Mode Selection in Multi-user Full-Duplex Systems Considering Inter-user Interference

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***Abstract*—This paper focuses on multi-user full-duplex (FD) systems. When multiple users share the same resources, using FD degrades the sum capacity compared to using half-duplex (HD) because of the inter-user interference (IUI) that arises between two FD users. This factor highlights the need for a good strategy for switching between FD and HD modes. We address this first by considering a two-user case and deriving the sum capacities. We then consider the general case of K users and compare the average sum capacities for all-FD mode, all-HD mode and the optimal mode case.**

***Index Terms*—Full-duplex, inter-user interference, mode selection**

I. Introduction

In-band full-duplex (FD) systems simultaneously transmit and receive data on the same frequency band, thereby ideally doubling the system capacity compared to conventional half-duplex (HD) systems [1]–[3]. One of the major difficulties in multi-user FD systems is inter-user interference (IUI) between FD users. When multiple FD users share time and frequency resources, the user equipment devices (UE) suffer not only from self-interference (SI) but also interferences transmitted from other users [1].

Several works in the literature have looked at cellular networks consisting of FD base stations (BS) and HD UEs [4], [5]. In this configuration, the UE in the downlink phase is interfered by the uplink signal from other HD UEs. Nguyen et al. designed a precoder for the FD cellular system that considered a FD BS and multiple HD UEs [6]. In that study, however, while the precoder was designed to optimize spectral efficiency and energy efficiency, IUI was not considered. Lee et al. analyzed the performance of hybrid heterogeneous networks which are composed of multi-tier access points operating either in FD mode or HD mode [7]. The focus of that paper was on the network throughput and it did not consider multi-user support. In short, the previous works did not deal with how UEs communicate with the BS when the BS and UEs both have FD capability.

Our goal in this paper is to identify the effect of IUI on multi-user systems with FD capability. We will consider a small-cell network as our candidate FD system model. Instead of beginning with a general multi-user model, we will use a system model with two UEs to identify the general tendencies. We first present the sum capacity of each mode and compare all combinations of UE modes to identify crossover points. After that, we extend to the K UE case and derive the sum capacity. Simulations are used to show the average sum capacities for the all-FD mode, all-HD mode and mode selection and the effect of the IUI.

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This work was supported by the National Research Foundation of Korea(NRF) grant funded by the Korea government (NRF-2015R1A2A1A01006162).

II. Full-duplex Small Cell Network Model

We begin in this subsection by describing the small cell model and characterizing the network interferences. A small cell has fewer UEs and lower transmit power of the BS than a macro cell, giving it more options for reducing IUI. This smaller transmit power also makes it easier to cancel the SI of the FD nodes. From these reasons, we use small cell scenario which is more appropriate for FD than macro cell.

A. System Model

Let us consider a scenario consisting of a small cell with a BS and K UEs as shown in Fig. 1. In this paper, we assume that frequency deployment of the macro cell and small cells are separated [8]. Each node is able to use FD or HD and operates on the same frequency channel. For FD implementation, there are two possible antenna configurations: shared antenna and separated antennas [1]. In this system model, the BS has K shared antennas and the UEs have a single shared antenna. If the BS has perfect channel information, it is possible to

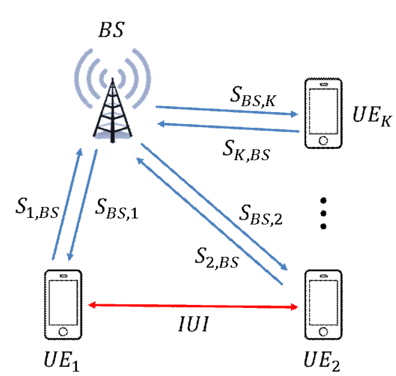

Fig. 1. System model for small-cell network. BS, UE_1, UE_2 and UE_K represent a small-cell base station and user equipment devices that are sharing the frequency resource, respectively.

achieve an ideal multiplexing gain with the multi-user MIMO (MU-MIMO) technique. Therefore, we assume that the signals from the BS are orthogonally transmitted to each UE and the signals from each UE are orthogonally received at the BS. Based on this assumption, there is no interference between downlink signals at the UEs, and between uplink signals at the BS, respectively.

