Generalized PF Scheduling for Bidirectional and User-Multiplexing Unidirectional Full-duplex Links

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***Abstract*—In-band full-duplex (IBFD) operation can potentially double the spectral efficiency of wireless networks. For IBFD operation, self-interference is a critical issue. In addition, in full-duplex cellular (FDC) networks, particularly when the cell size is small, inter-user interference would be another limiting factor for the performance. To overcome these issues, the scheduling scheme proposed in this paper is to adaptively utilize bidirectional IBFD in addition to half-duplex (HD) and unidirectional IBFD in FDC networks according to the residual self-interference after interference cancellation and inter-user interference. The proposed scheme is based on generalized proportional fair scheduling by using a fairness parameter. Extensive simulations are conducted to analyze the impact of the cell size. Simulation results revealed that the use of bidirectional IBFD is extremely effective for a small cell with few users if self-interference is sufficiently canceled because inter-user interference is large in small cell and the scheduler tends to select bidirectional IBFD in the cell with few users.**

I. Introduction

In in-band full-duplex (IBFD) operation [1]–[3], a wireless station simultaneously transmits and receives signals on the same frequency band, and thus IBFD operation has the potential to double the spectral efficiency. There are three basic types of IBFD operation: full-duplex relay (FDR), bidirectional full-duplex (BFD), and user-multiplexing unidirectional full-duplex (UFD) [4]. In this paper, we focus on the BFD and UFD in cellular networks. BFD means that the paired stations in IBFD operation simultaneously transmit and receive their signals on the same frequency band. UFD means that the base station (BS) simultaneously transmits signals to a wireless station and receives signals from another station on the same band.

A critical issue for BFD and UFD transmissions is the self-interference caused by transmitted signals, which interferes with signals arriving from intended transmitters. Many papers have discussed self-interference suppression techniques [1], [2], [5]–[7]. These techniques cancel the self-interference in the wireless-propagation, analog-circuit, and digital domain, and the feasibility of IBFD operation has been experimentally demonstrated. For a summary of implementation activities, we refer [3], [4].

Many papers have proposed scheduling schemes for full-duplex cellular (FDC) networks using UFD transmissions [8], [9] that are based on proportional fair scheduling (PFS), which is aimed towards high data rate systems [10] and user selection for systems with multiple carriers [11], [12] and multi-user multiple-input multiple-output (MIMO) broadcast channels [13]. Frequency-domain scheduling for FDC networks using BFD and UFD transmissions under frequency selective self-interference channel was discussed in [14].

In a small cell, the inter-user interference caused by signals transmitted from unintended users sharing the same transmission resources is the limiting factor for the performance of the UFD transmissions, and the BFD transmissions can achieve a higher capacity if self-interference is sufficiently canceled. In addition, the decrease in the number of users results in low probability that the pair of users with a small inter-user interference, and thus inter-user interference is also serious for the UFD transmissions in a cell with few users. However, the scheduling scheme for FDC networks of previous studies [8], [9] do not allow the scheduler to select the BFD transmissions. Frequency-domain scheduling for FDC networks using BFD and FDC was discussed in [14], but time-domain scheduling was not discussed.

In this paper, we propose a scheduling scheme for an FDC networks using not only UFD transmissions but also BFD transmissions. In the proposed scheme, the scheduler selects either half-duplex (HD) or IBFD operation containing BFD and UFD according to the residual self-interference after interference cancellation and inter-user interference. The proposed scheme is designed based on generalized PFS [15]. That is, we introduce a parameter which determines the data rate fairness among users.

The main contributions of this paper are: 1) derivation of the generalized PF scheduling for FDC with BFD transmissions; and 2) clarifying the impact of the cell size on the performance of FDC networks.

This paper is organized as follows. Section II describes the system model. Section III proposes the generalized scheduling scheme for the FDC networks. Section IV shows the simulation parameters and results. Section V concludes this paper.

