Full-Duplex Cellular Networks

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Abstract

Full-duplex (FD) communications with simultaneous transmission and reception on the same carrier have long been deemed a promising way to boost spectrum efficiency, but hindered by the techniques for self-interference cancellation (SIC). Recent breakthroughs in analog and digital signal processing yield the feasibility of over 100 dB SIC capability, and make it possible for FD communications to demonstrate nearly doubled spectrum efficiency for point-to-point links. Now it is time to shift at least partially our focus to FD networking, such as in cellular networks. FD networking has more complicated interference environments. Therefore, its performance improvement is not that straightforward compared with half-duplex networking. Before putting FD networking into practice, we need to understand to which scenarios FD communications should be applied under the current technology maturity, how bad the performance will be if we do nothing to deal with the newly introduced interference, and most importantly, how much improvement could be achieved after applying advanced interference management solutions. We will discuss all these questions in this article. In particular, we will investigate advanced interference management solutions, including power control and user scheduling, and show that up to 91 percent spectrum efficiency gain and 110 percent energy efficiency gain of FD cellular networks over its HD counterpart can be achieved by applying these solutions.

Introduction

To satisfy the surging traffic demand, mobile networks are facing unprecedented challenges to further improve their efficiency of spectrum usage. Currently, mobile networks operate in a half-duplex (HD) mode, which implies only one direction transmission on a frequency carrier at any time and no extra cost for spatial separation. For example, the base station (BS) can transmit to users (downlink (DL)) at one time and frequency radio resource, and receive from users (uplink (UL)) at another. These time and frequency radio resources are also known as channels. They can be separated by time or frequency dimension, called time-division duplex (TDD) or frequency-division duplex (FDD) mode, respectively. On the other hand, transmission and reception on the same channel at the same time, also known as full-duplex (FD) communication, has long been dreamed of but has been hindered by strong self-interference from a node's transmitter to its receiver. In an FD transceiver, the self-interfering signal from its transmitter is usually 100 dB stronger than the intended receiving signal. As hard as trying to hear a whisper while shouting at the top of your lungs, strong self-interference in an FD system will easily cause the radio chain at the receiver to be saturated [1] and unable to work properly, not to mention decoding the data.

However, recent breakthroughs in analog and digital signal processing facilitate the real application of FD communications. It is now feasible to have up to 110 dB self-interference cancellation (SIC) capability [2]. Therefore, self-interference is mostly removed with the residual strength reduced to the same level as the signal of interest before going through the decoding chain at the receiver, which makes data decoding feasible. As a result, there have been many real-time FD prototypes reported [2–5].

While roughly doubled throughput has been reported for single-link FD transmission [5], the performance improvement of FD networks is not that straightforward due to the new interference introduced by FD links. The deployment of FD networking needs to consider the following two factors. First, it is still costly to equip FD functionality with above 100 dB for all user equipment (UE), so most of the UEs may still work in HD mode at least in the near future. Therefore, we assume only BSs work in FD mode. Second, coexistence of both UL and DL transmission on the same channel at the same time in all cells introduces far more complicated interference, as illustrated in Fig. 1. From Fig. 1, besides the inter-cell BS-to-UE and UE-to-BS interference that already exists in HD networks, dynamic TDD networks[1] [6] and FD networks experience extra inter-cell inter-BS and inter-UE interference. Furthermore, FD networks face intra-cell inter-UE interference as well as residual self-interference after SIC. Hence, smart interference management techniques are necessary to deal with various types of interference and ensure performance improvement of FD networks compared with HD networks [7–11]. Therefore, given the current SIC and interference management capability, it is critical to carefully select application scenarios for FD communications and design protocols and algorithms to deal with the newly introduced interference.

Scope and Key Findings

In this section, we will first introduce the metrics for the performance evaluation of FD cellular networks and then briefly summarize our findings to facilitate FD cellular networks.

[1] In dynamic TDD networks, different BSs are designed to have the flexibility to configure different UL and DL subframe patterns, which aims to better adapt to dynamic variations in DL/UL traffic demands on the BS basis.

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Scope and Evaluation Framework

There is a wide consensus that applying FD communications to macrocells is not a good candidate scenario because of the large transmission power of macro BSs imposed by the large coverage requirement [9]. Direct calculation yields that above 140 dB SIC is required to bring down the transmission signal to a level of –100 dB [9] for the macro BSs transmitting at 46 dBm. Instead, the architectural progression toward short-range systems, such as small-cell (e.g., picocells) systems where the cell-edge path loss is less than that in macrocell systems, makes the self-interference reduction problem much more manageable. Therefore, in this article, we focus on cellular networks with pico BSs operating in FD mode while leaving macro BSs and UEs in HD mode. We will analyze how serious the problem could be if we directly introduce FD communications to the pico BSs in heterogeneous networks, and how effective different interference management strategies may be.

