Resource Allocation in Full-Duplex OFDMA Networks: Approachs for Full and Limited CSIs

Changwon Nam, Changhee Joo, Sung-Guk Yoon, and Saewoong Bahk

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 band. Due to the complexity of self-interference cancellation techniques, only base stations (BSs) are expected to be full-duplex capable while user terminals remain as legacy half-duplex nodes in the near future. In this case, two different nodes share a single subchannel, one for uplink and the other for downlink, which causes inter-node interference between them. In this paper, we investigate the joint problem of subchannel assignment and power allocation in a single-cell full-duplex orthogonal frequency division multiple access (OFDMA) network considering the inter-node interference Specifically, we consider two different scenarios: i) the BS knows full channel state information (CSI), and ii) the BS obtains limited CSI through channel feedbacks from nodes. In the full CSI scenario, we design sequential resource allocation algorithms which assign subchannels first to uplink nodes and then to downlink nodes or vice versa. In the limited CSI scenario, we identify the overhead for channel measurement and feedback in full-duplex networks. Then we propose a novel resource allocation scheme where downlink nodes estimate inter-node interference with low complexity. Through simulation, we evaluate our approaches for full and limited CSIs under various scenarios and identify full-duplex gains in various practical scenarios.

Index Terms: Full-duplex, inter-node interference, channel state information, subchannel allocation, low complexity

I. Introduction

ORTHOGONAL Frequency Division Multiple Access (OFDMA) has been a key technology in most 4G cellular systems [2]. Dividing the spectrum band into multiple orthogonal subchannels and distributing them over different nodes, OFDMA benefits from both multiuser and frequency diversities. To exploit such benefits, it needs efficient radio resource allocation algorithms that jointly handle subchannel assignment and power allocation. In downlink transmission, an optimal allocation for the sum-rate maximization turns out to be a combination of channel-gain-based subchannel assignment and the well-known water-filling power allocation [3], [4]. However, in

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uplink transmission, the 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. Most previous results provide suboptimal performance by solving a relaxed problem [5], [6], or using a randomized iteration method [7].

Recently, *in-band wireless full-duplex* has attracted great attention as a promising technology for next-generation wireless systems. A full-duplex radio can transmit and receive simultaneously on the same frequency band by cancelling *self-interference* that results from its own transmission, and thus potentially double the spectral efficiency. The main challenge in building a full-duplex system is in suppressing the self-interference to a sufficiently low level. There have been extensive researches for self-interference cancellation techniques. They can be categorized into antenna cancellation, analog cancellation, and digital cancellation [8].

In antenna cancellation techniques, a pair of transmission antennas are placed such that the signal from one antenna destructively adds with that from the other [9], [10], [11]. Analog cancellation methods tap a copy of the transmitted signal from the transmit chain, process it with delay and attenuation, and subtract it on the receive path [9], [12]. Lastly, digital cancellation is used to clean out any residual self-interference caused by non-ideal and non-linear components in RF chains [9], [12]. The state-of-the-art work has demonstrated that self-interference can be suppressed to the noise floor level by combining multiple cancellation techniques [13].

When the full-duplex technology is introduced in OFDMA networks, we expect that base stations (BSs) are full-duplex capable while mobile nodes (user terminals) operate in either full-duplex or half-duplex. If mobile nodes are also full-duplex capable, the BS can communicate with them in a bidirectional manner by assigning each subchannel to a single node for both uplink and downlink transmissions. However, in the foreseeable future, it is unlikely that mobile nodes are equipped with full-duplex radios due to the cost and complexity of self-interference cancellation techniques. Considering this limitation, a typical deployment scenario will be the full-duplex transmission between a full-duplex BS and legacy half-duplex nodes, where the BS assigns a subchannel to two different nodes, one for uplink and the other for downlink. In this case, there exists *inter-node interference* from uplink nodes to downlink nodes, which makes the already complicated resource allocation problem more challenging. To fully exploit the full-duplex technology, it is essential to allocate the radio resource considering the inter-node interference.

The resource allocation problem for maximizing sum-rate in a single-cell full-duplex OFDMA network has been extensively investigated in the literature. Yang *et al.* proposed a ran-

domized iteration method which achieves a near-optimal performance [7]. In [14], a resource allocation scheme that achieves local Pareto optimality in typical scenarios was proposed. However, the previous schemes have not covered the case with half-duplex nodes, which is more challenging due to inter-node interference. There are several works that consider half-duplex nodes. In [15], a subcarrier assignment algorithm has been proposed to maximize the system sum-rate, but there is no consideration of power allocation over subcarriers. In [16], Cirik *et al.* proposed a suboptimal resource allocation algorithm assuming that there is no inter-node interference. The authors in [17] considered inter-node interference and proposed a resource allocation algorithm using Karush-Kuhn-Tucker (KKT) conditions associated with the sum-rate maximization problem. In [18], the authors used the matching theory to solve the resource allocation problem. In [19], the authors considered a case where nodes have quality of service (QoS) requirements (predefined target rate) and proposed a scheduling algorithm that maximizes the sum-rate while satisfying each node's QoS requirements. In [20], the authors modeled the resource allocation problem as a non-cooperative game between the uplink and downlink nodes and proposed an iterative algorithm where the iteration continues until a Nash equilibrium is achieved. The common assumption in pervious works is that the BS knows full channel state information (CSI), which is not feasible in practice. Specifically, it is very difficult to obtain the inter-node channel gain between the uplink and downlink nodes with low complexity.

