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Hybrid full-/half-duplex cellular networks: user admission and power control*

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Abstract: We consider a single-cell network with a hybrid full-/half-duplex base station. For the practical scenario with N channels, K uplink users, and M downlink users ($\max\{K, M\} \leq N \leq K + M$), we tackle the issue of user admission and power control to simultaneously maximize the user admission number and minimize the total transmit power when guaranteeing the quality-of-service requirement of individual users. We formulate a 0–1 integer programming problem for the joint-user admission and power allocation problem. Because finding the optimal solution of this problem is NP-hard in general, a low-complexity algorithm is proposed by introducing the novel concept of adding dummy users. Simulation results show that the proposed algorithm achieves performance similar to that of branch and bound algorithm and significantly outperforms the random pairing algorithm.

Key words: Full-duplex; Half-duplex; User admission; Power control
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1 Introduction

With the proliferation of mobile devices and various newly emerging wireless services such as mobile gaming, mobile TV, and virtual reality, future wireless systems are expected to support a massive number of mobile terminals and provide extremely high data rate services. Given the limited available spectrum, adopting spectrally efficient techniques is a necessary requirement. In this regard, the in-band full-duplex (FD) technique has appeared as a promising technology for spectral efficiency improvement. Compared with the conventional frequency-division duplex and time-division duplexes, where two separate channels or time slots are used for uplink and downlink transmission, FD allows simultaneous transmission and reception over the same frequency band, which has the potential to double the spectral efficiency (Duarte and Sabharwal, 2010; Duarte et al., 2012; Sabharwal et al., 2014). Hence, FD has been shortlisted as one of the key enabling physical layer techniques for the fifth generation (5G) mobile communication systems.

To fully realize the spectral efficiency gain provided by the FD technique, the major challenge is how to effectively cancel the self-interference (SI) (Riihonen et al., 2011). To tackle this critical issue, various approaches have been proposed, including antenna separation, digital cancellation, analog cancellation, and spatial cancellation. It has been reported recently that the state-of-the-art cancellation methods could achieve more than 110 dB reduction of SI, paving the way for practical implementation of the FD technique. As such, a significant amount

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of effort has been devoted to the investigation of the achievable performance of various systems empowered with FD capability; for instance, the secrecy performance of the FD cellular system with joint information and jamming beamforming was characterized by Zhu et al. (2014), the outage performance of FD relay-assisted device-to-device systems in uplink cellular networks was studied by Dang et al. (2017), and the achievable throughput of a wireless powered FD relaying system was investigated by Zhong et al. (2014).

Although the FD technique has been demonstrated to double the spectral efficiency of a particular wireless link, how much gain can be realized at the network level remains unknown. Compared with the conventional half-duplex (HD) cellular network, the FD cellular network needs to deal with the extremely complicated interference environment. For instance, in addition to SI, the FD cellular network will also consider the interference from the uplink transmission to the downlink user. Therefore, to exploit the benefits of the FD technique, it is essential to devise efficient power control and resource allocation algorithms so that the interference can be mitigated properly. Di et al. (2014) studied the user pairing problem by applying the matching theory, whereas Wen and Yu (2016b) considered the joint user pairing and resource allocation problem to maximize the system throughput subject to the quality-of-service (QoS) requirement of individual users. An opportunistic interference cancellation technique was proposed by Yu et al. (2016) to suppress the co-channel interference. Moreover, Wen and Yu (2016a) studied the energy efficiency of the FD cellular network and found that FD has a better power efficiency than that of HD when the residual SI is weak or the users are located near the base station (BS). Recently, taking into account the fairness criteria, da Silva et al. (2016) proposed a novel joint fairness assignment maximization algorithm to solve the problem of grouping users into pairs and assigning frequency channels to each pair in a spectrally efficient and fair manner.

In all these prior studies, BS is constrained to work in only FD mode. However, due to severe interference, the performance of FD mode may not always be superior to that of HD mode. Responding to this, the hybrid FD/HD mode has been proposed, where BS can work in either FD or HD mode depending on the operating environment. Thus far, few studies have investigated the performance of hybrid FD/HD systems, and most of them focus on the cooperative relaying scenario (Yamamoto et al., 2011). Only in a recent work conducted by Lee and Quek (2015), was the achievable throughput of the hybrid FD/HD systems characterized using the stochastic geometry approach. Therefore, more research is needed to gain a better understanding of the performance of hybrid FD/HD cellular systems.

