

JOINT POWER AND SUBCARRIER ALLOCATION FOR MULTICARRIER FULL-DUPLEX SYSTEMS

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ABSTRACT

In this paper, we investigate resource allocation for multicarrier communication systems employing a full-duplex base station for serving multiple half-duplex downlink and uplink users simultaneously. We study the joint power and subcarrier allocation design for the maximization of the weighted sum throughput of the system. The algorithm design is formulated as a mixed combinatorial non-convex optimization problem and obtaining the globally optimal solution may require prohibitively high computational complexity. Therefore, a low computational complexity suboptimal iterative algorithm exploiting successive convex approximation is proposed to obtain a locally optimal solution. Simulation results confirm that the proposed suboptimal algorithm obtains a substantial improvement in system throughput compared to various existing baseline schemes.

1. INTRODUCTION

Multicarrier (MC) communication techniques have been widely investigated over the last decades, since they enable flexible resource allocation, e.g. dynamic subcarrier and power allocation, for serving multiple users [1]–[9]. In [7], the authors studied the resource allocation algorithm design for energy-efficient communication in multi-cell orthogonal frequency division multiple access systems. In [8] and [9], the joint power and subcarrier allocation algorithm design was investigated for weighted sum throughput maximization and power consumption minimization in MC non-orthogonal multiple access (NOMA) systems, respectively. However, despite the fruitful development of MC-based communication in [1]–[9], radio resources are not efficiently utilized, since base stations (BSs) operate in the half-duplex (HD) mode, where uplink (UL) and downlink (DL) transmissions are separated by orthogonal radio resources in either time or frequency leading to resource underutilization.

Recently, full-duplex (FD) communication has become an emerging technique for the fifth-generation (5G) communication networks which is capable of potentially doubling the spectral efficiency by performing simultaneous DL and UL transmission in the same frequency band [10]–[13]. Therefore, it is expected that the spectral efficiency of conventional HD-MC systems can be improved substantially by employing an FD BS. However, self-interference (SI) at the FD BS and co-channel interference (CCI) between DL and UL users on each subcarrier may degrade the quality of service (QoS) in FD communication systems. Therefore, different resource allocation designs for FD MC systems were proposed

to overcome these challenges [14, 15]. In [14], the authors proposed an optimal joint precoding and scheduling algorithm for the maximization of the weighted sum throughput of MIMO-MC-FD relaying systems. However, the optimal solution in [14] can only be obtained when the number of subcarriers approaches infinity which may not be achievable in practice. The authors of [15] proposed a suboptimal iterative subcarrier and power allocation algorithm for the maximization of the weighted sum throughput in an FD MC system. However, the iterative approach proposed in [15] divided the optimization problem into individual uplink and downlink subproblems which may lead to degradation in performance.

Motivated by the aforementioned observations, we formulate a mixed combinatorial non-convex optimization problem to maximize the weighted system sum throughput of an FD MC system. In order to strike a balance between computational complexity and optimality, we propose a suboptimal joint subcarrier and power allocation algorithm based on successive convex approximation to obtain a locally optimal solution.

2. SYSTEM MODEL

In this section, we present the adopted notation and the considered FD MC system model.

2.1. Notation

We use boldface lower case letters to denote vectors. \mathbf{a}^T denotes the transpose of vector \mathbf{a} ; \mathbb{C} denotes the set of complex values; \mathbb{R} denotes the set of non-negative real values; $\mathbb{R}^{N \times 1}$ denotes the set of all $N \times 1$ vectors with real entries and $\mathbb{R}_+^{N \times 1}$ denotes the non-negative subset of $\mathbb{R}^{N \times 1}$; $\mathbb{Z}^{N \times 1}$ denotes the set of all $N \times 1$ vectors with integer entries; $\mathbf{a} \leq \mathbf{b}$ indicates that \mathbf{a} is component-wise smaller than \mathbf{b} ; $|\cdot|$ denotes the absolute value of a complex scalar; $\mathcal{E}\{\cdot\}$ denotes statistical expectation. The circularly symmetric complex Gaussian distribution with mean w and variance σ^2 is denoted by $\mathcal{CN}(w, \sigma^2)$; and \sim stands for “distributed as”. $\nabla_{\mathbf{x}} f(\mathbf{x})$ denotes the gradient vector of function $f(\mathbf{x})$ whose components are the partial derivatives of $f(\mathbf{x})$.