In this paper, we investigate the resource allocation problem in a single-cell full-duplex OFDMA network, which consists of a full-duplex BS and multiple half-duplex nodes. Our goal is to maximize the sum-rate performance by optimizing the uplink and downlink resource allocations taking into account the inter-node interference. Specifically, we consider two different scenarios: i) the BS has full CSI, and ii) the BS obtains limited CSI through channel feedbacks from nodes. The former is of theoretical interest to solve the problem with ideal assumptions and the latter is of more practical interest to design a scheme for realistic environments. The contributions of this paper are three-fold:

• For the full CSI scenario, 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 subchannel assignment condition that leads each subchannel to be assigned to a pair of uplink and downlink nodes that experience low inter-node interference. Based on this condition, we develop sequential resource allocation algorithms, which assign subchannels to uplink and downlink nodes sequentially.
• For the limited CSI scenario, we observe the prohibitive channel measurement and feedback overhead in full-duplex networks. Then we propose a novel resource allocation scheme where downlink nodes estimate inter-node interference with low complexity, and analyze its sum-rate performance. To the best of our knowledge, this is the first resource allocation scheme for full-duplex networks that operates with limited CSI.
• Through simulation, we evaluate our algorithms under various scenarios. In the full CSI scenario, we compare our schemes with conventional schemes oblivious to the inter-node interference, and show the performance gain of full-duplex tranmis-

sions. In the limited CSI scenario, we compare the performance of our schemes with and without full CSI.

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 consider the problem where the BS has full CSI, and develop sequential resource allocation algorithms using a simple subchannel assignment condition. In Section IV, we consider a scenario where the BS obtains limited CSI through channel feedback, and propose a novel channel measurement and feedback protocol where downlink nodes measure inter-node interference with low complexity. The performance evaluation of our approaches is provided in Section V. Finally, we conclude this paper in Section VI.
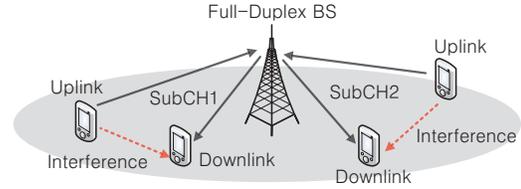

Fig. 1. A single-cell full-duplex OFDMA network which consists of one full-duplex base station and multiple half-duplex mobile nodes. Due to the simultaneous uplink and downlink transmissions, there exists inter-node interference from uplink nodes to downlink nodes.

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, as shown in Fig. 1. Suppose that each node is predetermined as either an uplink node or a downlink node. Let $\mathcal{N} = \{1, \cdots, N\}$ denote the set of uplink nodes, and $\mathcal{M} = \{1, \cdots, M\}$ denote the set of downlink nodes. The spectrum band is partitioned into S orthogonal subchannels, denoted by $\mathcal{S} = \{1, 2, \ldots, S\}$. Here, a subchannel[1] is the basic unit of channel assignment and all the subchannels are perfectly orthogonal to each other without inter-carrier interference. We assign a subchannel to one uplink node and one downlink node for full-duplex tranmission and assume perfect self-interference cancellation[2] at the BS exploiting various interference cancellation techniques [21], [22], [23]. Simultaneous uplink and downlink transmissions on the same subchannel, however, cause inter-node interference from uplink nodes to downlink nodes [21].

We denote the uplink and downlink subchannel assignments by two binary vectors $\mathbf{X^u} := \left\{\mathbf{x^u_{n,s}}\right\}_{\mathbf{n}\in\mathcal{N},\mathbf{s}\in\mathcal{S}}$ and $\mathbf{X^d} := \left\{\mathbf{x^d_{m,s}}\right\}_{\mathbf{m}\in\mathcal{M},\mathbf{s}\in\mathcal{S}}$, respectively, where $x^u_{n,s}$ and $x^d_{m,s}$ are defined as

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

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

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[1] In practical wireless systems, the basic scheduling unit can be a single physical subcarrier or a cluster of subcarriers.

[2] Even though perfect cancellation is infeasible in practice [13], we assume it to isolate physical layer issues and focus on the resource allocation as in [22], [23]. We identify performance degradation due to the residual self-interference through simulation, which will be provided later.

Let $\mathbf{X} := (\mathbf{X^u}, \mathbf{X^d})$, and given $\mathbf{X}$, the uplink and downlink nodes using subchannel s are denoted as n_s and m_s, respectively.

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

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

$$
\begin{aligned}
R_s(\mathbf{X}, \mathbf{P}) = &\sum_{n=1}^{N} x_{n,s}^u \log\left(1 + g_{n,s}^u p_{n,s}^u\right) \\
&+ \sum_{m=1}^{M} x_{m,s}^d \log\left(1 + \frac{g_{m,s}^d p_{m,s}^d}{1 + \sum_{n=1}^{N} x_{n,s}^u g_{n,m,s}^i p_{n,s}^u}\right),
\end{aligned}
\tag{1}
$$

where the first and second terms represent the uplink and downlink rates, respectively, and $\sum_n x_{n,s}^u g_{n,m,s}^i p_{n,s}^u$ represents the inter-node interference. Also, let $R(\mathbf{X}, \mathbf{P})$ denote the sum-rate over all the subchannels, i.e., $R(\mathbf{X}, \mathbf{P}) = \sum_{\mathbf{s=1}}^{\mathbf{S}} \mathbf{R_s}(\mathbf{X}, \mathbf{P})$.