Motivated by this, in this study, we consider a single-cell hybrid FD/HD system where BS can operate in either FD or HD mode, while all users operate in HD mode. Assuming a system with N channels, K uplink users, and M downlink users, we tackle the problem of joint-user admission and transmit power control. Also, due to the difficulty in obtaining instantaneous channel state information (CSI) of all communication links, we consider the practical scenario with only statistical CSI, i.e., the distances of the communication links.

The main contributions of this paper are summarized as follows:

1. We present a simple criterion to measure the feasibility of pairing any two uplink and downlink users based on the average channel gains. It is then used to define the admissible pairs for the optimization problem.

2. Considering the practical case where $\max\{K, M\} \leq N \leq K + M$, we propose a novel 'dummy user' assisted strategy, and transform the original optimization problem into a joint-user admission and power control problem, which can be solved efficiently using the Kuhn-Munkres (K-M) algorithm. Numerical results show that the proposed algorithm achieves better performance, compared with random pairing based power control algorithms.

2 System model

We consider a single cell system with N channels, serving simultaneously K uplink users denoted as $\left\{C_1^{\mathrm{U}}, C_2^{\mathrm{U}}, \cdots, C_K^{\mathrm{U}}\right\}$ and M downlink users denoted as $\left\{C_1^{\mathrm{D}}, C_2^{\mathrm{D}}, \cdots, C_M^{\mathrm{D}}\right\}$ (Fig. 1). Both BS and users are equipped with a single antenna. BS is empowered with FD capability, and can work in either FD or HD mode, while the user terminals can perform only HD operation due to hardware constraints.

We assume that one channel can be allocated to

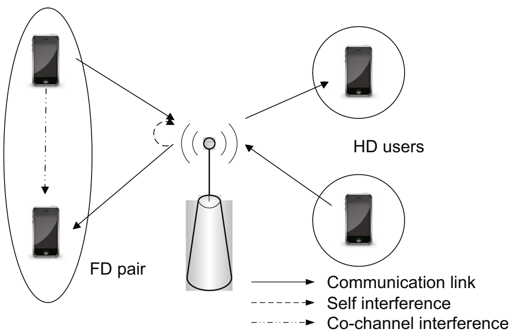

Fig. 1 The multi-user model with a mixed half-/full-duplex (HD/FD) base station

at most one user pair in FD mode, or one uplink or one downlink user in HD mode. Moreover, each user can occupy at most one channel.

FD mode: When BS is in FD mode, the uplink and downlink transmissions occupy the same channel. As such, BS is subject to SI, whereas the downlink user is subject to co-channel interference. Suppose that C_i^{U} and C_j^{D} form a pair. Then the achievable rates of C_i^{U} and C_j^{D} can be expressed as

$$\begin{cases} R_{i,j}^{\mathrm{U}} = \log_2\left(1+\frac{P_{i,j}^{\mathrm{U}}h_i^{\mathrm{U}}}{N_0^{\mathrm{U}}+P_{i,j}^{\mathrm{D}}\eta}\right), \\ R_{i,j}^{\mathrm{D}} = \log_2\left(1+\frac{P_{i,j}^{\mathrm{D}}h_j^{\mathrm{D}}}{N_0^{\mathrm{D}}+P_{i,j}^{\mathrm{U}}h_{i,j}}\right), \end{cases} \tag{1}$$

where $P_{i,j}^{\mathrm{U}}$ and $P_{i,j}^{\mathrm{D}}$ are the transmit power of C_i^{U} and C_j^{D}, respectively, N_0^{D} and N_0^{U} are the noise density at BS and the downlink user, respectively, the residual SI power is denoted by $P_{i,j}^{\mathrm{D}}\eta$, where η is a key parameter determined by SI cancellation mechanisms, h_i^{U} and h_j^{D} denote the channel gains of C_i^{U} and C_j^{D}, respectively, and $h_{i,j}$ denotes the channel gain of the interference channel between C_i^{U} and C_j^{D}.

HD mode: When BS is in HD mode, the uplink and downlink transmissions occupy separate channels. As such, the achievable rates of uplink and downlink users can be expressed as

$$\begin{cases} R_i^{\mathrm{U}} = \log_2\left(1+\frac{P_i^{\mathrm{U}}h_i^{\mathrm{U}}}{N_0^{\mathrm{U}}}\right), \\ R_j^{\mathrm{D}} = \log_2\left(1+\frac{P_j^{\mathrm{D}}h_j^{\mathrm{D}}}{N_0^{\mathrm{D}}}\right), \end{cases} \tag{2}$$

where P_i^{U} and P_j^{D} are the transmit power of C_i^{U} and C_j^{D}, respectively.