2.2. FD MC System

We consider a FD MC system which consists of an FD BS, K HD DL users, and J HD UL users. All transceivers are equipped with a single antenna. The entire frequency band of W Hertz is partitioned into N_F orthogonal subcarriers. In this paper, we assume that each subcarrier is allocated to at most one DL user and one UL user on each subcarrier, cf. Figure 1. Assuming DL user $m \in \{1, \dots, K\}$ and UL user $r \in \{1, \dots, J\}$ are selected and multiplexed on subcarrier $i \in \{1, \dots, N_F\}$, the received signals at DL user m and the

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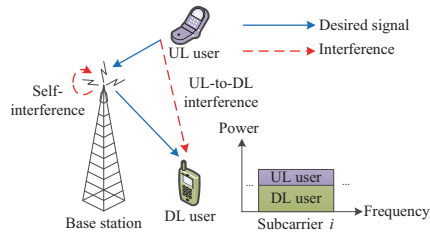


Fig. 1. An FD MC system where an FD BS serves $K = 1$ HD DL user and $J = 1$ HD UL user on N_F subcarriers.

FD BS are given by

$$y_{DL_m}^i = \sqrt{p_m^i \varpi_m} h_m^i x_{DL_m}^i + \underbrace{\sqrt{q_r^i \vartheta_{r,m}} f_{r,m}^i x_{UL_r}^i}_{\text{co-channel interference}} + z_{DL_m}^i, \quad (1)$$

$$y_{BS}^i = \sqrt{q_r^i \varrho_r} g_r^i x_{UL_r}^i + \underbrace{l_{SI}^i \sqrt{p_m^i} x_{DL_m}^i}_{\text{self-interference}} + z_{BS}^i, \quad (2)$$

respectively. Variables $x_{DL_m}^i \in \mathbb{C}$ and $x_{UL_r}^i \in \mathbb{C}$ denote the symbols transmitted by the FD BS to DL user m and by UL user r to the FD BS on subcarrier i , respectively. Besides, without loss of generality, $\mathcal{E}\{|x_{DL_m}^i|^2\} = \mathcal{E}\{|x_{UL_r}^i|^2\} = 1, \forall m, r$ is assumed. p_m^i is the transmit power of the signal intended for DL user m at the FD BS and q_r^i is the transmit power of the signal intended for the FD BS at UL user r on subcarrier i . Variables $h_m^i \in \mathbb{C}$, $g_r^i \in \mathbb{C}$, and $f_{r,m}^i \in \mathbb{C}$ denote the small scale fading coefficients for the link between the FD BS and DL user m , the link between UL user r and the FD BS, and the link between UL user r and DL user m on subcarrier i , respectively. $l_{SI}^i \in \mathbb{C}$ denotes the SI channel at the FD BS. Variables $\varpi_m \in \mathbb{R}$, $\varrho_r \in \mathbb{R}$, and $\vartheta_{r,m} \in \mathbb{R}$ represent the joint effect of path loss and shadowing between the FD BS and DL user m , between UL user r and the FD BS, and between UL user r and DL user m , respectively. $z_{DL_m}^i \sim \mathcal{CN}(0, \sigma_{z_{DL_m}}^2)$ and $z_{BS}^i \sim \mathcal{CN}(0, \sigma_{z_{BS}}^2)$ denote the complex additive white Gaussian noise (AWGN) on subcarrier i at DL user m and the FD BS, respectively. Besides, for the study of resource allocation algorithm design, we assume that the global channel state information (CSI) of all links in the network is available at the BS so as to unveil the performance upper bound of practical FD MC systems.

3. PROBLEM FORMULATION AND SOLUTION

In this section, after defining the adopted performance measure, we formulate the resource allocation problem. Then, we propose an iterative algorithm to solve the proposed problem.