Our goal for resource allocation is to maximize the sum-rate[3] under the given power budget constraints as

$$(\mathsf{P}) \quad \underset{\mathbf{X}, \mathbf{P}}{\text{maximize}} \quad R(\mathbf{X}, \mathbf{P}) \tag{2a}$$

$$\text{subject to} \quad \sum_{s=1}^{S} p_{n,s}^u \leq P_n, \forall n \in \mathcal{N}, \tag{2b}$$

$$\sum_{s=1}^{S}\sum_{m=1}^{M} p_{m,s}^d \leq P_{BS}, \tag{2c}$$

$$\sum_{n=1}^{N} x_{n,s}^u \leq 1, \forall s \in \mathcal{S}, \tag{2d}$$

$$\sum_{m=1}^{M} x_{m,s}^d \leq 1, \forall s \in \mathcal{S}, \tag{2e}$$

$$x_{n,s}^u \in \{0, 1\}, \forall n \in \mathcal{N}, \forall s \in \mathcal{S}, \tag{2f}$$

$$x_{m,s}^d \in \{0, 1\}, \forall m \in \mathcal{M}, \forall s \in \mathcal{S}, \tag{2g}$$

$$p_{n,s}^u \geq 0, \forall n \in \mathcal{N}, \forall s \in \mathcal{S}, \tag{2h}$$

$$p_{m,s}^d \geq 0, \forall m \in \mathcal{M}, \forall s \in \mathcal{S}. \tag{2i}$$

Notice that subchannel s is in full-duplex mode if $\sum_n x_{n,s}^u = \sum_m x_{m,s}^d = 1$, and in half-duplex mode otherwise. In the fol-

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[3]Since the goal of this paper is to investigate the spectral efficiency of full-duplex, we formulate the problem as the sum-rate maximization, which is a good measure for spectral efficiency. In this formulation, we have not considered the fairness among nodes and leave it for future work.

lowing, we solve problem P under two different cases of channel information availability: full CSI and limited CSI.

III. Resource Allocation with Full CSI

In this section, we solve the resource allocation problem assuming that the BS knows CSI in full. We first show that the problem is NP-hard, and approximate it to a convex problem applying a reasonable condition for subchannel assignment. We then design sequential resource allocation schemes by decomposing it into uplink and downlink subproblems.

A. Subchannel Assignment Condition

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

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

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. Suppose that $g_{n,s}^u = g_{m,s}^d = g_s$, and $g_{n,m,s}^i$ is sufficiently large for every subchannel s. In this case, it can be shown that an optimal solution uses half-duplex transmissions to avoid excessive inter-node interference, i.e., $x_{n,s}^u x_{m,s}^d = 0, \forall s \in \mathcal{S}$. Then the set of subchannels should be divided into two disjoint subsets where one is for uplink node n and the other for downlink node m, i.e., subchannel partition problem. It can be shown that the equipartition problem (which is NP-complete) is reducible to a subchannel partition problem in polynomial time, which means that the subchannel assignment problem is NP-hard. For details, refer to Theorem 2 in our technical report [24].

Given subchannel assignment $\mathbf{X}$, problem P reduces to the following power allocation problem:

$$(\mathsf{P_P}) \quad \underset{\mathbf{P}}{\text{maximize}} \quad \sum_{s=1}^{S} R_s(p_{n,s}^u, p_{m,s}^d) \tag{3}$$
$$\text{subject to} \quad (2b), (2c), (2h), \text{ and } (2i).$$

Problem $\mathsf{P_p}$ is not a convex problem since R_s is not a concave function in general, and it is hard to obtain an optimal power allocation $\mathbf{P}^*$ for given subchannel assignment $\mathbf{X}$. Therefore, we assign subchannels under the following additional intuitive condition: subchannel s is used for uplink node n and downlink node m in full-duplex mode, only if

$$g_{n,m,s}^i \leq g_{n,s}^u. \tag{4}$$

This condition prevents uplink nodes from generating excessive inter-node interference to protect downlink transmissions. Further it has the following desirable property.

Proposition 1: Let $\mathbf{X}$ be a given subchannel assignment vector. If $\mathbf{X}$ satisfies the condition (4), 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 $x_{n,s}^u = 1$ and $x_{m,s}^d = 1$. Then we can write R_s as

$$R_s(p_{n,s}^u, p_{m,s}^d) = \log\left(\frac{1+g_{n,s}^u p_{n,s}^u}{1+g_{n,m,s}^i p_{n,s}^u}\right)$$
$$+ \log(1 + g_{n,m,s}^i p_{n,s}^u + g_{m,s}^d p_{m,s}^d).$$

Clearly, the first term $\log\left(\frac{1+g_{n,s}^u p_{n,s}^u}{1+g_{n,m,s}^i p_{n,s}^u}\right)$ is a function of $p_{n,s}^u$. Thus, we only need to prove the concavity of $\log\left(\frac{1+g_{n,s}^u p_{n,s}^u}{1+g_{n,m,s}^i p_{n,s}^u}\right)$ with respect to $p_{n,s}^u$ to show that it is a concave function of $(p_{n,s}^u, p_{m,s}^d)$. The first term $\log\left(\frac{1+g_{n,s}^u p_{n,s}^u}{1+g_{n,m,s}^i p_{n,s}^u}\right)$ is a concave function of $p_{n,s}^u$, since it has a non-positive second-order derivative [25],

$$\frac{\partial^2}{\partial(p_{n,s}^u)^2}\log\left(\frac{1+g_{n,s}^u p_{n,s}^u}{1+g_{n,m,s}^i p_{n,s}^u}\right)$$
$$= \frac{(g_{n,m,s}^i - g_{n,s}^u)(2g_{n,s}^u g_{n,m,s}^i p_{n,s}^u + g_{n,s}^u + g_{n,m,s}^i)}{(g_{n,m,s}^i p_{n,s}^u + 1)^2 (g_{n,s}^u p_{n,s}^u + 1)^2} \le 0,$$

where the inequality comes from the assumption of $g_{n,m,s}^i \le g_{n,s}^u$. The second term is a logarithm of a linear function of $(p_{n,s}^u, p_{m,s}^d)$, which is a concave function of $(p_{n,s}^u, p_{m,s}^d)$. Thus, R_s is a sum of two concave functions, which is also a concave function of $(p_{n,s}^u, p_{m,s}^d)$ [25]. $\square$

From Proposition 1 and the standard dual optimization method, we can solve problem P_P for given subchannel assignment satisfying the condition (4). Using Proposition 1, we propose sequential resource allocation algorithms.