II. System Model

The proposed model of FDC networks is shown in Fig. 1, which consists of a BS and N users. It is assumed that the BS and users are able to use both HD and IBFD operation containing UFD and BFD transmissions, and the same frequency is used for the downlink (DL) and uplink (UL).

In the FDC networks, there are two modes using IBFD operation as shown in Fig. 2. Fig. 2(a) shows the UFD mode, where one user receives DL signals from the BS and another user transmits UL signals to the BS simultaneously.

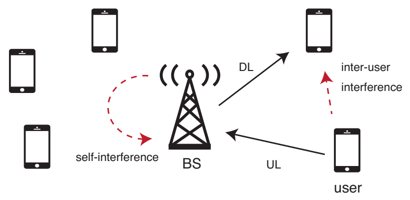
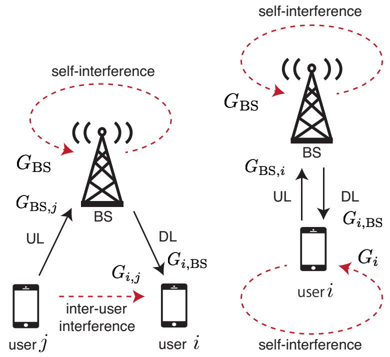


Fig. 1: Proposed model of FDC networks.



(a) UFD mode. (b) BFD mode.

Fig. 2: Two resource allocation modes in the proposed FDC networks.

Fig. 2(b) shows the BFD mode, where a scheduled user and BS simultaneously transmit and receive signals.

In the UFD mode shown in Fig. 2(a), the transmitted signals from the BS interfere with the desired signals arriving from the intended user; that is self-interference. Moreover, the transmitted signals from user j cause inter-user interference that deteriorates the quality of the intended signals at user i. In the BFD mode shown in Fig. 2(b), transmitted signals from the BS and user i cause self-interference that interferes with each entity's desired signals from the user i and the BS, and inter-user interference does not exist.

The average channel gains of the self-interference caused by the signals transmitted from BS and user i are denoted by G_{BS} and G_i, respectively. We denote the noise power density, the bandwidth, the transmission power of BS, and that of user i by N_0, W, P_{BS}, and P_i, respectively. When user i transmits UL signals to the BS, the UL signal-to-interference plus noise ratio (SINR) is denoted by

$$\mathrm{SINR}_{\mathrm{BS},i}^{\mathrm{UL}} = \frac{|h_{\mathrm{BS},i}|^2 G_{\mathrm{BS},i} P_i}{N_0 W + |h_{\mathrm{BS}}|^2 G_{\mathrm{BS}} P_{\mathrm{BS}}}, \tag{1}$$

where $h_{\mathrm{BS},i}$ denotes instantaneous complex unit-power channel gain for the link between the BS and user i, and $E(|h_{\mathrm{BS},i}|^2) = 1$. h_{BS} denotes that for the self-interference at the BS, and $E(|h_{\mathrm{BS}}|^2) = 1$. $G_{\mathrm{BS},i}$ denotes the average channel gain between BS and user i. When user i receives DL signals from the BS and user j transmits UL signals to the BS, the DL SINR in the UFD mode is written by

$$\mathrm{SINR}_{i,\mathrm{BS}}^{\mathrm{UFD,DL}} = \frac{|h_{i,\mathrm{BS}}|^2 G_{i,\mathrm{BS}} P_{\mathrm{BS}}}{N_0 W + |h_{i,j}|^2 G_{i,j} P_j}, \tag{2}$$

where $h_{i,\mathrm{BS}}$ denotes instantaneous complex unit-power channel gain for the link between the user i and BS, and $E(|h_{i,\mathrm{BS}}|^2) = 1$. $h_{i,j}$ denotes that for users i and j, and $E(|h_{i,j}|^2) = 1$. $G_{i,j}$ is the average channel gain between users i and j. The DL SINR in the BFD mode is denoted by

$$\mathrm{SINR}_{i,\mathrm{BS}}^{\mathrm{BFD,DL}} = \frac{|h_{i,\mathrm{BS}}|^2 G_{i,\mathrm{BS}} P_{\mathrm{BS}}}{N_0 W + |h_i|^2 G_i P_i}, \tag{3}$$

where h_i denots an instantaneous complex unit-power channel gain of the self-interference at user i, and $E(|h_i|^2) = 1$. Note that in HD mode, the interference term of SINR is 0.