3.1. Weighted System Throughput

Assuming DL user m and UL user r are allocated on subcarrier i , the weighted sum throughput on subcarrier i is:

$$U_{m,r}^i(p_m^i, q_r^i, s_{m,r}^i) \quad (3)$$

$$= s_{m,r}^i \left[w_m \log_2 \left(1 + \frac{H_m^i p_m^i}{F_{r,m}^i q_r^i + 1} \right) + \mu_r \log_2 \left(1 + \frac{G_r^i q_r^i}{\rho L_{SI}^i p_m^i + 1} \right) \right],$$

$$\text{where } H_m^i = \frac{\varpi_m |h_m^i|^2}{\sigma_{z_{DL_m}}^2}, G_r^i = \frac{\varrho_r |g_r^i|^2}{\sigma_{z_{BS}}^2}, F_{r,m}^i = \frac{\vartheta_{r,m} |f_{r,m}^i|^2}{\sigma_{z_{DL_m}}^2},$$

and $L_{SI}^i = \frac{|l_{SI}^i|^2}{\sigma_{z_{BS}}^2}$, respectively. $0 \leq \rho \leq 1$ is a constant modelling the quality of the SI cancellation at the FD BS. $s_{m,r}^i \in \{0, 1\}$ is the binary subcarrier allocation indicator. Specifically, $s_{m,r}^i = 1$ if DL user m and UL user r are multiplexed on subcarrier i . Otherwise, $s_{m,r}^i = 0$. Constants

$0 \leq w_m \leq 1$ and $0 \leq \mu_r \leq 1$ are the resource allocation weight for DL user m and UL user r , respectively.

3.2. Optimization Problem Formulation

The system objective is to maximize the weighted sum of the entire system throughput. The optimal joint power and subcarrier allocation policy is obtained by solving the following optimization problem:

$$\begin{aligned} & \underset{p_m^i, q_r^i, s_{m,r}^i}{\text{maximize}} \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J U_{m,r}^i(p_m^i, q_r^i, s_{m,r}^i) \quad (4) \\ & \text{s.t. C1: } \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J s_{m,r}^i p_m^i \leq P_{\max}^{\text{DL}}, \quad \text{C2: } p_m^i \geq 0, \forall i, m, \\ & \quad \text{C3: } \sum_{i=1}^{N_F} \sum_{m=1}^K s_{m,r}^i q_r^i \leq P_{\max}^{\text{UL}}, \forall r, \quad \text{C4: } q_r^i \geq 0, \forall i, r. \\ & \quad \text{C5: } s_{m,r}^i \in \{0, 1\}, \forall i, m, r, \quad \text{C6: } \sum_{m=1}^K \sum_{r=1}^J s_{m,r}^i \leq 1, \forall i. \end{aligned}$$

Constraint C1 is the power constraint for the BS with a maximum transmit power allowance of P_{\max}^{DL} . Constraint C3 limits the transmit power of UL user r to P_{\max}^{UL} . Constraints C5 and C6 are imposed to guarantee that each subcarrier is allocated to at most one DL user and one UL user. Here, we note that UL-to-DL user pairing is performed on every subcarrier. Constraints C2 and C4 are the non-negative transmit power constraints for the DL and UL users, respectively.

The problem in (4) is a mixed combinatorial non-convex problem due to the integer constraint for subcarrier allocation in C5 and the non-convex objective function. In general, there is no systematic approach for solving these problems efficiently. In some cases, an exhaustive search or branch-and-bound method is needed to obtain the globally optimal solution which is computationally infeasible even for small N_F , K , and J . Therefore, in the next section, we propose a computational efficient suboptimal algorithm based on successive convex approximation which obtains a locally optimal solution for the optimization problem in (4).

3.3. Joint Power and Subcarrier Allocation Algorithm

To facilitate the presentation of the resource allocation algorithm design, in the sequel, we rewrite the weighted throughput on subcarrier i in (3) in an equivalent form:

$$\begin{aligned} & \tilde{U}_{m,r}^i(\tilde{p}, \tilde{q}) \\ & = w_m \log_2 \left(1 + \frac{s_{m,r}^i H_m^i \tilde{p}_m^i}{s_{m,r}^i H_m^i \tilde{p}_m^i + 1} \right) + \mu_r \log_2 (1 + s_{m,r}^i H_n^i \tilde{q}_n^i) \\ & = w_m \log_2 \left(1 + \frac{H_m^i \tilde{p}_{m,r}^i}{H_m^i \tilde{p}_{m,r}^i + 1} \right) + \mu_r \log_2 (1 + H_n^i \tilde{q}_{m,r}^i) \quad (5) \end{aligned}$$

where $\tilde{p}_{m,r}^i = s_{m,r}^i p_m^i$ and $\tilde{q}_{m,r}^i = s_{m,r}^i q_r^i$ are auxiliary variables. Then, the original problem in (4) can be rewritten as

