Radio Resource Allocation with Inter-node Interference in Full-Duplex OFDMA Networks

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***Abstract*—In-band wireless full-duplex is a promising technology that enables a wireless node to transmit and receive at the same time on the same frequency spectrum. In OFDMA networks, the full-duplex transmission makes the resource allocation problem more challenging, in particular when user devices are not full-duplex capable. In this paper, we investigate the joint problem of subcarrier assignment and power allocation to maximize the sum-rate performance in full-duplex OFDMA networks. To achieve high throughput in the considered network, we propose to use a practical subcarrier assignment condition which allows a subcarrier to be allocated to a pair of uplink and downlink nodes when its inter-node channel gain is lower than its uplink channel gain. Considering this condition and the inter-node interference, we design three resource allocation algorithms which run for; i) uplink first, ii) downlink first, and iii) uplink and downlink in pair. Through simulation, we evaluate our solutions in comparison with conventional schemes with respect to performance gain.**

I. Introduction

Orthogonal Frequency Division Multiple Access (OFDMA) has been a key technology in most 4G cellular systems. Dividing the spectrum band into multiple orthogonal subcarriers and distributing them over different nodes, OFDMA benefits from both multiuser and frequency diversities. To exploit such benefits, radio resource allocation algorithms handle subcarrier assignment and power allocation. In downlink case, an optimal allocation for the sum-rate maximization is to assign each subcarrier to the node with the largest channel gain and allocate power according to the well-known water-filling algorithm [1]. In contrast, the uplink problem is in general difficult to solve due to the distributive nature of power constraints, i.e., each uplink node has its own power budget, and most previous works achieve suboptimal performance [2], [3], [4].

Recently, *in-band wireless full-duplex* has attracted great attention as a promising technology to boost the spectral efficiency. A full-duplex radio can transmit and receive simultaneously on the same frequency band by cancelling *self-interference* that results from its own transmission to the received signal [5], [6]. The main challenge of full-duplex implementation is in suppressing the self-interference to a sufficiently low level. The state-of-the-art implementation has suppressed the self-interference close to the receiver noise power level using a combination of analog and digital cancellation techniques [7].

When the full-duplex operation is adopted in OFDMA networks, a full-duplex capable base station transmits to downlink nodes while receiving from uplink nodes simultaneously. In this case, already complicated resource allocation problems become much more challenging due to i) the coexistence of uplink and downlink transmissions in the same subcarrier, and ii) resultant *inter-node interference* from uplink nodes to downlink nodes [8]. To fully exploit the full-duplex gain, it is essential to allocate the radio resource considering the inter-node interference.

There are several works that address the resource allocation problem in full-duplex networks. In [4], the authors proposed a randomized iteration method which achieves a near-optimal performance. However, it is assumed that mobile nodes are also full-duplex capable, and thus the inter-node interference has not been considered. In [9], the authors considered a full-duplex network with the inter-node interference, and proposed a resource allocation algorithm using matching theory. The proposed subcarrier allocation algorithm potentially leads to a non-convex power allocation problem, which is generally hard to solve.

In this paper, we investigate the joint problem of subcarrier assignment and power allocation in a single-cell full-duplex OFDMA network. Our goal is to maximize the sum-rate performance by optimizing the uplink and downlink resource allocations taking into account the inter-node interference. The contributions of this paper are three-fold:

- We show that the resource allocation problem is NP-hard due to the inter-node interference. To make the problem tractable, we propose to use a subcarrier assignment condition that leads each subcarrier to be allocated to a pair of uplink and downlink nodes that have lower inter-node channel gain compared to the uplink channel gain.
- Based on the above condition, we develop three resource allocation algorithms which allocate subcarriers to: i) uplink nodes first, ii) downlink nodes first, and iii) uplink and downlink nodes simultaneously.
- Through simulation, we evaluate our algorithms in various scenarios and confirm that they perform better than existing schemes oblivious to the inter-node interference.

The rest of this paper is organized as follows. In Section II, we present a detailed description of our system model and formulate the resource allocation problem. In Section III, we show that the considered problem is NP-hard, and design a simple subcarrier assignment condition. We develop three resource allocation algorithms in Section IV, and provide the performance evaluation of our solutions in Section V. We conclude this paper in Section VI.

