Capacity Gain of Full Duplex Self-Backhauling and Opportunistic Full Duplex Self-Backhauling

Kwonhue Choi, *Senior Member, IEEE*

***Abstract*—This paper investigates the capacity gain of full duplex (FD) self-backhauling over the half duplex (HD) counterpart in downlink cellular systems, and then proposes an opportunistic FD scheme. The first step is to derive the capacity gain of FD self-backhauling over the HD counterpart as a function of the system parameters in a computationally tractable form. Unlike previous studies on the capacity of FD self-backhauling, a practical constraint is imposed so that the end-to-end link achieves a target signal-to-interference-plus-noise ratio (SINR) for a successful link connection. Also, a condition under which FD is more beneficial than HD is derived. Specifically, the minimum allowable self interference cancellation factor and the maximum allowable cell radius for the benefit of FD are derived as an explicit function of system parameters. Their dependencies on the system parameters are investigated and compared with counterparts derived for single-hop point-to-point links. Lastly, to overcome the weak points of FD and HD, this paper proposes a user-wise opportunistic FD (OFD) self-backhauled scheme. To this end, an instantaneous channel gain-based FD/HD switching rule is derived from a condition under which FD cannot instantaneously satisfy the target SINR. We confirm the substantial capacity gain of the proposed user-wise instantaneous OFD over a cell-wise static duplex switching scheme, as well as the fixed duplex (HD or FD) schemes. When compared to the static duplex switching scheme, the proposed OFD is most beneficial at the boundary of HD-preferred and FD-preferred regions. Based on this, a system-level guideline is proposed for selecting the most practical scheme among OFD, FD, and HD by trading off capacity gain and switching overhead. Extensive simulation results are provided to confirm the correctness of the derivations and the related investigations.**

***Index Terms*—Self-backhauling, Full Duplex, Small Cell Networks**

I. Introduction

Self-backhauling is an attractive solution for the low-cost deployment of small cell networks (SCNs) which require many backhaul links. Unlike asymmetric data traffic between up/down links, access/backhaul links are fairly symmetric. Thus, full duplex (FD) of access/backhaul link pair has much higher spectral efficiency (capacity) gain than FD of up/down link pairs or FD of bidirectional link pairs [1]. FD of access/backhaul link pair is especially more meaningful in downlink than in uplink, because the demand for high spectral efficiency is ever-increasing in downlink. There have been a lot of studies on FD self-backhauling downlinks with a variety of research issues [2–7]. However, in these studies, more innovative studies on flexible FD self-backhauling, such as opportunistic FD or a mixture of FD links and HD links have not been explored.

Meanwhile, if the residual self-interference-to-power ratio (RSIPR)[1] and in-band interference from macro base station (MBS) to users under FD are not sufficiently low, it decreases the doubled spectral efficiency gain of FD, so FD may not outperform half duplex (HD) [9–15]. Therefore, hybrid duplexing that switches between FD and HD is a promising technique to maximize the benefit of FD. There are considerable studies on hybrid duplexing for up/down link pairs or bidirectional link pairs [9–15]. On the other hand, there are far fewer studies on the idea of switching between FD and HD in self-backhauling [16–18]. Access/backhaul link pair for downlink (or uplink) forms one-directional two hop link whereas up/down link pair forms bi-directional single hop link. Due to these different link topologies, the self-interference (SI) model of FD self-backhauling is different from those of FD for up/down link pairs or any other bi-directional link pairs.

A comparison between FD self-backhauling and its HD counterpart was made in [16], and the condition in which that FD outperforms HD was investigated, as well. But relying only on the simulation results limits any analysis to the case study. In [17, 18], the capacities of FD and HD for self-backhauled links were separately derived, but the capacity gain of FD over HD was not derived. Instead, the capacities of FD and HD were compared based on the numerically calculated results for the various cases. Also, the idea of switching between FD and HD was proposed in [17, 18]. But again, the additional capacity gain from duplex switching was investigated only via numerical results for the various cases. Hence, the results and discussions in those studies hardly provide an analytic view of the functional relations between the system parameters and the capacity gain of FD over HD, or the condition of FD outperforming HD. Another common issue faced by the studies in [16–18] is that they rely on an information-theoretic capacity-based performance analysis that does not care whether the individual user's connections (calls) satisfy the desired signal-to-interference-plus-noise ratio (SINR). Therefore, any connection contributes to the system throughput regardless of the SINR. In [10], a condition under which FD outperforms HD was provided in analytic form, but it was for single hop point-to-point (P2P) links, and is not applicable to self-backhauled links.

[1]The term RSIPR is equivalent to the inverse of self-interference (SI) cancellation factor, which is also a generally used term in the literature [8, 18, 24].

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The author is with the Department of Information and Communication Engineering, Yeungnam University, Gyeongsan 38541, Korea (e-mail: gonew@yu.ac.kr)

In the context of a relay system that is analogous to a self-backhauled system (in that both are based on two-hop link), hybrid duplex schemes (called hybrid relaying) which switch HD from, or to, FD were proposed [19–22]. In [19], duplex-scheme selection is made to maximize the end-to-end link capacity, assuming a fixed transmission power. Therefore, the desired SNR in each link can not be guaranteed. On top of that, the room for performance gain from transmit power optimization is basically excluded. Moreover, the result is not applicable to a self-backhauled cellular system. This is because in an FD self-backhauled cellular system, the MBS-to-user channel gain is possibly comparable to, or even larger than, the MBS-to-small base station (SBS) channel gain, depending on the user position or the propagation environments, and thus, there is in-band interference from the MBS to the users. On the other hand, in relay systems, the source-to-destination channel gain is normally assumed to be very weak, compared to the source-to-relay channel gain, and thus, the source-to-destination in-band interference (corresponding to MBS-to-user in-band interference from two hop link topology) was ignored in [19]. It was shown in [20] that with optimized transmit power in FD mode, FD and a hybrid duplex achieve an identical mean capacity. However, it was not considered that the path loss compensation for the users at the cell edge causes high SI in FD mode, which seriously degrades FD. A hybrid method with four duplex modes on relay was proposed in [21]. The optimized mode and power needed to be solved numerically by the sub-gradient method, which prevents an analytic view on the mode selection boundaries. In [22], a hybrid duplex was proposed to overcome the difficulty of SI channel estimation in FD mode, but instantaneous channel condition-based duplex scheme switching was not considered.

The purpose of this study is to address unsolved issues in the previous work on FD self-backhauling, as mentioned above. Specifically, the contributions of this study are threefold.

1) For self-backhauled cellular systems, the capacity gain of FD self-backhauling over its HD counterpart is derived as a function of the system parameters in a computationally tractable form. Unlike previous studies on the capacity of FD self-backhauling, a constraint is imposed so that the end-to-end link achieves a target SINR for a successful link connection. This SINR constraint not only adds practicality to the information-theoretic capacity-based performance measure but also enables a closed-form derivation of the capacity gain of FD.
2) For self-backhauled cellular systems, we derive the boundary of the regions where one of each HD or FD is preferred to (more beneficial than) the other as an explicit function of system parameters in a closed-form expression. We investigate how the boundary changes according to the system parameters such as the cell radius, RSIPR of FD, path loss exponent and carrier frequency. Specifically, we derive the maximum allowable RSIPR (or equivalently, the minimum allowable SI cancellation factor) and the maximum allowable cell radius, in order for FD to be more beneficial than HD. One of the remarkable results is their doubled dependencies on the target SINR, compared to the ones derived for single-hop P2P links in [10].
3) A user-wise opportunistic FD (OFD) self-backhauled scheme is proposed. To this end, an instantaneous channel gain-based FD/HD switching rule is derived from a condition under which FD cannot instantaneously satisfy the target SINR. We confirm the substantial capacity gain of the proposed user-wise instantaneous OFD over a cell-wise static duplex-switching scheme, as well as the fixed duplex (HD or FD) schemes. The derived boundary of FD and HD-preferred regions mentioned above is shown to provide an important guideline for selecting a practical choice from OFD, FD, and HD by trading off capacity gain and switching overhead.

