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Research Article

Outage Analysis of User Pairing Algorithm for Full-Duplex Cellular Networks

Hyun-Ho Choi [1] **and Wonjong Noh** [2]

[1] *Department of Electrical, Electronic and Control Engineering, Hankyong National University, Anseong 17579, Republic of Korea*
[2] *Department of Electronics and Communication Engineering, GTEC, Siheung 15073, Republic of Korea*

Correspondence should be addressed to Wonjong Noh; wonjong.noh@gmail.com

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In a full-duplex (FD) cellular network, a base station transmits data to the downlink (DL) user and receives data from uplink (UL) users at the same time; thereby the interference from UL users to DL users occurs. One of the possible solutions to reduce this interuser interference in the FD cellular network is *user pairing*, which pairs a DL user with a UL user so that they use the same radio resource at the same time. In this paper, we consider a user pairing problem to minimize outage probability and formulate it as a nonconvex optimization problem. As a solution, we design a low-complexity user pairing algorithm, which first controls the UL transmit power to minimize the interuser interference and then allows the DL user having a worse signal quality to choose first its UL user giving less interference to minimize the outage probability. Then, we perform theoretical outage analysis of the FD cellular network on the basis of stochastic geometry and analyze the performance of the user pairing algorithm. Results show that the proposed user pairing significantly decreases the interuser interference and thus improves the DL outage performance while satisfying the requirement of UL signal-to-interference-plus-noise ratio, compared to the conventional HD mode and a random pairing. We also reveal that there is a fundamental tradeoff between the DL outage and UL outage according to the user pairing strategy (e.g., throughput maximization or outage minimization) in the FD cellular network.

1. Introduction

Full-duplex (FD) technologies enable a wireless node to transmit and receive data on the same radio resource at the same time so that the system capacity can be increased up to two times in theory. However, this FD operation causes co-channel interferences between entities using the same resource, whereas the conventional half-duplex (HD) mode does not create such interferences. In FD cellular network, two types of co-channel interference occur: *self-interference* occurs from the transmit (Tx) antenna to the receive (Rx) antenna at the base station (BS) and *interuser interference* occurs from the uplink (UL) user to the downlink (DL) user [1, 2].

In an FD transceiver, the self-interference signal from its transmitter is typically 100 dB stronger than the intended receiving signal. This strong self-interference in the FD transceiver obviously makes the radio chain at the receiver saturated and the received data cannot be decoded properly [3]. However, this self-interference problem has recently been solved by advanced technologies of analog and digital signal processing. It is now feasible to achieve up to 110 dB self-interference cancellation (SIC) capability [4]. Thus, the self-interference is mostly reduced to the same level as the signal of interest before going through the decoding chain at the receiver; thus, data decoding is possible. In practice, there are many real-time prototypes demonstrated for FD communications [5–8].

Although a single-link FD transmission has become technically feasible, it is still expensive to equip SIC functionality with above 100 dB to all user equipment (UE) for the deployment of FD cellular network. Thus, most of the UEs may still operate in HD mode and it is more practical to suppose that only BSs operate in FD mode. As a result, coexistence of both UL and DL transmission on the same channel at the same time in the FD cellular network causes so-called interuser interference from UL users to DL users. Therefore, smart interference management techniques are necessary to manage this interuser interference and several algorithms including resource management, power control, user pairing/scheduling, and their optimization have been investigated to enhance performances in terms of system throughput, outage probability, and coverage [9–20].

Related to the resource allocation algorithm, a joint resource allocation was considered to reduce the interuser interference in FD cellular networks [9]. In [10], a simple two-user FD network was investigated and a noncooperative game was presented for resource allocation. In [11], energy efficient resource allocation was invented to minimize total transmit power in FD cellular networks. Regarding the power control, the transmit powers of the UL UE, BS, and relay were coordinated to mitigate the interference in an FD relay-enhanced cellular network [12]. In [13], an effective power control scheme was proposed to suppress interference between D2D and cellular communications for FD relay-assisted device-to-device communication. In [14], a distributed power control algorithm was suggested based on Fast-Lipschitz optimization to maximize the sum spectral efficiency in the three-node FD transmission mode.

Furthermore, various user pairing/scheduling algorithms for an FD network were investigated [15]. In [16], a cooperative FD relays- (FDRs-) based scheduling technique was proposed to achieve additional throughput by using cooperative FDRs. In [17], a suboptimal heuristic joint user scheduling and channel allocation algorithm with low complexity were devised in FD cellular networks. In [18], two kinds of user pairing schemes were presented to maximize throughput and minimize outage in a single-cell FD network. Thereafter, the throughput performance of the first throughput-maximizing user pairing algorithm was analyzed [19]. Moreover, a joint optimization problem was investigated by considering mode selection, user pairing, subcarrier allocation, and power control in order to maximize the aggregate network throughput in FD heterogeneous networks [20].

As an important issue, the user pairing problem has also been studied in other network scenarios [21–26]. A cross-layering method was proposed to solve the pairing problem for collaborative spatial multiplexing in IEEE 802.16 networks [21]. A user pairing scheme was proposed based on the generalized lattice code to improve the average sum rate in an amplify-and-forward multiway relay network [22]. User pairing stability was analyzed in device-to-device-relay networks and a metric to quantize it was proposed [23]. A distributed matching algorithm was proposed to optimize the user pairing in a downlink nonorthogonal multiple access (NOMA) network [24]. A low-complexity user pairing algorithm was proposed using a heuristic approach for NOMA-based cellular network [25]. Impact of user pairing was analyzed considering imperfect channel state information in NOMA-based energy harvesting relaying networks [26].

Many studies on user pairing approaches in FD networks have been conducted, where the throughput performance is mostly analyzed and optimized but the outage performance is relatively less studied. Unlike [18], this study considers a new multicell structure and performs a mathematical analysis on the basis of stochastic geometry for the outage-minimizing user pairing algorithm presented previously. Compared to the throughput analysis in [19], we here perform a new outage analysis on existing user pairing algorithms considering different system configurations, which have not been dealt with in [18, 19].

In this paper, we propose a user pairing algorithm to reduce the interuser interference from UL to DL users in FD cellular networks. We describe a user pairing problem for minimizing outage probability. To solve this problem, a very highly complexity is required and we devise a suboptimal algorithm with low complexity from a practical point of view. The basic approach of the proposed user pairing is that it first reduces the transmit power of UL users to satisfy the signal-to-interference-plus-noise ratio (SINR) threshold for minimizing the inter-user interference, and then makes the DL user having a worse signal quality select first its UL user who gives less interference for outage minimization. We perform an outage analysis of the FD network by using stochastic geometry to identify the influence of the user pairing algorithms. Results show that the FD system using the proposed pairing algorithm greatly improves outage probability compared to the conventional user pairing algorithms.

The remainder of this paper is organized as follows. In Section 2, the system of the considered FD cellular network is described. In Section 3, the user pairing algorithm for outage minimization is explained. In Section 4, a stochastic geometry-based analysis in terms of DL and UL outage probabilities is provided. In Section 5, simulation and analysis results are provided. Finally, we present our concluding remarks in Section 6.

