LOCATION-BASED BIDIRECTIONAL USER SCHEDULING AND MODE SELECTION IN FULL-DUPLEX SYSTEM

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ABSTRACT

This paper studies the bidirectional user scheduling and mode selection in single-cell full-duplex (FD) system, where a FD base station (BS) serves multiple uplink and downlink half-duplex (HD) users. Due to the existence of the inter-user interference from an uplink transmitting user to a downlink receiving user, the system operating in FD mode does not necessarily outperform HD mode, depending on the pairing of the bidirectional users. Different from existing studies based on perfect inter-user channel state information, we design the bidirectional user scheduling and mode selection based on imperfect location information of users. Simulation results show the gain of the proposed schemes over HD system.

Index Terms— Full duplex, inter-user interference, location-based scheduling, mode selection

1. INTRODUCTION

Full-duplex (FD) communication, enabling simultaneous transmission and reception over the same time-frequency channel, has been approved feasible at reasonable cost recently, thanks to the development of advanced self-interference cancellation techniques [1]. For point-to-point communications, the potential of FD in doubling the throughput of current half-duplex (HD) systems was experimentally demonstrated [2, 3], which makes FD an important candidate solution to address the challenging traffic demand of the fifth-generation (5G) cellular system.

In the scenarios other than point-to-point communications, however, doubling the spectral efficiency with FD is not easy due to the much more complicated interference environment in FD network [4]. Even in a single-cell multiuser system, where the FD BS serves multiple uplink and downlink HD users, operating in FD mode does not always outperform HD mode because of the inter-user interference (IUI) from an uplink transmitting user to a downlink receiving user [4]. Therefore, bidirectional user scheduling and the associated operating mode selection (i.e., scheduling one user or two bidirectional users) have a large impact on the performance of FD network.

There have been several works on the control of IUI via bidirectional user scheduling for FD systems. In [5], the bidirectional user scheduling and operating mode selection were designed for single-cell FD system. In [6] and [7], joint resource allocation problem involving bidirectional user scheduling, operating mode selection, and subcarrier and power allocation was studied for orthogonal frequency division multiple access (OFDMA) single-cell system and heterogeneous networks, respectively. Although these existing methods are effective to control the IUI in FD systems, they all assume that the FD BS has the knowledge of perfect channel state information between all uplink users and downlink users, which is usually very difficult to obtain in practical systems. To overcome this problem, an opportunistic scheduling scheme was proposed in [8] for single-cell FD system based on random transmit and receive beamforming at the FD BS. However, this scheme still requires the downlink users to estimate the channels from the uplink users, and generally performs well only for large number of transmit and receive antennas of the FD BS and large number of users.

Different from existing work, in this paper we employ localization information of users to perform bidirectional user scheduling and operating mode selection for single-cell FD system, where both the FD BS and the HD uplink or downlink users are not required to have the channel state information of the IUI links. By taking into account the impact of localization errors, random small-scale fading, and uncertain shadowing, we first propose a greedy-based user scheduling and mode selection scheme, and then develop a graph-based scheme to further improve the performance. Simulation results show that the proposed schemes can achieve evident performance gain over the HD system.

2. SYSTEM MODEL

Consider a small cell covered by a FD BS providing services to randomly scattered U HD uplink users and D HD downlink users. The FD BS has one transmit antenna and one receive antenna, and each user has a single antenna. Let $\mathcal{U}$ and $\mathcal{D}$ denote the sets of uplink and downlink users, respectively. We consider time-division multiple access (TDMA) based transmission. In each time slot the FD BS can operate in FD mode to serve one uplink user and one downlink user, or operate in HD mode to serve either one uplink or one downlink user.

