta^2)(1 - \exp(-\pi\lambda_b r_f^2)). \tag{3}$$

Proof: The probability density function (PDF) of the random variable (RV) R, that describes the distance from a typical UE to its closest BS is given by $f_R(r) = 2\pi\lambda_b r e^{-\pi\lambda_b r^2}, \forall r > 0$. Thus, considering the DS policy in (1) and by evaluating the cumulative density function (CDF) and the complementary CDF of R with respect to r_f and δ, respectively, we obtain (3). ■

Let us notice that $p \to 1$ when $\delta = 0$ and $r_f \to \infty$, whereas $p \to 0$ either when $r_f = 0$ or when $\delta \to \infty$. With (3), it is possible to define:

$$\lambda_F(r_f, \delta) = p(r_f, \delta)\lambda_b, \tag{4}$$

$$\lambda_H(r_f, \delta) = (1 - p(r_f, \delta))\lambda_b, \tag{5}$$

which represent the spatial density of Φ_F and Φ_H, respectively. To allow the derivation of further closed-form equations, we present the following additional assumption.

Assumption 2. *φ_F and φ_H form independent homogeneous PPPs of densities λ_F and λ_H, respectively.*

Assumptions 1 and 2 are validated by simulations in Section IV.

B. Downlink SINR

1) FD-enabled BS: Consider a randomly chosen DL user, u_0, connected to $b_0 \in \Phi_F$. We define the instantaneous SINR at u_0 and RB τ as:

$$\gamma_\tau^{\text{DL-FD}} = \frac{P_b h_{u_0,b_0} R^{-\alpha}}{I_{F' \to u_0} + I_{H \to u_0} + \sigma^2}, \tag{6}$$

where

$$I_{F' \to u_0} = \sum_{b_k \in \Phi_F \backslash b_0} P_b h_{b_k,u_0} D_{b_k,u_0}^{-\alpha} + \underbrace{\sum_{u_j \in \varphi_F} P_u h_{u_j,u_0} D_{u_j,u_0}^{-\alpha}}_{I_{\varphi_F \to u_0}} \tag{7}$$

and $I_{H \to u_0}$ equal to:

$$\mathbb{1}_{[\tau \in \neg_{\text{DL}}]} \sum_{b_k \in \Phi_H} P_b h_{b_k,u_0} D_{b_k,u_0}^{-\alpha} + \mathbb{1}_{[\tau \in \neg_{\text{UL}}]} \sum_{u_j \in \varphi_H} P_u h_{u_j,u_0} D_{u_j,u_0}^{-\alpha} \tag{8}$$

In the previous expressions, P_b and P_u are the RB's transmission power for BSs and users, respectively (with the ratio between them defined as $\rho = P_u/P_b$), and $h_{i,j} \sim \exp(1)$ is the small-scale fading experienced from node i to node j. Thus, (7) is the interference generated by the FD BSs and their associated UL users towards u_0. In (7) and (8), $\mathbb{1}_{[\cdot]}$ is the indicator function which is defined for any element θ and set Θ as:

$$\mathbb{1}_{[\theta \in \Theta]} = \begin{cases} 1, & \text{if } \theta \in \Theta, \\ 0, & \text{otherwise.} \end{cases}$$

Hence, the interference coming from the HD elements ($I_{H \to u_0}$) depends on the random position of τ along W, resulting in either the interference towards u_0 generated by the HD BSs, or by their associated UL users.

Expressing the Laplace transform of a RV X as $\mathscr{L}_X(\cdot)$, we proceed to the following Theorem.

Theorem 1 (CDF of the DL SINR for a FD-enabled BS)**.** *Under Assumptions 1 and 2 the $\mathbb{P}(\gamma_\tau^{DL\text{-}FD} \leq T)$ is given by:*

$$\int_0^\infty f_R(r) \left[1 - \mathscr{L}_{I_{F' \to u_0}}(s_1) \mathscr{L}_{I_{H \to u_0}}(s_1) e^{-s_1\sigma^2}\right] dr, \tag{9}$$

where $s_1 = Tr^\alpha/P_b$, and $\mathscr{L}_{I_{F' \to u_0}}(\cdot)$ and $\mathscr{L}_{I_{H \to u_0}}(\cdot)$ are found on top of the next page in (20) and (21), respectively.