2. System Model

We consider a multicell network where each cell is adjacent to N neighboring cells, as illustrated in Figure 1. The BS uses FD mode whereas DL and UL users use HD mode owing to the limited implementation cost of UE. We assume that there are total $2M$ users in each cell and both the numbers of UL users and of DL users are M evenly. In addition, one transmission frame has M resource blocks (RBs) and each user is allocated only one RB within a frame to transmit or receive data. This RB allocation is conducted in a way of round-robin in order to provide some degree of fairness for all users [27].

As shown in Figure 1, each channel coefficient is defined as follows.

(i) h_{i0}: channel from serving BS_0 to DL user i

(ii) h_{0j}: channel from the UL user j to serving BS_0

(iii) g_{00}: channel from Tx to Rx in the serving BS_0

(iv) g_{0n}: channel from neighboring BS n to serving BS_0

(v) g_{in}: channel from neighboring BS n to DL user i

(vi) f_{ij}: channel from UL user j to DL user i

(vii) f_{in}: channel from UL user in the n-th neighboring cell to DL user i

(viii) f_{0n}: channel from UL user in the n-th neighboring cell to serving BS_0

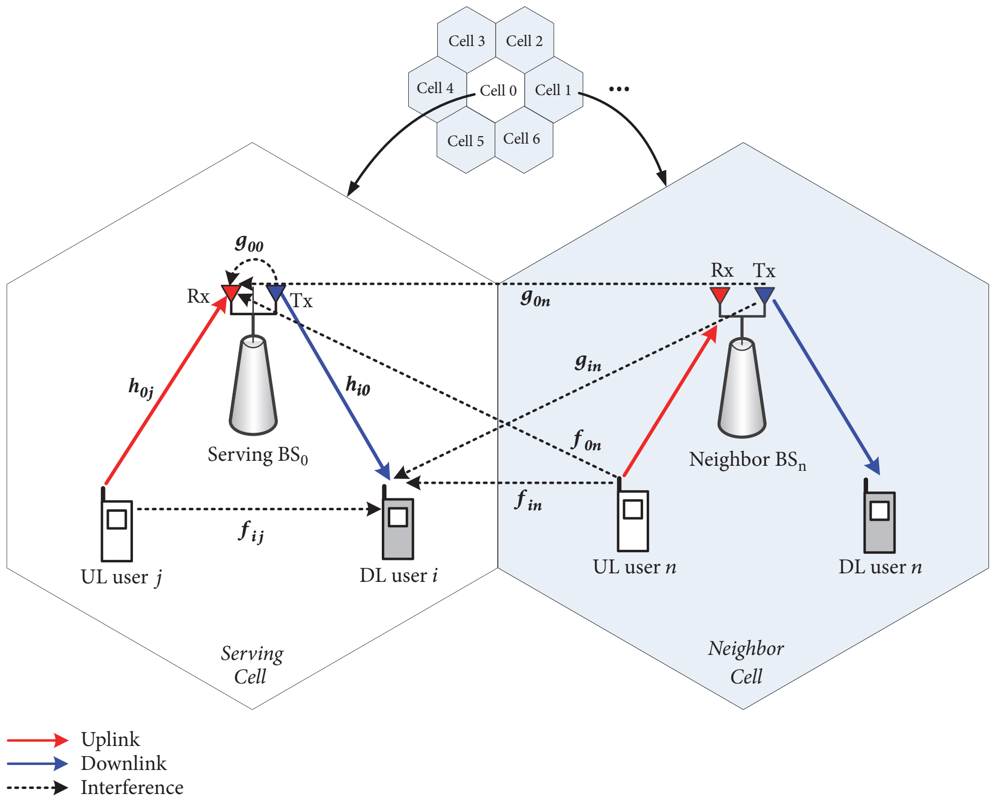

Figure 1: System model for full-duplex cellular networks considered.

Here, we assume that all the channel coefficients follow $\mathcal{CN}(0, \sigma^2/d_{ij}^{\alpha})$ where d_{ij} is the physical distance of the corresponding ij link and α is the path loss exponent. Further, n_i is the additive white Gaussian noise with zero mean and N_0 variance.

Since both the DL and UL users send data on the same frequency at the same time, the DL user suffers from three different interferences from (1) the UL user who uses the same RB within the serving cell, (2) the Tx of neighbor BSs, and (3) the UL users who use the same RB in neighbor cells. Thus, the received signal of DL user i is represented as

$$y_i = \sqrt{P_0} h_{i0} x_i + \underbrace{\sqrt{P_j} f_{ij} x_j}_{\text{inter-user intf.}} + \underbrace{\sum_{n=1}^{N} \sqrt{P_0} g_{in} \hat{x}_n}_{\text{intf. from neighbor BSs}} + \underbrace{\sum_{n=1}^{N} \sqrt{P_n} f_{in} \check{x}_n}_{\text{intf. from neighbor UL users}} + n_i \quad (1)$$

where P_0 and P_j are the transmission power of the serving BS and UL user j, respectively. Moreover, x_i, x_j, and x_n are the signals transmitted from the serving BS_0, the UL user j with the same RB, and the n-th neighboring cell, respectively.

Furthermore, the Rx of the BS suffers from three different interferences from (1) the Tx of the serving BS, (2) the Tx of neighbor BSs, and (3) the UL users who use the same RB in neighbor cells. Accordingly, the received signal at the serving BS_0 from the UL user j is represented as

$$y_j = \sqrt{P_j} h_{0j} x_j + \underbrace{\sqrt{P_0} g_{00} x_i}_{\text{self-interference}} + \underbrace{\sum_{n=1}^{N} \sqrt{P_0} g_{0n} \hat{x}_n}_{\text{intf. from neighbor BSs}} + \underbrace{\sum_{n=1}^{N} \sqrt{P_n} f_{0n} \check{x}_n}_{\text{intf. from neighbor UL users}} + n_0. \quad (2)$$

In the FD network, the BS's receiver suffers from severe interferences from the transmitters both the serving and neighbor BSs. (Relatively, we can regard the interferences from the Txs of UL users in the neighboring cells as weak interferences because the transmit power of UE is small and the UL signal is greatly attenuated by the long distance [16–20, 28].) However, the FD BS can remove these interference components through the interference cancellation and channel estimation techniques [4, 28]. For this channel estimation, we suppose that the Rx of the BS utilizes pilot symbols transmitted from the Txs of the serving BS_0 and neighbor BSs. Therefore, the received interference strength can be decreased to a similar level to the noise floor of receiver after sequentially applying analog and digital cancellation schemes [5–8]. In addition, we can estimate the channel coefficients g_{00} and g_{0n} by applying an appropriate channel estimation method [29]. (Details about channel estimation technique are out of the scope in this paper and the channel estimation at the BS is assumed to be perfect.) Based on the knowledge of the signals received from the serving BS_0 and neighbor BSs via the wired backhaul and the interference channel estimation, the Rx of the serving BS_0 can remove such interference components from the received signal. After interference cancellation, the signal of UL user j is given by

$$\begin{aligned}\widehat{y}_j &= \sqrt{P_j} h_{0j} x_j + \sqrt{P_0}\left(g_{00} - \widehat{g}_0\right) x_i \\ &\quad + \sum_{n=1}^{N} \sqrt{P_0}\left(g_{0n} - \widehat{g}_{0n}\right) \widehat{x}_n + \sum_{n=1}^{N} \sqrt{P_n} f_{0n} \check{x}_n + n_0\end{aligned} \tag{3}$$

where $\widehat{g}_0$ and $\widehat{g}_{0n}$ correspond to the estimated channel coefficients.