II. System Model and Parameters

We consider the downlink of the self-backhauled cellular network shown in Fig. 1 with the same system configuration as typical ones in the literature [1–3, 18]. The frequency band of the backhaul downlink is the same as that of the access downlink. In both the access and backhaul links, the users' signals are multiplexed using orthogonalized resource slots. The locations of the active users in a small cell are modeled as an independent Poisson point process (PPP) [9, 10]. Notations

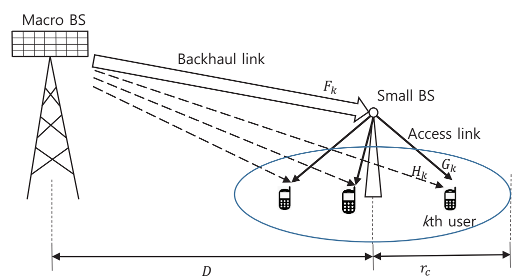

Fig. 1: Downlink of the self-backhauled cellular network.

TABLE I: List of symbols

Description	Symbol
Distance between MBS and SBS [m]	D
Small-cell radius [m]	r_c
Mean number of active users in a small cell	μ_K
Number of active users in a small cell	K
kth user's backhaul link channel gain	F_k
kth user's access link channel gain	G_k
Channel gain from the MBS to the kth user	H_k
Residual self-interference-to-power-ratio (RSIPR)	β
Backhaul link transmission power for the kth user	$p_{m,k}$
Access link transmission power for the kth user	$p_{s,k}$

In the backhaul link, the multiplexed user-signals pass through a common channel with very little scattering by assuming a highly probable line-of-sight path. Hence, F_k can be considered identical for different ks, so k in F_k is omitted hereafter. On the other hand, the channel gain to the kth user (G_k and H_k) are independent of k. We consider a case where the transmit power control and the duplex mode switching (if needed) at the SBS are agile enough to track the variations of G_k and H_k. This case matches the channel environment of small cell networks where the user speed is not very high.

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III. Capacities of HD and FD under the Target SINR Constraint

First, we review the typical SINR models of access and backhaul links for HD self-backhauled and FD self-backhauled downlink cellular systems, respectively [18]. Then, for deriving the capacity gain of FD over HD in the next section, we characterize the end-to-end downlink capacity of FD under a target SINR constraint.

A. Half duplex

Let $\gamma_k^{(A)}$ be the SINR of the access downlink for the kth user in a small cell, and let $\gamma_k^{(B)}$ be the SINR of its backhaul downlink link. Due to orthogonalized multiplexing among users, there is no interuser interference. Moreover in HD, access and backhaul links use the exclusive (orthogonal) resources, too. Thus, $\gamma_k^{(A)}$ and $\gamma_k^{(B)}$ are given as follows [18]:

$$\gamma_k^{(A)} = \frac{p_{s,k}G_k}{v}, \quad \gamma_k^{(B)} = \frac{p_{m,k}F}{v} \tag{1}$$

where v is noise power. From the bottleneck effect of a two-hop link, the overall end-to-end SINR is given as follows: $\gamma_k = \min\left[\gamma_k^{(A)}, \gamma_k^{(B)}\right]$ [20, 22]. Therefore, for target SINR γ_T, the most power-efficient settings for $p_{m,k}$ and $p_{s,k}$ are those that satisfy $\gamma_k^{(A)} = \gamma_T$ and $\gamma_k^{(B)} = \gamma_T$. Then, the solutions $p_{m,k}^*$ and $p_{s,k}^*$ for $p_{m,k}$ and $p_{s,k}$ are calculated as follows:

$$p_{m,k}^* = \frac{\gamma_T v}{F}, \quad p_{s,k}^* = \frac{\gamma_T v}{G_k}. \tag{2}$$

With these power settings, the capacity of the kth user in HD denoted by $C_{\mathrm{HD},k}$ is calculated as follows:

$$C_{\mathrm{HD},k} = 0.5\log(1+\gamma_k) = 0.5\log(1+\gamma_T), \forall k \tag{3}$$

where 0.5 is a resource division factor for HD [18, 20].

B. Full duplex

In FD, each user uses the same frequency and time slots in access and backhaul links [18]. This per-user self-backhauling decouples the complicated multiuser resource management (RM) problem, as discussed in [23] into a single user RM problem as done in [18]. Therefore, $\gamma_k^{(B)}$ in (1) changes as follows [18]:

$$\gamma_k^{(B)} = \frac{p_{m,k}F}{\beta p_{s,k} + v}. \tag{4}$$

The term $\beta p_{s,k}$ represents the residual SI power after cancellation assuming that the instantaneous residual SI follows a complex Gaussian distribution with mean $= 0$ and variance $= \beta p_{s,k}$. This is a common model for residual SI of FD [7, 9, 10, 18, 19, 23–26]. The parameter β is a system constant that depends on the specific SI cancellation algorithm employed in the SBS, but $p_{s,k}$ is a variable because it is determined by considering the channel conditions. Thus, the residual SI power $\beta p_{s,k}$ is also a variable.

Likewise, $\gamma_k^{(A)}$ in (1) changes as follows [18]:

$$\gamma_k^{(A)} = \frac{p_{s,k}G_k}{H_k p_{m,k} + v} \tag{5}$$

The term $H_k p_{m,k}$ represents the in-band interference (IBI) power from MBS to the kth user due to FD of backhaul and access link pair and is also a variable.

Note that under the same transmit powers, SINR for FD in (4) and (5) are lower than those for HD in (1). This is owing to two interference terms: the residual SI in the backhaul link ($\beta p_{s,k}$ in (4)) and IBI in the access link ($H_k p_{m,k}$ in (5)). The SI in the backhaul link is suppressed as much as possible in the employed cancellation algorithm. However, the IBI is unknown to the users and cannot be canceled on the user side [18]. Hence, in the case of a high IBI, for instance, for the users at the cell edge close to the MBS, the access link undergoes severe SINR degradation. Consequently, despite the intrinsic benefit of FD, that is, doubled spectral efficiency, the overall end-to-end capacity of FD is lower than that of HD. This is not the case for FD in the bidirectional link, such as FD between uplink and downlink because it has no IBI. To prevent this, the access link power of FD ($p_{s,k}$ in (5)) must be larger than $p_{s,k}^*$ in (2) to compensate the IBI term ($H_k p_{m,k}$ in (5)) and achieve an SINR level comparable to that of HD. In addition, the backhaul link power of FD ($p_{m,k}$ in (4)) needs to be increased accordingly to compensate for the increased SI term $\beta p_{s,k}$. Hence, in this study, we relax the same power consumption constraint. Instead, we adopt the target SINR constraint so that the SINR degradation by IBI and SI can be fundamentally recovered by properly adjusting the power. In addition, in order to add the power constraint consideration to the target SINR constraint, we adopt the total power limitation of the SBS rather than the same individual power to each user. This will be covered in Section VI.

Note that $\gamma_k^{(B)}$ in (4) is a decreasing function of $p_{s,k}$ whereas $\gamma_k^{(A)}$ in (5) is an increasing function of $p_{s,k}$. Again, for maximum power efficiency of a two-hop link with target SINR γ_T, $p_{m,k}$ and $p_{s,k}$ are set so that both $\gamma_k^{(A)}$ and $\gamma_k^{(B)}$ are equal to γ_T. We can derive the solutions $p_{m,k}^*$ and $p_{s,k}^*$ as follows.

$$p_{m,k}^* = \left(\frac{\gamma_T v}{F}\right)\frac{1+\frac{\gamma_T\beta}{G_k}}{1-\frac{\gamma_T^2\beta H_k}{FG_k}}, \quad p_{s,k}^* = \left(\frac{\gamma_T v}{G_k}\right)\frac{1+\frac{\gamma_T H_k}{F}}{1-\frac{\gamma_T^2\beta H_k}{FG_k}}. \tag{6}$$

This power allocation criterion is different from that in [23] in that the latter aims to maximize the sum-rate of the users, without regard to the QoS of the individual user link, such as the data rate or SINR.