Proof: See Appendix A ■

2) HD-enabled BS: If $b_0 \in \Phi_H$, the instantaneous SINR at u_0 and RB τ is:

$$\gamma_\tau^{\text{DL-HD}} = \frac{P_b h_{u_0,b_0} R^{-\alpha}}{\underbrace{\sum_{b_k \in \Phi_H \backslash b_0} P_b h_{u_0,b_k} D_{u_0,b_k}^{-\alpha}}_{I_{\Phi_H \backslash b_0 \to u_0}} + I_{F \to u_0} + \sigma^2}, \tag{10}$$

$$\mathscr{L}_{I_{F'\to u_0}}(s_1) = \exp\left(-2\pi\lambda_F(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{y^\alpha + Tr^\alpha} y\,dy\right)\exp\left(-2\pi\lambda_F(r_f,\delta)\int_\delta^\infty \frac{\rho Tr^\alpha}{x^\alpha+\rho Tr^\alpha}x\,dx\right) \quad (20)$$

$$\mathscr{L}_{I_{H\to u_0}}(s_1) = \exp\left(-2\pi\lambda_H(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{2(y^\alpha + Tr^\alpha)} y\,dy\right)\exp\left(-2\pi\lambda_H(r_f,\delta)\int_0^\infty \frac{\rho Tr^\alpha}{2(x^\alpha+\rho Tr^\alpha)}x\,dx\right) \quad (21)$$

$$\mathscr{L}_{I_{\Phi_H\setminus b_0\to u_0}}(s_1) = \exp\left(-2\pi\lambda_H(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{y^\alpha + Tr^\alpha} y\,dy\right) \quad (22)$$

$$\mathscr{L}_{I_{F'\to b_0}}(s_2) = \exp\left(-2\pi\lambda_F(r_f,\delta)\int_0^\infty \frac{Tr^\alpha}{\rho y^\alpha + Tr^\alpha} y\,dy\right)\exp\left(-2\pi\lambda_F(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{x^\alpha+Tr^\alpha}x\,dx\right) \quad (23)$$

$$\mathscr{L}_{I_{H\to b_0}}(s_2) = \exp\left(-2\pi\lambda_H(r_f,\delta)\int_0^\infty \frac{Tr^\alpha}{2(\rho y^\alpha + Tr^\alpha)} y\,dy\right)\exp\left(-2\pi\lambda_H(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{2(x^\alpha+Tr^\alpha)}x\,dx\right) \quad (24)$$

$$\mathscr{L}_{I_{\varphi_H\setminus u_0\to b_0}}(s_2) = \exp\left(-2\pi\lambda_H(r_f,\delta)\int_r^\infty \frac{Tr^\alpha}{x^\alpha + Tr^\alpha} x\,dx\right) \quad (25)$$

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where

$$I_{F\to u_0} = I_{\varphi_F\to u_0} + \sum_{b_k\in\Phi_F} P_b h_{b_k,u_0} D_{b_k,u_0}^{-\alpha}. \quad (11)$$

Theorem 2 (CDF of the DL SINR for a HD-enabled BS)**.** *Under Assumptions 1 and 2 the $\mathbb{P}(\gamma_\tau^{\text{DL-HD}} \le T)$ is given by:*

$$\int_0^\infty f_R(r)\left[1-\mathscr{L}_{I_{F'\to u_0}}(s_1)\Big|_{\delta=0}\mathscr{L}_{I_{\Phi_H\setminus b_0\to u_0}}(s_1)e^{-s_1\sigma^2}\right]dr, \quad (12)$$

where $\mathscr{L}_{I_{\Phi_H\setminus b_0\to u_0}}(\cdot)$ is found in (22).