B. Sequential Resource Allocations

We develop two resource allocation schemes: one assigns subchannels to downlink nodes first and then to uplink nodes, and the other in the opposite order. To this end, we consider partial resource allocation schemes, i.e., downlink allocation scheme given uplink resource allocation, and vice versa.

B.1 Downlink Resource Allocation

Given an uplink resource allocation $(\mathbf{X^u}, \mathbf{P^u})$, we solve the downlink problem. Recall that n_s denotes an uplink node using subchannel s. We define $\mathcal{M}_s = \{m \in \mathcal{M} | g_{n_s,m,s}^i \le g_{n_s,s}^u\}$, i.e., the set of downlink nodes which are eligible to use subchannel s under the condition (4). For each node $m \in \mathcal{M}_s$, we define the downlink channel gain to interference and noise ratio (CINR) $\tilde{g}_{m,s}^d$ over subchannel s as

$$\tilde{g}_{m,s}^d = \frac{g_{m,s}^d}{1 + g_{n_s,m,s}^i p_{n_s,s}^u}.$$

Also, for each node $m \notin \mathcal{M}_s$, we set $\tilde{g}_{m,s}^d = 0$. Then the downlink rate $R_{m,s}^d$ over subchannel s can be written as

$$R_{m,s}^d(\mathbf{X^d}, \mathbf{P^d}|\mathbf{n_s}, \mathbf{p_{n_s,s}^u}) = \sum_{m=1}^{\mathbf{N}} \mathbf{x_{m,s}^d}\log\left(1 + \tilde{\mathbf{g}}_{\mathbf{m,s}}^{\mathbf{d}} \mathbf{p_{m,s}^d}\right).$$

Since the uplink rate is independent of the downlink power, thanks to the self-interference cancellation techniques, we can formulate the problem as maximizing the sum of downlink rates

$\sum_s R_{m,s}^d$, i.e.,

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

Clearly, problem P_{DL} has the same solution with the previous problem in downlink OFDMA [3]. Thus, we obtain an optimal solution to (5) by assigning each subchannel 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 $\mathcal{M}_s = \emptyset$, subchannel s is used for the uplink node n_s in half-duplex mode. For details, refer to Algorithm 1 in our technical report [26].

The complexity for obtaining $\{\tilde{g}_{m,s}^d\}_{m \in \mathcal{M}, s \in \mathcal{S}}$ is $O(MS)$, the complexity for assigning each subchannel to a downlink node with the largest CINR is $O(MS)$, and the water-filling has the complexity of $O(N)$ [6]. As a result, the overall complexity for solving the downlink subproblem is $O(MS)$.

B.2 Uplink Resource Allocation

Given a downlink resource allocation $(\mathbf{X^d}, \mathbf{P^d})$, we solve the uplink allocation problem. We first consider power allocation given uplink subchannel assignment $\mathbf{X^u}$ satisfying the condition (4). Recall that m_s denotes an downlink node using subchannel s. Let $\mathcal{S}_n$ denote the set of subchannels assigned to uplink node n. Given $(\mathbf{X^d}, \mathbf{P^d})$ and $\mathbf{X^u}$, for each subchannel $s \in \mathcal{S}_n$, the full-duplex rate $R_{n,s}$ can be written as a function of $p_{n,s}^u$, i.e.,

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

Since $g_{n,m_s,s}^i \le g_{n,s}^u$, $R_{n,s}(p_{n,s}^u)$ is a concave function of $p_{n,s}^u$ from Proposition 1. Each uplink node n will allocate its power $p_{n,s}^u$ over subchannels $s \in \mathcal{S}_n$ to maximize $\sum_{s \in \mathcal{S}_n} R_{n,s}$:

$$(P_{UL}) \quad \text{maximize} \sum_{s \in \mathcal{S}_n} R_{n,s}(p_{n,s}^u)$$
$$\text{subject to} \sum_{s \in \mathcal{S}_n} p_{n,s}^u \le P_n. \tag{8}$$

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

We now determine uplink subcarrier assignment $\mathbf{X^u}$ in a greedy manner with a fixed number S of iterations. In each

iteration, we assign one subchannel to an uplink node which achieves the largest full-duplex rate. We use superscript k in square bracket to denote the k-th iteration.

Let $\mathcal{S}_n^{[k]}$ denote the set of subchannels assigned to uplink node n up to iteration k, and $\mathcal{A}_n^{[k]}$ denote the set of unassigned subchannels up to iteration k that can be assigned to uplink node n under (4). All the subchannels are unassigned at the beginning, i.e., $\mathcal{S}_n^{[0]} = \emptyset$ and $A_n^{[0]} = \{s|g_{n,m_s,s}^i \leq g_{n,s}^u\}, \forall n$.

At iteration k ($1 \leq k \leq S$), we choose a pair of an uplink node and a subcarrier with the largest full-duplex rate:

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

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

4. Update the result as

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

We repeat the above procedures S times to obtain the uplink subchannel assignment $\mathbf{X^u}$, and allocate the uplink power $\mathbf{P^u}$ by solving (8) given $\mathbf{X^u}$. For details, refer to Algorithm 2 in our technical report [26].

In each iteration, we perform power allocation for each uplink node with the complexity of $O(S)$. Given N uplink nodes, the complexity in each iteration becomes $O(NS)$. Considering S iterations, the overall complexity for solving the uplink subproblem becomes $O(NS^2)$.

C. Two Sequential Resource Allocation Schemes

We apply the previous partial downlink and uplink allocations, and develop two sequential resource allocation schemes: downlink first (D-First) and uplink first (U-First).