Using (1) and (3), the SINRs of the received signals y_i and $\widehat{y}_j$ are, respectively, given by

$$\Gamma_i = \frac{P_0 \left\|h_{i0}\right\|^2}{P_j \left\|f_{ij}\right\|^2 + \sum_{n=1}^{N} P_0 \left\|g_{in}\right\|^2 + \sum_{n=1}^{N} P_n \left\|f_{in}\right\|^2 + N_0}, \tag{4}$$

$$\Gamma_j = \frac{P_j \left\|h_{0j}\right\|^2}{P_0 \left\|g_{00} - \widehat{g}_0\right\|^2 + \sum_{n=1}^{N} P_0 \left\|g_{0n} - \widehat{g}_{0n}\right\|^2 + \sum_{n=1}^{N} P_n \left\|f_{0n}\right\|^2 + N_0}. \tag{5}$$

In the conventional HD mode that does not generate self-interference and interuser interference, the SINRs of DL user i and UL user j are, respectively, described as

$$\Gamma_i^{\mathrm{HD}} = \frac{P_0 \left\|h_{i0}\right\|^2}{\sum_{n=1}^{N} P_0 \left\|g_{in}\right\|^2 + N_0}, \tag{6}$$

$$\Gamma_j^{\mathrm{HD}} = \frac{P_j \left\|h_{0j}\right\|^2}{\sum_{n=1}^{N} P_n \left\|f_{0n}\right\|^2 + N_0}. \tag{7}$$

3. Proposed User Pairing Algorithm

On the basis of SINR expressions for DL and UL users given as (4) and (5), the controllable parameters are explicitly P_j and f_{ij}. The other parameters are generally fixed or are determined by the node position. Here, the channel coefficient f_{ij} depends on how we pair UL user j and DL user i to use the same RB. Namely, the user pairing determines the amount of interuser interference and directly influences the DL SINR Γ_i. In this context, we propose an effective user pairing algorithm to improve the system performance in the considered FD cellular network.

Our objective is to minimize the outage probability. Since the outage occurs when the SINR does not satisfy the required SINR, the outage probabilities of the DL user i and the UL user j are, respectively, defined as

$$P_{out}^{\mathrm{DL}} \triangleq \mathbb{P}\left\{\Gamma_i < \theta\right\} \quad \text{for } i \in \{1, 2, \ldots, M\}, \tag{8}$$

$$P_{out}^{\mathrm{UL}} \triangleq \mathbb{P}\left\{\Gamma_j < \theta\right\} \quad \text{for } j \in \{1, 2, \ldots, M\} \tag{9}$$

where θ is the required SINR threshold [30]. For the purpose of minimizing the outage probability of all users, the optimization problem can be formulated as

$$\pi_k = \arg\max_{(i,j)\in\pi_k} \min\left\{\Gamma_i, \Gamma_j\right\} \quad \text{for } i, j \in \{1, 2, \ldots, M\}. \tag{10}$$

Here, we denote (i, j) as a user pair of DL user i and UL user j using the same RB and define $\mathbf{\Pi}$ as the set of all possible user pairs (i, j) for $i, j \in \{1, 2, \ldots, M\}$. Also we denote π_k as the k-th element of $\mathbf{\Pi}$ where $k = 1, 2, \ldots, M!$.

Available user pairs are determined by selecting a number i in $\{1, 2, \ldots, M\}$ and a number j in $\{1, 2, \ldots, M\}$ under the condition that the selected number cannot be chosen again. Thus, the number of possible configurations for user pairing becomes $M!$. For instance of $M = 3$, $\mathbf{\Pi}$ becomes

$$\mathbf{\Pi} = \begin{bmatrix}\pi_1 \\ \pi_2 \\ \pi_3 \\ \pi_4 \\ \pi_5 \\ \pi_6\end{bmatrix} = \begin{bmatrix}\{(1,1),(2,2),(3,3)\} \\ \{(1,1),(2,3),(3,2)\} \\ \{(1,2),(2,1),(3,3)\} \\ \{(1,2),(2,3),(3,1)\} \\ \{(1,3),(2,1),(3,2)\} \\ \{(1,3),(2,2),(3,1)\}\end{bmatrix} \tag{11}$$

where six configurations exist. To solve this combinatorial problem, we must search the total $M!$ configurations. This complexity is $O(M!)$ and exponentially increases as the number of users (M) increases. Hence, we need to design a suboptimal pairing algorithm with low complexity from the practical point of view.

We can have an intuition for designing a new user pairing algorithm from (4) and (5). In (5), the SINR of UL user, Γ_j, is not relevant to DL users. If we suppose that both the interference cancellation and channel estimation are perfect and the interference from neighbor UL users is negligible, Γ_j is affected by mainly UL channel h_{0j} and UL transmit power P_j. On the other hand, the SINR of DL user, Γ_i, is relevant to the DL channel (h_{i0}), the direct channel from UL user j to DL user i (f_{ij}), and the UL transmit power (P_j). Namely, the user pairing affects the SINR of DL user Γ_i only. Therefore, the first parameter that can be adjusted to reduce the outage is the UL transmit power, P_j. Since the UL transmission gives the interference to the DL user, it is preferable that the UL user j controls its transmission power P_j to satisfy $\Gamma_j = \theta$. This UL power control is effective to reduce the interference from UL user to DL user and thus decreases the outage probability of DL users while satisfying the UL SINR requirement.

In addition, to avoid the outage from the perspective of DL users, it is reasonable to make the DL user with a worse signal quality receive less interference [31]. Thus, we make the DL users with a worse signal quality (i.e., a lower value of Γ_i^{HD}) select first the UL user causing a smaller interference (i.e., $P_j\|f_{ij}\|^2$) as its partner. By the way, if the SINR of DL user i, Γ_i, is smaller than θ although the best UL user is selected by this strategy, the DL user is convinced of its outage and does not finally select the corresponding UL user. Thus, we make this outage DL user yield its option to the next DL user and choose a UL user later among the remaining unpaired UL

Ensure: θ = SINR threshold
1: **Initialize:**
$$P_j \longleftarrow \frac{\theta N_0}{\left\|h_{0j}\right\|^2}, \quad j = 1, 2, \ldots, M$$
$U_j \longleftarrow 0$, $j = 1, 2, \ldots, M$ /* flag for selected or not */
2: Sort the DL users in order of low Γ_i^{HD} value
3: **for** i = [sorted DL users] **do**
4: Unpaired UL users $\longleftarrow$ find($U_j = 0$)
5: Measure the interference from unpaired UL user j to DL user i ($P_j \| f_{ij} \|^2$) where $j \in \{1, 2, \ldots, M\}$
6: Choose the UL user j causing the smallest interference $P_j \| f_{ij} \|^2$ among unpaired UL users
7: **if** $\Gamma_i > \theta$ when choosing the UL user j **then**
8: $U_j \longleftarrow 1$
9: Complete the user pair (i, j)
10: **else**
11: Outage DL users $\longleftarrow i$
12: **end if**
13: **end for**
14: **for** i = [sorted outage DL users] **do**
15: Unpaired UL users $\longleftarrow$ find($U_j = 0$)
16: Choose the UL user j causing the smallest interference $P_j \| f_{ij} \|^2$ among unpaired UL users
17: $U_j \longleftarrow 1$
18: Complete the user pair (i, j)
19: **end for**

Algorithm 1: Proposed user pairing algorithm.

users. For the outage DL users, the same policy is used with the remaining unpaired UL users in a way of maximizing the minimum SINR. Since this proposed user pairing approach gives more opportunities to the DL users with a lower signal quality, the outage probability can be decreased effectively.