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Let $h_{\mathrm{u},i}$, $h_{\mathrm{d},j}$ and h_{ij} denote the channels from the BS to the i-th uplink user (UE$_{\mathrm{u},i}$), from the BS to the j-th downlink user (UE$_{\mathrm{d},j}$), and from UE$_{\mathrm{u},i}$ to UE$_{\mathrm{d},j}$, respectively, for $i = 1, \ldots, U$ and $j = 1, \ldots, D$. We assume that the BS has the channels from it to the users, i.e., $h_{\mathrm{u},i}$ and $h_{\mathrm{d},j}$, but does not know the inter-user channels h_{ij}, $\forall i, j$. h_{ij} can be expressed as $h_{ij} = \sqrt{\alpha_{ij}} g_{ij}$, where α_{ij} and g_{ij} are large-scale and small-scale fading gains, respectively. The large-scale fading is modeled in dB as

$$\alpha_{ij} = \alpha_0 + \rho \log d_{ij} + s_{ij}, \tag{1}$$

where $\alpha_0 < 0$ is the pathloss at the reference distance, $\rho < 0$ is the pathloss exponent, d_{ij} is the distance between UE$_{\mathrm{u},i}$ and UE$_{\mathrm{d},j}$, and s_{ij} is the shadowing following log-normal distribution with zero mean and variance σ_S^2. The small-scale fading g_{ij} is assumed to follow independent and identically distributed (i.i.d.) complex Gaussian distribution $\mathcal{CN}(0, \sigma_G^2)$.

We assume that the BS has the imperfect location information of the users, which is a long-term information that can be estimated by the BS or fed back by the users. Specifically, let $\mathbf{x}_i \in \mathbb{R}^{2\times 1}$ and $\hat{\mathbf{x}}_i \in \mathbb{R}^{2\times 1}$ denote the real and estimated locations of UE$_{\mathrm{u},i}$ on the two-dimensional plane, which is modeled as

$$\mathbf{x}_i = \hat{\mathbf{x}}_i + \mathbf{e}_i, \tag{2}$$

where $\mathbf{e}_i$ is the localization error and is assumed to follow Gaussian distribution $\mathcal{N}(\mathbf{0}, \sigma_E^2 \mathbf{I})$. The same model is applicable to UE$_{\mathrm{d},j}$. Then, the distance between UE$_{\mathrm{u},i}$ and UE$_{\mathrm{d},j}$ can be expressed as

$$d_{ij} = \|\mathbf{x}_i - \mathbf{x}_j\| \triangleq \|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\|, \tag{3}$$

where $\hat{\mathbf{x}}_{ij} = \hat{\mathbf{x}}_i - \hat{\mathbf{x}}_j$ and $\mathbf{e}_{ij} = \mathbf{e}_i - \mathbf{e}_j$. It is easy to see that $\mathbf{e}_{ij}$ follows Gaussian distribution $\mathcal{N}(\mathbf{0}, 2\sigma_E^2 \mathbf{I})$

3. GREEDY-BASED SCHEDULING

We assume that the self-interference at the FD BS is suppressed to noise floor, which has been experimentally demonstrated feasible in small-cell scenario [2, 3]. Then, for uplink transmission operating in FD mode is always beneficial because the FD BS does not experience any interference in the considered single-cell system. However, this is not true for downlink transmission due to the existence of IUI. Thus, in the paper we focus on the performance of downlink users for the design of user scheduling and mode selection.

For every downlink user, the best companion uplink user is the one leading to the minimal IUI. Since we do no assume the knowledge of small-scale fading, shadowing, and localization errors, further considering that all the unknown random variables are i.i.d., one can find that statistically the best companion uplink user is the one located farthest from the downlink user.

For each best companion uplink and downlink user pair, we still need to investigate whether they should be served simultaneously in FD mode or should be served separately in different time slots in HD mode. To this end, we need to compare the data rates of the downlink user in FD mode and in HD mode, which are

$$R_{\mathrm{HD},\mathrm{d},j} = \frac{1}{2} \log_2 \left(1 + \frac{P_\mathrm{d} |h_{\mathrm{d},j}|^2}{\sigma_N^2}\right) \tag{4a}$$

$$R_{\mathrm{FD},\mathrm{d},j} = \log_2 \left(1 + \frac{P_\mathrm{d} |h_{\mathrm{d},j}|^2}{P_\mathrm{u} |h_{ij}|^2 + \sigma_N^2}\right), \tag{4b}$$

where the pre-log coefficient $\frac{1}{2}$ in (4a) reflects the loss of spectral efficiency of HD, P_d and P_u are the transmit power of the BS and each user, and σ_N^2 is the power of noise.