In the D-First scheme, subchannels are assigned first to downlink nodes, assuming $\mathbf{P^u} = \mathbf{0}$. That is, we solve problem $\mathsf{P_{DL}}$ with $\tilde{g}_{m,s}^d = g_{m,s}^d$. Next, given $(\mathbf{X^d}, \mathbf{P^d})$, we solve the uplink allocation problem to obtain $(\mathbf{X^u}, \mathbf{P^u})$. Finally, we take only the subchannel assignment $(\mathbf{X^u}, \mathbf{X^d})$ as the outcome, and reallocate both the uplink and downlink power by solving $\mathsf{P_P}$.

In the U-First scheme, subchannels are assigned first to uplink nodes, assuming $\mathbf{P^d} = \mathbf{0}$. Then given $(\mathbf{X^u}, \mathbf{P^u})$, we obtain the downlink allocation $(\mathbf{X^d}, \mathbf{P^d})$ by solving problem $\mathsf{P_{DL}}$. Again, we reallocate $(\mathbf{P^u}, \mathbf{P^d})$ by solving $\mathsf{P_P}$, given $(\mathbf{X^u}, \mathbf{X^d})$.

D. Asymtotic Analysis of Full-duplex Gain

We define *full-duplex gain* as the performance ratio of full-duplex transmissions to half-duplex transmissions. Although the analysis of full-duplex gain is in general difficult, a simple asymtotic method gives a rough idea on the full-duplex gain according to channel gains. Consider a single-subchannel network with one uplink node n and one downlink node m. Let g^u and g^d denote the uplink and downlink channel gains, respectively, and g^i denote the inter-node channel gain. We assume that the power budgets for the BS and uplink node n are the same, i.e., $P_{BS} = P_n = P$.

The sum-rate R_{HD} in half-duplex transmission is given by

$$R_{HD} = 0.5 \log(1 + g^u P) + 0.5 \log(1 + g^d P).$$

In the full-duplex case, the optimal power allocation happens when the downlink consumes all of its power budget P while the uplink power allocation is binary, i.e., allocating either the maximum P or none (refer to Proposition 2 in [24]). Assuming that it is optimal to use the maximum power in the uplink, the sum-rate R_{FD} in full-duplex transmission is obtained as

$$R_{FD} = \log(1 + g^u P) + \log\left(1 + \frac{g^d P}{1 + g^i P}\right).$$

Then the full-duplex gain G_{FD} is defined as

$$G_{FD} = \frac{R_{FD}}{R_{HD}} = \frac{\log(1 + g^u P) + \log\left(1 + \frac{g^d P}{1 + g^i p^u}\right)}{0.5 \log(1 + g^u P) + 0.5 \log(1 + g^d P)}.$$

If all the channel gains are sufficiently large, i.e., $g^u \approx g^d \approx g^i \to \infty$, we have the full-duplex gain as $G_{FD} \approx 1$. This indicates that if all the channel gains are sufficiently large, there is no full-duplex gain due to the excessive inter-node interference. In practice, this occurs when a large number of nodes are located near the base station.

On the other hand, if all the channel gains are sufficiently small, i.e., $g^u \approx g^d \approx g^i \ll 1$, we obtain the full-duplex gain as $G_{FD} \approx 2$. Since the inter-node interference level $g^i P$ is sufficiently smaller than the noise power (which is normalized as 1), the full-duplex gain approaches 2, i.e., doubles the spectral efficiency. In practice, this corresponds to a case where a few nodes are located at the cell edge. In addition, it is obvious that given g^u and g^d, the full-duplex gain increases with the distance between the uplink and downlink nodes, i.e., the inter-node channel gain smaller. Indeed, similar results are shown in Fig. 7 of [27].

IV. Resource Allocation with Limited CSI

In this section, we consider more practical scenarios where the BS does not have full CSI. We first discuss the difficulties in collecting channel information in full-duplex networks, and develop a novel resource allocation scheme that operates with limited CSI.

A. Overhead of Channel Measurement and Feedback

In general, full CSI is not available at the BS in practical OFDMA systems due to large overhead. In full-duplex networks, the problem of channel measurement and feedback is challenging due to the following reasons:
- Channel measurement overhead:
A typical method for channel measurement is using a training sequence, where a known signal is transmitted and the channel gain is estimated by comparing the transmitted and received signals. In half-duplex systems, the BS broadcasts a training

sequence that allows a node to measure its downlink channel gains and estimates its uplink channel gains using *channel reciprocity*[4]. In full-duplex networks, every uplink node needs to transmit a training sequence in turn to allow downlink nodes to estimate inter-node channel gains. Since a dedicated transmission opportunity should be given to each uplink node, the complexity linearly increases with the number of uplink nodes.

• Channel feedback overhead:

Each node measures each subchannel gain and feeds it back to the BS. The feedback overhead for a downlink subchannel is SB bits per node, where B is the number of bits required for channel quantization. Similarly, the feedback overhead for an uplink subchannel is SB bits per node. In addition, the feedback overhead for inter-node subchannel gains is NSB bits per downlink node. Then the total feedback overhead over N uplink nodes and M downlink nodes is $N(SB)+M(SB)+M(NSB)$ bits. The feedback overhead in full duplex networks, unlike that in half-duplex networks, increases by a factor of $O(MN)$ due to the inter-node channel information.

Considering the huge overhead for channel measurement and feedback, it is of great importance to design a low-complexity resource allocation scheme for full-duplex networks.

A well-known approach to reduce the feedback overhead is to use *opportunistic feedback*, where a node reports its channel gain to the BS if it is larger than a given threshold [28]. Suppose that all nodes contend in the shared feedback medium, which consists of multiple feedback slots associated with pre-defined threshold values. In each feedback slot, a node transmits a message to the BS if its channel gain is larger than the given threshold. The transmission opportunity is given to the node which makes a successful transmission in an earliest slot.