In Fig. 1, $S_{BS,1}$, $S_{BS,2}$ and $S_{BS,K}$ are the received signal power at UE_1, UE_2 and UE_K, respectively, which are transmitted from the BS. Let $S_{1,BS}$, $S_{2,BS}$ and $S_{K,BS}$ denote the received signal powers at the BS which are transmitted from UE_1, UE_2 and UE_K, respectively. The term IUI represents the inter-user interference. When all UEs use HD mode, there is no IUI. If at least one UE is selected to use FD mode, it creates IUI for the other UEs. We define $I_{i,j}$ as the IUI that is transmitted from UE_i and received at UE_j, where $i, j \in \{1, 2, \cdots, K\}$ and $i \neq j$. We then assume that the UEs have the same transmit power P_{UE}. Therefore, $I_{i,j}$ and $I_{j,i}$ are the same because they have the same transmit power and channel reciprocity.

B. Sum Capacity of the Small Cell

Now let us consider the sum capacity of the small cell. First, the uplink capacity of the K UEs can be derived as

$$\begin{aligned} C_{UL} =& \frac{1}{2}\sum_{i\in H}\log_2\left(1+\frac{S_{i,BS}}{1_F I_{SI,B}+N}\right) \\ &+\sum_{i\in F}\log_2\left(1+\frac{S_{i,BS}}{I_{SI,B}+N}\right), \end{aligned} \tag{1}$$

where $I_{SI,B}$ and N are the powers of the residual SI at the BS and noise, respectively. 1_F is a FD UE indicator which is defined as $1_F = 0$ if all UEs are HD UEs and $1_F = 1$ if there is at least one FD UE. When $1_F = 1$, the residual SI $I_{SI,B}$ occurs at the BS. In addition, the sets of FD UEs and of HD UEs are defined as F and H, respectively. The first term of (1) represents the capacity of the HD UEs and the second term shows the capacity of the FD UEs. From this equation, if the UEs have a high enough signal-to-interference and noise ratio, the uplink capacity is maximized when all UEs use FD mode.

Next, the downlink capacity of the K UEs is written as

$$\begin{aligned} C_{DL} =& \frac{1}{2}\sum_{i\in(H\cup F)}\log_2\left(1+\frac{S_{BS,i}}{\sum\limits_{j\in F} I_{j,i}+N}\right) \\ &+\frac{1}{2}\sum_{i\in F}\log_2\left(1+\frac{S_{BS,i}}{\sum\limits_{j\in(H\cup F)} I_{j,i}+N}\right), \end{aligned} \tag{2}$$

where $I_{j,j}$ is the residual SI power at the UE. Here, the first term indicates the capacity of all UEs when the HD UEs are operating in the downlink phase. In this case, the IUI is caused by the FD UEs. The second term is the capacity of the FD UEs when the HD UEs are operating in the uplink phase. Here, all the UEs are transmitting uplink signals and creating IUI. From this equation, we can see that using FD does not always guarantee an improvement in downlink capacity because of IUI. With (1) and (2), the sum capacity of K UEs can be written as

$$C_K = C_{UL} + C_{DL}. \tag{3}$$

III. Analysis when $K = 2$

In this section, the sum capacities of the BS and two UEs are considered for each UE mode combination. When $K = 2$, there are four candidates for UE mode combinations, i.e., (UE_1,UE_2) = (FD,FD), (FD,HD), (HD,FD), (HD,HD). Therefore, we define $C^{(\mathrm{FD,FD})}$, $C^{(\mathrm{FD,HD})}$, $C^{(\mathrm{HD,FD})}$ and $C^{(\mathrm{HD,HD})}$ which are the sum capacities for (FD,FD), (FD,HD), (HD,FD) and (HD,HD), respectively. Based on (1), (2) and (3), we can calculate the sum capacities for each case.

Next, we derive the crossover points between the four possible transmission modes. Without loss of generality, we can state that $S_{BS,1}$ and $S_{1,BS}$ are stronger than $S_{BS,2}$ and $S_{2,BS}$, respectively. In addition, we assume that the IUI and residual SI are strong enough such that the noise becomes negligible compared to these interferences [9].

Proposition 1. *$C^{(FD,HD)}$ is always larger than $C^{(HD,FD)}$.*

Proof: From (1), (2) and (3),

$$\begin{aligned} &C^{(\mathrm{FD,HD})} - C^{(\mathrm{HD,FD})} \\ &\approx \frac{1}{2}\log\left(\frac{I_{SI,U}+S_{BS,1}}{I_{SI,U}+S_{BS,2}}\times\frac{I_{1,2}+S_{BS,2}}{I_{2,1}+S_{BS,1}}\right) \\ &+\frac{1}{2}\log\left(\frac{I_{SI,B}+S_{1,BS}}{I_{SI,B}+S_{2,BS}}\times\frac{I_{SI,U}+I_{2,1}+S_{BS,1}}{I_{SI,U}+I_{1,2}+S_{BS,2}}\right), \end{aligned} \tag{4}$$