In order to operate in FD mode, we need to ensure $R_{\mathrm{FD},\mathrm{d},j} > R_{\mathrm{HD},\mathrm{d},j}$, which is equivalent based on (4) to

$$|h_{ij}|^2 < \frac{P_\mathrm{d} |h_{\mathrm{d},j}|^2}{P_\mathrm{u} \left(1 + \frac{P_\mathrm{d} |h_{\mathrm{d},j}|^2}{\sigma_N^2}\right)^{\frac{1}{2}} - P_\mathrm{u}} - \frac{\sigma_N^2}{P_\mathrm{u}} \triangleq \eta_j, \tag{5}$$

where η_j is a constant that can be computed at the BS.

Since $|h_{ij}|^2$ is unknown at the BS, we turn to compute the probability that condition (5) holds based on the locations of users. Based on (1) and (3), we can compute the probability as

$$\begin{aligned} &\Pr(|h_{ij}|^2 < \eta_j) \qquad (6) \\ &= \Pr(\alpha_0 + \rho \log \|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| + s_{ij} + 10 \log |g_{ij}|^2 < 10 \log \eta_j), \end{aligned}$$

where $\mathbf{e}_{ij}$, s_{ij}, and g_{ij} are random variables.

Given $\mathbf{e}_{ij}$ and g_{ij}, considering that s_{ij} follows log-normal distribution, it is easy to obtain the conditional probability

$$\begin{aligned} &\Pr(|h_{ij}|^2 < \eta_j | \mathbf{e}_{ij}, g_{ij}) \qquad (7) \\ &= \frac{1}{2}\Big(1 + \mathrm{erf}\big(\frac{10 \log \eta_j - \alpha_0 - \rho \log \|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| - 10 \log |g_{ij}|^2}{\sqrt{2}\sigma_S}\big)\Big). \end{aligned}$$

Since $\mathbf{e}_{ij}$ follows $\mathcal{N}(\mathbf{0}, 2\sigma_E^2 \mathbf{I})$, we know that the distance $\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\|$ follows non-central chi distribution with the probability density function (PDF)

$$f_d(x) = \frac{x}{2\sigma_E^2} e^{-\frac{x^2 + 2\lambda^2 \sigma_E^2}{4\sigma_E^2}} I_0\big(\frac{\lambda x}{\sqrt{2}\sigma_E}\big), \tag{8}$$

where $I_0(\cdot)$ is the zero-order modified Bessel function of the first kind, and $\lambda = \frac{\|\hat{\mathbf{x}}_{ij}\|}{\sqrt{2}\sigma_E}$ is the non-centrality parameter.

Further considering that $|g_{ij}|^2$ follows the exponential distribution with the PDF $f_g(y) = \frac{1}{2} e^{-\frac{y}{2}}$, we can compute the probability in (6) numerically as

$$\begin{aligned} &\Pr(|h_{ij}|^2 < \eta_j) \\ &= \int_0^\infty \int_0^\infty \Pr(|h_{ij}|^2 < \eta_j | \mathbf{e}_{ij}, g_{ij}) f_d(x) f_g(y) \mathrm{d}x \mathrm{d}y. \qquad (9) \end{aligned}$$

Then, we can define a mode selection threshold ϵ_0. When $\Pr(|h_{ij}|^2 < \eta_j) > \epsilon_0$, the BS operates in FD mode, otherwise in HD mode.

Fig. 1. Example of the drawback of greedy-base scheme.