II. System Model and Problem Formulation

We consider a single-cell OFDMA network which consists of one full-duplex base station (BS) and multiple half-duplex mobile nodes[1], as shown in Fig. 1. Each node is predetermined as either an uplink node or a downlink node. Let $\mathcal{N}$ denote the set of uplink nodes, and $\mathcal{M}$ denote the set of downlink nodes. Without loss of generality, we assume that the number of uplink nodes is equal to the number of downlink nodes, i.e., $|\mathcal{N}| = |\mathcal{M}| = N$. The spectrum band is partitioned into S orthogonal subcarriers, denoted by $\mathcal{S} = \{1, 2, \ldots, S\}$, where a subcarrier refers to the basic scheduling unit of the system rather than a physical subcarrier. We assume that the self-interference at the BS can be completely removed exploiting interference cancellation techniques, as in [4], [8]. However, due to simultaneous uplink and downlink transmissions in the same subcarrier, there exists inter-node interference from uplink nodes to downlink nodes.

Let us represent the uplink and downlink subcarrier assignment patterns by two binary vectors $\mathbf{X^u} := \{x^u_{n,s}\}_{n\in\mathcal{N},s\in\mathcal{S}}$ and $\mathbf{X^d} := \{x^d_{m,s}\}_{m\in\mathcal{M},s\in\mathcal{S}}$, respectively, where $x^u_{n,s}$'s and $x^d_{m,s}$'s are defined as

$$x^u_{n,s} = \begin{cases} 1, & \text{if subcarrier } s \text{ is assigned to node } n \in \mathcal{N}, \\ 0, & \text{otherwise,} \end{cases}$$

$$x^d_{m,s} = \begin{cases} 1, & \text{if subcarrier } s \text{ is assigned to node } m \in \mathcal{M}, \\ 0, & \text{otherwise.} \end{cases}$$

Also, let us define $\mathbf{X} := (\mathbf{X^u}, \mathbf{X^d})$. We assume that a subcarrier is exclusively assigned to at most one uplink node and one downlink node. Given $\mathbf{X}$, the uplink and downlink nodes using subcarrier s are denoted by n_s and m_s, respectively.

For each subcarrier s, let $g^u_{n,s}$ ($g^d_{m,s}$) denote the uplink (downlink) channel gain between uplink node n (downlink node m) and the BS, and let $g^i_{n,m,s}$ denote the inter-node channel gain[2] from uplink node n to downlink node m. Each channel gain includes the path loss and Rayleigh fading, and it is normalized by the noise power N_0. Let $p^u_{n,s}$ denote the uplink power allocated by uplink node n, and $p^d_{m,s}$ denote the downlink power allocated by the BS for downlink node m. The uplink and downlink power allocations are represented by two vectors $\mathbf{P^u} := \{p^u_{n,s}\}_{n\in\mathcal{N},s\in\mathcal{S}}$ and $\mathbf{P^d} := \{p^d_{m,s}\}_{m\in\mathcal{M},s\in\mathcal{S}}$, respectively, and let $\mathbf{P} := (\mathbf{P^u}, \mathbf{P^d})$. The power budgets at the BS and uplink node u are limited to P_{BS} and P_n, respectively.

[1]Due to the high cost and complexity of self-interference cancellation techniques, full-duplex radios will likely be implemented only at base stations in the near future.

[2]In current wireless systems, there is no protocol to measure inter-node channel gains, which is a challenging task. We leave this issue as future work.

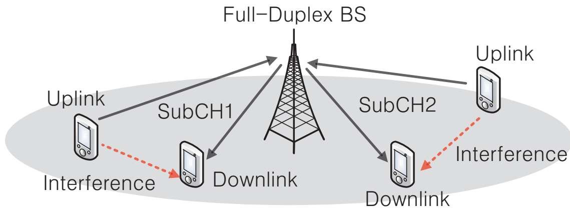


Fig. 1. A single-cell full-duplex OFDMA network which consists of one full-duplex base station and multiple half-duplex mobile nodes. Due to the simultaneous uplink and downlink transmissions, there exists inter-node interference from uplink nodes to downlink nodes.

Assuming that interference is treated as noise, the full-duplex rate R_s (the sum of uplink rate R^u_s and downlink rate R^d_s) for each subcarrier s is given by

$$R_s(\mathbf{X},\mathbf{P}) = \sum_{n=1}^{N} x^u_{n,s} \log\left(1 + g^u_{n,s} p^u_{n,s}\right) + \sum_{m=1}^{N} x^d_{m,s} \log\left(1 + \frac{g^d_{m,s} p^d_{m,s}}{1 + \sum_{n=1}^{N} x^u_{n,s} g^i_{n,m,s} p^u_{n,s}}\right), \quad (1)$$

where the first and second terms are the uplink and downlink rates, respectively, and $\sum_n x^u_{n,s} g^i_{n,m,s} p^u_{n,s}$ represents the inter-node interference. Also, let $R(\mathbf{X},\mathbf{P})$ denote the sum-rate over all the subcarriers, i.e., $R(\mathbf{X},\mathbf{P}) = \sum_{s=1}^{S} R_s(\mathbf{X},\mathbf{P})$.