With a slight abuse of terminology, an uplink (downlink) user in FD mode refers to a user who forms an FD pair with another downlink (uplink) user. Similarly, a user in HD mode refers to a user who occupies one channel alone for either uplink or downlink transmission.

Finally, Rayleigh fading is assumed. As such, h_i^{U}, h_j^{D}, and $h_{i,j}$ are exponential random variables with means σ_i^2, σ_j^2, and $\sigma_{i,j}^2$, respectively.

3 Problem formulation

In this study, our goals are to maximize the user admission number and minimize the total transmit power subject to the QoS requirement of the individual user by joint mode selection, channel allocation, and power control. In particular, we adopt the outage probability as the QoS criterion; namely, the transmission rate of uplink and downlink users should satisfy

$$\Pr(R_{i,j}^{\mathrm{U}} \geq R_{\min}^{\mathrm{U}}) \geq 1-a, \tag{3}$$

$$\Pr(R_{i,j}^{\mathrm{D}} \geq R_{\min}^{\mathrm{D}}) \geq 1-a, \tag{4}$$

where $R_{\min}^{\mathrm{U}}$ and $R_{\min}^{\mathrm{D}}$ are the minimum date rate requirements of uplink and downlink users, respectively, and a is the outage probability threshold.

A direct consequence of the QoS requirement is that not all users can be paired in FD mode. For instance, an uplink user will not be paired with any nearby downlink user due to the severe interference inflicted upon the downlink user. As such, it is imperative to establish the conditions under which the users can form a pair. However, analytical characterization of this condition appears difficult. Fortunately, in the high signal-to-noise ratio (SNR) regime, we have the following important result:

Lemma 1 In the high SNR regime, if

$$\frac{\sigma_i^2\sigma_j^2}{\sigma_{i,j}^2} > Q, \tag{5}$$

where $Q = -\frac{(1-a)(2^{R_{\min}^{\mathrm{D}}}-1)(2^{R_{\min}^{\mathrm{U}}}-1)\eta}{2a\ln(1-a)}$, then uplink user C_i^{U} and downlink user C_j^{D} can form a pair.

Proof Capitalizing on the results presented by Wen and Yu (2016a), the feasible power region in the high SNR regime can be derived in closed form as follows:

$$\begin{cases} P^{\mathrm{U}}_{i,j} \geq -\dfrac{(2^{R^{\mathrm{U}}_{\min}}-1)\eta P^{\mathrm{D}}_{i,j}}{2\sigma_i^2 \ln(1-a)} - \dfrac{N_0^{\mathrm{U}}}{2\sigma_i^2 \ln(1-a)}, \\ P^{\mathrm{U}}_{i,j} \leq \dfrac{a\sigma_j^2 P^{\mathrm{D}}_{i,j}}{(1-a)\sigma_{i,j}^2 (2^{R^{\mathrm{D}}_{\min}}-1)} - \dfrac{N_0^{\mathrm{D}}}{2(1-a)\sigma_{i,j}^2}, \\ P^{\mathrm{U}}_{i,j} \geq 0, \\ P^{\mathrm{D}}_{i,j} \geq 0. \end{cases} \tag{6}$$

The feasible power region is illustrated in Fig. 2, where lines l_1 and l_2 correspond to the first and second constraints in constraints (6), respectively. Let k_i denote the slope of line l_i, i.e.,

$$\begin{cases} k_1 = -\dfrac{(2^{R^{\mathrm{U}}_{\min}}-1)\eta}{2\sigma_i^2 \ln(1-a)}, \\ k_2 = \dfrac{a\sigma_j^2}{(1-a)(2^{R^{\mathrm{D}}_{\min}}-1)\sigma_{i,j}^2}. \end{cases} \tag{7}$$

Note that the y-intercept of line l_1 is positive while the Y-intercept of line l_2 is negative. Thus, it is not difficult to show that a feasible power region exists only if $k_1 < k_2$. Therefore, the necessary condition is given by

$$k_1 < k_2 \Rightarrow -\frac{(2^{R^{\mathrm{U}}_{\min}}-1)\eta}{2\sigma_i^2 \ln(1-a)} < \frac{a\sigma_j^2}{(1-a)(2^{R^{\mathrm{D}}_{\min}}-1)\sigma_{i,j}^2}. \tag{8}$$

The desired result can then be obtained after some algebraic manipulations.