The details of the proposed user pairing algorithm are described as Algorithm 1. Initially, the transmission power of all UL users is set to the minimum value to satisfy the SINR threshold (i.e., $P_j = \theta N_0 / \|h_{0j}\|^2$), in order to minimize the interuser interference from UL user to DL user. Moreover, the flag means whether the UL user is selected or not and is initially set to zero for all j. Then, the algorithm sorts the DL users from the lowest to the highest DL SINR value and runs in the order of these sorted DL users. For DL user i, the pairing algorithm measures the interference from the unpaired UL user j to the DL user i, $P_j \| f_{ij} \|^2$. Thereafter, the UL user with the smallest interuser interference $P_j \| f_{ij} \|^2$ among the unpaired UL users is chosen for pairing. If the DL SINR for this selected pair is greater than the SINR threshold, the flag of this UL user j is set to one. Namely, the DL user i and selected UL user j become a partner with each other. Otherwise, the DL user i belongs to the outage DL user. This pairing operation is iterated until all DL users are handled. If there is any outage DL user, there is additional user pairing between the outage DL users and the unpaired UL users. The rule is the same as Lines 3-13, but there is no requirement to satisfy the SINR threshold, as shown. In this way, the user pairing is completed to minimize the outage of all users. Notice that the proposed pairing algorithm performs one iteration and one search in each iteration for M users; thus, its computational complexity is $O(M^2)$, which is much less than the complexity of an exhaustive search (i.e., $O(M!)$).

For designing the proposed pairing algorithm, we assumed that the number of DL users and UL users are the same and the BS knows the necessary channel information. However, if the number of DL users and UL users is different, the excess link users will not be able to participate in pairing for FD and will have to operate in HD mode. This can lead to performance degradation. In addition, for the operation of the proposed algorithm, the UL user must report the amount of interference received from each DL user to the BS. This results in UL feedback overhead. Therefore, to realize the proposed pairing algorithm in an actual environment, we need to consider these practical issues to reduce such performance degradation and overhead, which are left as a future study.

4. Outage Analysis

4.1. Notations and Assumptions. For the analysis based on stochastic geometry, we suppose a homogeneous cellular network consisting of macrocell BSs and users [19]. The BSs are arranged in accordance with a Poisson point process (PPP) of density λ in the Euclidean plane [32, 33]. We also suppose that both DL and UL users are distributed independently with a homogeneous PPP of the same density λ. Therefore, the BS allocates one DL user and one UL user simultaneously during a given RB [33, 34]. And each user is associated with its nearest BS.

Figure 2 exhibits the system model where an FD BS_0 serves its DL user u_0 and UL user u_1 at the same time.

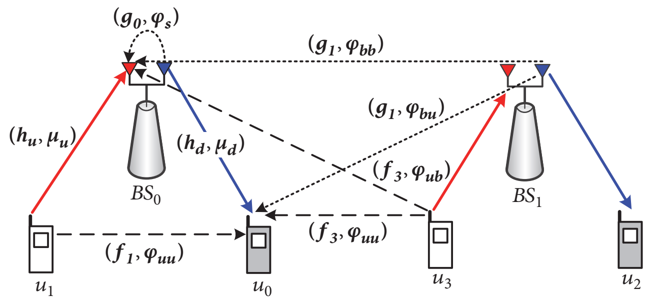

Figure 2: System model and notations.

u_0 experiences interferences from u_1, u_3, and BS_1 and u_1 experiences interferences from u_3, BS_0, and BS_1 while u_0 receives and u_1 transmits a signal from and to a BS_0 simultaneously. Solid line with $(h, \cdot)$ indicates the signal channel, dotted line with $(g, \cdot)$ indicates the interference channels by the neighboring BSs, and dashed line with $(f, \cdot)$ denotes the interference channels by users. Here, we suppose that a serving BS and its users experience Rayleigh fading with unit mean and they use a fixed transmission power of $1/\mu$. Moreover, the received signal strength at a certain node with a distance r to its BS is set to $hr^{-\alpha}$ where h follows an Exponential distribution with mean $1/\mu$ (i.e., $h \sim \exp(\mu)$), which is denoted as (h, μ). Also the path loss exponent of all BSs and users is denoted as α, and additive noise power is set to σ^2. All results are limited to the case of a single transmit/receive antenna.

4.2. Downlink Outage Probability. When a DL user, u_0, has a distance r and fading strength $h_d \sim \exp(\mu_d)$ from its serving BS, u_0 receives a signal with a strength of $h_d r^{-\alpha}$. Moreover, u_0 receives cumulative interference I_b and I_u from its neighbors. Here, I_b represents the total sum of the received powers from all neighboring BSs. When u_0 has a distance r_i and fading strength $g_i \sim \exp(\varphi_{bu})$ from to the neighboring BS i, I_b is expressed as

$$I_b = \sum_{i \in \Phi_b} g_i r_i^{-\alpha} \quad (12)$$

where Φ_b denotes the set of all interfering BSs. Moreover, I_u represents the total sum of the received powers from all other UL users. When u_0 has a distance r_i and fading strength $f_i \sim \exp(\varphi_{uu})$ from the other UL user i, I_u is expressed as

$$I_u = \sum_{i \in \Omega_u} f_i r_i^{-\alpha} \quad (13)$$

where Ω_u is the set of all interfering users. Then, the SINR of DL user u_0 is given by

$$\Gamma_{\mathrm{DL}} = \frac{h_d r^{-\alpha}}{I_b + I_u + \sigma^2}. \quad (14)$$

The outage probability of DL user is exactly represented as the cumulative distribution function (CDF) of SINR over the entire network, as follows.

$$P_{out}^{\mathrm{DL}}(\lambda, \theta) = \mathbb{P}\left[\Gamma_{\mathrm{DL}} < \theta\right]. \quad (15)$$

Since the probability that the nearest BS has a distance r being $e^{-\lambda\pi r^2} 2\pi\lambda r$, the outage probability is formulated as

$$\begin{aligned} P_{out}^{\mathrm{DL}}(\lambda, \theta) &= 1 - \int_{r>0} \mathbb{P}\left[h_d \geq \theta r^{\alpha}\left(I_b + I_u + \sigma^2\right) \mid r\right] \\ &\cdot e^{-\lambda\pi r^2} 2\pi\lambda r dr = 1 - \int_{r>0} e^{-\lambda\pi r^2 - \mu_d \theta r^{\alpha}\sigma^2} \\ &\cdot \mathcal{L}_{I_b}\left(\mu_d \theta r^{\alpha}\right) \cdot \mathcal{L}_{I_u}\left(\mu_d \theta r^{\alpha}\right) \cdot 2\pi\lambda r dr. \end{aligned} \quad (16)$$