Our goal is to find an optimal resource allocation that maximizes the sum-rate under given power budget constraints. We formulate the problem as

$$\begin{aligned}
(\mathsf{P}) \quad & \underset{\mathbf{X},\mathbf{P}}{\text{maximize}} \quad R(\mathbf{X},\mathbf{P}) && (2a)\\
& \text{subject to} \quad \sum_{s=1}^{S} p^u_{n,s} \le P_n, \forall n \in \mathcal{N}, && (2b)\\
& \sum_{s=1}^{S}\sum_{m=1}^{N} p^d_{m,s}, \le P_{BS}, && (2c)\\
& \sum_{n=1}^{N} x^u_{n,s} \le 1, \forall s \in \mathcal{S}, && (2d)\\
& \sum_{m=1}^{N} x^d_{m,s} \le 1, \forall s \in \mathcal{S}, && (2e)\\
& x^u_{n,s} \in \{0,1\}, \forall n \in \mathcal{N}, \forall s \in \mathcal{S}, && (2f)\\
& x^d_{m,s} \in \{0,1\}, \forall m \in \mathcal{M}, \forall s \in \mathcal{S}. && (2g)
\end{aligned}$$

Notice that subcarrier s is used in full-duplex if $\sum_n x^u_{n,s} = \sum_m x^d_{m,s} = 1$, or in half-duplex otherwise.

III. Subcarrier Assignment Condition

Due to the exclusive nature of subcarrier assignment, problem P is an integer optimization problem, which is generally difficult to solve. In fact, the following theorem proves that problem P is NP-hard.

Theorem 1. The resource allocation problem P is NP-hard.

Proof: Here, we provide an outline of the proof due to the lack of space. Let us consider a case where there are only one uplink node n and one downlink node m. We set the channel gains such that $g^u_{n,s} = g^d_{m,s} = g_s, \forall s$, and $g^i_{n,m,s}$, has a sufficiently large value for all s. In this case, it can be shown that in any optimal solution, all subcarriers are used in half-duplex to avoid the excessive inter-node interference, i.e., $x^u_{n,s} x^d_{m,s} = 0, \forall s \in \mathcal{S}$. Then the set of subcarriers should be divided into two disjoint subsets where one subset is for node n and the other one for node m. It can be shown that the equipartition problem (which is NP-complete) is reducible to the subcarrier partition problem in polynomial time, and the subcarrier partition problem is NP-hard. For detailed proof, refer to Theorem 2 in our technical report [10]. ■

Since it is difficult to obtain an optimal allocation, we instead assign subcarriers according to the following intuitive condition. Intuitively, it is reasonable to assign subcarrier s to a pair of (uplink node n, downlink node m) satisfying that i) the uplink $g^u_{n,s}$ and downlink $g^d_{m,s}$ channel gains are large, and ii) the inter-node channel gain $g^i_{n,m,s}$ is small. With a large $g^u_{n,s}$, if $g^i_{n,m,s} > g^u_{n,s}$, the inter-node interference is strong enough to reduce the downlink rate significantly. To avoid this situation, we propose to assign each subcarrier s to a pair of (uplink node n, downlink node m) such that

$$g^i_{n,m,s} \le g^u_{n,s}. \qquad (3)$$

That is, the inter-node channel gain should be smaller that the uplink channel gain to prevents the excessive inter-node interference.

When a certain subcarrier assignment is given, we can reduce problem P to the following power allocation problem:

$$(\mathsf{P_P}) \quad \underset{\mathbf{P}}{\text{maximize}} \quad \sum_{s=1}^{S} R_s(p^u_{n,s}, p^d_{m,s}) \qquad (4)$$
$$\text{subject to} \quad \text{(2b) and (2c).}$$

In half-duplex case, the optimal power allocation is the per-node water-filling allocation [2], [3]. In contrast, this does not hold in full-duplex case due to the inter-node interference. Moreover, problem $\mathsf{P_p}$ is not a convex problem since R_s is not a concave function in general. This implies that it is hard to obtain the optimal power allocation $\mathbf{P}^*$ even if the optimal subcarrier assignment $\mathbf{X}^*$ has been found.