Proof: Similar to Theorem 1. ■

C. Uplink SINR

1) FD-enabled BS: Let us consider a randomly chosen BS, $b_0 \in \Phi_F$, linked to an UL user u_0. The instantaneous SINR at b_0 and RB τ is:

$$\gamma_\tau^{\text{UL-FD}} = \frac{P_u h_{b_0,u_0} R^{-\alpha}}{I_{F'\to b_0} + I_{H\to b_0} + \underbrace{\beta P_b}_{I_{\text{SI}}} + \sigma^2}, \quad (13)$$

where

$$I_{F'\to b_0} = \sum_{b_k\in\Phi_F\setminus b_0} P_b h_{b_0,b_k} D_{b_0,b_k}^{-\alpha} + \sum_{u_j\in\varphi_F\setminus u_0} P_u h_{b_0,u_j} D_{b_0,u_j}^{-\alpha}, \quad (14)$$

and $I_{H\to b_0}$ is equal to:

$$\mathbb{1}_{[\tau\in\urcorner_{\text{DL}}]}\sum_{b_k\in\Phi_H} P_b h_{b_0,b_k} D_{b_0,b_k}^{-\alpha} + \mathbb{1}_{[\tau\in\urcorner_{\text{UL}}]}\sum_{u_j\in\varphi_H} P_u h_{u_j,b_0} D_{u_j,b_0}^{-\alpha}, \quad (15)$$

In (13), $I_{F'\to b_0}$ represents the interference generated by other FD BSs and their associated UL users towards b_0, $I_{H\to b_0}$ is the interference generated by rather the HD BSs or their associated UL users towards b_0 and I_{SI} represents the residual self-interference (RSI) that depends on a constant $\beta \ge 0$ related to the self-IC technique used at the BS.

Theorem 3 (CDF of the UL SINR for a FD-enabled BS)**.** *Under Assumption 1 and 2 the $\mathbb{P}(\gamma_\tau^{\text{UL-FD}} \le T)$ is given by:*

$$\int_0^{r_f} \tilde{f}_R(r)\left[1-\mathscr{L}_{I_{F'\to b_0}}(s_2)\,\mathscr{L}_{I_{H\to b_0}}(s_2)\,e^{-s_2(\beta P_b+\sigma^2)}\right]dr, \quad (16)$$

where $s_2 = Tr^\alpha/P_u$, $\tilde{f}_R(r) = 2\pi\lambda_b r e^{-\pi\lambda_b r^2}/(1-e^{-\pi\lambda_b r_f^2})$, and $\mathscr{L}_{I_{F'\to b_0}}(\cdot)$ and $\mathscr{L}_{I_{H\to b_0}}(\cdot)$ are found in (23) and (24), respectively.

Proof: See Appendix B. ■

2) HD-enabled BS: If $b_0 \in \Phi_H$, the instantaneous SINR at b_0 and τ is:

$$\gamma_\tau^{\text{UL-HD}} = \frac{P_u h_{u_0,b_0} R^{-\alpha}}{\sum_{u_j\in\varphi_H\setminus u_0} P_u h_{u_j,b_0} D_{u_j,b_0}^{-\alpha} + I_{F\to b_0} + \sigma^2}, \quad (17)$$

where,

$$I_{F\to b_0} = \sum_{b_k\in\Phi_F} P_b h_{b_0,b_k} D_{b_0,b_k}^{-\alpha} + \sum_{u_j\in\varphi_F} P_u h_{b_0,u_j} D_{b_0,u_j}^{-\alpha}. \quad (18)$$

Theorem 4 (CDF of the UL SINR for a HD-enabled BS)**.** *Under Assumption 1 and 2 the $\mathbb{P}(\gamma_\tau^{\text{UL-HD}} \le T)$ is given by:*

$$\int_0^\infty f_R(r)\left[1-\mathscr{L}_{I_{F'\to b_0}}(s_2)\,\mathscr{L}_{I_{\varphi_H\setminus u_0\to b_0}}(s_2)\,e^{-s_2\sigma^2}\right]dr, \quad (19)$$

where $\mathscr{L}_{I_{\varphi_H\setminus u_0\to b_0}}(\cdot)$ is found in (25).