Here, the Laplace transform of I_b is calculated as

$$\begin{aligned} &\mathcal{L}_{I_b}\left(\mu_d \theta r^{\alpha}\right) \\ &= \exp\left(-2\pi\lambda \int_r^{\infty}\left(1 - \frac{\varphi_{bu}}{\varphi_{bu} + \mu_d \theta r^{\alpha} v^{-\alpha}}\right) v dv\right) \\ &= \exp\left(-2\pi\lambda \int_r^{\infty} \frac{\beta_{d,bu}\theta}{\beta_{d,bu}\theta + (v/r)^{\alpha}} v dv\right) \\ &= \exp\left(-2\pi\lambda \int_r^{\infty} \frac{1}{1 + \left(\beta_{d,bu}\theta\right)^{-1}(v/r)^{\alpha}} v dv\right) \\ &= \exp\left(-\pi r^2 \lambda \rho_{db}(\theta)\right) \end{aligned} \quad (17)$$

where $\rho_{db}(\theta) = (\beta_{d,bu}\theta)^{2/\alpha} \int_{(\beta_{d,bu}\theta)^{-2/\alpha}}^{\infty} 1/(1 + u^{\alpha/2}) du$ is used for calculation. In the same way, the Laplace transform of I_u is obtained as

$$\mathcal{L}_{I_u}\left(\mu_d \theta r^{\alpha}\right) = \exp\left(-\pi r^2 \lambda \rho_{du}(\theta)\right) \quad (18)$$

where $\rho_{du}(\theta) = (\beta_{d,uu}\theta)^{2/\alpha} \int_0^{\infty} 1/(1 + u^{\alpha/2}) du$.

Therefore, when a randomly located mobile user experiences Exponential interference, the outage probability for DL users is characterized as

$$\begin{aligned} P_{out}^{\mathrm{DL}}(\lambda, \theta) &= 1 - \int_{r>0} e^{-\lambda\pi r^2 - \mu_d \theta r^{\alpha}\sigma^2} \cdot e^{-\pi r^2 \lambda \rho_{db}(\theta)} \\ &\cdot e^{-\pi r^2 \lambda \rho_{du}(\theta)} \cdot 2\pi\lambda r dr = 1 \\ &- \pi\lambda \int_0^{\infty} e^{-\lambda\pi v(1 + \rho_{db}(\theta) + \rho_{du}(\theta)) - \mu_d \theta \sigma^2 v^{\alpha/2}} dv. \end{aligned} \quad (19)$$

4.3. Uplink Outage Probability. When a UL user u_1 has a distance r and fading strength $h_u \sim \exp(\mu_u)$ to its serving BS, u_1 receives a signal with a strength of $h_u r^{-\alpha}$. In addition, u_1 receives cumulative interference I_b, I_u, and I_s. Here, I_b represents the total sum of the received powers from all neighboring BSs. When the serving BS of u_1 has a distance r_i and fading strength $g_i \sim \exp(\varphi_{bb})$ from the neighboring BS i, I_b is expressed as

$$I_b = \sum_{i\in\Phi_b} g_i r_i^{-\alpha} \tag{20}$$

where Φ_b is the set of all interfering BSs. Moreover, I_u represents the total sum of the received powers from all other UL users. When the serving BS of u_1 has a distance r_i and fading strength $f_i \sim \exp(\varphi_{ub})$ from the interfering UL user i, I_u is expressed as

$$I_u = \sum_{i\in\Omega_u} f_i r_i^{-\alpha} \tag{21}$$

where Ω_u is the set of all interfering users. Also, I_s indicates the self-interference in the serving BS of user u_1 and we simply assume that I_s becomes η times as much as the noise power (i.e., $I_s = \eta\sigma^2$). Therefore, the SINR of typical UL user u_1 is given by

$$\Gamma_{\text{UL}} = \frac{h_d r^{-\alpha}}{I_b + I_u + I_s + \sigma^2}. \tag{22}$$

The outage probability of UL user is exactly represented as the CDF of SINR over the entire network, as follows.

$$P_{out}^{\text{UL}}(\lambda,\theta) = \mathbb{P}\left[\Gamma_{\text{UL}} < \theta\right]. \tag{23}$$

Since the probability that the closest BS has a distance r being $e^{-\lambda\pi r^2} 2\pi\lambda r$, the outage probability is formulated as

$$\begin{aligned} P_{out}^{\text{UL}}(\lambda,\theta) &= 1 \\ &- \int_{r>0} \mathbb{P}\left[h_u \ge \theta r^{\alpha}\left(\sigma^2 + I_b + I_u + I_s\right) \mid r\right] \\ &\cdot e^{-\pi\lambda r^2} 2\pi\lambda r dr = 1 - \int_{r>0} e^{-\lambda\pi r^2 - \mu_u\theta r^{\alpha}(\sigma^2+\eta\sigma^2)} \\ &\cdot \mathscr{L}_{I_b}\left[\mu_u\theta r^{\alpha}\right] \cdot \mathscr{L}_{I_u}\left[\mu_u\theta r^{\alpha}\right] \cdot 2\pi\lambda r dr. \end{aligned} \tag{24}$$

Here, the Laplace transform of I_b is calculated as

$$\begin{aligned} &\mathscr{L}_{I_b}\left(\mu_u\theta r^{\alpha}\right) \\ &= \exp\left(-2\pi\lambda\int_r^{\infty}\left(1 - \frac{\varphi_{bb}}{\varphi_{bb} + \mu_u\theta r^{\alpha} v^{-\alpha}}\right) v dv\right) \end{aligned} \tag{25}$$

$$= \exp\left(-2\pi\lambda\int_r^{\infty}\frac{\beta_{u,bb}\theta}{\beta_{u,bb}\theta + (v/r)^{\alpha}} v dv\right) \tag{26}$$

$$= \exp\left(-2\pi\lambda\int_r^{\infty}\frac{1}{1 + \left(\beta_{u,bb}\theta\right)^{-1}(v/r)^{\alpha}} v dv\right) \tag{27}$$

$$= \exp\left(-\pi r^2\lambda\rho_{ub}(\theta)\right) \tag{28}$$

where $\rho_{ub}(\theta) = (\beta_{u,bb}\theta)^{2/\alpha}\int_{(\beta_{u,bb}\theta)^{-2/\alpha}}^{\infty} 1/(1+u^{\alpha/2})du$. In the same way, the Laplace transform of I_u is calculated as

$$\mathscr{L}_{I_u}\left(\mu_u\theta r^{\alpha}\right) = \exp\left(-\pi r^2\lambda\rho_{uu}(\theta)\right) \tag{29}$$

where $\rho_{uu}(\theta) = (\beta_{u,ub}\theta)^{2/\alpha}\int_{(\beta_{u,ub}\theta)^{-2/\alpha}}^{\infty} 1/(1+u^{\alpha/2})du$.