where $I_{SI,U}$ is the residual SI power at the UE. From the definitions that $S_{BS,1} > S_{BS,2}$, $S_{1,BS} > S_{2,BS}$ and $I_{1,2} = I_{2,1}$, the second term of this equation is always larger than zero. Therefore, the condition that $C^{(\mathrm{FD,HD})}$ is larger than $C^{(\mathrm{HD,FD})}$ is satisfied when the first term is larger than zero and it can be rearranged as

$$(S_{BS,1} - S_{BS,2})(I_{1,2} - I_{SI,U}) > 0. \tag{5}$$

With this result, the inequality (5) is satisfied if $I_{1,2} > I_{SI,U}$. To compare $I_{1,2}$ with $I_{SI,U}$, large-scale fading is considered, such as the pathloss model in [10], which is defined as $l(d_i) = 140.7 + 36.7\log_{10}(d_i)\,(dB)$ for $2GHz$, where d_i is the distance between the BS and UE_i in km. If the radius of the small cell is $50m$, for example, the maximum pathloss between two UEs is $104dB$ and $I_{1,2} > P_{UE} - 104dB$. Meanwhile, SI cancellation can achieve $110dB$ of cancellation gain, as shown in [11]. With this result, $I_{SI,U} \approx P_{UE} - 110dB$. Therefore, the IUI is stronger than the residual SI. Based on this, we can conclude that (4) is always larger than zero. ∎

Proposition 2. *$C^{(FD,FD)}$ is larger than $C^{(HD,HD)}$ if*

$$S_{BS,1}S_{1,BS}S_{BS,2}S_{2,BS} > \frac{(I_{1,2}+I_{SI,U})^4 {I_{SI,B}}^4}{N^4}. \tag{6}$$

Proof: Given the assumption of a high SINR, $C^{(\mathrm{FD,FD})} - C^{(\mathrm{HD,HD})} > 0$ reduces directly to inequality (6). ∎

Based on this observation, the UEs should have strong desired signals compared to the IUI for achieving capacity gain through the application of FD communication.

Proposition 3. *$C^{(FD,FD)}$ is larger than $C^{(FD,HD)}$ if*

$$S_{BS,2}S_{2,BS} > \frac{(I_{1,2}+I_{SI,U})^3 I_{SI,B}}{I_{1,2}I_{SI,U}}. \quad (7)$$

Proof: Given the assumption of a high SINR, $C^{(\text{FD,FD})} - C^{(\text{FD,HD})} > 0$ reduces directly to inequality (7). ■

In this case, $S_{BS,1}$ and $S_{1,BS}$ do not affect the performance comparison. This means that UE_2 can use FD mode when $S_{BS,2}$ and $S_{2,BS}$ are strong enough compared to the IUI.

Proposition 4. *$C^{(FD,HD)}$ is larger than $C^{(HD,HD)}$ if*

$$S_{BS,1}S_{1,BS} > \frac{(I_{1,2}+I_{SI,U})\, I_{1,2}I_{SI,U}{I_{SI,B}}^3}{N^4}. \quad (8)$$

Proof: Given the assumption of a high SINR, $C^{(\text{FD,HD})} - C^{(\text{HD,HD})} > 0$ reduces directly to inequality (8). ■

In this case, $S_{BS,2}$ and $S_{2,BS}$ do not affect the inequality (8). As in the other cases, UE_1 can use FD mode when $S_{BS,1}$ and $S_{1,BS}$ are strong enough compared to the IUI.

IV. Numerical Results

In this section, the sum capacities of $K = 2$ and $K > 2$ are represented by simulation results. We check the average sum capacity of the optimal mode selection by comparing it with the all-HD case and all-FD case.

A. Numerical Results for $K = 2$

We begin in this subsection by comparing the sum capacity of each mode for a given UE location using numerical simulations. The BS transmit power P_{BS} and UE transmit power P_{UE} are $30dBm$ and $20dBm$, respectively. The antenna gain at the BS is $5dBm$ and the noise floor level is $-104dBm$.