Although problem $\mathsf{P_p}$ is difficult to solve in general, fortunately it becomes a convex problem if the given subcarrier assignment satisfies the condition (3).

Proposition 1. Let $\mathbf{X}$ be a given subcarrier assignment vector. If $\mathbf{X}$ satisfies the condition (3), the power allocation problem $\mathsf{P_p}$ is a convex optimization problem.

Proof: Since the power constraints (2b) and (2c) are linear and the objective function is the sum of R_s's, problem $\mathsf{P_p}$ is a convex optimization problem if each R_s is a concave function. Let $x^u_{n,s} = 1$ and $x^d_{m,s} = 1$. Then we can write R_s as

$$R_s(p^u_{n,s}, p^d_{m,s}) = \log\left(\frac{1+g^u_{n,s}p^u_{n,s}}{1+g^i_{n,m,s}p^u_{n,s}}\right) + \log(1 + g^i_{n,m,s}p^u_{n,s} + g^d_{m,s}p^d_{m,s}).$$

The first term is a concave function of $p^u_{n,s}$, since it has a non-positive second-order derivative [11]

$$\frac{\partial^2}{\partial\left(p^u_{n,s}\right)^2}\log\left(\frac{1+g^u_{n,s}p^u_{n,s}}{1+g^i_{n,m,s}p^u_{n,s}}\right) = \frac{(g^i_{n,m,s} - g^u_{n,s})(2g^u_{n,s}g^i_{n,m,s}p^u_{n,s} + g^u_{n,s} + g^i_{n,m,s})}{(g^i_{n,m,s}p^u_{n,s}+1)^2(g^u_{n,s}p^u_{n,s}+1)^2} \le 0,$$

where the inequality comes from the assumption of $g^i_{n,m,s} \le g^u_{n,s}$. The second term is a logarithm of a linear function, which is (jointly) concave. Thus, R_s is a concave function of $(p^u_{n,s}, p^d_{m,s})$. ■

From Proposition 1 and the standard dual optimization method, we can easily solve problem $\mathsf{P_P}$ in low-complexity for any given subcarrier assignment satisfying the condition (3). In the following, we propose three resource allocation algorithms under the condition (3).

IV. Proposed Resource Allocation Algorithms

In this section, we develop three resource allocation algorithms under the condition (3). Before describing these algorithms, we first consider downlink and uplink resource allocation algorithms separately.

A. Downlink and Uplink Resource Allocation Problems

We first solve the downlink problem given an uplink resource allocation, and solve the uplink problem given a downlink resource allocation.

1) Downlink Resource Allocation: Given an uplink allocation $(\mathbf{X^u}, \mathbf{P^u})$, we solve the downlink allocation problem to maximize the sum-rate. Recall that n_s denotes the uplink node using subcarrier s. We define $\mathcal{M}_s = \{m \in \mathcal{M} | g^i_{n_s,m,s} \le g^u_{n_s,s}\}$, i.e., the set of downlink nodes which are allowed to use subcarrier s under the condition (3). For each node $m \in \mathcal{M}_s$, we define the downlink channel gain to interference and noise ratio (CINR) $\tilde{g}^d_{m,s}$ in subcarrier s as

$$\tilde{g}^d_{m,s} = \frac{g^d_{m,s}}{1 + g^i_{n_s,m,s}p^u_{n_s,s}}.$$

Also, for each node $m \notin \mathcal{M}_s$, we set $\tilde{g}^d_{m,s} = 0$ to satisfy the condition (3). Then the downlink rate $R^d_{m,s}$ in subcarrier s is given by

$$R^d_{m,s}(\mathbf{X^d}, \mathbf{P^d} | n_s, p^u_{n_s,s}) = \sum_{m=1}^{N} x^d_{m,s} \log\left(1 + \tilde{g}^d_{m,s}p^d_{m,s}\right).$$

Since the uplink rate is independent of the downlink power, the optimal downlink allocation is the one which maximizes the sum of downlink rates $\sum_s R^d_{m,s}$. We formulate the problem as

$$(\mathsf{P}_{\mathsf{DL}}) \quad \underset{\mathbf{X^d},\mathbf{P^d}}{\text{maximize}} \ \sum_{s=1}^{S}\sum_{m=1}^{N} x_{m,s}^{d} \log\left(1+\tilde{g}_{m,s}^{d} p_{m,s}^{d}\right) \quad \text{subject to (2c), (2e), and (2g).} \tag{5}$$