When a randomly located mobile user experiences exponential interference, the outage probability of UL users is finally characterized as

$$\begin{aligned} P_{out}^{\text{UL}}(\lambda,\theta) &= 1 - \int_{r>0} e^{-\lambda\pi r^2 - \mu_u\theta r^{\alpha}(\sigma^2+\eta\sigma^2)} \cdot e^{-\pi r^2\lambda\rho_{ub}(\theta)} \\ &\cdot e^{-\pi r^2\lambda\rho_{uu}(\theta)} \cdot 2\pi\lambda r dr = 1 \\ &- \pi\lambda\int_0^{\infty} e^{-\lambda\pi v(1+\rho_{ub}(\theta)+\rho_{uu}(\theta)) - \mu_u\theta(\sigma^2+\eta\sigma^2)v^{\alpha/2}} dv. \end{aligned} \tag{30}$$

5. Results and Discussions

For comparison, we consider (1) the typical *HD mode* where the BS does not employ the FD mode and the DL and UL resources are equally divided [35], (2) the FD with the *random pairing* that pairs a DL user with a UL user randomly, (3) *maximizing throughput (MaxThr)* method proposed in [18, 19] that determines the user pairs in a way that the DL user with better channel quality receives a smaller inter-user interference for the purpose of maximizing the sum throughput, and (4) the FD with the *optimal pairing* that optimally pairs users by exhaustive search. For a fair comparison, because the HD mode uses only half of the resource, its SINR, Γ^{HD} in (6) and (7), is recalculated as $\Gamma_{\text{new}}^{\text{HD}} = \sqrt{1+\Gamma^{\text{HD}}} - 1$ from the relationship of $\log(1+\Gamma_{\text{new}}^{\text{HD}}) = (1/2)\log(1+\Gamma^{\text{HD}})$, and its outage probability is redefined as $P_{out}^{\text{HD}} \triangleq \mathbb{P}\{(1/2)\log(1+\Gamma^{\text{HD}}) < \log(1+\theta)\}$.

The parameters used for evaluation are listed in Table 1 [19]. We evaluate the system rate by varying the user density λ from 0.1 to 1. Here, the users with $\lambda = 1$ correspond to the density of one user in 100 m^2 on average [34]. Also we use the same network configuration in the simulation as in the analysis [28]. The same number of DL and UL users is distributed randomly with varying the density λ in the multicell coverage. We consider the SINR threshold of 0 dB by default and change its range from -10 to 40 dB to determine the outage performance. Here, the channel parameter from UL user to serving BS, μ_u, and the channel parameter from UL user to DL user, φ_{uu}, are affected by user pairing algorithms so that their values are determined by the simulation after applying each user pairing algorithm. Moreover, we set the associated channel values (i.e., φ_{bu}, φ_{ub}, and φ_{bb}) to be large enough to minimize the influence from neighboring cells.

Figure 3(a) plots the CDF of the interuser interference when the number of DL/UL users (M) is 10 and the SINR threshold (θ) is 0 dB. The distribution of interuser interference is important to check whether the user pairing algorithm operates properly. Here, the interuser interference level is measured by simulation when each user pairing

Table 1: Parameter setup.

Parameter	Description	Value
λ	User density	0.1~1 (default=0.5)
θ	SINR threshold	-10~40 dB (default=0 dB)
σ^2	Noise power	1
α	Path loss exponent	2~4 (default=3)
η	Self-interference ratio	0~10 (default=0)
μ_d	Channel parameter from serving BS to DL user	0.01
μ_u	Channel parameter from UL user to serving BS	0.01~1 (determined by simulation)
φ_{bu}	Channel parameter from neighbor BS to DL user	100
φ_{ub}	Channel parameter from neighbor UL user to serving BS	100
φ_{bb}	Channel parameter from neighbor BS to serving BS	100
φ_{uu}	Channel parameter from UL user to DL user	1~100 (determined by simulation)

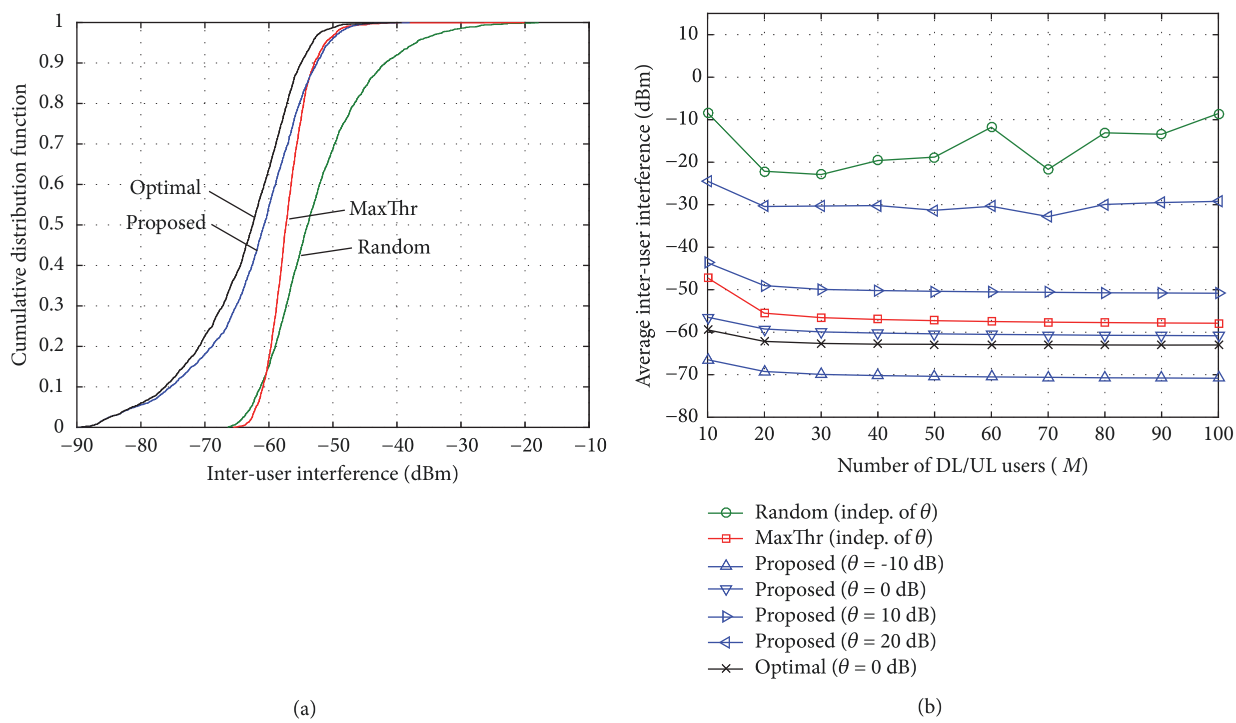

Figure 3: (a) CDF of interuser interference when $M = 10$ and $\theta = 0$ dB and (b) average inter-user interference versus number of DL/UL users (M).

algorithm is applied. Compared with the random pairing, the proposed pairing algorithm significantly decreases the interuser interference. This is because the proposed pairing selects the UL user with low interference as much as possible by considering the amount of interuser interference. Moreover, the proposed pairing shows even smaller interuser interference than MaxThr because it uses UL transmit power control and so reduces the interuser interference to the DL users effectively. Note that there is a slight difference between the proposed and the optimal pairing algorithms.