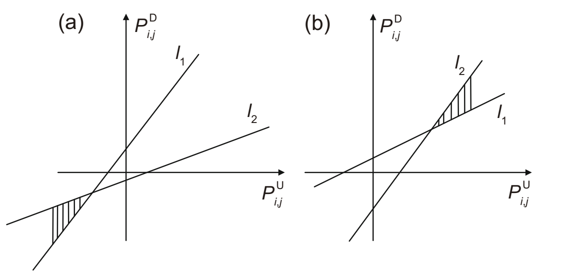

Fig. 2 Feasible power region: (a) $k_1 > k_2$; (b) $k_1 < k_2$

Note that the intersections of l_1 and l_2 are the optimal transmit powers for an uplink and downlink user pair, denoted as $\hat{P}^{\mathrm{U}}_{i,j}$ and $\hat{P}^{\mathrm{D}}_{i,j}$, respectively, which can be derived as Eq. (9) shown on the bottom of this page.

Based on the above important observation, we can compute the $K \times M$ pairing feasibility matrix $\boldsymbol{C}$ with elements $c_{i,j}$, which is a binary number taking a value of either zero or one. In particular, $c_{i,j} = 1$ implies that C_i^{U} and C_j^{D} can form an FD pair, whereas $c_{i,j} = 0$ indicates that C_i^{U} and C_j^{D} cannot form an FD pair.

To this end, let us define the $(K+1)\cdot(M+1)$ mode selection matrix $\boldsymbol{\Gamma} = \{\gamma_{i,j}\}$, where

$$\gamma_{i,j} = \begin{cases} 1, & \text{if } C_i^{\mathrm{U}} \text{ and } C_j^{\mathrm{D}} \text{ are paired together}, \\ 0, & \text{otherwise}, \end{cases} \quad 1 \leq i \leq K,\ 1 \leq j \leq M. \tag{10}$$

$$\gamma_{i,M+1} = \begin{cases} 1, & \text{if } C_i^{\mathrm{U}} \text{ is in HD mode}, \\ 0, & \text{otherwise}, \end{cases} \quad 1 \leq i \leq K. \tag{11}$$

$$\gamma_{K+1,j} = \begin{cases} 1, & \text{if } C_j^{\mathrm{D}} \text{ is in HD mode}, \\ 0, & \text{otherwise}, \end{cases} \quad 1 \leq j \leq M. \tag{12}$$

Note that $\gamma_{K+1,M+1}$ is an artificial variable with no physical meaning. Then, the user admission number maximization problem can be formulated as

$$\max_{\gamma_{i,j}} \sum_{i=1}^{K}\sum_{j=1}^{M} 2\gamma_{i,j} + \sum_{i=1}^{K} \gamma_{i,M+1} + \sum_{i=1}^{K} \gamma_{K+1,j} \tag{13}$$

subject to

$$\gamma_{i,j} \in \{0,1\},\ \forall 1 \leq i \leq K+1,\ 1 \leq j \leq M+1, \tag{14}$$

$$\gamma_{i,j} \leq c_{i,j},\ \forall 1 \leq i \leq K,\ 1 \leq j \leq M, \tag{15}$$

$$\sum_{i=1}^{K+1} \gamma_{i,j} \leq 1,\ \forall 1 \leq j \leq M, \tag{16}$$

$$\begin{cases} \hat{P}^{\mathrm{D}}_{i,j} = \dfrac{(2^{R^{\mathrm{D}}_{\min}}-1)(N_0^{\mathrm{U}}(1-a)\sigma_{i,j}^2 - N_0^{\mathrm{D}}\sigma_i^2 \ln(1-a))}{-(2^{R^{\mathrm{U}}_{\min}}-1)(2^{R^{\mathrm{D}}_{\min}}-1)(1-a)\eta\sigma_{i,j}^2 - 2a\ln(1-a)\sigma_i^2\sigma_j^2}, \\ \hat{P}^{\mathrm{U}}_{i,j} = \dfrac{2aN_0^{\mathrm{U}}\sigma_j^2 + N_0^{\mathrm{D}}(2^{R^{\mathrm{U}}_{\min}}-1)(2^{R^{\mathrm{D}}_{\min}}-1)\eta}{-2(2^{R^{\mathrm{U}}_{\min}}-1)(2^{R^{\mathrm{D}}_{\min}}-1)(1-a)\eta\sigma_{i,j}^2 - 4a\ln(1-a)\sigma_i^2\sigma_j^2}. \end{cases} \tag{9}$$

$$\sum_{j=1}^{M+1} \gamma_{i,j} \le 1, \ \forall 1 \le i \le K, \tag{17}$$

$$\sum_{i=1}^{K+1} \sum_{j=1}^{M+1} \gamma_{i,j} \le N. \tag{18}$$

Constraint (14) indicates that the above optimization problem is a combinatorial problem, constraint (15) is due to the feasibility of user pairing in FD mode, constraints (16) and (17) ensure that each user works in either FD or HD mode, and constraint (18) comes from the fact that there are at most N subchannels.