Proof: Similar to Theorem 2. ■

D. Reference Models

From the analysis of Sections III-B and III-C, we can derive as well the CDF expressions for a "reference FD" scheme in which all BSs work under FD and all users under HD, and also for a "reference HD" system in which both BSs and users are HD-enabled.

Corollary 1. *If we consider the case in which $\Phi_b = \Phi_F$ (hence, $\varphi = \varphi_F$ also holds), the network is only characterized* *by FD-enabled BSs, thus $\lambda_F = \lambda_b$. Then, the CDF of the DL SINR is given by:*

$$\int_0^\infty f_R(r) \left[1 - \mathscr{L}_{I_{F' \to u_0}}(s_1)\Big|_{\delta=0} e^{-s_1\sigma^2}\right] dr, \quad (26)$$

and the CDF of the UL SINR is given by:

$$\int_0^\infty f_R(r) \left[1 - \mathscr{L}_{I_{F' \to b_0}}(s_2)\, e^{-s_2(\beta P_b + \sigma^2)}\right] dr. \quad (27)$$

Proof: By considering $r_f \to \infty$ and $\delta = 0$, then $\lambda_H = 0$ and $\lambda_F = \lambda_b$. Hence, (9) becomes (26) and (16) becomes (27). ■

Corollary 2. *If we consider the case in which $\Phi_b = \Phi_H$ (hence, $\varphi = \varphi_H$ also holds), the network is only characterized by HD-enabled BSs, thus $\lambda_H = \lambda_b$. Then, the CDF of the DL SINR is given by:*

$$\int_0^\infty f_R(r) \left[1 - \mathscr{L}_{I_{\Phi_b \setminus b_0 \to u_0}}(s_1)\, e^{-s_1\sigma^2}\right] dr, \quad (28)$$

and the CDF of the UL SINR is given by:

$$\int_0^\infty f_R(r) \left[1 - \mathscr{L}_{I_{\varphi_H \setminus u_0 \to b_0}}(s_2)\, e^{-s_2\sigma^2}\right] dr, \quad (29)$$

Proof: By considering $r_f \to 0$ or $\delta \to \infty$, then $\lambda_H = \lambda_b$ and $\lambda_F = 0$. Hence, (12) becomes (28) and (19) becomes (29). ■

Finally, it is possible to recall that the proposed CDFs of the SINRs for the reference HD system are equivalent to the analytical equations found in [13] and [14], when the parameters of the different schemes are adjusted to match between each other.

E. Average Spectral Efficiency

We define the instantaneous SE ($\mathcal{S}$) achieved in the cell described by a FD BS b_k with two scheduled users in RB τ as:

$$\mathcal{S}_\tau^{\text{FD}}(b_k) = \log_2(1 + \gamma_\tau^{\text{DL-FD}}) + \log_2(1 + \gamma_\tau^{\text{UL-FD}}). \quad (30)$$

Whereas, if b_k is a HD BS, the instantaneous SE at RB τ is:

$$\mathcal{S}_\tau^{\text{HD}}(b_k) = \begin{cases} \log_2(1 + \gamma_\tau^{\text{UL-HD}}), & \text{if } \tau \in \daleth_{\text{UL}}, \\ \log_2(1 + \gamma_\tau^{\text{DL-HD}}), & \text{otherwise.} \end{cases} \quad (31)$$