Pairing every downlink user with the farthest uplink user may lead to unfairness among multiple uplink users, e.g., in the case where one uplink user is very far away from all downlink users. We employ the round-robin principle to address this issue, i.e., the selected downlink and uplink users in each time slot are removed from the candidate user pools in the subsequent time slots. The remaining problem is how to determine the order of the downlink users selecting their uplink companions. Finding the optimal order requires exhaustive searching, which is not feasible when the number of users is large. To circumvent this, we resort to the greedy-based method to sort the downlink users according to their data rates in HD modes, i.e., channel gains $|h_{\mathrm{d},j}|^2$ based on (4a), $\forall j$. Considering that the IUI has larger impact on the users with weak signal power, we let the users with small channel gains select first.

The greedy-based scheduling and mode selection scheme can be summarized in the following Algorithm 1.

Algorithm 1 Greedy-based Scheme

```
Initialize $\mathcal{U}_0 = \mathcal{U}$, $\mathcal{D}_0 = \mathcal{D}$, and select the threshold $\epsilon_0$.
for $j = 1, \ldots, D$ do
    Select the downlink user with the smallest channel gain from $\mathcal{D}_{j-1}$, denoted by $D_j$.
    Select the uplink user farthest away from $\mathrm{UE}_{\mathrm{d},D_j}$ from $\mathcal{U}_{j-1}$, denoted by $U_j$.
    Compute $\Pr(|h_{U_j D_j}|^2 < \eta_{D_j})$ with (9). If it is larger than $\epsilon_0$, then select the FD mode; otherwise, select the HD mode.
    Update $\mathcal{U}_j = \mathcal{U}_{j-1} \setminus \{U_j\}$ and $\mathcal{D}_j = \mathcal{D}_{j-1} \setminus \{D_j\}$ according to the round-robin priciple. If $\mathcal{U}_j$ is empty, i.e., all uplink users have been scheduled, let $\mathcal{U}_j = \mathcal{U}$.
end for
```

The greedy-based scheme can effectively reduce the searching space but suffer from the performance penalty. Specifically, although selecting the farthest uplink user is statistically optimal for the specific downlink user, it may not be optimal from the system point of view. An example is given in Fig. 1, where with the greedy-based scheme $\mathrm{UE}_{\mathrm{d},2}$ will first select $\mathrm{UE}_{\mathrm{u},2}$, making $\mathrm{UE}_{\mathrm{d},1}$ experience severe IUI from $\mathrm{UE}_{\mathrm{u},1}$. Alternatively, if $\mathrm{UE}_{\mathrm{d},2}$ selects $\mathrm{UE}_{\mathrm{u},1}$ and $\mathrm{UE}_{\mathrm{d},1}$ selects $\mathrm{UE}_{\mathrm{u},2}$, then both the downlink users experience weak IUI. In next section, we improve the scheduling and mode selection scheme to address this issue.

4. GRAPH-BASED SCHEDULING

In this section we strive to propose a user scheduling and mode selection scheme for pairing the bidirectional users from the system point of view. The basic idea is to first specify a FD-feasible range for each downlink user, then determine which uplink users can be paired with each downlink user, based on which a bipartite graph between the bidirectional users is finally built for user scheduling and mode selection, aimed at maximizing the number of FD pairs. Such a graph-based scheme is easy to implement when perfect inter-user channels are available at the BS, which however is not straightforward when only location information is known.

To characterize the FD-feasible range of downlink user $\mathrm{UE}_{\mathrm{d},j}$, we define a distance κ_j so that when an uplink user, say $\mathrm{UE}_{\mathrm{u},i'}$, has the distance κ_j from $\mathrm{UE}_{\mathrm{d},j}$, the probability of $R_{\mathrm{FD,d},j}$ being larger than $R_{\mathrm{HD,d},j}$ equals to ϵ_1. This condition can be expressed based on (4)∼(9) as

$$\int_0^\infty \frac{1}{2}\Big(1+\mathrm{erf}\big(\frac{10\log\eta_j - \alpha_0 - \rho\log\kappa_j - 10\log|g_{i'j}|^2}{\sqrt{2}\sigma_S}\big)\Big) \cdot f_g(y)\mathrm{d}y = \epsilon_1. \tag{10}$$

Since the left-hand side of (10) is an increasing function of κ_j, it is easy to solve κ_j, e.g., by using a bisection method.