We use the two important indicators for system performance evaluation, i.e., system spectrum efficiency (SE) and system energy efficiency (EE). The system SE is defined as the overall UL and DL throughput per unit bandwidth. Mathematically, it is given by

$$SE = \frac{T_{\text{tot}}^{\text{UL}} + T_{\text{tot}}^{\text{DL}}}{B_{\text{tot}}}, \qquad (1)$$

where $T_{\text{tot}}^{\text{UL}}$, T_{tot} and $B_{\text{tot}}^{\text{DL}}$ indicate the UL and DL throughput and the allocated bandwidth, respectively. On the other hand, the system EE is defined as the aggregated bits transmitted in both UL and DL in unit bandwidth per joule energy consumed. Here we only consider transmission energy and ignore signal processing energy since the previous "air interface" radiated power is more tightly related to interference management strategies involved in the article. Then it could be mathematically formulated as

$$EE = \frac{\left(T_{\text{tot}}^{\text{UL}} + T_{\text{tot}}^{\text{DL}}\right) \times T_i / B_{\text{tot}}}{E_{\text{tot}}^{\text{UL}} + E_{\text{tot}}^{\text{DL}}} = \frac{SE}{P_{\text{tot}}^{\text{UL}} + P_{\text{tot}}^{\text{DL}}}, \qquad (2)$$

where E_{tot} and P_{tot} stand for energy and power consumption, respectively, T_i denotes the transmission time, thus $E_{\text{tot}} = P_{\text{tot}} \times T_i$. In Eq. 2, the superscripts UL and DL are used to indicate the UL and DL energy, power, and throughput. From Eq. 2, system SE and EE are correlated. It has been demonstrated that there exists an interesting SE-EE tradeoff relationship in different types of networks, since the maximization of total SE and the minimization of the total P_{tot} are usually not achieved at the same time. In this article, we will investigate the behavior of such a relationship in FD networks.

Key Findings

In the rest of the article, we start our evaluation from a single-cell FD network. An optimization problem is formulated to maximize the system SE with the transmission power and user selection as control variables. We will show a surprising observation from the analytical solution, that for a given pair of UL and DL UEs, the power control for both the BS and the selected UL UE has a binary feature, i.e., either transmitting at its full power level or completely muting. Based on this observation, a joint power control and user selection problem reduces to a UE scheduling problem only, and interference awareness will play an important role in such a process. As a step further, we investigate multi-cell FD networks and identify the dominant interference for different network configurations based on system level simulations. We will demonstrate through system SE and EE evaluation that up to 91 percent SE gain and 110 percent EE gain can be achieved with different interference management schemes. In other words, FD networking will work, at least for the considered heterogeneous network setting with 110 dB SIC capability.

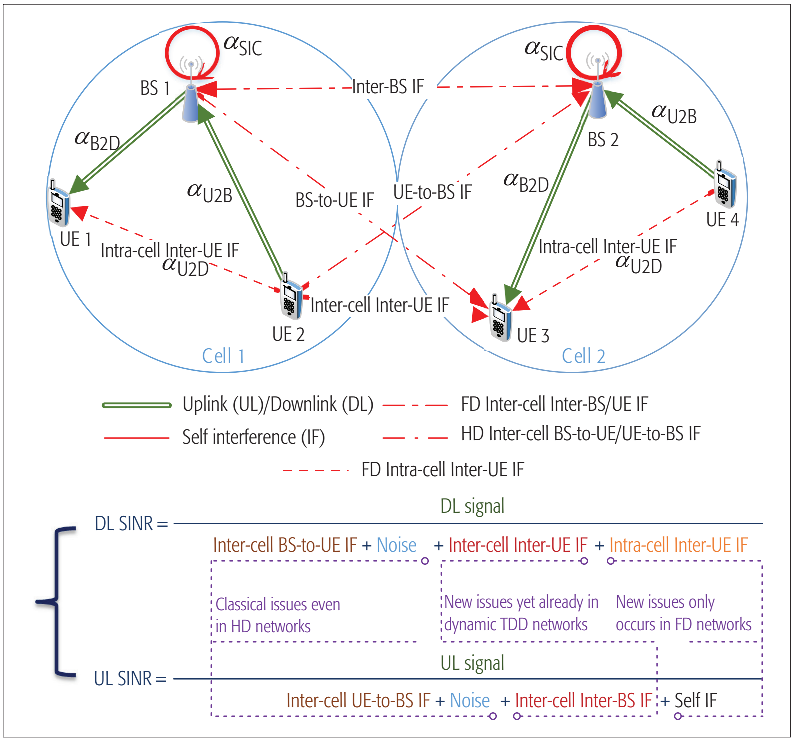

Figure 1. An illustration of different types of interference in FD networking.