From the denominators in (6), we know that if $FG_k \le \gamma_T^2\beta H_k$, there are no positive solutions for the target SINR. The condition $FG_k \le \gamma_T^2\beta H_k$ implies a situation where the cross link SI coefficients H_k and β are too big, and therefore, increasing $p_{s,k}$ and $p_{m,k}$ results in high SIs as shown in (4) and (5) and is useless for achieving the target SINR. Although in this case it is still possible to achieve the target SINR by lowering the data rate, we drop the call for the following two reasons. First, the required powers for the target SINR in (6) were derived under the condition of a target data rate, which is another basic system requirement. This is because the target SINR is meaningful as a QoS metric only when the desired data rate is also guaranteed. Second, for the total-power-limited case, which will be covered in Section VI, how

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to distribute the total power to users is crucial. If achieving the target SINR is impossible for a certain user, it is more beneficial to drop the call and allocate the reserved power to other users who can attain the target SINR for the maximum number of QoS-guaranteed calls. Hence, if $FG_k \leq \gamma_T^2\beta H_k$, then we set $p_{m,k} = 0$ and $p_{s,k} = 0$, which indicate a call drop equivalent to $C_{FD,k} = 0$. Overall, the capacity of the kth user in FD, $C_{\mathrm{FD},k}$, is given as:

$$C_{\mathrm{FD},k} = \begin{cases} \log(1+\gamma_T)(=2C_{\mathrm{HD},k}) & \text{if } FG_k > \gamma_T^2\beta H_k \\ 0 & \text{else} \end{cases} \tag{7}$$

where the doubled scaling factor (=1) applied to log term compared to (3) comes from the frequency reuse factor of FD.

IV. Full Duplex Gain and the FD-preferred and HD-preferred Regions

A. Mean capacity of FD, and capacity gain of FD over HD

From (7), the mean $C_{\mathrm{FD},k}$ denoted by $C_{\mathrm{FD}}^{(m)}$ is calculated as follows:

$$\begin{aligned} C_{\mathrm{FD}}^{(m)} &= \mathrm{E}_{F,G_k,H_k}\left[C_{\mathrm{FD},k}\right] \\ &= \Pr[FG_k > \gamma_T^2\beta H_k] \times \log(1+\gamma_T) \\ &= 2\Pr[FG_k > \gamma_T^2\beta H_k] \times C_{\mathrm{HD},k}. \end{aligned} \tag{8}$$

There is no index (k) in $C_{\mathrm{FD}}^{(m)}$ because G_k and H_k channel gain is statistically identical for each k, and $C_{\mathrm{HD},k}$ is constant, assuming that the total power is large enough to satisfy the target SINR for all active users in HD. With an insufficient total power margin, $C_{\mathrm{HD},k}$ becomes a random variable, which is discussed in Section VI.

Use $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ to denote the FD gain over HD. Then, from (8), we have

$$\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = \frac{C_{\mathrm{FD}}^{(m)}}{C_{\mathrm{HD,k}}} = 2\Pr[FG_k > \gamma_T^2\beta H_k]. \tag{9}$$

To proceed with the derivation of $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$, we need to set mathematical models for channel gain. Due to the fixed wireless nature of the backhaul link, and assuming a tight beamforming of the MBS, we just consider the path loss in the channel gain, F, as follows: $F = \kappa D^{-n}$ where D is the distance between the MBS and the SBS, n is the path loss exponent, and $\kappa = (c_L/4\pi f_c)^2$, in which c_L is the speed of light and f_c is the carrier frequency. Whereas, since G_k and H_k denote the channel gain for the mobile users, a fading term is included as follows: $G_k = g_k\kappa d_{s,k}^{-n}$ and $H_k = h_k\kappa d_{m,k}^{-n}$ where g_k and h_k are independent exponential random variables for Rayleigh fading, $d_{s,k}$ is the distance between SBS and the kth user terminal, and $d_{m,k}$ is the distance between MBS and the kth user terminal. By substituting these channel models into (9) and rewriting the inequality in terms of $d_{s,k}$, we have

$$\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = 2\Pr\left[d_{s,k} < \frac{d_{m,k}}{D}\left(\frac{\kappa g_k/h_k}{\gamma_T^2\beta}\right)^{1/n}\right] \tag{10}$$

which does not allow a tractable derivation, as is. From the small cell condition where $r_c \ll D$, the distance between the MBS and the kth user, $d_{m,k}$, is approximately equal to D. According to the simulation results (see Fig. 3), there is a negligible difference between the results with and without this approximation. With this approximation, (10) can be changed to

$$\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = 2\Pr\left[d_{s,k} < \left(\frac{\kappa\alpha_k}{\gamma_T^2\beta}\right)^{1/n}\right] \tag{11}$$

where $\alpha_k = g_k/h_k$, implying the fading gain ratio.

By following the calculations in Appendix A, we can derive a compact expression for $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ as follows:

$$\begin{aligned} \eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = & \frac{2{\gamma_T}^2\beta\, n\, {r_c}^n}{\kappa(2+n)}\,{}_2\mathrm{F}_1\left(2, \frac{2}{n}+1;\ \frac{2}{n}+2;\ -\frac{{\gamma_T}^2\beta {r_c}^n}{\kappa}\right) \\ & + \frac{2\kappa}{\kappa + {\gamma_T}^2\beta {r_c}^n} \end{aligned} \tag{12}$$

where ${}_2\mathrm{F}_1(a,b;c;z)$ denotes a hypergeometric function whose generic form is given as a summation of the infinite power series[27]. We use a tight closed form approximation for ${}_2\mathrm{F}_1(a,b;c;z)$ given as follows [28]:

$${}_2\mathrm{F}_1(a,b;c;z) \approx \frac{c^c}{\sqrt{cu}}\left(\frac{y}{a}\right)^a\left(\frac{1-y}{c-a}\right)^{c-a}\left(\frac{1}{1-xy}\right)^b \tag{13}$$

where $u = \frac{y^2}{a} + \frac{(1-y)^2}{c-a} - \frac{bx^2y^2(1-y)^2}{(1-xy)^2a(c-a)}$ and $y = \frac{2a}{\sqrt{(z(b-a)-c)^2-4az(c-b)}-(z(b-a)-c)}$. This approximation has very light computation complexity due to the reasonable amount of simple arithmetic. The numerical results in the next section show that the approximation error is negligible for the considered simulation parameters. The integration in (36) has the exact closed forms for several integers. For instance, we have

$$\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = \begin{cases} \dfrac{2\kappa\log\left(\beta\gamma_T^2r_c^2/\kappa+1\right)}{\gamma_T^2\beta r_c^2} & \text{if } n=2 \\ \dfrac{\sqrt{\kappa}\left\{\pi - 2\arctan\left(\frac{\sqrt{\kappa}}{\gamma_T\sqrt{\beta}r_c^2}\right)\right\}}{\gamma_T\sqrt{\beta}r_c^2} & \text{if } n=4. \end{cases} \tag{14}$$

From (3) and the closed-form expression for $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ in (12), the closed-form expression for the mean capacity of FD denoted by $C_{\mathrm{FD}}^{(m)}$ is straightforward as follows:

$$C_{\mathrm{FD}}^{(m)} = \eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} C_{\mathrm{HD,k}} = \eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} \times \frac{1}{2}\log\left(1+\gamma_T\right). \tag{15}$$

B. Boundary between HD-preferred and FD-preferred regions

If the FD gain $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ is larger than 1, then FD outperforms HD. Hence, the boundary between FD-preferred and HD-preferred regions is equal to the solution of the equation $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = 1$. It is not mathematically tractable to find the analytic solution from $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ in (12), as is. The simulation results reveal that FD gain $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ for cases with and without fading are quite different. However, it is also revealed that limiting our interest to the solution of $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} = 1$, there is a negligible difference between the simulation result with fading and the derived solution without fading. Hence, for a tractable derivation of the boundary, we use the non-fading version of FD gain denoted by $\eta_{\frac{\text{FD}}{\text{HD}}}^{(\alpha_k=1)}$, which is obtained by setting fading gain ratio α_k in (11) to 1, as follows:

$$\begin{aligned}\eta_{\frac{\text{FD}}{\text{HD}}}^{(\alpha_k=1)} &= 2\int_{-\infty}^{\left(\frac{\kappa}{\gamma_T^2\beta}\right)^{\frac{1}{n}}} f_{d_{s,k}}(y)\mathrm{d}y \\ &= \begin{cases} 2\left(\frac{\left(\kappa/(\gamma_T^2\beta)\right)^{\frac{1}{n}}}{r_c}\right)^2 & \text{if} \left(\frac{\kappa}{\gamma_T^2\beta}\right)^{\frac{1}{n}} \le r_c \\ 2 & \text{else}\end{cases} \quad (16)\end{aligned}$$

Then, the boundary equation (the solution of the equation $\eta_{\frac{\text{FD}}{\text{HD}}}^{(\alpha_k=1)} = 1$) is equivalent to $2\left(\left(\kappa/\left(\gamma_T^2\beta\right)\right)^{1/n}/r_c\right)^2 = 1$. By rewriting this boundary equation in terms of β, we can find a threshold for β that splits FD and HD-preferred regions, as follows:

$$\beta_0 = \frac{c_L^2 2^{n/2}}{(4\pi f_c)^2\gamma_T^2 r_c^n}. \quad (17)$$

If $\beta < \beta_0$, FD outperforms HD. Otherwise, HD outperforms FD. In other words, β_0 is the maximum allowable β to obtain the benefit of FD.