Fig. 2 depicts the contour graphs comparing the sum capacities according to the location of UE_2. The numbers on the contour graphs represent $R_{(FD,FD),(HD,HD)}$ which is

$$R_{(\text{FD,FD}),(\text{HD,HD})} = \frac{C^{(\text{FD,FD})}}{C^{(\text{HD,HD})}}. \quad (9)$$

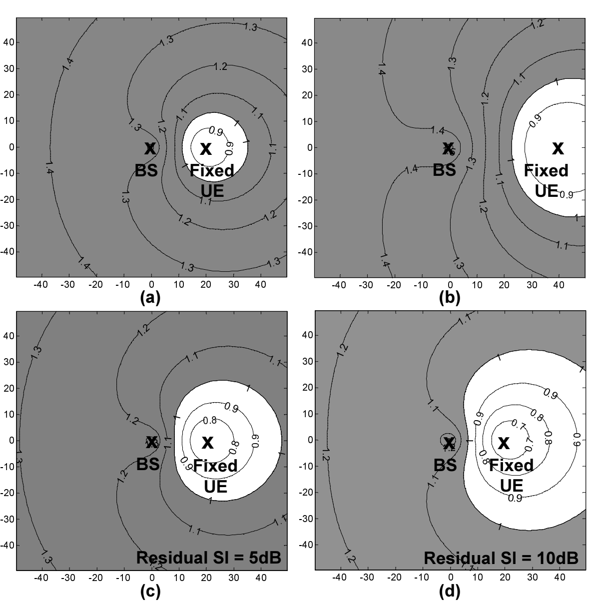

Fig. 2. Ratio of $C^{(\text{FD,FD})}$ to $C^{(\text{HD,HD})}$ according to the location of UE_2.

The colored region, where $R_{(FD,FD),(HD,HD)} > 1$, means $C^{(\text{FD,FD})}$ is greater than $C^{(\text{HD,HD})}$.

In Fig. 2 (a), the BS and UE_1 are fixed at (0,0), (20,0), respectively. Then, we move UE_2 to 10000 candidate locations. We assume that the SI is suppressed below noise level, allowing us to focus on the effects of IUI [12]. To show the effect of IUI on the sum capacity more precisely, we consider only the large-scale fading channel using the pathloss model in [10]. We can see that applying FD to UEs improves the sum capacity of the small-cell network when the UEs are far enough apart. However, when UE_2 is close to UE_1, using FD with both UEs degrades the sum capacity of the small-cell network compared to having both UEs use HD. This results from the fact that the capacity loss from IUI is more dominant than the capacity gain achieved by full utilization of the time or frequency resources.

In Fig. 2 (b), UE_1 is fixed at (40,0) compared to Fig. 2 (a). The uncolored region is extended based on the increased distance between the BS and UE_1. When the UE is far from the BS, the desired signal is weakened and the impact of the IUI becomes more important. For that reason, it is hard to use FD near a UE that is far from the BS.

Fig. 2 (c) and (d) show results with the residual SI, which are $5dB$ and $10dB$, respectively. Increasing the residual SI seriously reduces the superior region for FD. Because the FD UE is already suffering IUI, $C^{(\text{FD,FD})}$ can be smaller than $C^{(\text{HD,HD})}$ with even a small amount of residual SI.

Fig. 3 shows $C^{(\text{FD,FD})}$, $C^{(\text{HD,HD})}$ and $C^{(\text{FD,HD})}$ according to the position of UE_2. In this simulation, the BS and UE_1 are fixed at (0,0), (20,0), respectively and the position of UE_2 is expressed as (x,0). When $x < 8$, $C^{(\text{FD,FD})}$ is larger than $C^{(\text{HD,HD})}$ and $C^{(\text{FD,HD})}$. This result allows us to see the first design point where both UEs can use FD mode when the IUI is weak. If $13 < x < 31$, $C^{(\text{HD,HD})}$ is better than all the others. This means that when the IUI is strong, UEs should use HD mode. Lastly, when $8 < x < 13$ or $31 < x < 50$, $C^{(\text{FD,HD})}$ is larger than all the others. This shows that if the UE has a

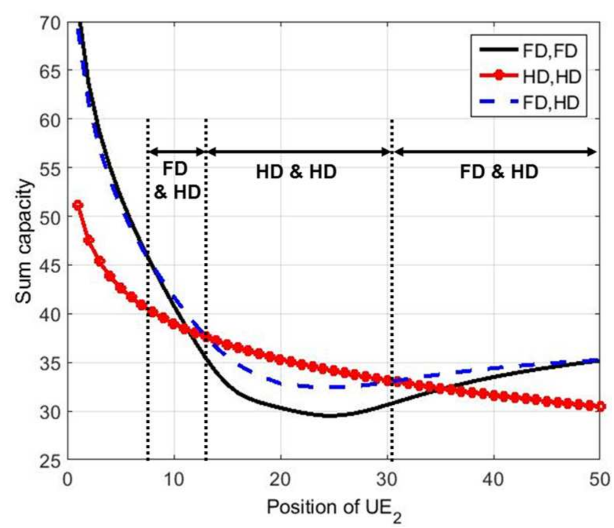

Fig. 3. Sum capacities according to the position of UE_2. BS and UE_1 are fixed at (0,0), (20,0), respectively.

strong enough desired signal compared to the IUI, it can use FD mode even if the IUI is strong.