There have been many resource allocation schemes based on the opportunistic feedback for downlink transmissions [28], [29], [30], [31] or uplink transmissions [32]. Since the conventional schemes for half-duplex networks assume interference-free environments, they are not applicable for full-duplex networks, where the inter-node interference should be taken into account. Due to the large overhead, it may not be feasible for a downlink node to measure all the inter-node channel gains for all uplink nodes. To address the difficulty, we exploit the idea behind the U-First scheme, where a downlink node estimates only the interference from the scheduled uplink node. Now our question is: *how can a downlink node estimate the inter-node interference level with low-complexity?* In the following, we answer this question for low-complexity interference measurement.

B. Proposed Low-complexity Resource Allocation Scheme

We design a scheduling frame that consists of training sequence, feedback and scheduling period, followed by data transmission period, as shown in Fig. 2. The scheduling frame is the basic unit of resource allocation, during which channel gains are assumed invariant. The feedback and scheduling period can be further decomposed into uplink and downlink parts. The key idea for inter-node interference measurement is to let downlink nodes overhear messages transmitted from uplink nodes during the uplink feedback period. The detailed operation is as follows.

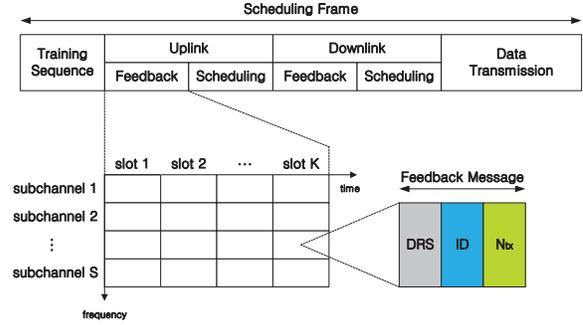[4]Forward (downlink) and reverse (uplink) channel gains are the same.

Fig. 2. Scheduling frame structure which consists of training sequence, feedback and scheduling period, followed by data transmission period.

In the beginning of every scheduling frame, the BS broadcasts a training sequence to allow each node to measure its downlink channel gains. We assume no channel measurement error. Each uplink node n estimates its uplink channel gain $g_{n,s}^u$ assuming the channel reciprocity, i.e., $g_{n,s}^u = g_{n,s}^d$ [34].

Uplink nodes send messages in the uplink feedback period. In time domain, there are K feedback slots associated with K thresholds $\delta_1, \cdots, \delta_K$, which are in decreasing order, i.e., $\delta_1 > \cdots > \delta_K$. In slot k ($1 \le k \le K$), an uplink node n transmits a message to the BS over subchannel s if its uplink channel gain $g_{n,s}^u$ satisfies the condition $\delta_{k-1} > g_{n,s}^u \ge \delta_k$, where $\delta_0 = \infty$. Since δ_k's are in decreasing order, uplink nodes with larger channel gains could transmit in earlier slots. If node n transmits alone in slot k, the BS can decode the feedback message successfully and know that it is from node n. If two or more nodes transmit at the same time, then a collision occurs and the BS cannot decode any colliding messages. Each subchannel uses the same thresholds $\delta_1, \cdots, \delta_K$, and the BS notifies the thresholds to each node during the initial association process. The feedback processes for each subchannel are identical and performed in parallel.

A message consists of three parts: demodulation reference signal (DRS), transmitter identifier (ID), and the number of simultaneously transmitted messages N_{tx}. The DRS is a predefined signal that enables uplink channel measurement and coherent signal demodulation at the BS. When an uplink node n transmits N_{tx} messages in a slot (over N_{tx} subchannels), it equally distributes its maximum transmission power P_n over the suchannels in use. Also, we limit the power allocated for each subchannel in use to P^f, controlling inter-node interference. Thus, when an uplink node n transmits N_{tx} messages in a slot, it transmits over each subchannel s in use with the power of $p_{n,s}^f = \min(\frac{P_n}{N_{tx}}, P^f)$. From successfully received messages, the BS measures the uplink channel gain $g_{n,s}^u$ since it knows the transmitted signal from the DRS and the power from N_{tx}.

Then the BS determines the uplink subchannel assignment $\mathbf{Y^u} := \{\mathbf{y_1^u}, \cdots, \mathbf{y_S^u}\}$, where y_s^u ($1 \le y_s^u \le S$) represents the scheduling decision for subchannel s. For each subchannel s, the BS selects a node with the largest channel gain among the nodes whose messages were successfully received. Specifically, the BS selects an earliest slot k^* where it has received a message successfully, and sets $y_s^u = k^*$ to indicate that subchannel s is assigned to the node which has transmitted in slot k^*. If there

is no slot with a successfully received message, the BS leaves subchannel s unassigned by setting $y_s^u = 0$. After receiving $\mathbf{Y^u}$, each uplink node knows which subchannel has been assigned to itself, by comparing $\mathbf{Y^u}$ with its message transmission history.

On the other hand, in the uplink feedback period, each downlink node m measures the received signal strength $I_{m,s,k}$ over subchannel s and slot k. If uplink node n transmits alone over subchannel s and slot k, $I_{m,s,k} = g_{n,m,s}^i p_{n,s}^f$. Downlink nodes estimate the received signal strength of a message from its DRS part even when the message is not correctly decoded. Next, in the uplink scheduling period, each downlink node overhears the uplink scheduling vector $\mathbf{Y^u}$ to know which slot has been selected for each subchannel. If slot k^* has been selected for subchannel s ($y_s^u = k^*$), downlink node m can estimate the inter-node interference level $I_{m,s}$ from its measurement, i.e., $I_{m,s} = I_{m,s,k^*}$. Otherwise, if subchannel s is unassigned ($y_s^u = 0$), there will be no interference, i.e., $I_{m,s} = 0$. Since the uplink scheduling result is given in slot number instead of node ID, downlink node m can determine the inter-node interference level even when it fails to decode the message.