III. Generalized PF Scheduling for FDC Networks

Let $\boldsymbol{s} = (i_1, i_2)$ be the vector of the index of DL user and that of UL user, where $i_1 \in \{0, 1, 2, \ldots, N\}$ denotes the index of the DL user, and $i_2 \in \{0, 1, 2, \ldots, N\}$ denotes the index of the UL user. Note that $i_1 = 0$ indicates that no user is scheduled to receive DL signals, and $i_2 = 0$ indicates that no user is scheduled to transmit UL signals. Condition $i_1 = i_2$ means the BFD mode and condition $i_i \neq i_2$ means the UFD mode.

At each time slot, PF scheduling for FDC networks selects user and mode that maximize the sums of the logarithmic-average DL and UL throughput. PF scheduling for the FDC networks is proposed in the next theorem, which is based on the scheduling scheme for non-orthogonal transmissions in [16].

Theorem 1. The scheduler that maximizes the sums of the logarithmic-average DL and UL throughput selects the user vector $\boldsymbol{s}^\star$ according to the following criterion:

$$\boldsymbol{s}^\star = \arg\max_{\boldsymbol{s}} f(\boldsymbol{s}), \tag{4}$$

$$f(\boldsymbol{s}) = \sum_{k=1}^{2} \frac{r_k(i_k \mid \boldsymbol{s}; t)}{R_k(i_k \mid \boldsymbol{s}; t-1)}, \tag{5}$$

where $f(\boldsymbol{s})$ is the scheduling metric for the user vector $\boldsymbol{s}$. $r_1(i_1; t)$ and $r_2(i_2; t)$ are the DL data rate of user i_1 and UL data rate of user i_2 at time slot t, respectively. If $i_1 = 0$, $r_1(i_1; t) = 0$; if $i_2 = 0$, $r_1(i_2; t) = 0$. $R_1(i_1; t)$ and $R_2(i_2; t)$ are the average DL throughput of user i_1 and average UL throughput of user i_2, respectively.

Proof. In the FDC networks, the scheduler maximizes the sums of the logarithmic-average DL and UL throughput. That is, the proposed scheme maximizes the following function:

$$u(t) = \sum_{k=1}^{2} \sum_{i=1}^{N} \log R_k(i; t). \tag{6}$$

The average throughput $R_k(i;t)$ is updated by

$$R_k(i;t) = \left(1 - \frac{1}{T}\right) R_k(i;t-1) + \frac{1}{T} a_k(i;t) r_k(i;t), \tag{7}$$

where T is the weight of the moving average and $\{a_k(i;t)\}$ indicates which user and mode are selected in time slot t. That is, if $i = i_k$, $a_k(i;t) = 1$, and if $i \neq i_k$, $a_k(i;t) = 0$.

By substituting (7) into (6), we obtain

$$u(t) = \sum_{k=1}^{2} \sum_{i=1}^{N} \log \left(\left(1 - \frac{1}{T}\right) R_k(i;t-1) \right) + \sum_{k=1}^{2} \sum_{i=1}^{n} \log \left(1 + \frac{a_k(i;t) r_k(i;t)}{(T-1) R_k(i;t-1)} \right). \tag{8}$$

The first term of (8) does not depend on the choice of user at time slot t. When $T \gg 1$, the second term can be approximated as

$$\frac{1}{T} \sum_{k=1}^{2} \sum_{i=1}^{N} \left(\frac{a_k(i;t) r_k(i;t)}{R_k(i;t-1)} \right). \tag{9}$$