Figure 3(b) exhibits the average inter-user interference level versus the number of DL/UL users, M. At $\theta = 0$ dB, the proposed pairing is much better than the random pairing and is slightly better than MaxThr, regardless of the number of users, as shown in Figure 3(a). Note that the interuser interference in the random and MaxThr pairing algorithms are independent of the SINR threshold θ. However, the SINR threshold affects the transmit power of UL users in the proposed pairing. That is, the higher is the SINR threshold, the greater is the UL transmit power. Thus, the average interuser interference level increases as the SINR threshold increases in the proposed algorithm. Overall, the interuser interference decreases slightly when the number of users initially increases because the user diversity occurs as the number of users increases and so MaxThr and the proposed algorithm have more chance to have a user pair with less interuser interference. On the other hand, in the case of the random pairing, the interuser interference is

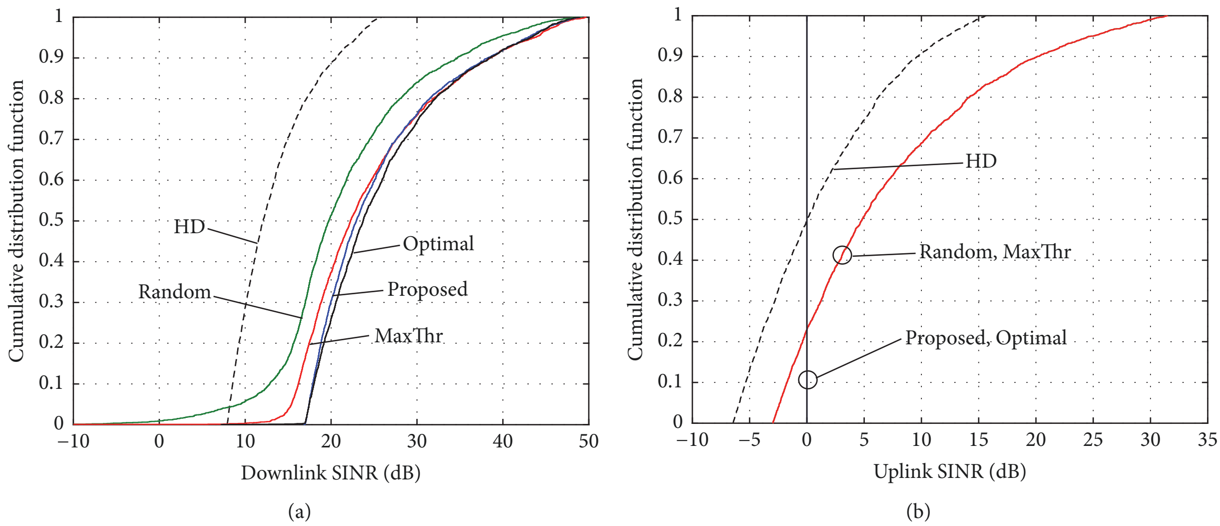

FIGURE 4: (a) CDF of DL SINR and (b) CDF of UL SINR when $M = 10$ and $\theta = 0$ dB.

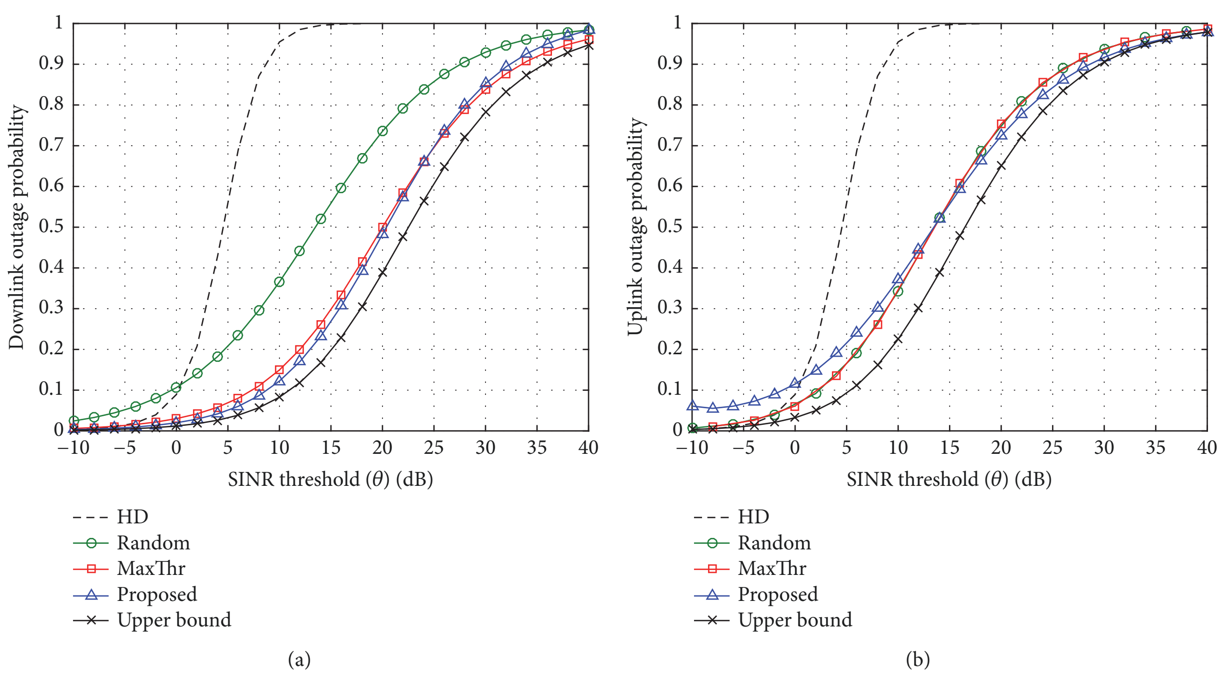

FIGURE 5: (a) DL outage probability and (b) UL outage probability versus SINR threshold (θ) when $\lambda = 0.5$.

fluctuated between -8 and -22 dBm because it often generates uncontrolled stronger interferences between the randomly selected DL and UL users as the number of users increases.

Figure 4 plots the CDF of the DL SINR and UL SINR when $M = 10$ and $\theta = 0$ dB. In the case of DL SINR, the proposed pairing shows better SINR than MaxThr and random pairing because it experiences the lower interuser interference. The HD mode has a significantly lower SINR and also the proposed scheme is close to optimal. In the case of UL SINR, the proposed and optimal pairing algorithms show that all UL users have the same UL SINR as 0 dB because their UL transmit power is adjusted to the SINR threshold. This result clearly shows that the proposed pairing algorithm significantly improves the DL SINR at the expense of the UL SINR to minimize the outage probability.