$$\begin{aligned} & \underset{\tilde{p}, \tilde{q}, \mathbf{s}}{\text{maximize}} \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J \tilde{U}_{m,r}^i(\tilde{p}, \tilde{q}) \\ & \text{s.t. C1: } \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J \tilde{p}_{m,r}^i \leq P_{\max}^{\text{DL}}, \quad \text{C2: } \tilde{p}_{m,r}^i \geq 0, \forall m, r, i, \\ & \quad \text{C3: } \sum_{i=1}^{N_F} \sum_{m=1}^K \tilde{q}_{m,r}^i \leq P_{\max}^{\text{UL}}, \forall r, \quad \text{C4: } \tilde{q}_{m,r}^i \geq 0, \forall m, r, i, \\ & \quad \text{C5, C6,} \quad (6) \end{aligned}$$

Algorithm 1 Successive Convex Approximation

- 1: Initialize the maximum number of iterations I_{\max} , penalty factor $\eta \gg 1$, iteration index $k = 1$, and initial point $\tilde{\mathbf{p}}^{(1)}$, $\tilde{\mathbf{q}}^{(1)}$, and $\mathbf{s}^{(1)}$
 - 2: **repeat**
 - 3: Solve (23) for a given $\tilde{\mathbf{p}}^{(k)}$, $\tilde{\mathbf{q}}^{(k)}$, and $\mathbf{s}^{(k)}$ and store the intermediate resource allocation policy $\{\tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \mathbf{s}\}$
 - 4: Set $k = k + 1$ and $\tilde{\mathbf{p}}^{(k)} = \tilde{\mathbf{p}}$, $\tilde{\mathbf{q}}^{(k)} = \tilde{\mathbf{q}}$, and $\mathbf{s}^{(k)} = \mathbf{s}$
 - 5: **until** convergence or $k = I_{\max}$
 - 6: $\tilde{\mathbf{p}}^* = \tilde{\mathbf{p}}^{(k)}$, $\tilde{\mathbf{q}}^* = \tilde{\mathbf{q}}^{(k)}$, and $\mathbf{s}^* = \mathbf{s}^{(k)}$
-

where $\tilde{\mathbf{p}} \in \mathbb{R}^{N_F K J \times 1}$, $\tilde{\mathbf{q}} \in \mathbb{R}^{N_F K J \times 1}$, and $\mathbf{s} \in \mathbb{Z}^{N_F K J \times 1}$ are the collection of all $\tilde{p}_{m,r}^i$, $\tilde{q}_{m,r}^i$, and $s_{m,r}^i$, respectively.

We note that the product terms $\tilde{p}_{m,r}^i = s_{m,r}^i p_{m,r}^i$ and $\tilde{q}_{m,r}^i = s_{m,r}^i q_{m,r}^i$ in (6) are the obstacles for the design of a computationally efficient resource allocation algorithm. In order to circumvent this difficulty, we adopt the big-M formulation to decompose the product terms [16]. In particular, we impose the following additional constraints:

$$\text{C7: } \tilde{p}_{m,r}^i \leq P_{\max}^{\text{DL}} s_{m,r}^i, \quad \forall i, m, r, \quad (7)$$

$$\text{C8: } \tilde{p}_{m,r}^i \leq p_{m,r}^i, \quad \forall i, m, r, \quad (8)$$

$$\text{C9: } \tilde{p}_{m,r}^i \geq p_{m,r}^i - (1 - s_{m,r}^i) P_{\max}^{\text{DL}}, \quad \forall i, m, r, \quad (9)$$

$$\text{C10: } \tilde{p}_{m,r}^i \geq 0, \quad \forall i, m, r, \quad (10)$$

$$\text{C11: } \tilde{q}_{m,r}^i \leq P_{\max}^{\text{UL}} s_{m,r}^i, \quad \forall i, m, r, \quad (11)$$

$$\text{C12: } \tilde{q}_{m,r}^i \leq q_{m,r}^i, \quad \forall i, m, r, \quad \text{C13: } \tilde{q}_{m,r}^i \geq 0, \quad \forall i, m, r, \quad (12)$$

$$\text{C14: } \tilde{q}_{m,r}^i \geq q_{m,r}^i - (1 - s_{m,r}^i) P_{\max}^{\text{UL}}, \quad \forall i, m, r. \quad (13)$$