The expression in (17) provides an explicit view of the functional dependency of β_0 on the related system parameters (f_c, γ_T, r_c and n). First, there is the rather trivial property that β_0 decreases as γ_T increases. This is because for higher SINRs, tighter SI cancellation is required to obtain the benefit of FD [10]. However, a notable property is that β_0 in (17) has a factor of γ_T^{-2}, whereas the counterpart for a single-hop P2P network in the equation (41) in [10] has a factor of γ_T^{-1}. This implies a remarkable difference in that β_0 for self-backauled links has a doubled dependency (in log scale) on the target SINR compared to the one derived for single-hop P2P links. This comes from a feature of two-hop links, where the SINRs of both links need to satisfy the target SINR and the SI terms in access and backhaul links are cross-coupled with their transmission powers. In $\gamma_k^{(B)}$ in (4), proportionally increasing $p_{m,k}$ in response to the increase of the target SINR results in the proportionally increased IBI (=$H_k p_{m,k}$) to $\gamma_k^{(A)}$ in (4). Due to this linearly increased IBI, $p_{s,k}$ in $\gamma_k^{(A)}$ needs to be increased in proportion to the *square* of the target SINR increase assuming $H_k p_{m,k} \gg \upsilon$. Accordingly, to suppress the SI power (=$\beta p_{s,k}$) in $\gamma_k^{(B)}$ to the original level, β should be decreased in inverse proportion to the *square* of the target SINR increase.

The boundary equation in (17) indicates that for FD to outperform HD, β needs to be decreased as r_c increases. More quantitatively, as the cell radius increases, we need tighter SI cancellation to obtain the benefit of FD, and the degree of tightness is proportional to r_c^n. There is an analogy between β_0 in (17) and the counterpart for FD in a single-hop P2P network (see the equation (41) of [10]) in light of the fact that both of them contain a factor of r_c^n in the denominator, although r_c in [10] implies a *fixed* distance for all bidirectional links, not the cell radius.

By rewriting the boundary equation in terms of r_c, we can find the maximum cell radius, $r_c^{\max}$, as follows:

$$r_c^{\max} = \frac{\sqrt{2}c_L^{2/n}}{(4\pi f_c)^{2/n}\gamma_T^{2/n}\beta^{1/n}}, \quad (18)$$

only below which FD outperforms HD. Quantitatively again, as β increases, i.e., as SI cancellation gets poor, we need to decrease the cell radius in proportion to $\beta^{-1/n}$ to obtain the benefit of FD.

V. The Proposed Opportunistic Full Duplex Scheme

A. The switching rule and capacity gain

As shown in (7), FD can instantaneously achieve double capacity, compared to HD or it may drop a call depending on the channel condition. If we encounter and catch the situations in which FD drops a call, then we can switch the duplex mode to HD to avoid that. This idea was the motivation to develop the proposed opportunistic FD scheme. Specifically, based on the call success/drop conditions of FD in (7), the proposed scheme opportunistically selects the duplex mode as follows:

$$\begin{aligned}&\text{Duplex mode for } k\text{th user} \\ &= \begin{cases}\text{FD with (6)} & \text{if } FG_k > \gamma_T^2\beta H_k \\ \text{HD with (2)} & \text{else.}\end{cases}\end{aligned} \quad (19)$$

Recall that the preferred region boundary equation in (17) is determined by comparing the *mean* capacities of HD and FD, which are averaged over the instantaneous channel gain for F, G_k, and H_k of the random user positions in the cell. On the other hand, the switching condition ($FG_k > \gamma_T^2\beta H_k$) in (19) is obtained by comparing the *instantaneous* capacities of HD and FD given the instantaneous channel gain. Therefore, it is expected that duplex switching to the better of HD or FD in terms of instantaneous capacity will result in a capacity increase in the mean sense.

Let $C_{\text{OFD},k}$ be the kth user's capacity of the proposed opportunistic full duplex; then, from (19), we have

$$C_{\text{OFD},k} = \begin{cases} C_{\text{FD},k}(=2C_{\text{HD},k}) & \text{if } FG_k > \gamma_T^2\beta H_k \\ C_{\text{HD},k} & \text{else}\end{cases} \quad (20)$$

and thus, the mean capacity of the proposed OFD, $C_{\text{OFD}}^{(m)}$, is derived in closed form as follows:

$$\begin{aligned}C_{\text{OFD}}^{(m)} &= \mathrm{E}_{F,G_k,H_k}\left[C_{\text{OFD},k}\right] \\ &= \Pr\left[FG_k > \gamma_T^2\beta H_k\right](2C_{\text{HD},k}) \\ &\quad +(1-\Pr\left[FG_k > \gamma_T^2\beta H_k\right])C_{\text{HD},k} \\ &= \left(1+\Pr\left[FG_k > \gamma_T^2\beta H_k\right]\right)C_{\text{HD},k} \\ &= \left(1+\frac{\eta_{\frac{\text{FD}}{\text{HD}}}}{2}\right)C_{\text{HD},k} \end{aligned} \quad (21)$$

where we use the relation $\Pr\left[FG_k > \gamma_T^2\beta H_k\right] = \frac{\eta_{\frac{\text{FD}}{\text{HD}}}}{2}$ from (9).

Let η_{OFD} be the mean capacity gain of the proposed OFD over the fixed duplex schemes (the better of HD or FD in terms of mean capacity). Then, its closed form expression is obtained by using $\eta_{\frac{\rm FD}{\rm HD}}$ as follows:

$$\eta_{\rm OFD} \triangleq \frac{C_{\rm OFD}^{(m)}}{\max[C_{\rm FD}^{(m)}, C_{{\rm HD},k}]} \tag{22}$$

$$= \begin{cases} C_{\rm OFD}^{(m)}/C_{{\rm HD},k} & \text{if } C_{\rm FD}^{(m)} < C_{{\rm HD},k} \\ C_{\rm OFD}^{(m)}/C_{\rm FD}^{(m)} & \text{else,} \end{cases}$$

$$= \begin{cases} 1+\frac{\eta_{\frac{\rm FD}{\rm HD},k}}{2} & \text{if } \eta_{\frac{\rm FD}{\rm HD}} \le 1 \\ \frac{1}{\eta_{\frac{\rm FD}{\rm HD}}}+\frac{1}{2} & \text{else.} \end{cases} \tag{23}$$

The denominator of (22) is the capacity of the sort of static duplex switching scheme, in light of which the better of FD or HD is selected. This corresponds to the system that selects FD or HD according to the *mean* capacity, averaged over the instantaneous channel gain of the random user positions in the cell. Therefore, this is equivalent to the case when duplex switching is determined by the boundary between HD-preferred and FD-preferred regions in (17). Specifically, if β of a certain SBS is larger than β_0 in (17), HD is selected for all users in the cell; ortherwise, FD is selected for all users in the cell. Meanwhile, recall that the proposed OFD in the numerater of (22) selects FD or HD according to the *instantaneous capacity,* and thus, user-by-user duplex switching is made by each user's instantaneous channel gain-dependent switching rule in (19). Hence, $\eta_{\rm OFD}$ implies the capacity gain of the *user-wise instantaneous (or fast)* OFD over the *cell-wise static* duplex switching scheme.