B. Numerical Results for $K > 2$

In this subsection, the average sum capacity for the optimal mode selection is presented using numerical simulations. The UE position is randomly located within a circle of radius $30m$ and we repeat this 10000 times to calculate the average sum capacities. We compare three strategies: all-FD mode, all-HD mode and the mode selection, as presented in Fig. 4. The strategy of the mode selection is selecting optimal mode to maximize sum capacity with considering all possible UE mode combination candidates. We then consider two separate cases: without SI and with $5dB$ residual SI.

Two clear trends emerge from Fig. 4. The first trend is that if there are many UEs, the performance of the all-HD case is superior to that of the all-FD mode. When the number of UEs is more than 7, the performance of the all-FD mode is lower than that of the all-HD mode, even there is no residual SI. This can be attributed to the fact that the SINR degradation due to the IUI overwhelms the FD gain derived from the full use of time and frequency. The IUI is amplified quantitatively and qualitatively due to the increasing number of FD UEs. The greater number of FD UEs causes them to act directly like sources of interference. The distance from the nearest FD UE naturally becomes shorter, thus creating stronger interference. That is why the performance of the all-FD mode is degraded by the presence of a large number of UEs.

With a residual SI of $5dB$, all UEs have to use HD mode if the number of UEs is larger than 3. The residual SI intensifies the effect of IUI and seriously degrades the sum capacity of the small cell. This means that we need to pay more attention to using FD when IUI and residual SI are present. Therefore, the FD UEs should be kept at a distance from the other FD UEs if they are to retain a mutual benefit.

Secondly, when the number of UEs is small, the UEs need to use mode selection. Fig. 4 shows that the sum capacity of the mode selection approaches the sum capacity of the all-HD case as the number of UEs increases. This means that if there are large numbers of UEs, all the UEs need to use HD mode and therefore do not need to use mode selection. However, when the number of UEs is small, appropriate mode selection needs to be applied to decide which UEs can use FD mode. We determine this by counting how many UEs are selected to use FD mode by application of the optimal co-existence mode. The numbers on the graphs represent the probabilities of selecting FD mode. This result shows that there is a need to use mode selection even when there are only two UEs in a small cell. The probability of using FD increases as the number of UEs decreases, but is always less than 100%. For example, with two UEs, there is a 13.5% probability that the UE cannot use FD mode. Therefore, appropriate mode selection will always be needed to avoid critical IUI.

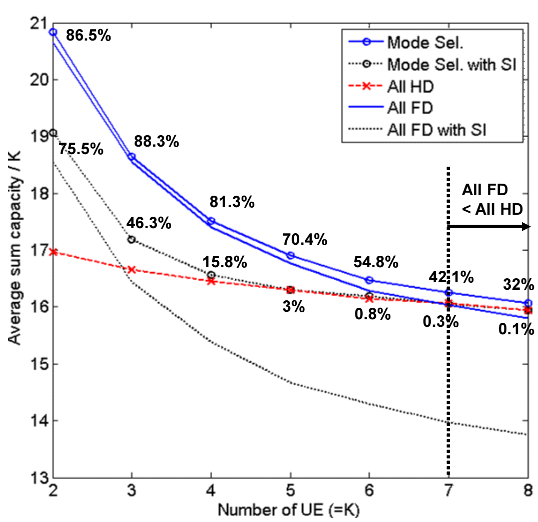

Fig. 4. Average sum capacities per K versus number of UEs. The residual SI is $5dB$.

V. Conclusion

The overall contribution of this paper is an evaluation of the effect of IUI in a small-cell network when the UE can change communication modes between FD and HD. Unlike in HD mode, the sum capacity of FD UEs is seriously degraded by IUI. Simulation results show that the performance of a small-cell is seriously degraded by the IUI caused by the FD UEs, making it necessary to apply appropriate UE mode selection.

The insights of our study open several issues for future research on FD small-cell networks, including multi-user support for the general K UE case and a UE mode selection scheme.

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