Single-Cell FD Network

In a single-cell FD network, the interference situation is much less complicated. However, as shown in Fig. 1, the FD network still needs to deal with the intra-cell interference from UL UE to DL UE and the residual self-interference at the transceiver of the BS. In this case, the problem to maximize the total system throughput of both UL and DL can be formulated as follows,

$$\max_{i,j,P_i^{\text{DL}},P_j^{\text{UL}}} \quad f = \log\left(1 + \frac{\alpha_{\text{B2D}} P_i^{\text{DL}}}{N_0 + \alpha_{\text{U2D}} P_j^{\text{UL}}}\right) + \log\left(1 + \frac{\alpha_{\text{U2B}} P_j^{\text{UL}}}{N_0 + \alpha_{\text{SIC}} P_i^{\text{DL}}}\right)$$

$$s.t. \quad 0 < P_i^{\text{DL}} \le P_{\max}^{\text{DL}}, 0 < P_j^{\text{UL}} \le P_{\max}^{\text{UL}}, \qquad (3)$$

where N_0 denotes the noise power, P_i^{DL} and P_j^{UL} denote the transmission power of the BS (to DL UE i) and UL UE j, and are limited by the corresponding maximum values $P_{\max}^{\text{DL}}$ and $P_{\max}^{\text{UL}}$, respectively, α_{B2D}, α_{U2D}, and α_{U2B} characterize the

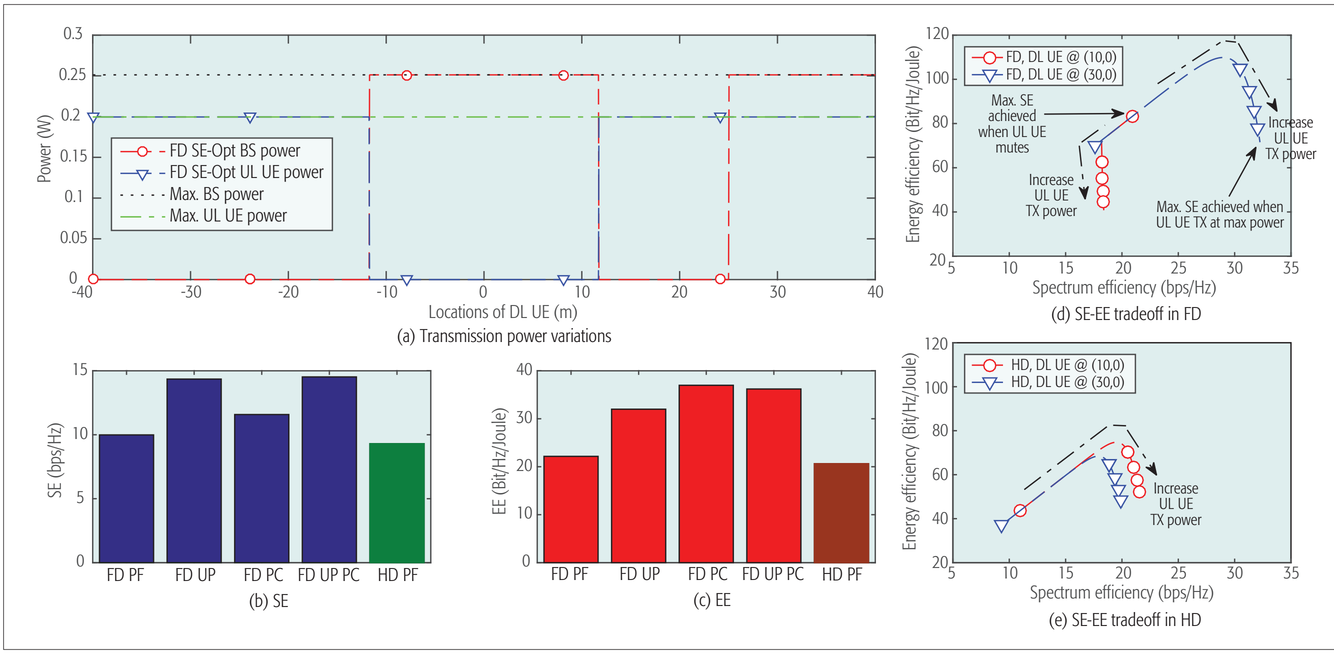

Figure 2. Performance of single-cell network: a) the optimal transmission power of the pico BS and the UL UE in terms of SE maximization; b, c) the SE and EE performance improvement of FD network over HD network under power control (PC) and/or user pairing (UP); d, e) the SE-EE relation for with a given pair of UL and DL UEs at different positions.

Key Findings: (1) For a given pair of UEs, the SE-optimized power control result has a binary feature. (2) The SE-EE relationship in single-cell FD network is dependent on the positions of UEs and might be different from that in HD network.

channel power gains from the BS to the DL UE, from the UL UE to the DL UE, and from the UL UE to the BS, respectively, and will be affected by UL and DL UE scheduling. α_{SIC} indicates the SIC capability. Notably, we do not consider fast fading in these channels, and also regard the self-interfering channel after SIC as a line-of-sight channel with the pathloss equaling the SIC capability.[2]

In this section, we will first dive into the power control problem with only one given pair of UL and DL UEs, and then extend to a multiple UE situation and investigate the problem of UE scheduling. Finally, we will provide the system-level analyses for its SE and EE performance, as well as the tradeoff between them.