In (23), $1+\frac{\eta_{\frac{\rm FD}{\rm HD}}}{2}$ ($=\eta_{\rm OFD}$ for $\eta_{\frac{\rm FD}{\rm HD}} \le 1$) is an increasing function of $\eta_{\frac{\rm FD}{\rm HD}}$ whereas $\frac{1}{\eta_{\frac{\rm FD}{\rm HD}}}+\frac{1}{2}$ ($=\eta_{\rm OFD}$ for $\eta_{\frac{\rm FD}{\rm HD}} > 1$) is a decreasing function of $\eta_{\frac{\rm FD}{\rm HD}}$. Thus, $\eta_{\rm OFD}$ has a maximum at $\eta_{\frac{\rm FD}{\rm HD}} = 1$, and the maximum is 1.5. The condition $\eta_{\frac{\rm FD}{\rm HD}} = 1$ corresponds to the boundary condition of FD-preferred and HD-preferred regions; i.e., when $\beta = \beta_0$. This implies that the mean capacity gain of the proposed OFD over the static duplex switching scheme is maximized at the boundary of FD-preferred and HD-preferred regions, and the mean capacity gain reaches up to 50%. In other words, the proposed OFD scheme becomes more beneficial as β approaches β_0. If β is sufficiently smaller than β_0, the performance gap between OFD and FD becomes negligible, so it is more practical to use FD rather than OFD because OFD incurs overhead in terms of switching complexity. Likewise, if β is much larger than β_0, it is more practical to use HD. Therefore, the equation for β_0 in (17) is not only the boundary of FD and HD-preferred regions, but it is also an important guideline to determine whether FD, HD, or the proposed OFD is most suitable for the self-backhauled system, given parameters (r_c, f_c, γ_T, n).

B. Reduced-feedback version of the proposed OFD

For duplex scheme switching in the proposed OFD in (19), it is necessary to check whether $FG_k > \gamma_T^2\beta H_k$. Hence, the SBS needs to know not only its own downlink channel gain, G_k, but also the channel gain from the MBS to the user, H_k. To this end, the users need to feed back H_k to the SBS, which imposes an additional burden on the system. To alleviate this, we consider a simplified version of duplex scheme switching by just ignoring the fading gain in H_k, i.e., setting $h_k = 1$. By this along with the approximation $d_{m,k} \approx D$, we can approximate $H_k(= h_k\kappa d_{m,k}^{-n}) \approx F(=\kappa D^{-n})$. Then, checking $FG_k > \gamma_T^2\beta H_k$ boils down to $G_k > \gamma_T^2\beta$, and the switching rule is modified to

$$\text{Duplex mode for } k\text{th user} = \begin{cases} \text{FD} & \text{if } G_k > \gamma_T^2\beta \\ \text{HD with (2)} & \text{else.} \end{cases} \tag{24}$$

and for FD, the transmission powers for backhaul and access links in (6) are also modified by setting $H_k = F$ as follows:

$$p_{m,k}^* = \left(\frac{\gamma_T v}{F}\right)\frac{1+\frac{\gamma_T\beta}{G_k}}{1-\frac{\gamma_T^2\beta}{G_k}}, \quad p_{s,k}^* = \left(\frac{\gamma_T v}{G_k}\right)\frac{1+\gamma_T}{1-\frac{\gamma_T^2\beta}{G_k}}. \tag{25}$$

This simplified version demands that users only feed back G_k to the SBS, which is a nominal procedure in cellular systems. Due to the mismatch in the switching rule and the gap of the transmit power setting, compared to those of the full-feedback version in (19), performance degradation is inevitable, but the numerical results in the next section confirm that the amount of degradation is acceptable, considering a more feasible implementation.

VI. Applying the Power Constraint

Generally, for the base station, a large power capacity is guaranteed by a dedicated power supply infrastructure. Thus, the power constraint is less tight, compared to the user terminals. However, considering the small range of an SBS's transmit power amplifier, and aiming for bounded inter-cell interference among SBSs, the instantaneous total power of the SBS should be kept lower than a certain threshold. Let P_T be the total downlink power limit at each SBS, which is set identical to the different duplex schemes for fairness.

First, for a non-opportunistic (fixed-mode) duplex scheme, the following algorithm is applied. Without loss of generality, rearrange user index k so that $\cdots p_{s,k-1} < p_{s,k} < p_{s,k+1}, \cdots$ where $p_{s,k}$ is obtained using (2) for HD and (6) for FD. Let U be the maximum number of allowable users that the SBS can support with P_T. Then, we have

$$U = \max J, \text{s.t.} \sum_{k=1}^{J} p_{s,k} \le P_T. \tag{26}$$

All of the remaining $K-U$ users' power levels (i.e., $p_{s,U+1}$, $p_{s,U+2}$, $\cdots$, $p_{s,K}$) are set to 0, which is equivalent to the instantaneous capacities of the remaining $K-U$ users being equal to 0. Therefore, with a total power limit, U as well as K is a random variable, and thus, $C_{{\rm HD},k}$ (as well as $C_{{\rm FD},k}$) becomes a random variable that is equal to 0 or (3) ((7) for $C_{{\rm FD},k}$), depending on whether or not k is larger than U. Therefore, the mean capacities for HD and FD are calculated as follows:

$$C_{\rm HD}^{(m)} = {\rm E}_{K,K\neq 0}\left[{\rm E}_{\overline{G},\overline{H}}\left[\frac{1}{K}\sum_{k=1}^{K} C_{{\rm HD},k}\right]\right],$$

$$C_{\rm FD}^{(m)} = {\rm E}_{K,K\neq 0}\left[{\rm E}_{\overline{G},\overline{H}}\left[\frac{1}{K}\sum_{k=1}^{K} C_{{\rm FD},k}\right]\right] \tag{27}$$

where K follows a Poisson process with mean μ_K, $\overline{G}$ and $\overline{H}$ denote channel gain vectors $\{G_1, G_2, \cdots G_K\}$ and $\{H_1, H_2, \cdots H_K\}$, respectively. The trivial case of $K = 0$ is excluded in the expectation operation.

On the other hand, for the OFD scheme, there is one more consideration for the total power limit when selecting each user's duplex scheme (FD or HD). Recall that without a power limit constraint, the duplex scheme for each user is determined only based on (19). However, in some situations with the power limit constraint, it might be better to select HD for a certain user, even if FD outperforms HD according to (19). This is because, if required power $p_{s,k}$ for the user selecting FD is accidentally too high, there may not be available power for the other users, and then, fewer users will be supported, compared to selecting HD, and this results in the loss of the sum capacity of the cell. Therefore, to find the optimal duplex modes for users, we need to check the sum capacity of the users for all possible combinations of their duplex modes, and then, we need to find the solution that achieves the maximum sum capacity denoted by ΣC as follows:

$$\Sigma C_{\text{OFD}} = \max_{\{\text{DM}(k)\}_{k=1}^{k=K}} \left(\sum_{k=1}^{K} C_{\text{DM}(k),k} \right) \text{ s.t. } \sum_{k=1}^{K} p_{s,k} \leq P_T. \quad (28)$$

where $\text{DM}(k)$ means the kth user's duplex mode having the two possibilities, i.e., HD or FD. The set $\{\text{DM}(k)\}_{k=1}^{k=K}$ means the duplex modes of K users. Then, the mean capacity of OFD is calculated by averaging $\Sigma C_{\text{OFD}}/K$ over the channel gain vectors, as follows:

$$C_{\text{OFD}}^{(m)} = \text{E}_{K,K\neq 0} \left[\text{E}_{\overline{G},\overline{H}} \left[\frac{\Sigma C_{\text{OFD}}}{K} \right] \right]. \quad (29)$$

Because DM(k) is a binary variable, there are 2^K combinations of the duplex mode vector, $\{\text{DM}(k)\}_{k=1}^{k=K}$. Therefore, a brutal search for maximization in (28) requires 2^K iterations of sum capacity calculation. We can reduce the number of iterations by excluding unnecessary combinations. For a certain J smaller than K, if $\sum_{k=1}^{J} p_{s,k}$ is already larger than P_T for a given combination of duplex modes for the first J users, only the first $J-1$ users will be served and thus, we do not need to go through the combinations of the last $K-J$ users. Instead, we simply set $C_{\text{DM}(J),J}$, $C_{\text{DM}(J+1),J+1}$, $C_{\text{DM}(J+2),J+2}$, ..., $C_{\text{DM}(K),K}$ to zeros to calculate the sum capacity. There might be a more sophisticated algorithm to reduce the computational complexity. This is not covered here, because it is outside the scope of this work.

VII. Simulation Results

The simulation parameters were set as shown in Table II unless specified separately.