Further, the overall ASE per cell ($\mathcal{A}_{\text{cell}}$) can be defined as the expected value of $\mathcal{S}$, where the average is taken over all RBs and the different SINR distributions. Then, we can write $\mathcal{A}_{\text{cell}}^{\text{FD}}$ as:

$$\mathbb{E}_{\gamma_\tau^{\text{DL-FD}}}\left[\log_2(1 + \gamma_\tau^{\text{DL-FD}})\right] + \mathbb{E}_{\gamma_\tau^{\text{UL-FD}}}\left[\log_2(1 + \gamma_\tau^{\text{UL-FD}})\right]. \quad (32)$$

Theorem 5 (ASE of a FD-enabled cell)**.** *The cell ASE is given by:*

$$\mathcal{A}_{cell}^{FD} = \mathcal{A}^{DL\text{-}FD} + \mathcal{A}^{UL\text{-}FD}, \quad (33)$$

where

$$\mathcal{A}^{\ell-FD} = \int_0^\infty \frac{1 - \mathbb{P}\left(\gamma_\tau^{\ell-FD} \le T\right)}{\ln(2)(1+T)} dT \quad (34)$$

and $\ell \in \{DL, UL\}$.

Proof: See Appendix C. ■

For the HD case, let us assume symmetric allocation between UL and DL. Then a RB is UL with probability (w.p.) 1/2 and DL w.p. 1/2. So after averaging over all RBs, we have:

$$\frac{1}{2}\log_2(1 + \gamma_\tau^{\text{DL-HD}}) + \frac{1}{2}\log_2(1 + \gamma_\tau^{\text{UL-HD}}). \quad (35)$$

Thus, $\mathcal{A}_{\text{cell}}^{\text{HD}}$ is:

$$\frac{1}{2}\mathbb{E}_{\gamma_\tau^{\text{DL-HD}}}\left[\log_2(1+\gamma_\tau^{\text{DL-HD}})\right] + \frac{1}{2}\mathbb{E}_{\gamma_\tau^{\text{UL-HD}}}\left[\log_2(1+\gamma_\tau^{\text{UL-HD}})\right]. \quad (36)$$

Theorem 6 (ASE of a HD-enabled cell)**.** *The cell ASE is given by:*

$$\mathcal{A}_{cell}^{HD} = \mathcal{A}^{DL\text{-}HD} + \mathcal{A}^{UL\text{-}HD}, \quad (37)$$

where

$$\mathcal{A}^{\ell-HD} = \int_0^\infty \frac{1 - \mathbb{P}\left(\gamma_\tau^{\ell-HD} \le T\right)}{2\ln(2)(1+T)} dT. \quad (38)$$

Proof: Similar to Theorem 5. ■

With the previous results, we can now write the ASE achieved by a random cell in the proposed DS environment as:

$$\mathcal{A}_{\text{cell}} = p(r_f, \delta)\mathcal{A}_{\text{cell}}^{\text{FD}} + (1 - p(r_f, \delta))\mathcal{A}_{\text{cell}}^{\text{HD}}. \quad (39)$$

IV. Simulation and Performance Evaluation

The system is simulated according to the parameters in Table I, which were chosen to be consistent with related works (e.g. [6], [7], [9]) and 3GPP parameters [15].

Fig. 2 shows the simulated and analytical CDFs of the SINR for the reference HD and FD systems (in the ideal case of $\beta = 0$) for UL and DL. We first remark that simulated and analytical results match well. This means that Assumptions 1 and 2 are reasonable. The highest difference is observed for UL FD because the approximation of Assumption 1 is less accurate for BSs, which transmit at higher power. We have noticed that a small difference in the CDF may result in a slight difference in the ASE, without altering the conclusions of the paper.