Therefore, because T is constant and $a_k(i;t) \in \{0,1\}\ \forall k, i, t$, maximizing $u(t)$ is equivalent to maximizing $f(\boldsymbol{s})$. □

We derive the proposed scheme by introducing the fairness parameter, α_k, to the above theorem. At each time slot, the proposed scheme selects the user vector $\boldsymbol{s}^\star$ according to the following criterion:

$$\boldsymbol{s}^\star = \arg\max_{\boldsymbol{s}} g(\boldsymbol{s}), \tag{10}$$

$$g(\boldsymbol{s}) = \sum_{k=1}^{2} \frac{r_k(i_k \mid \boldsymbol{s}; t)}{R_k(i_k \mid \boldsymbol{s}; t-1)^{\alpha_k}}, \tag{11}$$

where $g(\boldsymbol{s})$ denotes the scheduling metric for the user vector $\boldsymbol{s}$.

Note that $g(\boldsymbol{s}^\star) = r_1(i;t)/R_1(i;t-1)^{\alpha_1}$ means that user i receives DL signals in HD mode at time slot t, $g(\boldsymbol{s}^\star) = r_2(i;t)/R_2(i;t-1)^{\alpha_2}$ means that user i transmits UL signals in HD mode at time slot t, and $g(\boldsymbol{s}^\star) = r_1(i;t)/R_1(i;t-1)^{\alpha_1} + r_2(j;t)/R_2(j;t-1)^{\alpha_2}$ means that user i receives DL signals, and user j transmits UL signals at time slot t; $i = j$ indicates the BFD mode and $i \neq j$ indicates the UFD mode.

The user selection depends on the fairness parameter, α_k. When α_k is small, the scheduler tends to ignore the data rate fairness. If $\alpha_1 = \alpha_2 = 0$, the scheduler ignores the data rate fairness and selects the user who maximizes an instantaneous data rate. If $\alpha_1 = \alpha_2 = 1$, (11) is equivalent to (5).

IV. Simulation Parameters and Results

In this section, we evaluate the performance of the proposed scheme through a simulation. It is assumed that the data rate is given by Shannon's capacity formula $W \log_2(1 + \mathrm{SINR})$ where SINR is given by (1), (2), and (3). The simulation parameters are given in Table I. We assume that $\alpha_1 = \alpha_2 = 1$.

TABLE I: Major system parameters.

Time slot duration	1 ms
Transmission power of BS P_{BS}	20 dBm
BS ant. gain	14 dBi
Transmission power of user P_i	0 dBm
User ant. gain	0 dBi
Thermal noise power density N_0	-174 dBm/Hz
Bandwidth W	10 MHz
Path loss	$128.1 + 37.6 \log_{10}(D)$ dB (D in km)
Carrier frequency	2 GHz
Weight of moving average T	100
Channel model	Quasi-static Rayleigh fading

We also assume that the users are distributed uniformly and randomly in a circular cell with radius d, and instantaneous complex channel gains for communication channels $h_{\mathrm{BS},i}$ and $h_{i,\mathrm{BS}}$, and inter-user interference channel $h_{i,j}$ are Rayleigh fading. It is also assumed that the average channel gain of self-interference is constant, the self-interference channel at every user, h_i, is Rayleigh fading[1], and that at the BS is assumed to be constant, i.e., $|h_{\mathrm{BS}}|^2 = 1$. Transmission queues of the BS and users are assumed to be always nonempty.

Fig. 3(a) shows the percentage of three modes, i.e., HD, UFD, and BFD mode when $G_{\mathrm{BS}} = -90$ dB, $N = 10$, and $d = 100$ m. In this figure, the curves are the borders of different areas of mode selection. When G_i is small, the ratio of BFD mode is higher than that of UFD mode. The ratio of BFD mode decreases and the ratio of UFD mode and that of HD mode increase as G_i increases, and the ratio of BFD mode approaches to 0 %.