Then, we determine which uplink users having the distance to $\mathrm{UE}_{\mathrm{d},j}$ larger than κ_j. We cannot exactly obtain the distance between two users under the imperfect localization model. Instead, we compute the probability of $d_{ij} > \kappa_j$, i.e.,

$$\begin{aligned} &\Pr(\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| > \kappa_j) \\ &= 1 - e^{-\lambda/2} \textstyle\sum_{n=0}^{\infty} \frac{(\lambda/2)^n}{(n!)^2} \Upsilon(1+n, \frac{\kappa_j^2}{4\sigma_E^2}), \end{aligned} \tag{11}$$

which is obtained considering that $\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\|$ follows noncentral chi distribution with the PDF in (8), where λ is defined in (8) and $\Upsilon(n, x)$ is the lower incomplete Gamma function.

To determine whether $\mathrm{UE}_{\mathrm{u},i}$ is in the FD-feasible range of $\mathrm{UE}_{\mathrm{d},j}$, we introduce another threshold ϵ_2. When $\Pr(\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| > \kappa_j) > \epsilon_2$, we let $\mathrm{UE}_{\mathrm{u},i}$ be a candidate FD companion of $\mathrm{UE}_{\mathrm{d},j}$. Denote by $\overline{\mathcal{U}}_j$ the set of all candidate uplink FD companions of $\mathrm{UE}_{\mathrm{d},j}$, $\overline{\mathcal{U}}_j \subset \mathcal{U}, \forall j$.

With $\{\overline{\mathcal{U}}_j\}$ we can build a bipartite graph, where the uplink and downlink users are the two parts of nodes and the edges connect all possible candidate FD pairs specified by $\{\overline{\mathcal{U}}_j\}$. Based on this graph, we schedule the users to maximize the number of user pairs operating in FD mode. This is a maximum matching problem, which can be solved with the Hungarian algorithm [9]. Based on the obtained scheduling results, we employ the round-robin principle to serve the paired bidirectional users in FD mode and serve the unpaired uplink or downlink users in HD mode.

The graph-based scheduling and mode selection scheme can be summarized in the following Algorithm 2.

5. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed two scheduling and mode selection schemes. We simulate a small cell with the radius of 40 m, where the BS is located at

Algorithm 2 Graph-based Scheme

```
Initialize $\overline{\mathcal{U}}_j$ as empty set, $\forall j$, and select the thresholds $\epsilon_1$ and $\epsilon_2$.
Compute the FD-feasible range parameter $\kappa_j$ by solving (10), $\forall j$.
Compute the probability $\Pr(\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| > \kappa_j)$ with (11).
for $j = 1, \ldots, D$ and $i = 1, \ldots, U$ do
    Add $\mathrm{UE}_{\mathrm{u},i}$ into $\overline{\mathcal{U}}_j$ if $\Pr(\|\hat{\mathbf{x}}_{ij} + \mathbf{e}_{ij}\| > \kappa_j) > \epsilon_2$.
end for
Build the bipartite graph based on $\{\overline{\mathcal{U}}_j\}$, and solve the maximum matching problem.
```

the center and $U = 5$ uplink users and $D = 5$ downlink users are randomly scattered in the cell. The FD BS has a single transmit and receive antenna and a transmit power of 30 dBm, while each user has a single antenna and each uplink user has a transmit power of 23 dBm [10]. The pathloss is modeled as $-30.1 - 36.7\log_{10}(d)$, and the shadowing is log-normal distributed with standard deviation of 4 dB [10]. The average downlink receive signal-to-noise ratio (SNR) of users located at the cell edge is set as 20 dB, based on which the noise power can be obtained, which takes into account both thermal noises and the inter-cell interference. The three thresholds in the proposed two schemes are set as $\epsilon_0 = 0.5$, $\epsilon_1 = 0.95$, and $\epsilon_2 = 0.75$, respectively. As explained before, we focus on the downlink performance and show the cumulative distribution function (CDF) of the downlink rates.