Besides, constraint C5 in (6) is a combinatorial constraint. Hence, we rewrite constraint C5 in the following equivalent form:

$$\text{C5a: } \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J s_{m,r}^i - (s_{m,r}^i)^2 \leq 0 \quad \text{and} \quad (14)$$

$$\text{C5b: } 0 \leq s_{m,r}^i \leq 1, \quad \forall i, m, r. \quad (15)$$

Now, $s_{m,r}^i$ is a continuous optimization variable having values between zero and one. We note that constraint C5a is the difference of two convex functions which is known as a reverse convex function [17]–[19]. In order to handle constraint C5a, we reformulate the problem in (6) as

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \mathbf{s}}{\text{minimize}} \quad & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J -U_{m,r}^i(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) \\ & + \eta \left(\sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J s_{m,r}^i - \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J (s_{m,r}^i)^2 \right) \\ \text{s.t.} \quad & \text{C1–C4, C5b, C6–C14,} \end{aligned} \quad (16)$$

where $\eta \gg 1$ is a large constant which acts as a penalty factor to penalize the objective function for any $s_{m,r}^i$ that is not equal to zero or one. It can be shown that the problems in (16) and (6) are equivalent for $\eta \gg 1$ [17, 18]. Therefore, we consider the resource allocation algorithm design for (16).

Although the constraints in (16) span a convex set, the optimization problem in (16) is still non-convex because of the objective function. To handle this difficulty, we rewrite the problem as

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \mathbf{s}}{\text{minimize}} \quad & F(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) - G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) + \eta(H(\mathbf{s}) - M(\mathbf{s})) \\ \text{s.t.} \quad & \text{C1–C3, C4b, C5–C15,} \end{aligned} \quad (17)$$

where

$$\begin{aligned} F(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) = & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J -w_m \log_2(1 + H_{m,r}^i \tilde{p}_{m,r}^i + F_{r,m}^i \tilde{q}_{m,r}^i) \\ & - \mu_r \log_2(1 + G_{r,m}^i \tilde{q}_{m,r}^i + \rho L_{\text{SI}}^i \tilde{p}_{m,r}^i) \end{aligned} \quad (18)$$

$$H(\mathbf{s}) = \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J s_{m,r}^i, \quad M(\mathbf{s}) = \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J (s_{m,r}^i)^2, \quad (19)$$

$$\begin{aligned} G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) = & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J -w_m \log_2(1 + F_{r,m}^i \tilde{q}_{m,r}^i) \\ & - \mu_r \log_2(1 + \rho L_{\text{SI}}^i \tilde{p}_{m,r}^i). \end{aligned} \quad (20)$$

We note that $F(\tilde{\mathbf{p}}, \tilde{\mathbf{q}})$, $G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}})$, $H(\mathbf{s})$, and $M(\mathbf{s})$ are convex functions and the problem in (17) belongs to the class of difference of convex (d.c.) function programming. As a result, we can apply successive convex approximation [19] to obtain a locally optimal solution for (17). Since $G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}})$ and $M(\mathbf{s})$ are differentiable convex functions, for any feasible point $\tilde{\mathbf{p}}^{(k)}$, $\tilde{\mathbf{q}}^{(k)}$, and $\mathbf{s}^{(k)}$, we have the following inequalities:

$$\begin{aligned} G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) \geq & G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)}) + \nabla_{\tilde{\mathbf{p}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(k)}) \\ & + \nabla_{\tilde{\mathbf{q}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{q}} - \tilde{\mathbf{q}}^{(k)}) \quad \text{and} \end{aligned} \quad (21)$$

$$M(\mathbf{s}) \geq M(\mathbf{s}^{(k)}) + \nabla_{\mathbf{s}} M(\mathbf{s}^{(k)})^T (\mathbf{s} - \mathbf{s}^{(k)}), \quad (22)$$

where the right hand sides of (21) and (22) are affine functions representing the global underestimation of $G(\tilde{\mathbf{p}}, \tilde{\mathbf{q}})$ and $M(\mathbf{s})$, respectively. Therefore, for any given $\tilde{\mathbf{p}}^{(k)}$, $\tilde{\mathbf{q}}^{(k)}$, and $\mathbf{s}^{(k)}$, we can obtain an upper bound for (17) by solving the following convex optimization problem:

$$\begin{aligned} \underset{\tilde{\mathbf{p}}, \tilde{\mathbf{q}}, \mathbf{s}}{\text{minimize}} \quad & F(\tilde{\mathbf{p}}, \tilde{\mathbf{q}}) - G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)}) - \nabla_{\tilde{\mathbf{p}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(k)}) \\ & - \nabla_{\tilde{\mathbf{q}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{q}} - \tilde{\mathbf{q}}^{(k)}) + \eta(H(\mathbf{s}) - M(\mathbf{s}^{(k)})) \\ & - \nabla_{\mathbf{s}} M(\mathbf{s}^{(k)})^T (\mathbf{s} - \mathbf{s}^{(k)}) \\ \text{s.t.} \quad & \text{C1–C4, C5b, C6–C14,} \end{aligned} \quad (23)$$

where

$$\begin{aligned} & \nabla_{\tilde{\mathbf{p}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{p}} - \tilde{\mathbf{p}}^{(k)}) \\ = & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J -\frac{\mu_r \rho L_{\text{SI}}^i (\tilde{p}_{m,r}^i - \tilde{p}_{m,r}^{(k)})}{(1 + \rho L_{\text{SI}}^i \tilde{p}_{m,r}^{(k)}) \ln(2)}, \end{aligned} \quad (24)$$

$$\begin{aligned} & \nabla_{\tilde{\mathbf{q}}} G(\tilde{\mathbf{p}}^{(k)}, \tilde{\mathbf{q}}^{(k)})^T (\tilde{\mathbf{q}} - \tilde{\mathbf{q}}^{(k)}) \\ = & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J -\frac{w_m F_{r,m}^i (\tilde{q}_{m,r}^i - \tilde{q}_{m,r}^{(k)})}{(1 + F_{r,m}^i \tilde{q}_{m,r}^{(k)}) \ln(2)} \end{aligned} \quad (25)$$

$$\begin{aligned} & \nabla_{\mathbf{s}} M(\mathbf{s}^{(k)})^T (\mathbf{s} - \mathbf{s}^{(k)}) \\ = & \sum_{i=1}^{N_F} \sum_{m=1}^K \sum_{r=1}^J 2s_{m,r}^{i(k)} (s_{m,r}^i - s_{m,r}^{i(k)}). \end{aligned} \quad (26)$$

Then, we employ an iterative algorithm to tighten the obtained upper bound as summarized in **Algorithm 1**. In each iteration, the convex problem in (23) can be solved efficiently by standard convex program solvers such as CVX [20]. By solving the convex upper bound problem in (23), the proposed iterative scheme generates a sequence of feasible solutions $\tilde{\mathbf{p}}^{(k+1)}$, $\tilde{\mathbf{q}}^{(k+1)}$, and $\mathbf{s}^{(k+1)}$ successively. The proposed sub-optimal iterative algorithm converges to a locally optimal solution of (23) with polynomial time computational complexity [19].

4. SIMULATION RESULTS

In this section, we investigate the performance of the proposed resource allocation scheme through simulations. We

Table 1. Simulation Parameters.

Carrier center frequency	2.5 GHz
System bandwidth	5 MHz
Number of subcarriers, N_F	64
Bandwidth per subcarrier	78 kHz
Path loss exponent	3.6
SI cancellation constant, ρ	-90 dB
DL user noise power, $\sigma_{z_{DL,m}}^2$	-125 dBm
UL BS noise power, $\sigma_{z_{BS}}^2$	-125 dBm
Maximum transmit power for UL users, P_{\max}^{UL}	18 dBm
BS antenna gain	10 dBi

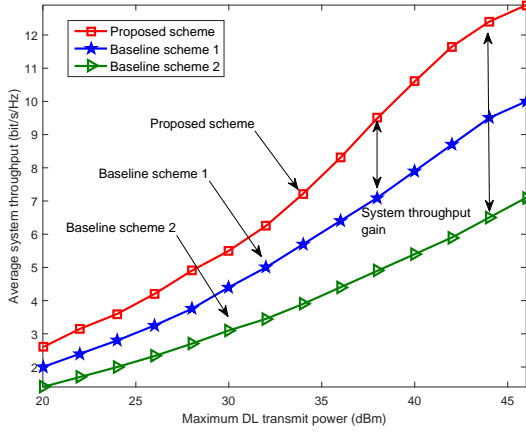


Fig. 2. Average system throughput (bits/s/Hz) versus the maximum DL transmit power at the BS (dBm), P_{\max}^{DL} , for different resource allocation schemes and $K = J = 10$. The double-sided arrows indicate the performance gain brought by the proposed scheme.