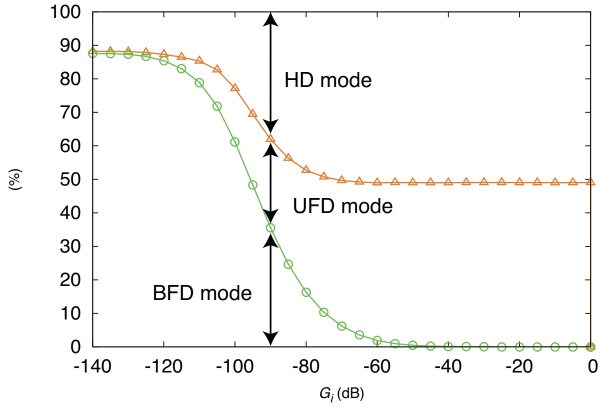
Fig. 3(b) shows the percentage of three modes when $G_{\mathrm{BS}} = -70$ dB, $N = 10$, and $d = 100$ m. The scheduler rarely selects the UFD mode even if G_i is large. The ratio of BFD mode with $G_{\mathrm{BS}} = -70$ dB is lower than that with $G_{\mathrm{BS}} = -90$ dB, that of BFD mode becomes 0 when G_i is large. Therefore, it is necessary that the self-interference caused at user and that at BS are small in order to select the BFD mode and UFD mode, respectively, as shown in Figs. 3(a) and 3(b).

Hereafter, for the ease of exposition, we refer to i) the proposed scheme as "HD+UFD+BFD scheme," ii) the scheme that does not allow the scheduler to select BFD similar to the scheme in [8] as "HD+UFD scheme" which is general assumption in FDC networks, iii) and the scheme that selects only HD mode as "HD scheme."

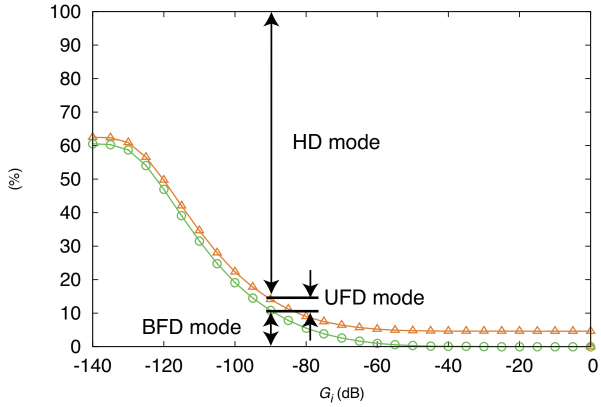
To discuss the detail of the effect of introducing the BFD mode to the FDC networks, Fig. 4 shows the impact of G_i on the system throughput, when $G_{\mathrm{BS}} = -90$ dB, $N = 10$, and $d = 100$ m. When G_i is small, HD+UFD+BFD scheme has the higher system throughput than the other schemes because the scheduler tends to select the BFD mode as shown in Fig. 3(a). In contrast, when G_i is large, it has little impact on the FDC networks.

To investigate the influence of inter-user interference in UFD mode on the mode selection, Fig. 5 shows the impact of

[1]Ref. [17] described that self-interference channel can be approximated as Rayleigh fading channel.



(a) $G_{\mathrm{BS}} = -90\,\mathrm{dB}$.



(b) $G_{\mathrm{BS}} = -70\,\mathrm{dB}$.

Fig. 3: The percentage of three modes vs. G_i ($N = 10$, and $d = 100\,\mathrm{m}$).