Note that there may exist many solutions for optimization problem (13). Now, let us denote the set of optimal solutions as $\varPi^* = \{\boldsymbol{\varGamma}_1^*, \boldsymbol{\varGamma}_2^*, \cdots, \boldsymbol{\varGamma}_q^*\}$. Then, the remaining task is to choose the solution with minimum total transmit power, which can be obtained by solving the following optimization problem:

$$\begin{aligned} \min_{\boldsymbol{\varGamma}_m^*} & \sum_{i=1}^{K} \sum_{j=1}^{M} \gamma_{i,j} (\hat{P}_{i,j}^{\mathrm{U}} + \hat{P}_{i,j}^{\mathrm{D}}) + \sum_{i=1}^{K} \gamma_{i,M+1} \hat{P}_i^{\mathrm{U}} \\ & + \sum_{j=1}^{M} \gamma_{K+1,j} \hat{P}_j^{\mathrm{D}} \\ \text{s.t.} \ & \boldsymbol{\varGamma}_m^* \in \varPi^*. \end{aligned} \tag{19}$$

Note that $\hat{P}_i^{\mathrm{U}}$ and $\hat{P}_j^{\mathrm{D}}$ are the minimum required transmit power when operating in HD mode, and can be derived as (Wen and Yu, 2016a)

$$\begin{cases} \hat{P}_i^{\mathrm{U}} = \dfrac{(2^{R_{\min}^{\mathrm{U}}} - 1) N_0^{\mathrm{U}}}{2\sigma_i^2 \ln(1-a)}, \\ \hat{P}_j^{\mathrm{D}} = \dfrac{(2^{R_{\min}^{\mathrm{D}}} - 1) N_0^{\mathrm{D}}}{2\sigma_j^2 \ln(1-a)}. \end{cases} \tag{20}$$

As mentioned before, optimization problem (13) is a 0-1 integer optimization problem, which is nondeterministic polynomial (NP) hard in general. The standard approach is to use the branch and bound (BnB) method to solve this kind of problem. However, the computational complexity of the BnB method is extremely high. Therefore, it is of great interest to devise an alternative optimal algorithm with a low computational complexity, which will be pursued in Section 4.

4 A novel low-complexity algorithm

In this section, we propose low-complexity algorithms to solve optimization problem (19). In particular, we consider the practical case where $\max\{K, M\} \le N \le K + M$. In this scenario, all users can be admitted potentially into the system if some users work in FD mode while others work in HD mode. The cases $\max\{K, M\} > N$, where not all users can be admitted to the system even if all users work in FD mode, and $N > K + M$ where all users can work in HD mode, are easy to handle. Hence, these scenarios are not mentioned in this study.

A close observation shows that for the special case $K = M = N$, the user admission number maximization problem becomes a two-dimensional matching problem, which can be solved by the K-M algorithm efficiently. However, in general, K, M, and N are unequal in practice. To tackle this issue, we introduce a novel concept of adding dummy users.

Specifically, if an uplink or downlink user is in HD mode, an artificial dummy user is introduced to form a fictitious FD pair. Therefore, by adding $N - K$ dummy uplink users $\{C_{K+1}^{\mathrm{U}}, C_{K+2}^{\mathrm{U}}, \cdots, C_N^{\mathrm{U}}\}$ and $N - M$ dummy downlink users $\{C_{M+1}^{\mathrm{D}}, C_{M+2}^{\mathrm{D}}, \cdots, C_N^{\mathrm{D}}\}$, as illustrated in Fig. 3, we have a new scenario with N uplink users, N downlink users, and N available channels.

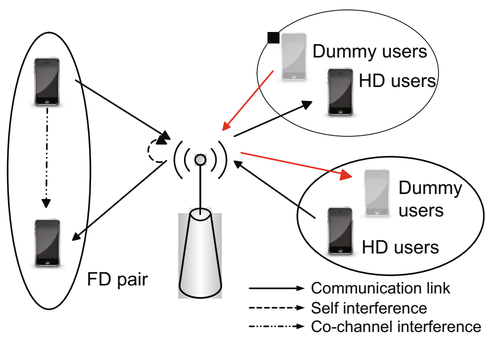

Fig. 3 System model after adding dummy users

FD: full-duplex; HD: half-duplex

Now, instead of taking the two-step procedure of first maximizing the user admission number and then looking for the power minimization solution, we focus directly on the power minimization problem. To do so, the transmit power consumption of each pair needs to be specified. A number of different cases need to be considered: (1) For $1 \le i \le K$ and $1 \le j \le M$, if uplink user C_i^{U} and downlink user C_j^{D}