Clearly, problem P_{DL} and the resource allocation problem in downlink OFDMA have an identical structure. Thus, we obtain an optimal solution by assigning each subcarrier s to downlink node $d \in \mathcal{M}_s$ with the largest $\tilde{g}_{m,s}^{d}$ while allocating the power according to the water-filling algorithm, i.e.,

$$m^* = \underset{m\in\mathcal{M}_s}{\arg\max}\left(\tilde{g}_{m,s}^{d}\right) \text{ and } x_{m^*,s}^{d} = 1, \tag{6a}$$

$$p_{m,s}^{d} = \begin{cases} \left[\alpha - 1/\tilde{g}_{m,s}^{d}\right]^{+}, & \text{if } x_{m,s}^{d} = 1, \\ 0, & \text{if } x_{m,s}^{d} = 0, \end{cases} \tag{6b}$$

where $[\cdot]^{+} := \max(\cdot, 0)$ and α is the water-level satisfying $\sum_m \sum_s p_{m,s}^{d} = P_{BS}$. Note that if $\mathcal{M}_s = \emptyset$, subcarrier s is not assigned to any downlink node and it is used in half-duplex.

2) Uplink Resource Allocation: Given a downlink resource allocation $(\mathbf{X^d}, \mathbf{P^d})$, we solve the uplink allocation problem. Let us first show how an uplink node n can optimally allocate its power given an uplink subcarrier assignment $\mathbf{X^u}$ satisfying the condition (3). Let $\mathcal{S}_n$ denote the set of subcarriers assigned to uplink node n. Given $(\mathbf{X^d}, \mathbf{P^d})$ and $\mathbf{X^u}$, in each subcarrier $s \in \mathcal{S}_n$, the full-duplex rate $R_{n,s}(p_{n,s}^{u})$ is a function of $p_{n,s}^{u}$, defined as

$$\begin{aligned} R_{n,s}(p_{n,s}^{u}) &:= R_s\left(p_{n,s}^{d}, p_{m_s,s}^{d}\right) \\ &= \log\left(1+g_{n,s}^{u} p_{n,s}^{u}\right) + \log\left(1 + \frac{g_{m_s,s}^{d} p_{m_s,s}^{d}}{1+g_{n,m_s,s}^{i} p_{n,s}^{u}}\right). \end{aligned} \tag{7}$$

Since $\mathbf{X^u}$ satisfies (3), $R_{n,s}(p_{n,s}^{u})$ is a concave function of $p_{n,s}^{u}$ by Proposition 1. Each uplink node n allocates its power $p_{n,s}^{u}$ over subcarriers $s \in \mathcal{S}_n$ to maximize $\sum_{s\in\mathcal{S}_n} R_{n,s}$. Then we formulate the problem as

$$\begin{aligned} (\mathsf{P}_{\mathsf{UL}}) \quad \text{maximize} \quad & \sum_{s\in\mathcal{S}_n} R_{n,s}(p_{n,s}^{u}) \\ \text{subject to} \quad & \sum_{s\in\mathcal{S}_n} p_{n,s}^{u} \le P_n. \end{aligned} \tag{8}$$

Since this is a convex optimization problem, we can easily solve it through the dual optimization. Specifically, we can obtain the solution by using the bisection method with the complexity of $O(S)$.

We now explain the proposed uplink resource allocation algorithm. The algorithm operates in an iterative manner and runs for S times, where S is the number of subcarriers. In each iteration, we assign a single subcarrier to an uplink node with the largest full-duplex rate. We use superscript k in square bracket to indicate the result up to iteration k.

Let $\mathcal{S}_n^{[k]}$ denote the set of subcarriers assigned to uplink node n up to iteration k, and $\mathcal{A}^{[k]}$ denote the set of unassigned subcarriers up to iteration k. Also, let us define $\mathcal{A}_n^{[k]} = \{s \in \mathcal{A}^{[k]} \mid g_{u,m_s,s}^{i} \le g_{n,s}^{u}\}$, i.e., the set of subcarriers which can be allocated to uplink node n under the condition (3). All the subcarriers are unassigned in the beginning, i.e., $\mathcal{A}^{[0]} = \mathcal{S}$ and $\mathcal{S}_n^{[0]} = \emptyset, \forall n$.