TABLE II: The simulation parameter settings

Parameter	Setting
D	1,000 m
μ_K	8
γ_T	8 dB
f_c	28 GHz
n	3.4
ν	3.9811×10^{-14} W [29]

Next, set the total power limit P_T of the SBS as follows:

$$P_T = P_0 10^{\zeta/10} \quad (30)$$

where P_0 is the reference power subject to the employed power setting criterion, and parameter ζ is an additional power margin in decibels.

We consider two criteria for setting P_0 as follows:

- *Cell radius and traffic density (CRnTD)-based P_0*: Consider the worst case scenario in which all the active users are at the cell boundary, and the power is set such that each user's received SNR is equal to the target SINR, γ_T. Then, the per-user required power should be equal to $\frac{\gamma_T \nu}{\kappa r_c^{-n}}$ where $\frac{1}{\kappa r_c^{-n}}$ is the inverse of the path loss. The number of active users, K, is equal to μ_K in the average sense. Hence, the reference power P_0 is set as:

$$P_0 = \frac{\mu_K \gamma_T \nu}{\kappa r_c^{-n}}. \quad (31)$$

  Despite the additional power margin term, $10^{\zeta/10}$ in (30), the total required power can be larger than P_T when K is larger than μ_K, or the users close to the cell boundary undergo deep fading. In this case, the number of supported users is limited, as seen in (26).
- *Only traffic density (oTD)-based P_0:* In this criterion, the reference power P_0 is irrespective of the cell radius and is determined only by the traffic density. Hence, r_c in (31) is replaced by a constant r_0. This criterion results in a higher call drop rate compared to CRnTD-based power setting for the case when the number of far users whose distances from the SBS are greater than r_0 increases. The aim of this criterion is to prevent an excessive increase in SBS power by dropping calls from users far from the SBS.

A. Comparison between FD and HD and boundary of their preferred regions

Prior to assessing the performance under the target SINR constraint, let us see a preliminary result for the performance under the same power condition. Fig. 2 shows the capacity of HD $C_{\text{HD},k}$ in (3) and the mean capacity of FD $C_{\text{FD}}^{(m)}$ over the plane of (r_c, β), when the transmission powers for FD are not those in (6) but are set equal to those for HD given in (2). To obtain the mean capacity, 10^4 random combinations of $\left[K, \overline{G}, \overline{H}\right]$ are generated for each point of (r_c, β) and this is common to all the simulation results in this paper. In accordance with the discussion in Section III-B, it is shown that FD achieves lower capacity compared to HD under the same power condition.

Fig. 3 shows the capacity of HD and the mean capacity of FD under the target SINR constraint, i.e., $C_{\text{HD},k}$ in (3) and $C_{\text{FD}}^{(m)}$ in (15), over the plane of (r_c, β). To evaluate ${}_2\text{F}_1(a, b; c; z)$ in (12), we use the compact approximate in (13). For reference, the simulation result for $C_{\text{FD}}^{(m)}$ is also included. A two-dimensional version is plotted in the lower subfigure, where the cell radius is taken as the x-axis on a linear scale. It is shown that $C_{\text{FD}}^{(m)}$ in (15) almost perfectly matches the simulation result in the small-cell radius range. This confirms

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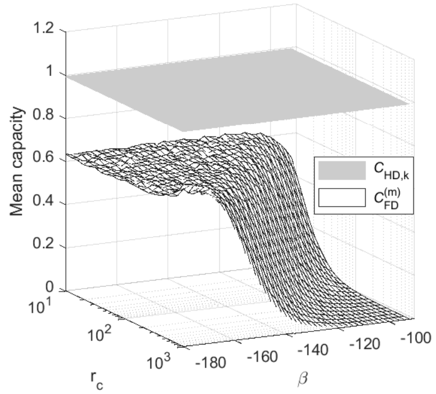

Fig. 2: Mean capacities of HD and FD over (r_c, β) plane under same power consumption.

that the approximation, that is, $d_{m,k} \approx D$, employed in (10) to get (11), works well in the small-cell radius range. As r_c increases, the derivation deviates from the simulation result. This is because $d_{m,k}$ ranges from $D - r_c$ to $D + r_c$; thus, the approximation ($d_{m,k} \approx D$) becomes unacceptable as r_c increases. Most differently from Fig. 2, FD outperforms HD for small β and small r_c due to intrinsic benefit of FD, i.e., doubled spectral efficiency. As expected, as β increases, FD becomes worse because there is less cancellation of SI, and it eventually reaches a lower capacity compared to HD. Furthermore, as r_c increases, FD becomes even worse because the larger distance between the users and the SBS requires a larger $p_{s,k}$, which causes a larger residual SI in the backhaul link.

Fig. 4 shows the simulation results of $C_{\text{HD}}^{(m)}$ and $C_{\text{FD}}^{(m)}$ for the total power-limited case with CRnTD-based P_0, $\zeta = 4$ and $\zeta = 0$. While the trend of $C_{\text{FD}}^{(m)}$ on β and r_c holds as it does without the power limit in Fig. 3, it is shown that due to the power limit, the capacity decreases in both of HD and FD. In particular, FD becomes severely worse in the FD-preferred region, so the FD gain decreases. This is because FD requires higher transmission power than HD to compromise in-band SI for a target SINR as shown in (6) and thus, under the total power constraint, the call drops in FD will happen more frequently than in HD.

At each r_c in Fig. 3 and Fig. 4, there is a corresponding threshold for β above which HD achieves a higher capacity than FD. This threshold has been denoted by β_0 in (17). Fig. 5 shows the simulated β_0 results as a function of r_c for different cases of P_T (ζ), μ_K, n, f_c, and γ_T. For reference, the derived β_0 in (17) is also included and is shown to approximate the simulation results quite well, although it was obtained by assuming path loss-only channel gain in addition to the approximation of $d_{m,k} \approx D$. Remarkably, although the total power-constraint degrades the capacities of both HD and FD, as shown in Fig. 4, it has almost no impact on β_0. This is also confirmed from the observation that the crossing lines of the capacity surfaces for HD and FD in Fig. 3 and Fig. 4 are invariant. In addition, β_0 is also invariant to μ_K. Therefore, the equation for β_0 in (17) universally holds for the various

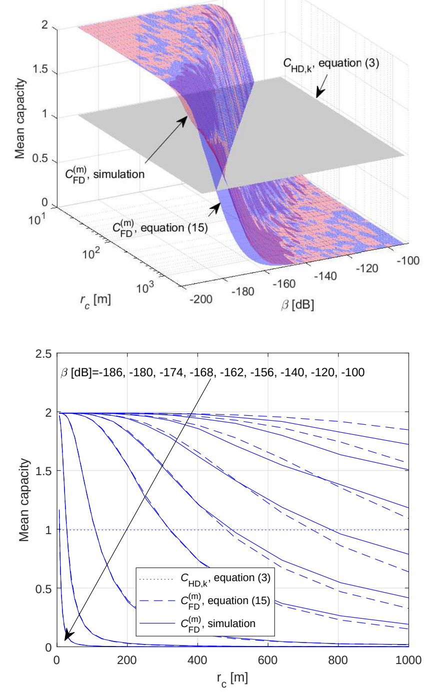

Fig. 3: Mean capacities of HD and FD over (r_c, β) plane under the target SINR constraint (upper subfigure), and its two dimensional version (lower subfigure).

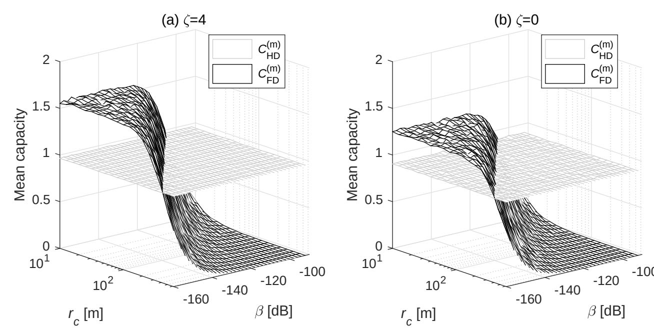

Fig. 4: Mean capacities of HD and FD over the (r_c, β) plane in total power-limited cases, CRnTD-based P_0.

systems with different system parameters. Comparing β_0 for $\gamma_T = 3$ dB and $\gamma_T = 8$ dB confirms that the decrement of β_0 (10 dB) is double the increment of γ_T (5 dB).