form an FD pair, the optimal sum transmit power is $P_{i,j}^{\rm F} = \hat{P}_{i,j}^{\rm U} + \hat{P}_{i,j}^{\rm D}$. Because not all the uplink and downlink users can form FD pairs due to severe co-channel interference, we set $P_{i,j}^{\rm F}$ with a very large value L for these uplink and downlink user pairs, which does not satisfy Lemma 1. (2) For $1 \leq i \leq K$ and $M+1 \leq j \leq N$, if uplink user $C_i^{\rm U}$ is paired up with a dummy downlink user (i.e., user $C_i^{\rm U}$ is in HD mode), the optimal transmit power of the uplink user is given by $\hat{P}_i^{\rm U}$. (3) For $K+1 \leq i \leq N$ and $1 \leq j \leq M$, if the downlink user $C_j^{\rm D}$ is paired up with a dummy uplink user (i.e., user $C_j^{\rm D}$ is in HD mode), the optimal transmit power of the downlink user is given by $\hat{P}_j^{\rm D}$. (4) For $K+1 \leq i \leq N$ and $M+1 \leq j \leq N$, we assume that the dummy uplink user and downlink user cannot form a pair; as such, we assign a very large value L as the total transmit power.

Let $P_{i,j}^{\rm All}$ represent the sum transmit power of an arbitrary pair (i,j) $(1 \leq i \leq N, 1 \leq j \leq N)$. Then according to the above discussions, $P_{i,j}^{\rm All}$ is given by

$$P_{i,j}^{\rm All} = \begin{cases} P_{i,j}^{\rm F}, & 1 \leq i \leq K,\ 1 \leq j \leq M, \\ \hat{P}_i^{\rm U}, & 1 \leq i \leq K,\ M+1 \leq j \leq N, \\ \hat{P}_j^{\rm D}, & K+1 \leq i \leq N,\ 1 \leq j \leq M, \\ L, & K+1 \leq i \leq N,\ M+1 \leq j \leq N. \end{cases} \tag{21}$$

To this end, optimization problem (19) can be reformulated as an assignment problem in its standard form with the associated cost matrix $P_{i,j}^{\rm All}$ as follows:

$$\begin{aligned} &\min_{\rho_{i,j}} \sum_{i=1}^{N}\sum_{j=1}^{N} \rho_{i,j} P_{i,j}^{\rm All} \\ &\text{s.t.}\ \ \rho_{i,j} \in \{0,1\},\ \forall\, i,j; \\ &\sum_{j=1}^{N} \rho_{i,j} = 1,\ \forall\, i;\ \sum_{i=1}^{N} \rho_{i,j} = 1,\ \forall\, j. \end{aligned} \tag{22}$$

Let us define an $N \times N$ matrix $\boldsymbol{\Phi} = \{\rho_{i,j}\}$ as the solution to optimization problem (22). Then $\boldsymbol{\Phi}$ can be obtained efficiently by invoking the K-M algorithm. However, $\boldsymbol{\Phi}$ does not necessarily yield the final solution to the original optimization problem (19). Instead, two different cases need to be discussed: (1) All the users can be admitted into the cellular network, implying that the optimal solution $\boldsymbol{\Phi}$ does not include any infeasible FD pairs, i.e., $P_{i,j}^{\rm F} \neq L$ for $1 \leq i \leq K,\ 1 \leq j \leq M$. In this case, $\boldsymbol{\Phi}$ is also the optimal solution to the original optimization problem (19). (2) Not all users can be admitted into the cellular network, implying that optimal solution $\boldsymbol{\Phi}$ includes some infeasible FD pairs; i.e., there exists some $P_{i,j}^{\rm F} = L$ with $1 \leq i \leq K$ and $1 \leq j \leq M$. In this case, we delete the impossible FD pairs from $\boldsymbol{\Phi}$; then the vacant channels can be assigned to users who do not have access to the cellular network, to maximize the user admission number.

Therefore, the joint-user admission and power allocation algorithm (JUPA) is summarized in Algorithm 1, where FDLIST contains the set of feasible FD pairs, HDLIST contains the set of feasible HD users, WAITLIST is the set of infeasible FD pairs, and $\varnothing$ denotes the empty set.