In iteration k ($1 \le k \le S$), given $\mathcal{S}_n^{[k-1]}$ and $\mathcal{A}^{[k-1]}$, we compute the full-duplex rate $R_{n,s}$ of each pair of uplink node n and unassigned subcarrier s as follows:

1) For each uplink node n, allocate the uplink power $p_{n,s}^{u}$ to subcarriers $s \in \mathcal{S}_n^{[k-1]} \cup \mathcal{A}_n^{[k-1]}$ by solving (8). That is, $p_{n,s}^{u}$ is allocated as if subcarriers $s \in \mathcal{A}_n^{[k-1]}$ are assigned to uplink node n.
2) Compute the full-duplex rate $R_{n,s}(p_{n,s}^{u})$ for each subcarrier $s \in \mathcal{A}_n^{[k-1]}$ by (7).

Among the unassigned subcarriers, we assign subcarrier $s \in \mathcal{A}_n^{[k-1]}$ to uplink node n with the largest full-duplex rate as follows:

$$(n^*, s^*) = \underset{n\in\mathcal{N}, s\in\mathcal{A}_n^{[k-1]}}{\arg\max} R_{n,s} \text{ and } x_{n^*,s^*}^{u} = 1. \tag{9}$$

Then we update the result as follows:

$$\mathcal{S}_{n^*}^{[k]} \leftarrow \mathcal{S}_{n^*}^{[k-1]} \cup \{s^*\} \text{ and } \mathcal{A}^{[k]} \leftarrow \mathcal{A}^{[k-1]} \backslash \{s^*\}.$$

We repeat the above procedures S times and obtain the uplink subcarrier assignment $\mathbf{X^u}$. Then we allocate the uplink power $\mathbf{P^u}$ by solving (8) with $\mathbf{X^u}$.

In each iteration, we perform the power allocation for each uplink node, which has the complexity of $O(S)$. Considering N nodes and S iterations, the total complexity is $O(NS^2)$.

B. Proposed Resource Allocation Algorithms

When we apply the above downlink and uplink allocation algorithms, we consider two different orders in application, i.e., downlink first or uplink first. Then we consider a pairwise allocation algorithm where each subcarrier is assigned to a pair of uplink and downlink nodes at a time.

1) Downlink First (DF) Allocation Algorithm: Subcarriers are first assigned to downlink nodes, assuming $\mathbf{P^u} = 0$. That is, we solve problem P_{DL} with $\tilde{g}_{m,s}^{d} = g_{m,s}^{d}$. Next, given $(\mathbf{X^d}, \mathbf{P^d})$, we obtain the uplink allocation $(\mathbf{X^u}, \mathbf{P^u})$ by solving the uplink problem. Finally, we take the subcarrier assignment $\mathbf{X} = (\mathbf{X^u}, \mathbf{X^d})$ as the outcome and reallocate the (uplink and downlink) power by solving P_{P}, i.e., the power allocation obtained in each individual solution is discarded.

2) Uplink First (UF) Allocation Algorithm: Subcarriers are first assigned to uplink nodes, assuming $\mathbf{P^d} = 0$. Then given $(\mathbf{X^u}, \mathbf{P^u})$, we obtain the downlink allocation $(\mathbf{X^d}, \mathbf{P^d})$ by solving problem P_{DL}. Finally, we reallocate the power by solving P_{P}.

3) Pairwise (PW) Allocation Algorithm: In this algorithm, we assign each subcarrier to a pair of uplink and downlink nodes at a time in an iterative manner, differently from the previous two sequential algorithms. Specifically, each subcarrier is assigned to a pair of uplink and downlink nodes with the largest full-duplex rate, assuming constant power allocation.

In iteration k ($1 \le k \le S$), given $\mathcal{S}_n^{[k-1]}$ and $\mathcal{A}^{[k-1]}$, we first compute the full-duplex rate $R_{n,m,s}$ of (uplink node n, downlink node m) in subcarriers $s \in \mathcal{A}^{[k-1]}$ as follows:

1) Allocate an equal uplink power $p^u_{n,s}$ to subcarriers $s \in \mathcal{S}_n^{[k-1]} \cup \mathcal{A}^{[k-1]}$, i.e.,

$$p^u_{n,s} = \frac{P_n}{|\mathcal{S}_n^{[k-1]} \cup \mathcal{A}_n^{[k-1]}|}.$$

The downlink power $p^d_{m,s}$ is simply given by $p^d_{m,s} = P_{BS}/S$.