Note that in Figures 2, 3 and 4, HD achieves a constant capacity irrespective of the cell radius. This is because unlike FD, there is no SI or IBI for HD. Hence, as long as the SBS has enough power to compensate for the path loss to the users, every user can achieve the target SINR by the appropriate power allocation irrespective of the location in the cell. In addition, for the total-power-limited case in Fig.4, we adopted the CRnTD-based P_0 setting in which the total power limit is inversely proportional to the path loss of the user at the cell boundary, as shown in (31). Hence, the total power limit increases accordingly as the cell radius increases. Consequently, the average capacity of HD is maintained to be

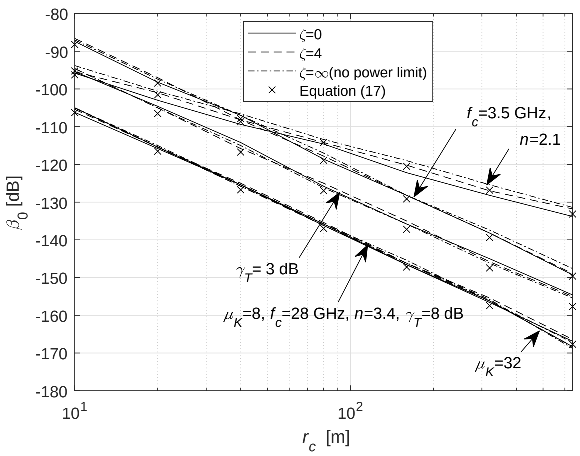

Fig. 5: β_0 versus r_c.

identical irrespective of the cell radius. This is not the case for oTD-based P_0 settings. Fig. 6 shows the results of $C_{\text{HD}}^{(m)}$ and $C_{\text{FD}}^{(m)}$ for the total-power-limited case with oTD-based P_0 with r_0= 50 m. In contrast to the case with CRnTD-based P_0 in Fig. 4(a), both $C_{\text{FD}}^{(m)}$ and $C_{\text{HD}}^{(m)}$ decrease as the cell radius r_c increases. This is because for an oTD-based P_0 setting, the power limit is fixed irrespective of the cell radius. Therefore, as the cell radius increases, the total power becomes insufficient to compensate the path losses of the far users from the SBS and thus, the probability of call drop accordingly increases. On the contrary, as r_c decreases, $C_{\text{FD}}^{(m)}$ is higher than that in Fig. 4(a). This is because for r_c smaller than r_0, more power is available than the case with CRnTD-based P_0 in Fig. 4(a) and thus fewer calls are dropped. However, it is remarkable that the FD-preferred and HD-preferred regions remain roughly the same as those in Fig. 4(a).

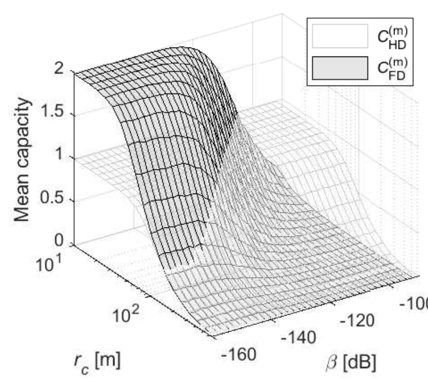

Fig. 6: Mean capacities of HD and FD over (r_c, β) plane in total-power-limited case, oTD-based P_0 with r_0=50 m, $\zeta = 4$.

B. Capacity gain of Opportunistic FD

In Fig. 7, $C_{\text{OFD}}^{(m)}$ in (21) is overlaid on $C_{\text{FD}}^{(m)}$ and $C_{\text{HD},k}$ in Fig. 3 for comparison. The simulated $C_{\text{OFD}}^{(m)}$ is also included. It shows that $C_{\text{OFD}}^{(m)}$ in (21) matches quite well with the simulation results. Overall, the proposed OFD substantially outperforms FD and HD in (HD-preferred) and FD-preferred regions, respectively. For reference, Fig. 7 includes the results for FD in [20] where $p_{s,k}$ is optimized for maximum capacity. FD in [20] does not drop calls, even with a lower SINR than the target SINR, so it achieves higher capacity compared to FD with $p_{s,k}$ in (6) in Section III-B, which achieves the target SINR. However, FD in [20] still becomes even worse than HD, not to mention OFD, as β increases or r_c increases. This contradicts the result in [20] where, with an optimized transmit power in FD mode, FD and the hybrid (opportunistic) duplex achieve the identical mean capacity. This is because it was not considered in [20] that the path loss compensation for the users far from the SBS causes high SI in FD, which seriously degrades FD despite the power optimization.

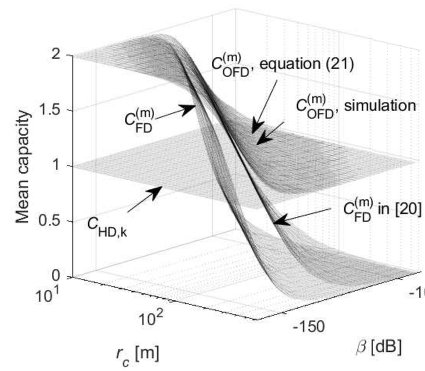

Fig. 7: Mean capacities of HD, FD, and proposed OFD, CRnTD-based P_0.

Note that $C_{\text{HD}}^{(m)}$, $C_{\text{FD}}^{(m)}$ and $C_{\text{OFD}}^{(m)}$ in Fig. 7 are obtained under the target SINR constraint without the transmission power constraint. If the transmission powers for FD are set equal to those for HD, the capacity gain of FD against HD disappear as shown in Fig. 2. Also, the capacity gain of OFD against HD disappears as well, because FD and HD are alternatively used in OFD. This implies that if the target SINR needs to be met for a successful link connection, the power constraint for the individual links needs to be relaxed for FD and OFD, and a different form of power constraint such as the total power limit needs to be considered for a meaningful comparison with HD as we applied in Fig. 4 and Fig. 6. Fig. 8 shows the simulation results of $C_{\text{HD}}^{(m)}$, $C_{\text{FD}}^{(m)}$ and $C_{\text{OFD}}^{(m)}$ for the total power-limited cases with $\zeta = 4$ and $\zeta = -4$. Note that the proposed OFD scheme recovers to some extent the reduced capacity of FD in the FD-preferred region caused by total power limit which was observed in Fig. 4. The relative gain of the proposed OFD over FD is emphasized more as the total power limit gets tighter. This is because if the required power for FD is very high for a certain user, the proposed OFD selects HD for that user, whereas the FD scheme always sticks to FD without considering possible call drops of the other active users due to insufficient power.

When a call is successful in FD, FD needs higher power at an SBS (compared to HD) in order to compromise the SI. Accordingly, the OFD requires a higher mean power than HD because FD and HD are alternatively used in OFD. Hence, for

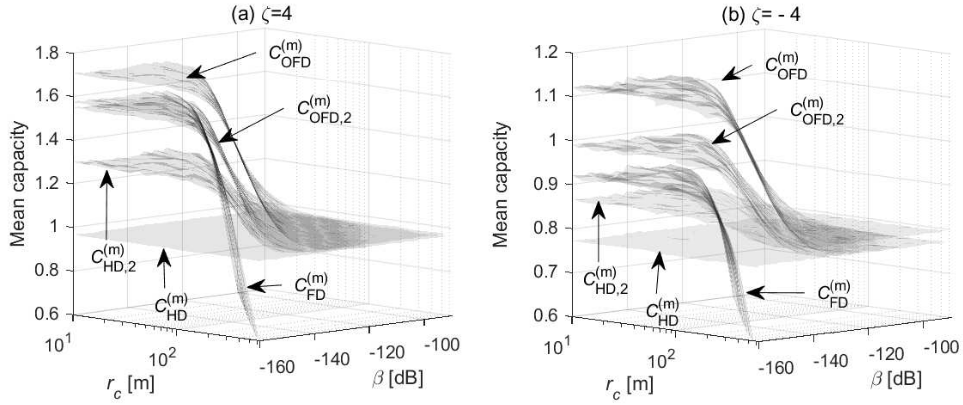

Fig. 8: Mean capacities of HD, FD and the proposed OFD with the power constraint, CRnTD-based P_0.

a comparison under a mean power constraint in addition to the total power constraint, we consider the modified version of HD, to which more power is allocated so that the mean power of HD is equal to that of OFD. The mean capacity of this modified HD is denoted by $C^{(m)}_{\mathrm{HD},2}$ and is included in Fig. 8. As expected, $C^{(m)}_{\mathrm{HD},2}$ is higher than $C^{(m)}_{\mathrm{HD}}$ in the HD-preferred region. However, the gain of $C^{(m)}_{\mathrm{OFD}}$ over $C^{(m)}_{\mathrm{HD},2}$ is still substantial.