Figure 5 shows the DL and UL outage probabilities versus the SINR threshold when λ is fixed to 0.5. These outage probabilities are obtained from the numerical analysis in Section 4 and the used channel parameters for this result are derived from the simulation of the considered user pairing algorithms. Here, the performance of upper bound indicates the perfect FD assuming that there is no interuser interference and the reduction of UL transmit power. The proposed pairing algorithm improves the DL

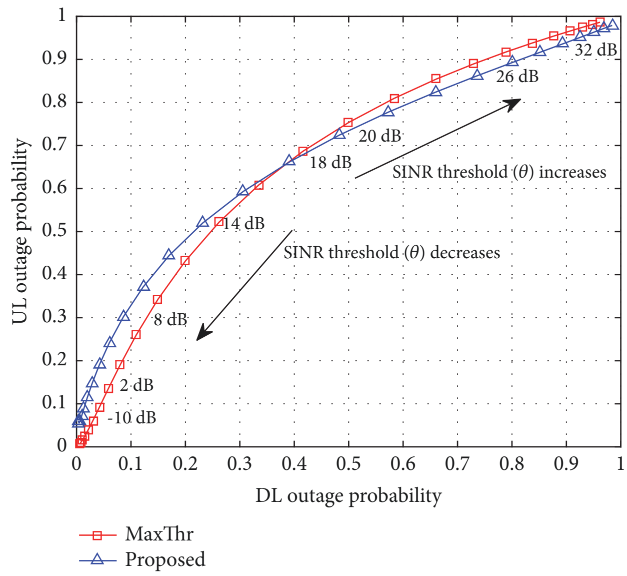

FIGURE 6: UL outage probability versus DL outage probability according to the change of SINR threshold (θ).

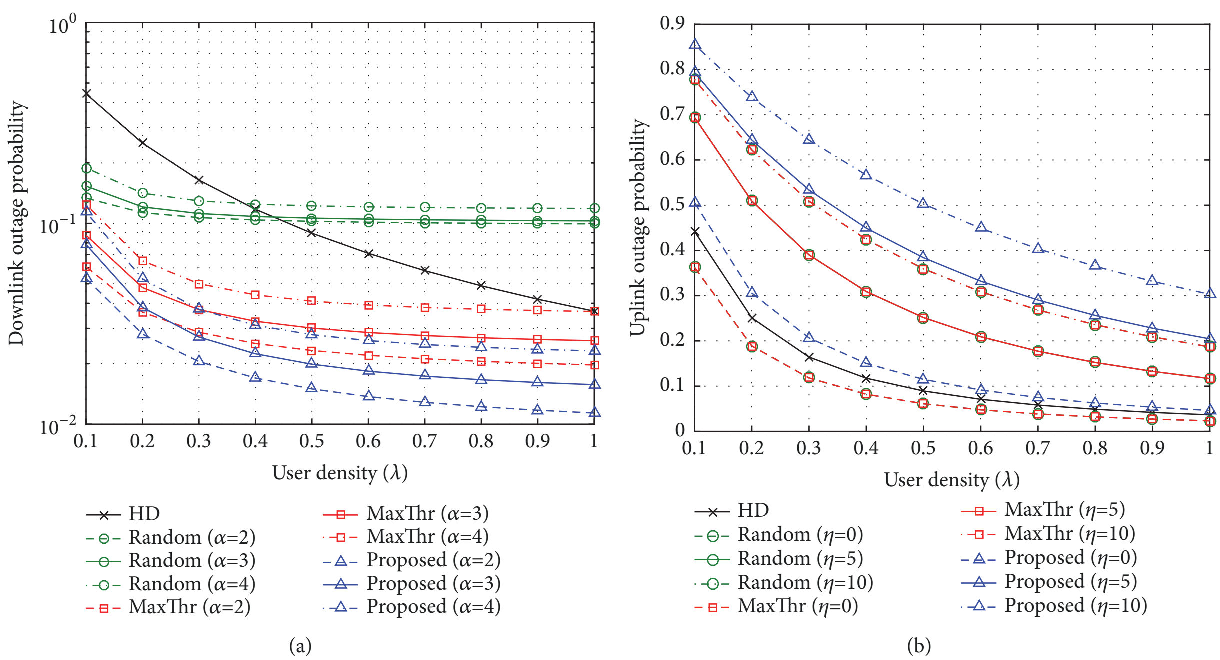

FIGURE 7: (a) DL outage probability and (b) UL outage probability versus user density (λ) when θ = 0 dB.

outage probability compared to the random pairing. The random pairing and MaxThr pairing have the same UL outage probability because they do not control UL transmit power equally. Compared to MaxThr, the proposed scheme shows the tradeoff performance according to the SINR threshold. When the SINR threshold is small, the DL outage of the proposed pairing is better than that of MaxThr but the UL outage is not. On the contrary, when the SINR threshold is large, the UL outage of the proposed pairing is better than that of MaxThr but the DL outage is not. As the SINR threshold increases, the proposed pairing should increase the UL transmit power to satisfy the UL SINR requirement. This decreases the UL outage probability, but increases the interuser interference, thereby increasing the DL outage probability.

Figure 6 plots the UL outage probability versus the DL outage probability as the SINR threshold changes from -10 to 40 dB. This graph clearly shows the tradeoff performance between MaxThr and the proposed pairing according to the SINR threshold. As the SINR threshold decreases, the proposed pairing decreases the UL transmit power to satisfy the UL SINR requirement. This eventually decreases the interuser interference and so decreases the DL outage probability. Therefore, the proposed scheme has the smaller DL outage than the MaxThr scheme when the SINR threshold decreases. On the contrary, as the SINR threshold increases, the proposed pairing increases the UL transmit power, which increases the interuser interference; thereby increasing the DL outage probability. Hence, the proposed scheme shows the smaller UL outage of the MaxThr scheme when the SINR threshold increases. Therefore, there exists a cross point between two schemes and there is a fundamental tradeoff between the DL outage and UL outage performances in the considered user pairing algorithms in the FD cellular network.

Figure 7 shows the DL and UL outage probabilities versus the user density (λ) when θ is fixed to 0 dB according to the variation of related parameters: path loss exponent (α) and self-interference ratio (η). The user density corresponds to the number of users and means how many pairing opportunities are given. Thus, the outage probabilities decrease as the user density increases. Regarding the path loss exponent α, the DL outage probability in all schemes increases as α increases because all SINRs become smaller with the greater α. Regarding the self-interference ratio, η greater than zero means that there remains the self-interference at the BS using FD. Thus, the UL outage probability increases in all the FD schemes as η increases. This implies that the UL outage performance depends heavily on the SIC capability at the BS.

6. Conclusion

In this study, we dealt with user pairing problems in FD cellular networks. We proposed a low-complexity user pairing algorithm to minimize outage probability. The proposed pairing algorithm was invented in a way that the UL user reduces its transmit power to satisfy the SINR threshold for minimizing the interuser interference and the DL user with a worse signal quality preferentially selects its UL user who gives less interference for outage minimization. The simulation and analysis results showed that the proposed algorithm significantly decreased the interuser interference and thus improves the DL outage performance while satisfying the UL SINR requirement, compared to the conventional HD mode and a random user pairing. It is also observed that there is a tradeoff between the DL outage and UL outage probabilities according to the user pairing strategy. We expect that the considered user pairing algorithms and their analysis results will be applicable for the protocol design and implementation of the future FD cellular network.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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