The second conclusion of Fig. 2 is that the performance of the FD UL is extremely lower than the HD UL. This is due to the extra interference that arises from BS transmissions in FD. Finally, UL performance is notably worst than the DL performance in the reference FD system. This can be explained by the higher transmission powers of BSs when compared to

TABLE I
SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
α	3.5	λ_b	6.25×10^{-6} [m^{-2}]
λ_u	$30\lambda_b$	W	20 [MHz]
RB bandwidth	180 [kHz]	BS height	10 [m]
BS power	30 [dBm]	UE height	1.5 [m]
UE power	23 [dBm]	Thermal noise density	-174 [dBm/Hz]
Noise figure	8 [dB]		

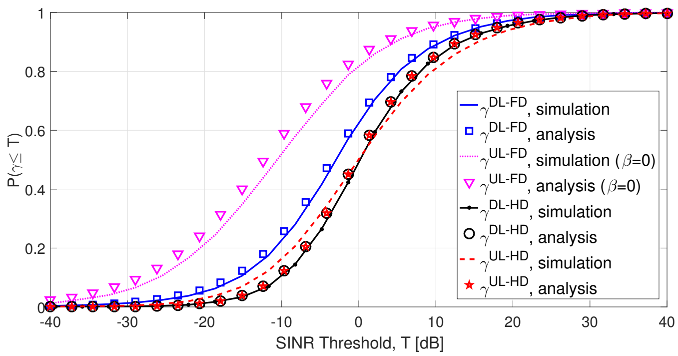

Fig. 2. CDF of SINRs for reference HD and FD networks with $\beta = 0$.

UEs ($P_b > P_u$). This phenomenon is even more pronounced when self-IC is not perfect.

Table II shows the ASE for the different network configurations: DL, UL and UL+DL (cell), with imperfect self-IC ($\beta = \beta_1 \triangleq -100$ dB, an achievable value according to [16]) and different values of r_f when the DS policy is implemented. Note that analytical and simulated results almost match for the DL, whereas for the UL there is a slight difference, as expected. Further, we can observe that FD increases the DL ASE performance, although HD's SINR levels are higher because FD makes a better usage of radio resources. On the other hand, FD affects the UL performance by reducing the ASE level. The general conclusion found in the literature is that FD improves the SE. In fact, this is true because of the sharp increase of the DL SE, which compensates a decrease of the UL SE.

The analytical ASE performance of the DS system for $\beta = \beta_1$ and different values of $\{r_f, \delta\}$ is depicted in Fig. 3. Recall that in a PPP-based network, the average distance between a UE and its linked BS, $\bar{R}$, is $\bar{R} = \mathbb{E}_R[r] = 1/(2\sqrt{\lambda_b})$. Thus $\bar{R} = 200$ m with our setting.

Regarding the DL performance, we can observe that the ASE level achieved by a HD-only network acts as a lower bound, reassuring the fact that FD increases the DL performance. For all (r_f, δ) values, DS outperforms the HD lower bound. Additionally, for a given δ, the DL performance increases with r_f, yet the maximum ASE level is reached when the percentage of FD BSs can not be further increased. If δ decreases, the number of FD BSs grows; however the intra-cell interference gets larger as well. There is thus an optimal value for δ, which is approximately $\delta = 100$ m in our setting.

TABLE II
SIMULATED (SIM.) AND ANALYTICAL (AN.) ASE PERFORMANCES IN [BPS/HZ] (r_f AND δ ARE IN METERS).

Network Configuration	DL Sim.	DL An.	UL Sim.	UL An.	cell Sim.	cell An.
HD	0.87	0.86	0.93	0.86	1.80	1.72
FD	1.28	1.29	0.66	0.58	1.94	1.87
DS ($r_f, \delta = 500, 100$)	1.35	1.36	0.68	0.57	2.03	1.93
DS ($r_f, \delta = 85, 0$)	0.95	0.96	0.97	1.07	1.92	2.03
DS ($r_f, \delta = 125, 0$)	1.03	1.04	0.91	1.03	1.94	2.07
DS ($r_f, \delta = 182, 100$)	1.13	1.15	0.81	0.86	1.94	2.01