Fig. 8 also includes the mean capacity of the reduced feedback version of the proposed OFD in Section V-B, which does not need MBS-to-user channel gain information $(= H_k)$ from the users. The mean capacity of this version is denoted as $C^{(m)}_{\mathrm{OFD},2}$. The capacity degradation is significant, compared to the original OFD, but the capacity gain over HD or FD is still meaningful considering the more feasible implementation.

Fig. 9 shows η_{OFD} over the (r_c, β) plane. In Fig. 9.a which corresponds to no power limit case, the derivation result in (23) is also plotted and shows nice matching with the simulation result. The contour lines of the peak in Fig. 9 coincide with the graph of β_0 vs. r_c in Fig.5. This confirms the conclusion made from (23), i.e., the capacity gain of the proposed user-wise OFD over the static duplex switching scheme is maximized at the boundary of FD-preferred and HD-preferred regions. Although the total power constraint slightly reduces η_{OFD} from its maximum of 1.5 (η_{OFD}=1.47 for $\zeta = 4$, η_{OFD}=1.42 for $\zeta = 0$), the peak still occurs along the curve of β_0 vs. r_c. As the power limit gets tighter, the capacity gain of OFD is relatively more amplified in the FD-preferred region. This is due to the large capacity loss of FD by total power limit.

VIII. Conclusions

In this paper, the capacity gain of FD self-backhauling over its HD counterpart was derived as a function of the system parameters in a computationally tractable form. Also, the condition under which FD is more beneficial than HD was derived. To overcome the weak points of FD and HD, a user-wise opportunistic FD self-backhauled scheme was proposed. It was confirmed that there is a substantial capacity gain of the proposed OFD over a cell-wise static duplex switching scheme as well as fixed duplex schemes. Although the total power constraint slightly reduces the capacity gain of the proposed OFD over the cell-wise static duplex switching scheme from its maximum of 1.5, the peak still occurs along the derived boundary of the FD-preferred and HD-preferred regions.

In addition, by using the derived boundary of the FD-preferred and HD-preferred regions, an important guideline is provided for selecting the most practical scheme among OFD, FD, and HD by trading off capacity gain and switching overhead. Overall, the proposed OFD scheme and the guideline could be a promising solution to increase the capacity of the forthcoming self-backhauled cellular systems.

Appendix A
Derivation of $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$

Because α_k as well as $d_{s,k}$ in (11) are random variables, $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ can be calculated as

$$\begin{aligned} \eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} &= 2\int_{-\infty}^{\infty}\left(\Pr\left[d_{s,k} < \left(\frac{\kappa\alpha_k}{\gamma_T^2\beta}\right)^{1/n} \mid \alpha_k = x\right]\right) f_{\alpha_k}(x)\mathrm{d}x \\ &= 2\int_{-\infty}^{\infty}\left(\int_{-\infty}^{\left(\frac{\kappa x}{\gamma_T^2\beta}\right)^{1/n}} f_{d_{s,k}}(y)\mathrm{d}y\right) f_{\alpha_k}(x)\mathrm{d}x \end{aligned} \tag{32}$$

where $f_{\alpha_k}(x)$ and $f_{d_{s,k}}(y)$ are the probability density functions (PDFs) of α_k and $d_{s,k}$, respectively. Because the locations of the users are modeled as an independent PPP, they are uniformly distributed in a cell, and thus, $f_{d_{s,k}}(x) = 2x/r_c^2$ for $0 \le x \le r_c$, and $f_{d_{s,k}}(x) = 0$ otherwise. By substituting $f_{d_{s,k}}(x)$ into (32), the inner integrand term in (32) is calculated as

$$\begin{aligned} &\int_{-\infty}^{\left(\frac{\kappa x}{\gamma_T^2\beta}\right)^{\frac{1}{n}}} f_{d_{s,k}}(y)\mathrm{d}y \\ &= \begin{cases} \left(\frac{\left(\kappa x/\left(\gamma_T^2\beta\right)\right)^{1/n}}{r_c}\right)^2 & \text{if } \left(\kappa x/\left(\gamma_T^2\beta\right)\right)^{1/n} \le r_c \\ 1 & \text{else.} \end{cases} \end{aligned} \tag{33}$$

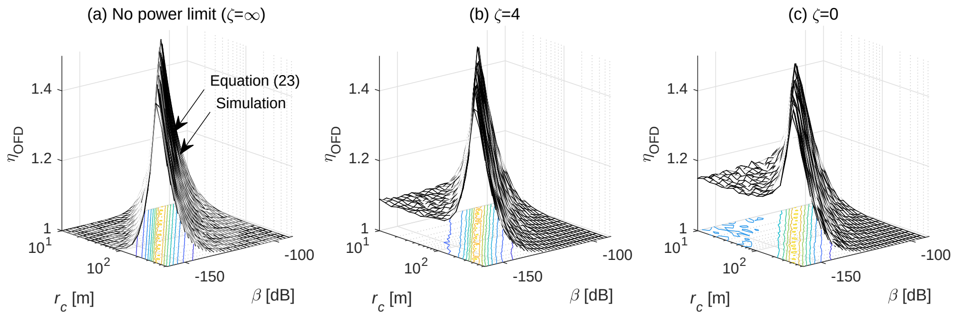

Fig. 9: Capacity gain of the proposed user-wise opportunistic OFD over the cell-wise static duplex switching scheme, CRnTD-based P_0.

To calculate the outer integration in (32), we need to derive $f_{\alpha_k}(x)$ in closed form. To this end, we start by deriving the cumulative distribution function (CDF) of α_k as follows:

$$\begin{aligned}\Pr[\alpha_k \le x] &= \Pr\left[g_k/h_k \le x\right] = \Pr\left[g_k \le x h_k\right] \\ &= \int_{-\infty}^{\infty} \Pr\left[g_k \le xy\right] f_{h_k}(y) \mathrm{d}y \\ &= \begin{cases} \frac{x}{1+x} & \text{if } x \ge 0 \\ 0 & \text{else} \end{cases} \end{aligned} \tag{34}$$

where we use the fact that g_k and h_k follow an exponential distribution. From the relation between the PDF and the CDF, we have

$$f_{\alpha_k}(x) = \frac{\mathrm{d}}{\mathrm{d}x}\left(\Pr[\alpha_k \le x]\right) = \begin{cases} \frac{1}{(1+x)^2} & \text{if } x \ge 0 \\ 0 & \text{else.} \end{cases} \tag{35}$$

Substituting (33) and (35) into (32), we have

$$\begin{aligned}\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}} &= 2\int_0^{x_0} \left(\left(\kappa x/\left(\gamma_T^2 \beta\right)\right)^{1/n}/r_c\right)^2 \frac{1}{(1+x)^2}\mathrm{d}x \\ &+ 2\int_{x_0}^{\infty} \frac{1}{(1+x)^2}\mathrm{d}x \end{aligned} \tag{36}$$

where x_0 is a maximum x satisfying the condition $\left(\kappa x/\left(\gamma_T^2\beta\right)\right)^{1/n} \le r_c$, and thus,

$$x_0 = (\gamma_T^2 \beta r_c^n)/\kappa. \tag{37}$$

Using the integration formula for the first integrand in (36), we can derive a compact expression for $\eta_{\frac{\mathrm{FD}}{\mathrm{HD}}}$ as (12).

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Kwonhue Choi received the B.S., M.S., and Ph.D. degrees in electronic and electrical engineering from the Pohang University of Science and Technology, Pohang, South Korea, in 1994, 1996, and 2000, respectively. From 2000 to 2003, he was with the Electronics and Telecommunications Research Institute, Daejeon, South Korea, as a Senior Research Staff Member. In 2003, he joined the Department of Information and Communication Engineering, Yeungnam University, Gyeongsan, South Korea, where he is currently a Professor. He has authored a text book Problem-Based Learning in Communication Systems Using MATLAB and Simulink (Wiley, 2016). His research areas include signal design for the communication systems, multiple access schemes, diversity schemes for wireless fading channels, multiple antenna systems and in-band full duplex systems.