The downlink feedback and scheduling period is similar to the uplink case except that two different types of thresholds are used depending on the uplink scheduling result. If subchannel s is unassigned for the uplink, then the threshold values $\delta_1, \cdots, \delta_K$ are used and each downlink node m selects a slot according to its downlink channel gain $g_{m,s}^d$. In contrast, if subchannel s is assigned for some uplink node, then the thresholds $\gamma_1, \cdots, \gamma_K$ have been used, and a downlink node m selects a slot based on its channel to interference and noise ratio (CINR) $\tilde{g}_{m,s}^d = g_{m,s}^d / (1 + I_{m,s})$. That is, it transmits a message in slot k if $\tilde{g}_{m,s}^d$ satisfies the condition $\gamma_{k-1} > \tilde{g}_{m,s}^d \geq \gamma_k$. After receiving messages, the BS assigns each subchannel to the downlink node which has transmitted alone in an earliest slot, and broadcasts the downlink scheduling vector $\mathbf{Y^d} = \{\mathbf{y_1^d}, \cdots, \mathbf{y_S^d}\}$.

In the data transmission period, the BS and uplink nodes allocate their powers according to the subchannel assignments $\mathbf{Y^u}$ and $\mathbf{Y^d}$. For each subchannel s, let n_s and m_s denote the scheduled uplink and downlink nodes, respectively. Each uplink node n first calculates its power $p_{n,s}^u$ over subchannel s by the water-filling algorithm, i.e.,

$$
p_{n,s}^u = \begin{cases} \left[\alpha - \frac{1}{g_{n,s}^u} \right]^+, & \text{if } n = n_s, \\ 0, & \text{otherwise,} \end{cases}
$$

where α is the water-level satisfying $\sum_s p_{n,s}^u = P_n$. If $p_{n,s}^u$ is larger than the feedback power $p_{n,s}^f$, node n sets $p_{n,s}^u = p_{n,s}^f$. This is to ensure that the actual interference level in the data period is not greater than the interference level measured in the uplink period. For the downlink power allocation, the BS also uses the water-filling algorithm as

$$
p_{m,s}^d = \begin{cases} \left[\beta - \frac{1}{g_{m,s}^d} \right]^+, & \text{if } m = m_s \text{ and } y_s^u = 0, \\ \left[\beta - \frac{1}{\tilde{g}_{m,s}^d} \right]^+, & \text{if } m = m_s \text{ and } y_s^u > 0, \\ 0, & \text{otherwise,} \end{cases}
$$

where β is the water-level satisfying $\sum_m \sum_s p_{m,s}^d = P_{BS}$.

C. Calculation of Thresholds

The threshold values determine the feedback probability in each slot, which in turn impacts overall performance. Since the optimal threshold values depend on the distribution of channel gain, the number of nodes, and the considered objective function [35], finding optimal thresholds is a difficult design issue and is out of the scope of this paper. Instead, we try to set the feedback probability in each time slot to a same value p [29], [33], [35].

For analytical tractability, we assume that $g_{n,s}^u$, $g_{m,s}^d$, and $g_{n,m,s}^i, \forall n, m, s$ are independent and identically distributed (*i.i.d.*) exponential random variables[5]. Let $\bar{g}$ denote the average channel gain, i.e., $\bar{g} = E[g_{n,s}^u] = E[g_{m,s}^d] = E[g_{n,m,s}^i], \forall n, m, s$. The cumulative distribution function (CDF) and probability density function (PDF) of each channel gain are given by $F_g(x) = 1 - \exp\left(-\frac{x}{\bar{g}}\right)$ and $f_g(x) = \frac{1}{\bar{g}} \exp\left(-\frac{x}{\bar{g}}\right)$, respectively.

We first calculate the values of $\delta_1, \cdots, \delta_K$. Targeting the feedback probability at p in slot 1, we have

$$
\Pr\left(g_{n,s}^u \geq \delta_1\right) = 1 - F_g(\delta_1) = \exp\left(-\frac{\delta_1}{\bar{g}}\right) = p.
$$

Thus we set $\delta_1 = \bar{g} \ln(\frac{1}{p})$. The feedback probability in slot 2 is given by

$$
\Pr\left(\delta_1 > g_{n,s}^u \geq \delta_2\right) = F_g(\delta_1) - F_g(\delta_2) = \exp\left(-\frac{\delta_2}{\bar{g}}\right) - p = p,
$$

which results in $\delta_2 = \bar{g} \ln\left(\frac{1}{2p}\right)$. In a similar manner, we have $\delta_k = \bar{g} \ln\left(\frac{1}{kp}\right)$ for all k.

To calculate the values of $\gamma_1, \cdots, \gamma_K$, we need to derive the distribution of CINR $\tilde{g}_{m,s}^d$ of downlink node m over subchannel s. Recall that n_s represents an uplink node using subchannel s and $p_{n_s,s}^f$ is its message transmission power. Then $\tilde{g}_{m,s}^d$ is given by

$$
\tilde{g}_{m,s}^d = \frac{g_{m,s}^d}{1 + g_{n,m,s}^i p_{n_s,s}^f},
$$

where $g_{n,m,s}^i p_{n_s,s}^f$ represents the interference level $I_{m,s}$ measured during the uplink feedback period. Since $p_{n_s,s}^f$ is determined by the number of simultaneously transmitted messages, it is not easy to calculate its exact value. Thus, we set $p_{n_s,s}^f = P^f$, which is a conservative assumption that leads to the maximum interference level $g_{n,m,s}^i P^f$. In this case, the CDF of $\tilde{g}_{m,s}^d$ is given by

$$
F_{\tilde{g}}(x) = 1 - \frac{\exp\left(-\frac{x}{\bar{g}}\right)}{1 + x P^f},
$$

where the detailed derivation is provided in Appendix I in our technical report [26]. From $F_{\tilde{g}}(x)$, the probability that each downlink node m transmits its feedback message in slot 1 is given by

$$
\Pr\left(\tilde{g}_{m,s}^d \geq \gamma_1\right) = 1 - F_{\tilde{g}}(\gamma_1) = p.
$$

---

[5]The *i.i.d.* assumption is widely used in the literature [29], [35].