Except the two proposed schemes, we also simulate other six relevant schemes for comparison:

(1) *HD mode*, where uplink and downlink users are scheduled in a round-robin manner.

(2) *Random FD*, where uplink and downlink users are randomly paired for FD transmission without any channel state information of users.

(3) *Ideal greedy-based*, where the greedy-based scheme is implemented by assuming perfect inter-user channel state information available at the BS.

(4) *Ideal graph-based*, where the graph-based scheme is implemented by assuming perfect inter-user channel state information available at the BS.

(5) *Estimated greedy-based*, where the imperfect location information of users is employed to estimate the pathloss, $\widehat{\mathrm{PL}}_{ij} = \alpha_0 + \rho\log\|\hat{\mathbf{x}}_{ij}\|$, which is then regarded as the perfect inter-user channels, i.e., $|h_{ij}|^2 \leftarrow \widehat{\mathrm{PL}}_{ij}$, to implement the greedy-based scheme.

(6) *Estimated graph-based*, where the method for scheme (5) is applied to the graph-based scheme.

Figure 2 shows the CDF of the downlink rates achieved by the eight scheduling and mode selection schemes, where the localization error is modeled as Gaussian distributed random variables with $\sigma_E = 20$ m. Compared to the HD mode, we can see that with perfect knowledge of inter-user channels transmitting in FD mode with the two proposed scheduling schemes can significantly improve the performance. Randomly pairing the uplink and downlink users for FD transmission has no any control on the IUI, which leads to very bad cell-edge performance. Simple usages of the location information, such as the simulated "Estimated greedy-based" and "Estimated graph-based" schemes, suffer from the degradation of cell-edge performance, which is worse than the HD mode. Nevertheless, with the proposed two scheduling schemes, the location information can be used to effectively improve the performance of cell medium-center area, without sacrificing the performance of the cell-edge users. Moreover, we can observe that the proposed graph-based scheme outperforms the greedy-based scheme because the former can guarantee the optimality from the system point of view as explained before.

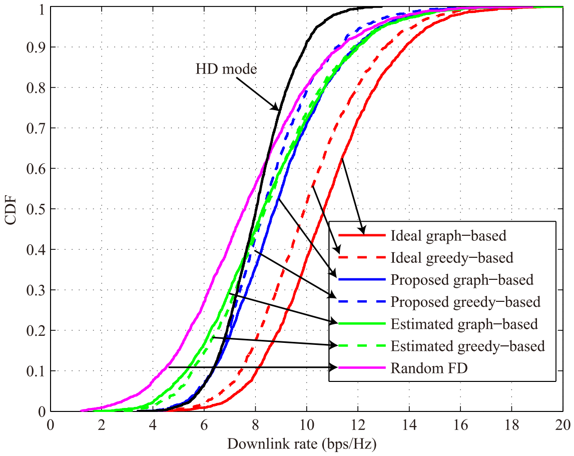

Fig. 2. Performance comparison of eight scheduling schemes.

6. CONCLUSIONS

In this paper we studied the bidirectional user scheduling and operating mode selection for single-cell FD system, where a FD BS serves multiple HD uplink and downlink users. We proposed two scheduling and mode selection schemes, namely the greedy-based scheme and the graph-based scheme, both of which do not require the channel state information between uplink and downlink users, but only rely on the imperfect location information of users. Simulation results show that the proposed schemes can exploit the rough location information to effectively improve the performance of cell medium-center area without degrading the cell-edge performance.

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