Binary Power Control

For a given UL and DL UE pair, the problem in Eq. 3 reduces to joint optimization of the transmission powers of the BS and the UL UE. Without loss of generality, when the transmission power of the UL UE, P_j^{UL}, is fixed, by taking the derivative of Eq. 3 with respect to the transmission power of the BS, P_i^{DL}, we can find that there exists at most one minimum point and no maximum point in the interval $[0, P_{\max}^{\mathrm{DL}}]$ for the function in Eq. 3. Therefore, the optimal value for P_i^{DL} to maximize the sum rate lies at the two end points of the interval, i.e., 0 or $P_{\max}^{\mathrm{DL}}$. Hence, the BS either transmits no signal to turn the network into HD mode or with the maximum power level. A similar result can be obtained for the transmission power of the UL UE. The joint optimization of both, as a generalized case, offers three solution candidate pairs: $(0, P_{\mathrm{UEmax}})$, $(P_{\mathrm{BSmax}}, 0)$, and $(P_{\mathrm{BSmax}}, P_{\mathrm{UEmax}})$, which shows exactly the binary feature and demonstrates appealing computational efficiency to obtain the solution in Eq. 3.

To demonstrate the binary power control feature more clearly, Fig. 2 depicts our simulation results. In our simulation, the pico BS and the UL UE are located at (0,0) and (–25,0), respectively, and other parameters are set as in Table 1. By moving the DL UE along the horizontal axis from (–40,0) to (40,0), we show the optimal power control solutions for both the UL UE and the BS under 110 dB SIC capability [2] in Fig. 2a. Here, instead of applying our analytical observation above, we perform optimization by exhaustive search. From Fig. 2a, to achieve the maximum system SE, the BS and the UL UE either transmit at their maximum power levels or just mute to fall back to HD mode, which is consistent with our analytical observation. Moreover, Fig. 2a also implies that along with the moving of the DL UE, the system will fall back to HD mode for most of the DL UE positions. Hence, for the network with multiple UEs, it is essential to schedule one UL UE and one DL UE to form a pair in FD mode and thus obtain a larger SE gain.

Interference-Aware User Scheduling

Given the binary feature of power control, the SE maximization problem in Eq. 3 reduces to a UE scheduling problem, namely, for a given time-frequency resource, how to select one UL UE and one DL UE from all active UEs to properly work together. Basically, there have been many existing scheduling methods in the HD network, such as proportional fairness (PF) [7] and round-robin, which the FD network could directly take advantage of. For example, the FD network could follow the standard PF procedure to select DL UE and UL UE independently and pair them. However, the ignorance of inter-UE interference in such a method could degrade the performance. Further-

[2] Usually, Rician fading has been leveraged to model the channel after analog cancellation [12], and it is also found that the residual self-interference after SIC follows circular symmetric complex normal distribution.

more, our simulation results will show that interference awareness should be an important feature for the UE pairing process. There are different levels of interference awareness and also various procedures to achieve that awareness. If we can track the inter-user interference channel fast enough, the short-term interference can be captured, which would be best for performance but with the highest overhead in tracking such information. On the other hand, we may only exploit long-term statistics of interference, such as the path-loss, which can be easily derived from the relative user positions. In this case, the interference-aware user scheduling problem turns into a distance-aware problem, and has been investigated in [11, 13].

Here we give an example of a distance-aware joint PF UE pairing algorithm, in which the BS takes turns to select the first user sorted by the PF criterion in the UL or the DL, and then pairs a DL or UL UE with the largest distance. To show the benefit of the binary power control (PC for short) and distance-aware joint PF UE pairing (UP for short) schemes, we simulate a single-cell FD network with eight randomly deployed UL or DL UEs. Without loss of generality, the baseline HD network in our simulation is assumed to work in FDD mode, i.e., the UL or the DL uses half of the total bandwidth. Meanwhile, despite the existence of advanced user scheduling methods applicable to the HD networks as well, we only consider the standard PF method for the HD networks here as an example. The system SE and EE under different strategies are shown in Fig. 2b and Fig. 2c, respectively. From the figures, the FD network shows trivial gain over the traditional HD network without power control or UE pairing. However, when either power control or UE pairing is used, the performance gain can be significantly improved. In particular, the joint power control and UE pairing scheme can provide around 45 percent and 60 percent boost in system SE and EE, respectively.

SE-EE Relationship

As before, we consider one BS with a given UL and DL UE pair but at different locations and find the SE-EE relationship by varying the transmission power of the UL UE from 0 to 23 dBm while fixing the transmission power of the BS. Figure 2d and Fig. 2e demonstrate the SE-EE relationship for the FD and HD networks, respectively. From the figures, the shape of the SE-EE relation does not change with the UE locations in the HD network since there is no interference between the UL UE and the DL UE. However, due to the inter-user interference in the FD network, the relative location between the UL and DL UEs significantly affects the SE-EE relationship, which confirms the effectiveness of the proposed UE pairing method with location awareness. Moreover, for different UE locations, the maximum system SE is derived either when the UL UE transmits at its maximum power or when it is completely muted, which again aligns with our binary power control results in Fig. 2a. In brief, different from the HD network, the SE-EE relationship for the FD network will be dependent on the positions of the UEs. Nevertheless, with advanced interference management strategies in the FD network, EE performance can be improved by around 60 percent when the maximized SE is increased by around 45 percent.