2) If $g^u_{n,s} \geq g^i_{n,m,s}$, we compute $R_{n,m,s}$ as

$$R_{n,m,s}\left(p^u_{n,s}, p^d_{m,s}\right) = \log\left(1 + g^u_{n,s} p^u_{n,s}\right) + \log\left(1 + \frac{g^d_{m,s} p^d_{m,s}}{1 + g^i_{n,m,s} p^u_{n,s}}\right).$$

On the other hand, if $g^u_{n,s} < g^i_{n,m,s}$, we set $R_{n,m,s} = 0$ to satisfy the condition (3).

Then we assign subcarrier $s \in \mathcal{A}^{[k-1]}$ to (uplink node n^*, downlink node m^*) with the largest full-duplex rate as follows:

$$(n^*, m^*, s^*) = \underset{n \in \mathcal{N}, m \in \mathcal{M}, s \in \mathcal{A}^{[k-1]}}{\arg\max} R_{n,m,s}.$$

We update $\mathcal{S}_{n^*}^{[k]}$ and $\mathcal{A}^{[k]}$ according to the subcarrier assignment result.

We repeat the above procedures S times, and obtain the subcarrier assignment $\mathbf{X}$. Then we allocate the (uplink and downlink) power $\mathbf{P}$ by solving problem P_P.

In each iteration, we calculate the sum-rates of all possible pairs with the complexity of $O(N^2)$. Considering S iterations, the total complexity is $O(N^2 S)$.

V. Numerical Evaluation

A. Simulation Setting

Simulation parameters are configured according to the typical values of LTE system [12]. We assume 10 MHz spectrum band with 50 subcarriers, each with a bandwidth of 180 kHz. The Hata urban propagation model is used for the path loss. Also, we assume *i.i.d.* Rayleigh fading across nodes and subcarriers. The power budgets are set as $P_{BS} = 43$ (dBm) and $P_n = 24$ (dBm) for all uplink nodes.

We assume a time-slotted system and in each slot, nodes are uniformly distributed within a given cell radius. We adopt the model of *i.i.d.* Rayleigh block fading channel in [4], where all channel gains $g^u_{n,s}$, $g^d_{m,s}$, and $g^i_{n,m,s}, \forall n, m, s$ are time-invariant in each time slot and change independently over time slots. We conduct simulations for 100 time slots and obtain the average result.

For performance comparison, we consider the following existing schemes:

- Baseline (BL): An optimal solution [1] is used for the downlink while a near-optimal solution [3] is used for the uplink. Note that this is an allocation algorithm for full-duplex networks without considering the inter-node interference.
- Half-duplex (HD): Downlink and uplink transmissions switch over time slots, i.e., TDMA, using the algorithms [1] and [3], respectively.

B. Simulation Results

We evaluate the sum-rates of our schemes with different cell sizes. We set the number of uplink (downlink) nodes as 50, i.e., $N = 50$, and vary the cell radius from 300 m to 1000 m. Fig. 2(a) shows the sum-rate of each scheme. Among our algorithms, PW achieves the best performance, followed by DF and UF. As shown in Figs. 2(b) and 2(c), UF gives priority to the uplink traffic and achieves a higher uplink rate while DF runs in the opposite way. In contrast, PW balances the uplink and downlink traffic and outperforms DF and UF. This indicates that PW is the best algorithm to maximize the sum-rate.

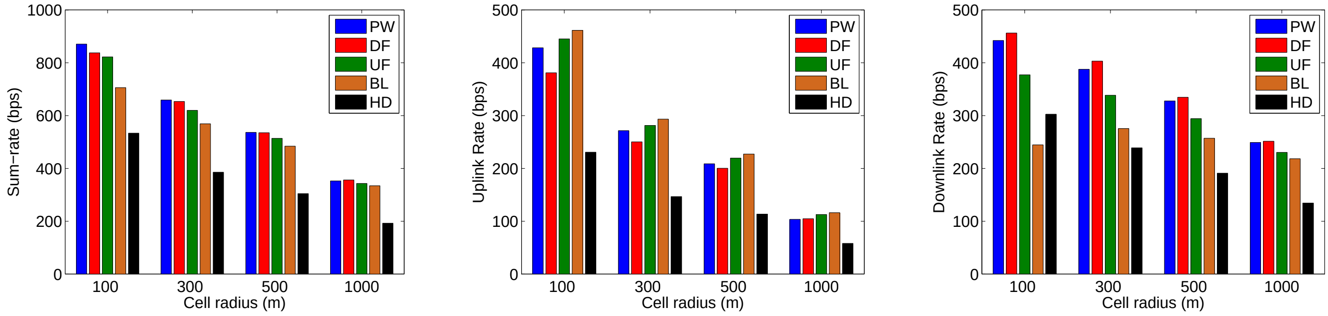
We also compare our schemes with the baseline scheme. As shown in Fig. 2(a), in small-size cells, our schemes outperform the baseline scheme with a substantial gain. Although the baseline scheme achieves the highest uplink rate, its downlink rate is severely low due to the excessive inter-node interference. As the cell size reaches 1000 m, the performance gain shrinks and all the schemes show a similar performance. With a fixed number of nodes, the average distance between any two nodes increases with the cell size. As a result, the inter-node interference becomes weaker in large-size cells than in small-size cells. Since the impact of inter-node interference on the sum-rate diminishes, our schemes and the baseline scheme achieve a similar sum-rate.