adopt the simulation parameters given in Table 1 [21, 22], unless specified otherwise. A single cell with two ring-shaped boundary regions is considered [23]–[25]. The outer boundary and the inner boundary have radii of 30 meters and 600 meters, respectively. The K DL and J UL users are randomly and uniformly distributed between the inner and the outer boundary. The FD BS is located at the center of the cell. The maximum transmit power of the FD BS is P_{\max}^{DL} . We set the same weight for all the users, i.e., $w_m = \mu_r = 1, \forall m, r$. The penalty term η for the proposed algorithm is set to $10 \log_2(1 + \frac{P_{\max}^{\text{DL}}}{\sigma_{z_{DL,m}}^2})$. The small-scale fading of the DL channels, the UL channels, and the channel between the DL and UL users is modeled as independent and identically distributed Rayleigh fading. The fading coefficients of the SI channel on each subcarrier are generated as independent and identically distributed Rician random variables with Rician factor 5 dB. The results shown in this section were averaged over different realizations of both path loss and multipath fading.

In Figure 2, we investigate the average system throughput versus the maximum transmit power at the FD BS, P_{\max}^{DL} , for $K = 10$ DL users and $J = 10$ UL users. The number of iterations for the proposed iterative resource allocation algorithm is 5. As can be observed, the average system throughput increases monotonically with the maximum transmit power P_{\max}^{DL} . In fact, the proposed scheme is able to obtain a locally optimal solution of (4) which can effectively exploit the increased transmit power budget to improve the received signal-to-interference-plus-noise ratio (SINR) at the

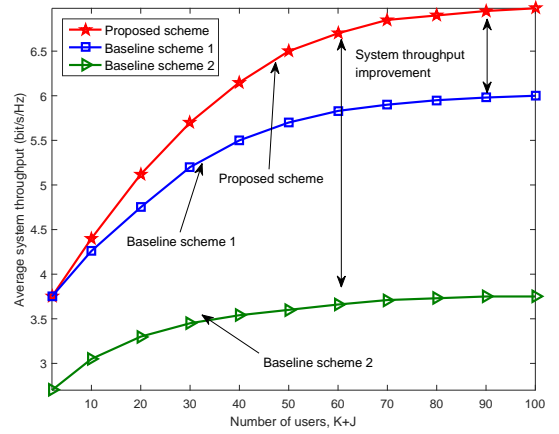


Fig. 3. Average system throughput (bits/s/Hz) versus the number of users for different resource allocation schemes with $P_{\max}^{\text{DL}} = 45$ dBm.

users. For comparison, Figure 2 also shows the average system throughput of two baseline schemes. For baseline scheme 1, we adopt the suboptimal power and subcarrier allocation for the considered FD MC system proposed in [15]. For baseline scheme 2, a traditional HD MC system is considered. As can be observed, the proposed scheme achieves a considerably higher average system throughput than baseline scheme 1 due to the joint power and subcarrier allocation. Besides, baseline scheme 2 can only achieve a substantially lower average system throughput compared to the proposed scheme due to its underutilization of the spectral resource. For instance, for $P_{\max}^{\text{DL}} = 46$ dBm, the proposed scheme achieves roughly a 30% and 86% higher average system throughput than baseline schemes 1 and 2, respectively.

In Figure 3, we investigate the average system throughput versus the number of users for a maximum transmit power of $P_{\max}^{\text{DL}} = 31$ dBm. We assume that there are equal numbers of DL and UL users in the system. As can be observed, the average system throughput for the proposed scheme and baseline schemes increase with the number of users since all schemes are able to exploit multiuser diversity. Besides, it can be observed from Figure 3 that the average system throughput of the proposed scheme grows faster with an increasing number of users than that of the baseline schemes. In fact, baseline scheme 1 divides the subcarrier and power allocation problem into two individual sub-problems which leads to performance degradation. In particular, the performance gap between the proposed scheme and baseline scheme 1 is enlarged for an increasing number of users. On the other hand, baseline scheme 2 achieves a lower average system throughput compared to the proposed scheme and baseline 1, since DL and UL transmission are separated into orthogonal radio resources which leads to inefficient spectrum utilization.

5. CONCLUSION

In this paper, we studied the joint power and subcarrier allocation for an FD MC system. The resource allocation design was formulated as a non-convex optimization problem with the objective to maximize the weighted system throughput. A suboptimal resource allocation algorithm design based on successive convex approximation was proposed. Simulation results unveiled that the proposed scheme for FD MC systems achieves a significant improvement in system performance compared to two baseline schemes.

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