Category	Sub-category	Configuration
TTI		1 ms
Bandwidth		UL or DL in HD: 10 MHz; UL or DL in FD: 20 MHz
Topology	Macro	500 m inter-site distance (ISD) at static positions with three sectors
	Pico	3, 6, …, or 18 picos uniformly distributed in 500 m-ISD macro's region
	UE	*Uniform:* 192 users uniformly distributed in 500 m-ISD macro's region
		Clustered: eight users uniformly distributed in 40 m-radius picocell's region
Propagation model	Pathloss	Strictly following Table A. 1-3 in 3GPP TR 36.828 [14]
	Shadowing	Macro to pico: 6 dB; macro to UE: 10 dB; pico to UE: 10 dB
		UE to UE: 12 dB; pico to pico: 6 dB
	Noise figure	Macro: 5 dB; pico: 13 dB; UE: 9 dB
Maximum transmission power		Macro: 46 dBm; pico: 24 dBm; UE: 23 dBm
SIC capability		50 dB to 120 dB, 110 dB by default
Cell range extension (bias)		6 dB
Proportional fairness		Window length: 500; exponent factor: 0.05

Table 1. Main parameters in the system-level simulator, which are compatible with 3GPP TR 36.828 [14].

Multi-Cell FD Networks

In this section, we investigate multi-cell FD networks. As illustrated in Fig. 1, multi-cell FD networks suffer from more complicated interference. Therefore, we first take a look at how bad the interference situation is and which type of interference is dominant. Then we will discuss which solution is most effective, especially to deal with the dominant interference, and how much gain we might expect in terms of system SE and EE from the FD networks.

As mentioned earlier, we consider a multi-cell heterogeneous network with the macro BSs working in HD mode and the pico BSs working in FD mode. System-level simulations are used to answer the aforementioned questions. Specifically, seven macro BSs in total are located at the vertices and the center of a hexagon, and the pico BSs are randomly scattered in each sector of the macro BSs [14]. The system parameters are listed in Table 1. Moreover, we consider two network configurations:

- *Uniform Case*: UEs are uniformly dropped in the coverage of the macro BSs and associate with the macro BSs or the pico BSs following the standard strongest received signal strength (RSS) criterion. Besides, cell range expansion toward the pico BSs is leveraged by virtually adding 6 dB bias to the received power of the pico BSs. Moreover, the macro BSs and the pico BSs operate in the same band.
- *Clustered Case*: UEs are uniformly dropped in the coverage of the pico BSs and only associated with the pico BSs. In other words, randomly distributed UEs form different clusters, and the positions of UEs in each cluster are limited to the range of one pico BS. The macro BSs and the pico BSs operate in different bands.