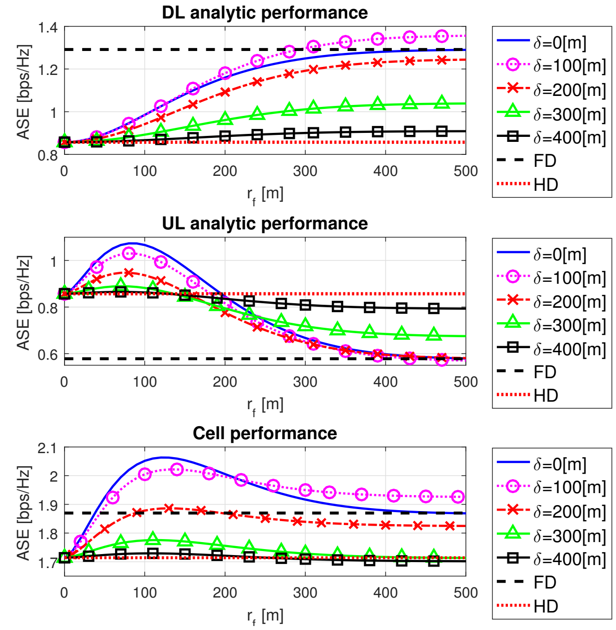

Fig. 3. Analytical ASE performance with $\beta = \beta_1$.

In contrast, when analyzing the UL ASE, the results show that the DS policy outperforms the reference FD model for almost all (r_f, δ) values, except for a nearly negligible loss seen for $\delta = 100$ m and $r_f > 440$ m. Moreover, for $r_f < 200$ m and $\delta = \{0, 100, 200, 300\}$ m, the DS system can even outperform the reference HD performance, with maximum value at $\{r_f, \delta\} = \{85, 0\}$ m. This is due to the fact that there are few FD BSs and in every FD cell the UL distance is small. This can be observed in (13) where the terms $I_{F' \to b_0}$ and R are small in these cases.

While considering both UL and DL, the cell performance is maximized for $\{r_f, \delta\} = \{125, 0\}$ m, where DS outperforms both FD (+11%) and HD (+20%) reference systems. In this case, UL and DL surpass the reference HD ASE, while the DL performance is 19% lower than the ASE achieved by the reference FD system, as seen in Table II.

As a conclusion, the operator can tune the parameters (r_f and δ) to favor more or less the DL vs. UL. In Table II, the values $\{r_f, \delta\} = \{182, 100\}$ m provide a good trade-off between DL and UL: DS exhibits a gain of 48% compared to FD and no loss compared to HD on the UL. The loss is 11% compared to FD and the gain is 34% compared to HD on the DL. This demonstrates the interest of the proposed scheme.

V. CONCLUSIONS

This work proposes a duplex-switching policy (DS) for cellular networks, where BSs are FD capable. The objective is to solve the problem of UL performance degradation observed in FD systems where all BSs adopt FD. In the proposed policy, a BS adopts FD only if its UL scheduled user is close, and the scheduled DL user is far from the UL user. These distances are controlled by two parameters r_f and δ. An analytical study using tools from stochastic geometry shows that our scheme is able to improve the UL performance at the cost of a small DL degradation compared to a FD model. The DS policy offers thus a flexible tool for the operator to favor more or less one link against the other. When δ and r_f are optimized, our DS policy outperforms both HD and FD in terms of cell average spectral efficiency.

Appendix A

We can write $\mathbb{P}(\gamma_\tau^{\text{DL-FD}} \leq T | R = r, I_{F' \to u_0}, I_{H \to u_0})$ as:

$$\mathbb{P}\left(h \leq s_1 \left[I_{F' \to u_0} + I_{H \to u_0} + \sigma^2\right]\right). \quad (40)$$

Then, by knowing that $h \sim \exp(1)$, tanking the averages of $I_{F' \to u_0}$ and $I_{H \to u_0}$, writing their expected values in terms of the Laplace transform and finally integrating over the distribution of r we obtain (9).