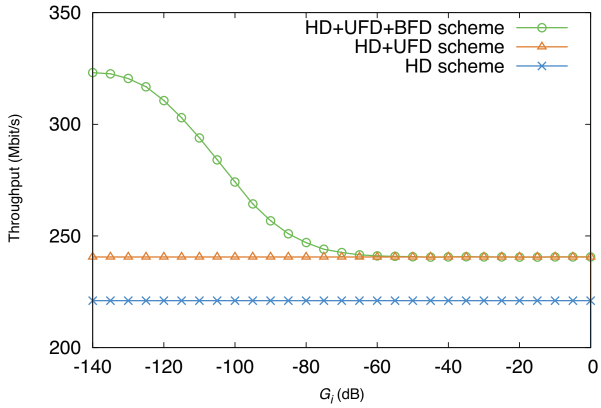


Fig. 4: System throughput vs. G_i ($G_{\mathrm{BS}} = -90\,\mathrm{dB}$, $N = 10$ and $d = 100\,\mathrm{m}$).

the cell radius, d, on the percentage of three modes when G_{BS}, $G_i = -90\,\mathrm{dB}$, $\forall i$, and $N = 10$. The ratio of the UFD mode increases as d increases because a small cell radius indicates that the number of pairs of users with a small inter-user interference in the UFD mode decreases. In contrast, the ratio of BFD mode decreases as d increases, and becomes lower than that of HD mode because the received signal power is small in a large cell, and self-interference has much impact

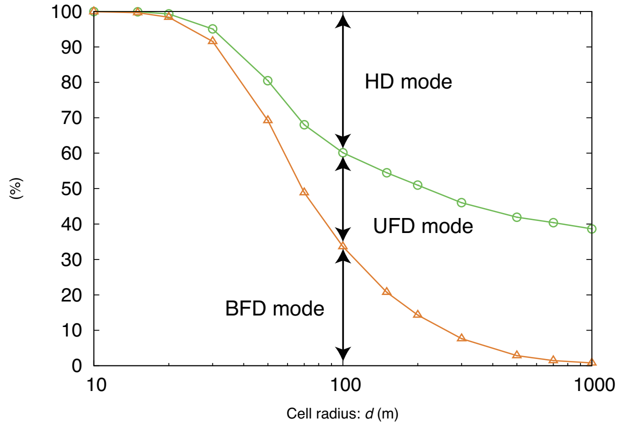


Fig. 5: Percentage of three modes vs. cell radius d (G_{BS}, $G_i = -90\,\mathrm{dB}$, $\forall i$, and $N = 10$).

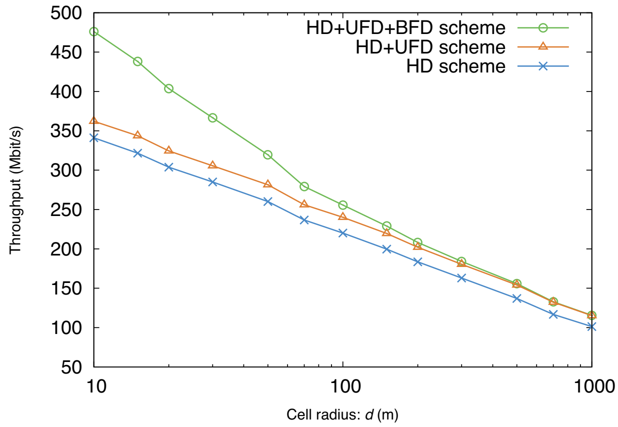


Fig. 6: System throughput vs. cell radius d (G_{BS}, $G_i = -90\,\mathrm{dB}$, $\forall i$, and $N = 10$).

on the SINR.

To confirm the effect of introducing the BFD mode to the FDC system, Fig. 6 shows the impact of the cell radius, d, on the system throughput when G_{BS}, $G_i = -90\,\mathrm{dB}$, $\forall i$ and $N = 10$. A smaller cell radius results in a larger difference in system throughputs between HD+UFD+BFD scheme and HD+UFD scheme because the UFD mode is selected more frequently in the cell with a large size as shown in Fig. 5. Thus, the BFD mode is effective for small cells.