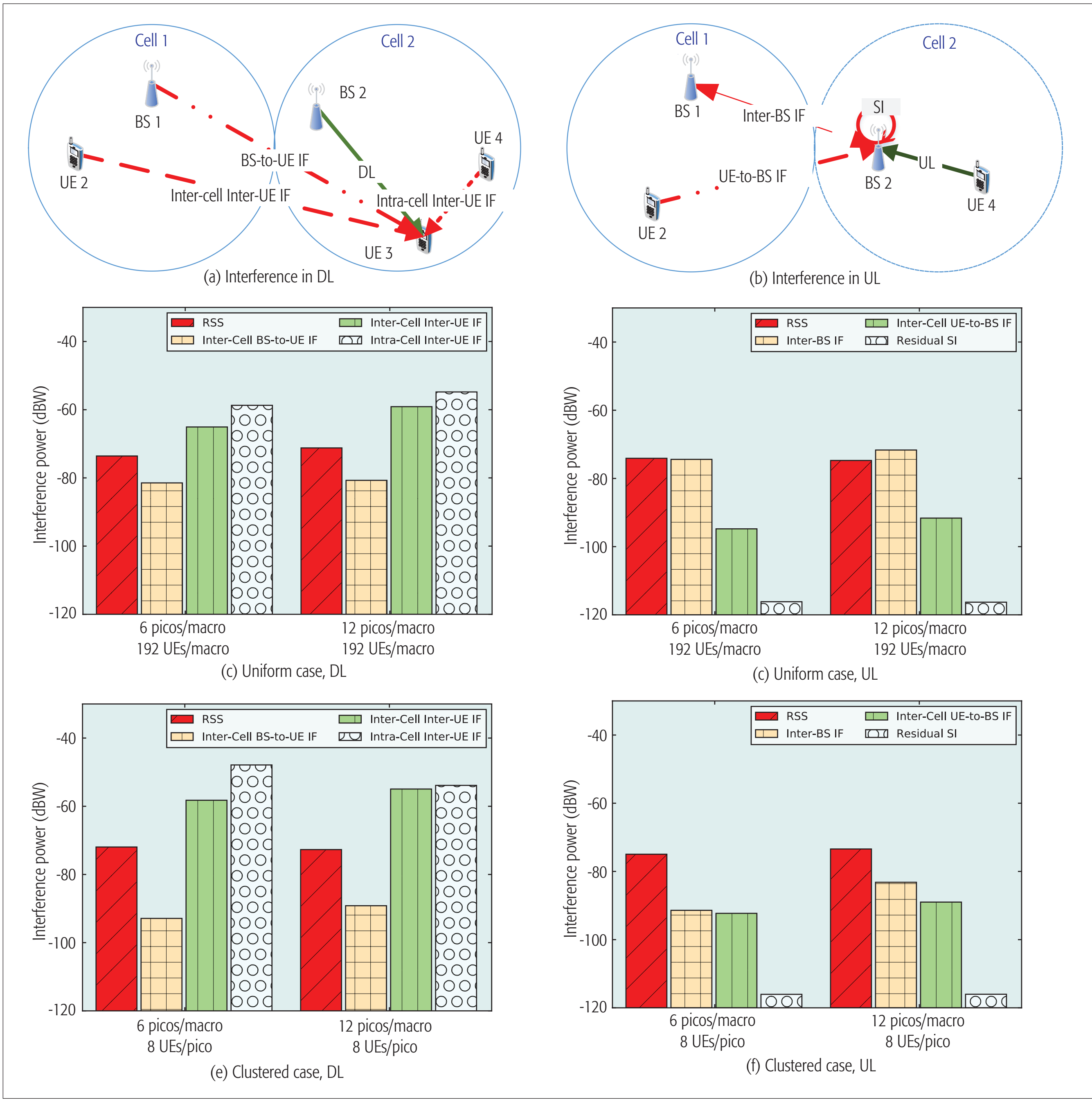

Figure 3. a) Interference in DL; b) UL and corresponding powers in two typical scenarios: c, d) uniform case; e, f) clustered case. Key findings: The intra-cell inter-UE interference dominates in DL, while UL transmission suffers in cochannel heterogeneous networks.

As before, the results are averaged over 100 user drops for both cases.

Interference Analyses

In this section, we investigate the strength of different types of interference for both network configurations by exploiting the standard PF scheduling method for UL and DL UEs separately and not applying any smart interference management scheme. Furthermore, since the interference situation is different, we present the results separately in Fig. 3a and Fig. 3b. We shall see which direction is affected more seriously and which interference is more dominant.

Uniform Case: Figure 3c and Fig. 3d show the interference powers for the UL and DL UEs, respectively. Two groups of results are shown in each figure, corresponding to the two settings (i.e., 6 and 12) of the pico BS density for each macrocell.[3]

From Fig. 3c, for DL transmission, the strongest interference in most cases is from the UL UE of the same cell, which is a unique problem in the FD networks. Meanwhile, DL transmission, on average, is affected more by inter-cell inter-UE interference than by inter-cell BS-to-UE interference for the first group.[4] On the other hand, for UL transmission, the interference from the neighboring BSs, including both the pico BSs and the macro BSs, dominates, as demonstrated by the first group of results in Fig. 3d. Inter-cell interference power increases with the number of pico

[3] As may be needed for result comparison, when there are 192 uniformly distributed UEs per macro BS, statistically around four to eight UEs are associated to each pico BS.

[4] Given the random drop of UEs, the second-order statistic also shows that the inter-cell inter-UE interference has much larger dynamic range that that of inter-cell BS-to-UE interference.