Algorithm 1 Joint user admission and power allocation scheme

// Initialization:
Add $N-K$ dummy uplink users and $N-M$ dummy downlink users, and construct a cost matrix $P_{i,j}^{\rm All}$ for $1 \leq i \leq N,\ 1 \leq j \leq N$;
Set FDLIST = $\varnothing$, HDLIST = $\varnothing$, WAITLIST = $\varnothing$, and $n=0$;
// Primary channel allocation:
Find optimal solution $\boldsymbol{\Phi}$ by the K-M algorithm;
// Checking feasibility:
for $(i,j) \in \boldsymbol{\Phi}$ **do**
  // (i,j) are possible FD pairs
  if $1 \leq i \leq K,\ 1 \leq j \leq M$ **then**
    // (i,j) are feasible FD pairs
    if $c_{i,j} = 1$ **then**
      add pair (i,j) to FDLIST;
    end if
    // (i,j) are infeasible FD pairs
    if $c_{i,j} = 0$ **then**
      add i and j to WAITLIST;
      $n = n+1$;
    end if
  else
    if $1 \leq i \leq K,\ M+1 \leq j \leq N$ **then**
      add i to HDLIST;
    end if
    if $K+1 \leq i \leq N,\ 1 \leq j \leq M$ **then**
      add j to HDLIST;
    end if
  end if
end for
// Secondary channel allocation:
Select n HD users from WAITLIST with minimum power;

We now discuss the complexity of the proposed algorithm. It is easy to show that the complexity of exhaustive search is $O(2^{(K+1)(M+1)})$ for optimization problem (13) because there are $(K+1)(M+1)$ variables in problem (13). Similarly, the BnB approach has exponential complexity even though certain branch cutting strategies are used. On the other hand, for a standard assignment problem, the complexity is $O(k^3)$, where k is the order of the associated cost matrix. Therefore, the proposed Algorithm 1 has a complexity of $O(N^3)$, because the cost matrix is an $N \times N$ matrix, where N is the channel number.

5 Numerical results

In this section, we provide numerical simulation results to illustrate the performance of the proposed algorithms. For all simulations, we assume that BS is located at the center of the cell, while the uplink and downlink users are distributed uniformly within the cell. The simulation parameters are summarized in Table 1.

Table 1 Simulation parameters

Parameter	Value
Uplink user number	10
Downlink user number	10
Minimum uplink data rate	2.0 bits/(s · Hz)
Minimum downlink data rate	2.0 bits/(s · Hz)
Cell radius	0.1 km
Noise spectral density	−174 dBm
Path loss between the user and BS	$128.1 + 37.6 \log d$
Path loss between users	$148 + 40 \log d$
Outage probability	0.1

The unit of d is kilometer. BS: base station

Fig. 4 compares the performance of the proposed Algorithm 1 with that of the BnB algorithm with different system configurations. As can be observed readily, in both cases, the proposed Algorithm 1 attains performance identical to that of the BnB algorithm, demonstrating the superiority of the proposed algorithm.

Fig. 5 illustrates the percentages of admitted users with different channel number N. As a benchmark for comparison, we consider a random paring scheme, where an uplink user and a downlink user are paired randomly together. If the randomly formed pair does not meet the QoS constraints, one of the users will be selected to occupy the channel. As expected for both algorithms, when the channel number increases, more users can be admitted into the system. It can be observed that the proposed algorithm always attains better performance, compared with the random pairing scheme.

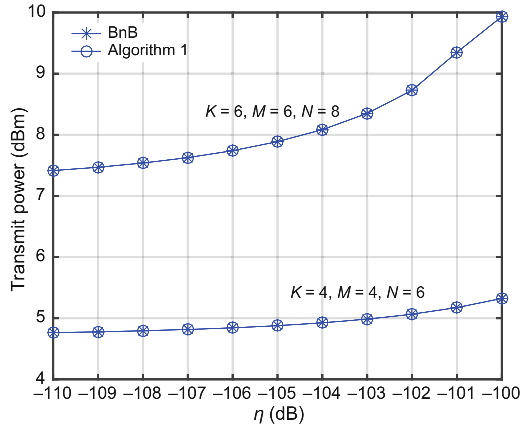

Fig. 4 Performance comparison: BnB (branch and bound) vs. Algorithm 1

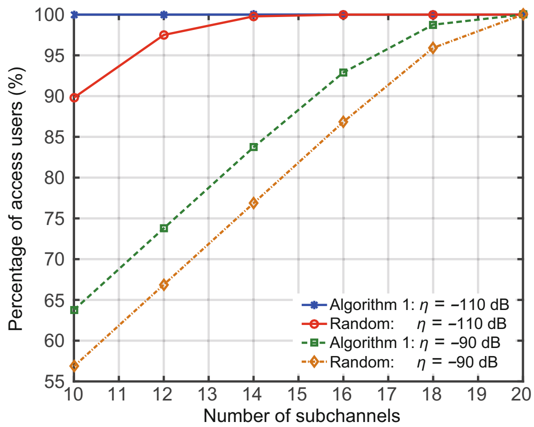

Fig. 5 Percentage of admitted users with different numbers of subchannels

However, the advantage of the proposed algorithm depends heavily on N and η. The performance gap is much more significant for small N and large η, and narrows down gradually when N becomes larger or η becomes smaller.