To investigate the influence of the number of users on the mode selection, Fig. 7 shows the impact of the number of users, N, on the percentage of three modes when G_{BS}, $G_i = -90\,\mathrm{dB}$, $\forall i$, and $d = 100\,\mathrm{m}$. The scheduler tends to select the BFD mode with higher probability in a cell with few users than in a cell with many users. The ratio of the BFD mode decreases and that of the UFD mode increases as N increases because the increase in the number of users results in higher probability that the pair of users with a small inter-user interference in the UFD mode exists.

To confirm the effect of introducing the BFD mode on the FDC networks, Fig. 8 shows the impact of the number of users, N, on the system throughput when $G_{\mathrm{BS}}, G_i = -90\,\mathrm{dB}$, $\forall i$ and $d = 100\,\mathrm{m}$. The difference in system throughputs between

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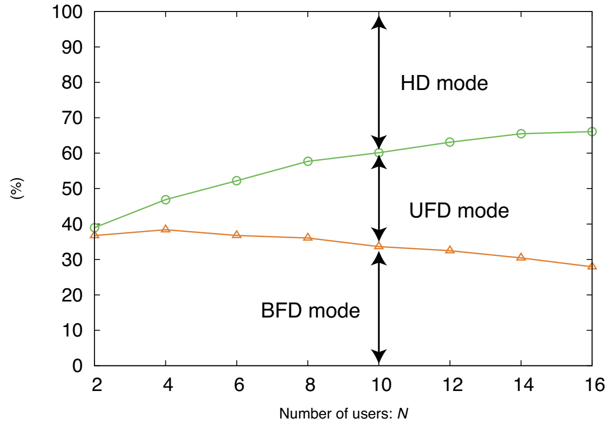

Fig. 7: Percentage of three modes vs. number of users N, $(G_{\mathrm{BS}},\ G_i = -90\,\mathrm{dB},\ \forall i,\ \text{and}\ d = 100\,\mathrm{m})$.

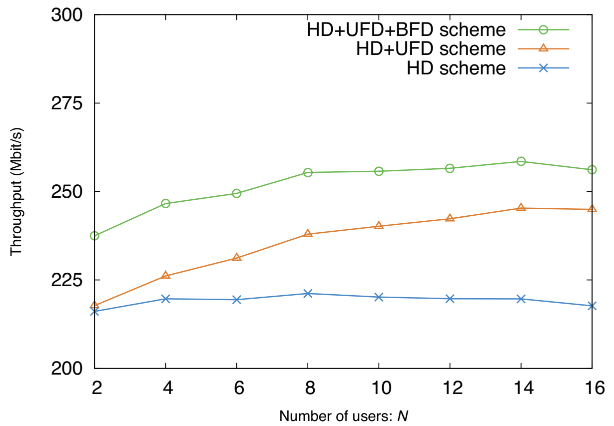

Fig. 8: System throughput vs. number of users N $(G_{\mathrm{BS}},\ G_i = -90\,\mathrm{dB},\ \forall i,\ \text{and}\ d = 100\,\mathrm{m})$.

HD+UFD+BFD scheme and HD+UFD scheme becomes small as N increases because the ratio of BFD mode is high in the cell with few users as shown in Fig. 7. Therefore, the BFD mode is effective for the cell with few users.

V. Conclusions

In this paper, we proposed a scheduling scheme based on generalized PFS for FDC networks using not only UFD transmissions but also BFD transmissions. The proposed scheme selects HD, UFD or BFD mode depending on the residual self-interference after interference cancellation and inter-user interference. Simulation results showed that in a small cell, the availability of the BFD transmissions achieved higher capacity compared to general FDC networks assumed in previous studies if self-interference was well-managed because a small cell radius resulted in small number of pairs of users with a small inter-user interference in the UFD mode. It is also shown that the proposed scheme selected BFD mode more frequently than UFD mode in a cell with few users if self-interference was cancelled sufficiently because the decrease in the number of users resulted in lower probability that the pair of users with a small inter-user interference exists.

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