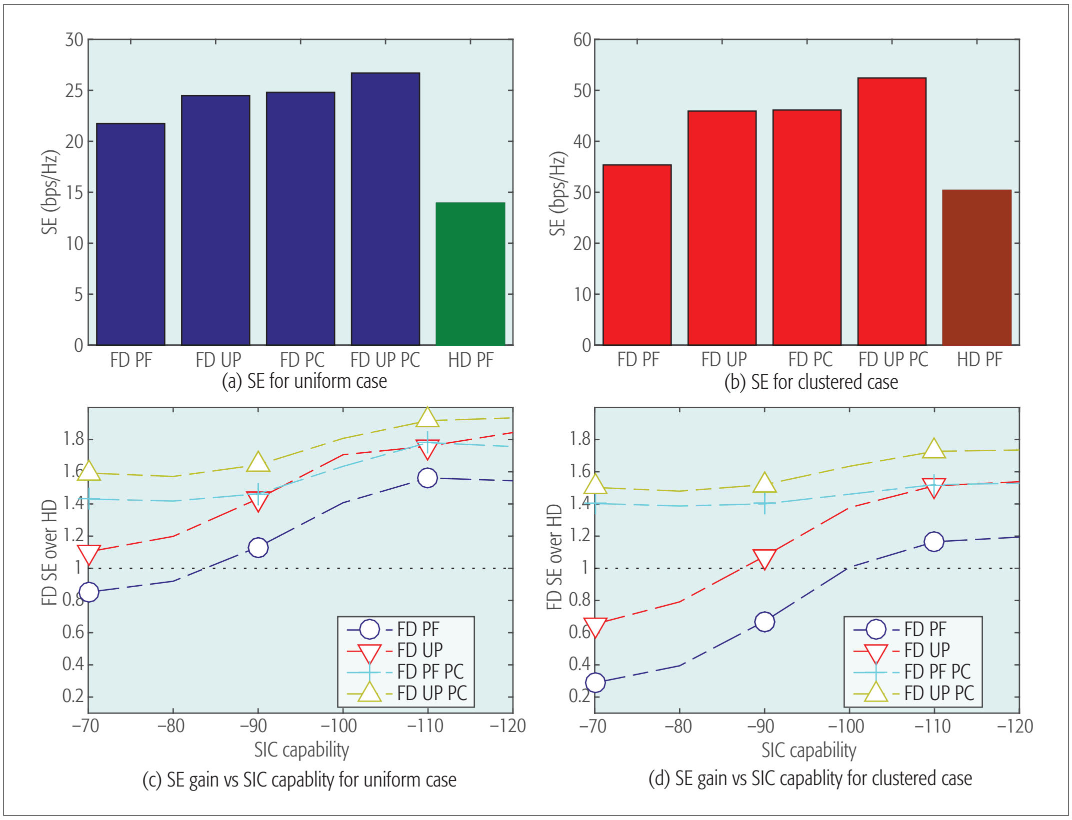

Figure 4. SE performance between uniform case (6 pico BSs/Macro BS, 192 UEs/Macro BS) and clustered case (6 pico BSs/Macro BS, 8 UEs/Pico BS): a, b) the SE under power control (PC) and/or user pairing schemes, 110 dB SIC assumed; c, d): the SE gain of FD networks over HD networks versus the SIC capability.

Key findings: (1) The combination of power control and user pairing algorithm effectively mitigates the annoying interference and provides 91% and 72% SE gain for the uniform and clustered case, respectively; (2) The minimum required SIC capability to obtain SE gain in FD networks are 83 dB and 100 dB for the uniform and clustered case, respectively.

It is encouraging to see an extra 20 percent or 35 percent gain by applying single-cell based power control or UE pairing on top for the uniform case and clustered case, respectively. This verifies the earlier observation that the intra-cell inter-UE interference is most dominant under our setting.

BSs. Moreover, it also implies that more users in the FD networks will incur larger inter-cell inter-UE interference for both UL and DL from Fig. 3c and Fig. 3d.

Clustered Case: In this scenario, we discuss the impact of interference when UEs are clustered. The corresponding results are shown in Fig. 3e and Fig. 3f. Compared with the uniform case, both the inter-cell BS-to-UE interference in the DL and the inter-BS interference in the UL becomes significantly smaller due to the absence of the macro BSs. However, the inter-UE interference is still very strong and needs interference management schemes, so as to exploit the potential benefit of FD communications. Moreover, similar to that in the uniform distribution case, along with the increase in the number of the pico BSs, the interference problem becomes more severe.

Network SE and EE

In this section, we will investigate how the interference management schemes in the single-cell FD network could contribute to improving the multi-cell performance in terms of SE and EE and provide the corresponding results in Fig. 4. From Fig. 4a and Fig. 4b, under the assumption of 110 dB SIC capability for both network configurations, positive gains (56 percent and 16 percent for the uniform and clustered cases respectively) of FD networking in system SE can be achieved even when no extra interference management strategy is used. This is because the inter-cell interference leads to a smaller SE in each cell than that in the single-cell case in Fig. 2b. However, all bandwidth could be used for both UL and DL UEs, so user diversity helps maintain system throughput in the FD case. It is encouraging to see an extra 20 percent or 35 percent gain by applying single-cell based power control or UE pairing on top for the uniform case and clustered case, respectively. This verifies the earlier observation that the intra-cell inter-UE interference is most dominant under our setting. From the figure, the gain for the clustered case is higher because the intra-cell inter-UE interference is more severe, as in Fig. 3. Moreover, an extra 56 percent gain for the clustered case can be obtained when these two interference management strategies are combined, which implies that the FD networks will perform interference-aware UE pairing and even fall back to HD mode to ensure no performance degradation.

Next, we discuss how the SE gain of the FD networks over the HD networks could be with different SIC capabilities. Figure 4c shows for the standard PF scheduling method in the uniform case, it needs at least an 83 dB SIC capability to achieve the sum rate gain of the FD networks, and requires a less effective SIC capability if better interference management schemes are leveraged. Moreover, with power control,

For both configurations, the FD networks with the standard PF scheduling method could yield larger EE (24 percent and 4 percent for the uniform and clustered cases respectively) than the HD networks. By exploiting the power control and the UE pairing methods, the EE performance improvement could be as large as 110 percent.