Fig. 6 depicts the total transmit power of the proposed algorithm and random pairing algorithm. To make the comparison between the two algorithms meaningful, the admitted number of users should be the same. Therefore, in the simulations, only the trials that meet such criteria are counted. As can be observed readily, the proposed Algorithm 1 attains substantial transmit power gain, compared with the random pairing algorithm when N is small, and the performance gain diminishes gradually as N becomes larger. When $N = 20$, the total transmit power of both algorithms becomes identical. This is also intuitive, because in such a case, all the users will operate in HD mode.

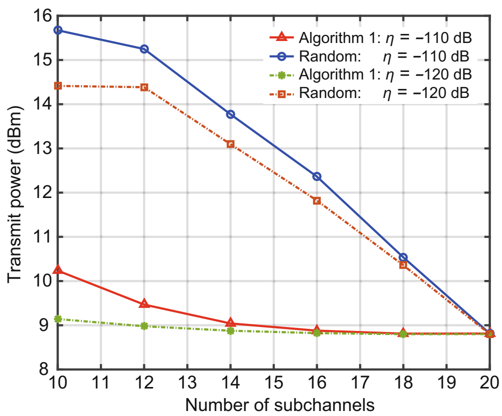

Fig. 6 Comparison of total transmit power: Algorithm 1 vs. random pairing

Fig. 7 shows the impact of η on the total transmit power for different channel number N. Intuitively, the total transmit power decreases when the number of channels increases. However, the amount of reduced power depends heavily on the capability of SI cancellation. For instance, for $\eta = -95$ dB, N increasing from 10 to 20 results in a power reduction of almost 60%, while for $\eta = -110$ dB, a power reduction of only 10% is observed. The main reason is that when N becomes large, more users can work in HD mode. This requires less power to meet the QoS constraint. When η is large, more power should be used to compensate for SI in the uplink and co-channel interference in the downlink; therefore, the gain of transmit power reduction becomes much more substantial by operating in HD mode.

Fig. 8 shows the impact of cell size on the total transmit power with different η's. In all cases, it is observed that the total transmit power increases as the cell radius becomes larger. This is rather intuitive, because the path loss effect becomes much more significant in a large cell. In this regard, FD is attractive particularly for small cell networks with short distances.

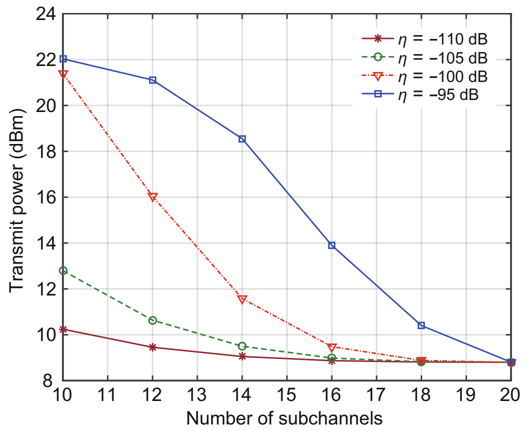

Fig. 7 Impact of η on the total transmit power

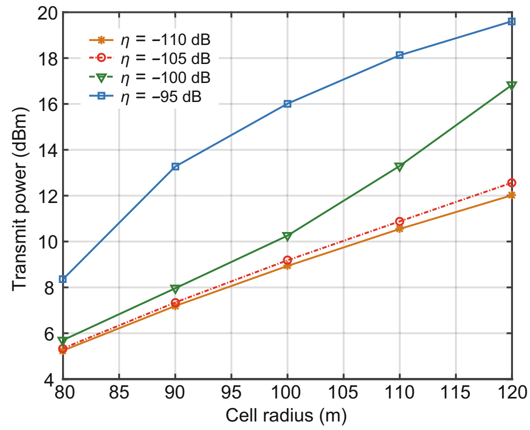

Fig. 8 Impact of cell radius on the total transmit power

6 Conclusions

We have studied the joint-user admission and power control problem in a single cell hybrid FD/HD network. By introducing the concept of dummy users, the original 0-1 integer programming problem was transformed into a standard assignment problem, which was then solved efficiently. Numerical results suggest that the proposed pairing scheme attains much better performance, compared with random pairing.

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