We next vary the number of nodes and see how it affects the performance in Fig. 3. The cell radius is set to 500 m and the number of uplink (downlink) nodes is changed from 10 to 70. When there are 10 uplink (downlink) nodes, our schemes and the baseline scheme achieve a similar sum-rate. As the node density increases, our scheme outperforms the baseline scheme, and the sum-rate increases with the node density.

Lastly, we compare PW and HD to see how much gain the full-duplex operation brings. Even though the full-duplex technology potentially doubles the capacity, its achievable gain is smaller than the expected due to inter-node interference. Fig. 4 shows the gain of PW over HD in accordance with the cell size and the number of nodes. The gain increases with the cell size, and it reaches 82% when the cell radius is 1000 m. In contrast, PW achieves a smaller gain when there are more nodes. This result indicates that the full-duplex gain is maximized in weak interference environments, i.e., large cell size or sparse node distribution.

VI. Conclusion

To fully exploit the promising gain of full-duplex technology, it is of great importance to design a resource allocation algorithm tailored for a full-duplex network. In this paper, we have considered the radio resource allocation problem in a single-cell full-duplex OFDMA network. We have proved that the problem is NP-hard, and proposed a subcarrier allocation condition, where each subcarier is assigned only when its inter-node channel gain is smaller than its uplink channel gain. Using this condition, we have designed three resource allocation algorithms, which allocate subcarriers considering



(a) Sum-rate $\sum_s R_s$ (b) Sum of uplink rates $\sum_s R_s^u$ (c) Sum of downlink rates $\sum_s R_s^d$

Fig. 2. Performance comparison with different cell sizes. Pairwise (PW) achieves the best performance by balancing the uplink and downlink traffic. The performance gain of our schemes over the baseline scheme decreases with the cell size.

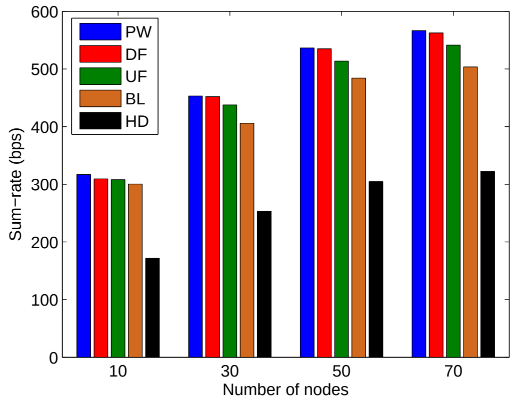


Fig. 3. Impact of the number of nodes on the performance. The performance gain of our schemes over the baseline scheme increases with more nodes.

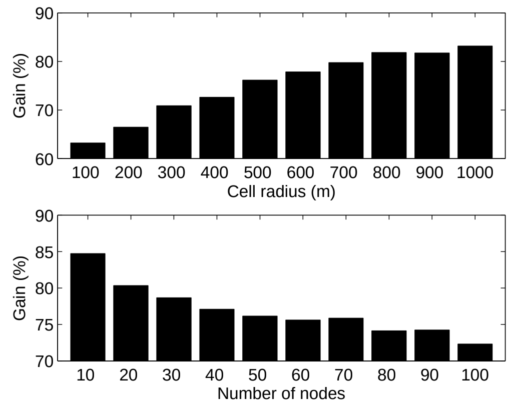


Fig. 4. Performance gain of full-duplex (PW) over half-duplex (HD). The full-duplex gain is maximized in weak interference environments..

the inter-node interference. Through simulations, we have confirmed that our algorithms perform better than other algorithms oblivious to the interference, and identified the gain of full-duplex over hall-duplex in practical scenarios.

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