A. Derivation of $\mathscr{L}_{I_{F' \to u_0}}(s_1)$

Let us express D_{b_k,u_0} and D_{u_j,u_0} as D_k and D_j, respectively, and h_{u_0,b_k} and h_{u_0,u_j} as h, given the fact that the fading function is the same between all network elements. From Assumption 2, D_k and D_j are independent, thus $\mathscr{L}_{I_{F' \to u_0}}(s_1)$ is equal to:

$$\underbrace{\mathbb{E}_{D_k,h}\Big[\prod_{k \in \Phi_F \setminus b_0} \exp\Big(-\frac{Tr^\alpha}{D_k^\alpha} h\Big)\Big]}_{(*)} \underbrace{\mathbb{E}_{D_j,h}\Big[\prod_{j \in \varphi_F} \exp\Big(-\frac{\rho Tr^\alpha}{D_j^\alpha} h\Big)\Big]}_{(**)} \quad (41)$$

Further, $(*)$ can be simplified following these steps:

$$(*) = \mathbb{E}_{D_k}\Big[\prod_{k \in \Phi_F \setminus b_0} \mathbb{E}_h\Big[\exp\Big(-\frac{Tr^\alpha}{D_k^\alpha} h\Big)\Big]\Big] \quad (41a)$$

$$= \mathbb{E}_{D_k}\Big[\prod_{k \in \Phi_b \setminus b_0} \frac{D_k^\alpha}{D_k^\alpha + Tr^\alpha}\Big] \quad (41b)$$

$$= \exp\left(-2\pi\lambda_F(r_f, \delta) \int_r^\infty \frac{Tr^\alpha}{y^\alpha + Tr^\alpha} y \, dy\right). \quad (41c)$$

Where (41a) is due to the independence between D_k and h, (41b) by knowing that $h \sim \exp(1)$ and (41c) is given by the probability generating functional (PGF) of Φ_F [17]. Finally, $(**)$ can be simplified similar to $(*)$.

B. Derivation of $\mathscr{L}_{I_{H \to u_0}}(s_1)$

We obtain (21) following the same steps that for $\mathscr{L}_{I_{F' \to u_0}}(s_1)$. Yet, the $1/2$ factors appear due to the expected value of the indicator functions in (8). ∎

Appendix B

Let us consider a UE $u_0 \in \varphi_F$ linked to a BS b_0. Given the DS policy in (1), $D_{u_0,b_0} \leq r_f$. Hence, we can write the CDF of the RV D_{u_0,b_0}, such that the latter condition holds as:

$$\mathbb{P}\left(D_{u_0,b_0} \leq r | D_{u_0,b_0} \leq r_f\right) = \phi(r) = \frac{1 - e^{-\pi\lambda_b r^2}}{1 - e^{-\pi\lambda_b r_f^2}}. \quad (42)$$

Now, by deriving (42) we obtain the PDF $\tilde{f}_R(r)$:

$$\frac{\mathrm{d}\phi(r)}{\mathrm{d}r} = \tilde{f}_R(r) = \frac{2\pi\lambda_b r e^{-\pi\lambda_b r^2}}{1 - e^{-\pi\lambda_b r_f^2}}. \quad (43)$$

The rest of the proof is similar to Theorem 1. ∎

Appendix C

From positivity of (6), $\mathbb{E}_{\gamma_\tau^{\text{DL-FD}}}\left[\log_2\left(1 + \gamma_\tau^{\text{DL-FD}}\right)\right]$ can be written as:

$$\int_0^\infty \mathbb{P}\left(\log_2\left(1 + \gamma_\tau^{\text{DL-FD}}\right) > T\right) dT = \int_0^\infty \frac{\mathbb{P}\left(\gamma_\tau^{\text{DL-FD}} > T\right)}{\ln(2)(1+T)} dT. \quad (44)$$

Then, the same can be done for the UL in $\mathbb{E}_{\gamma_\tau^{\text{UL-FD}}}[\cdot]$. ∎

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