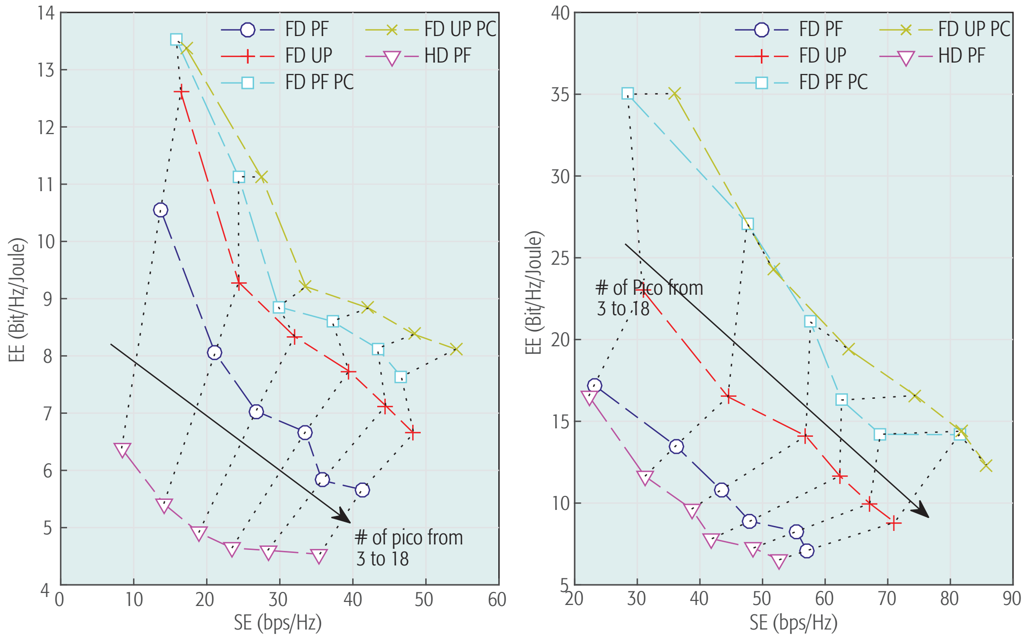

Figure 5. The SE and EE performance of FD cellular networks: a) uniform case with 192 UEs per macro BS; b) clustered case with 8 clustered UEs per pico BS.

Key Findings: (1) FD networks yield similar SE-EE trend but better tradeoff curves to HD networks. (2) By exploiting power control and UE pairing schemes, the EE performance improvement could be as large as 110%.

the FD networks could fall back to HD mode whenever necessary to reap a larger SE at some transmission direction (i.e., UL and DL). Hence, it always exhibits performance improvement even when the SIC capability is not so effective. On the other hand, Fig. 4d shows that stronger SIC capability, around 100 dB, is needed to mitigate the negative impact of other kinds of interference in the clustered case, such as the intra-cell inter-UE interference.

SE-EE Relationship

Figure 5 further presents the system SE and EE performance of the FD networks. From the figures, there are similar SE-EE tradeoff curves in both network configurations. When the number of pico BSs per macro BS increases from three to 18, it leads to distinct variation trends in SE and EE, because more pico BSs imply a higher frequency reuse ratio and thus lead to a larger SE. However, deploying more pico BSs also adds to the total power consumption and incurs larger inter-cell interference. Consequently, the SE gain cannot compensate for the loss in interference and power consumption, resulting in the EE decrease. Meanwhile, in addition to the benefit to SE performance improvement already validated in Fig. 4, the FD networks could also benefit system EE, as shown in Fig. 5. For both configurations, the FD networks with the standard PF scheduling method could yield larger EE (24 percent and 4 percent for the uniform and clustered cases respectively) than the HD networks. By exploiting the power control and the UE pairing methods, the EE performance improvement could be as large as 110 percent.

Conclusions and Future Works

From the discussion in this article, we found that equipping pico BSs with FD functionality will be most practical and promising for FD communications in cellular networks. Starting with a single-cell FD network, we discovered that the power control solution for any given UL and DL UE pair has a binary feature, and thus the system SE optimization problem reduces to a UE pairing problem. We further demonstrated the importance of interference-awareness in pairing UEs. For the multi-cell scenario, our interference analysis results showed intra-cell inter-UE interference is most dominant under our setting. Therefore, we further combined the UE pairing scheme based on distance-aware joint PF scheduling and the binary power control scheme as the interference management solution for the multi-cell FD networks. The system-level simulation has proven up to 91 percent and 72 percent SE gains over the traditional HD networks for the uniform and clustered cases, respectively, under 110 dB SIC capability. Therefore, we could conclude that FD works for cellular networks!

However, there still exist demanding challenges to address, including the combination of FD functionality with multiple-input mutiple-output (MIMO) systems, the protocol and algorithm design to take advantage of interference cancellation at the receiver or even to combine with the non-orthogonal multiple access schemes [15], as well as the extension to UEs with FD capability in both cellular and device-to-device (D2D) communications.

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Biographies

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Geoffrey Ye Li [S'93, M'95, SM'97, F'06] (liye@ece.gatech.edu) is a full professor with the School of Electrical and Computer Engineering at the Georgia Institute of Technology as an associate professor and then a full professor. He also holds a Cheung Kong Scholar title at the University of Electronic Science and Technology of China since 2006. His general research interests include statistical signal processing and communications, with an emphasis on cross-layer optimization for spectral- and energy-efficient networks, cognitive radios and opportunistic spectrum access, and practical issues in LTE systems. In these areas, he has published around 400 papers in various journals and conferences in addition to 26 granted patents. His publications have been well cited from Google Citations, and he has been recognized as a Highly-Cited Researcher by Thomson Reuters. He has received several paper and/or achievement awards. Recently, he received the 2015 Distinguished Faculty Achievement Award from the School of Electrical and Computer Engineering, Georgia Tech.

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The system-level simulation has proven up to 91 percent and 72 percent SE gains over the traditional HD networks for the uniform and clustered cases, respectively, under 110 dB SIC capability. Therefore, we could conclude that FD works for cellular networks!