We set $\gamma_1 = F_{\tilde{g}}^{-1}(1-p)$ and γ_k's accordingly through numerical methods.

D. Performance Analysis and Optimal Feedback Probability

In this subsection, we investigate the sum-rate performance of the proposed scheme and obtain the optimal feedback probability p^*. We first derive the scheduling probability over each subchannel. Without loss of generality, let us focus on the uplink feedback over a random subchannel s. The probability $P_{k,1}$ that only one node transmits in slot k is given by

$$P_{k,1} = \Pr\left(1 \text{ feedback in slot } k\right) = Np(1-p)^{N-1}. \quad (10)$$

Then the probability P_k that slot k is selected for scheduling is obtained as

$$P_k = \Pr\left(x_s^u = k\right) = P_{k,1} \prod_{i=1}^{k-1} (1 - P_{i,1}). \quad (11)$$

Lastly, the scheduling probability P_{sch} over subchannel s (i.e., subchannel s is assigned to some uplink node) is given by

$$P_{sch} = \Pr\left(x_s^u \geq 0\right) = \sum_{k=1}^{K} P_k. \quad (12)$$

Note that $P_{k,1}$, P_k, and P_{sch} can be applied to other subchannels and the downlink.

We now derive the uplink rate R_s^u over a random subchannel s. To obtain R_s^u, we need to know the uplink power over subchannel s. Suppose that subchannel s is assigned to uplink node n_s. Since node n_s allocates its power by the water-filling algorithm, the uplink power $p_{n_s,s}^u$ over subchannel s depends on the channel gains of other subchannels which are also assigned to node n_s. Therefore it is not easy to obtain $p_{n_s,s}^u$.

To circumvent this problem, we resort to a well-known property of the water-filling algorithm that leads to a near-flat power allocation at high SNR regimes [36]. If p is small and the corresponding threshold values are sufficiently large (i.e., high SNR), uplink node n allocates an almost-equal power to the assigned subchannels. In addition, since all nodes are equally likely to use each subchannel due to the *i.i.d.* channel conditions, node n_s uses SP_{sch}/N subchannels on average. Thus, we approximately obtain the uplink power $p_{n_s,s}^u$ over subchannel s as

$$p_{n_s,s}^u = \min\left(P^f, \frac{NP_n}{SP_{sch}}\right). \quad (13)$$

Then we obtain

$$R_s^u = \sum_{k=1}^{K} P_k \log\left(1 + \delta_k p_{n_s,s}^u\right). \quad (14)$$

Since the expected uplink rate over each subchannel is the same, the uplink sum-rate R^u over all the subchannels is given by

$$R^u = \sum_{s=1}^{S} R_s^u = SR_s^u. \quad (15)$$

Table 1. Simulation Parameters

Parameter	Value
Center frequency	2.1 GHz
Subchannel bandwidth	180 kHz
Noise power	-119 dBm
Base station's power P_{BS}	43 dBm
Node n's power P_n	24 dBm
Base station's height h_{BS}	30 m
Node n's height h_N	1.5 m

We next derive the downlink rate R_s^d over a random subchannel s. Again, we assume that the BS allocates an equal power p_s^d for each subchannel s, which is given by

$$p_s^d = \frac{P_{BS}}{SP_{sch}}, \forall s. \quad (16)$$

The uplink scheduling result determines which type of threshold has been used in the downlink feedback, i.e., δ_k or γ_k. When subchannel s is unassigned in the uplink, we obtain R_s^d as

$$R_s^d = \sum_{k=1}^{K} P_k \log\left(1 + \delta_k p_s^d\right). \quad (17)$$

On the other hand, if subchannel s is assigned to some uplink node, R_s^d is given by

$$R_s^d = \sum_{k=1}^{K} P_k \log\left(1 + \gamma_k p_s^d\right). \quad (18)$$

From Eqs. (17) and (18), we have

$$R_s^d = \sum_{k=1}^{K} P_k \left\{(1 - P_{sch}) \log\left(1 + \delta_k p_s^d\right) + P_{sch} \log\left(1 + \gamma_k p_s^d\right)\right\}. \quad (19)$$

As in the uplink case, the downlink sum-rate over all the subchannels is

$$R^d = \sum_{s=1}^{S} R_s^d = SR_s^d. \quad (20)$$

Lastly, combining Eqs. (15) and (20), we obtain the sum-rate R as

$$R = R^u + R^d. \quad (21)$$

To validate this, we compare analysis results with the simulation results, which is shown in Fig. 3 for $N = 60$, $K = 8$, $S = 20$, and $\bar{g} = 733$. It shows a close match between analysis and simulation.

Since the sum-rate $R(p)$ is a function of p, we can numerically obtain the optimal feedback probability p^* from (21). Fig. 4 shows the value p^* when $S = 50$ and $\bar{g} = 733$. We can see that p^* decreases with the increase of N to avoid experiencing high collision probability.
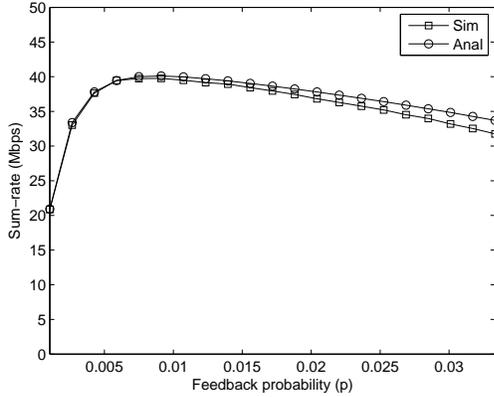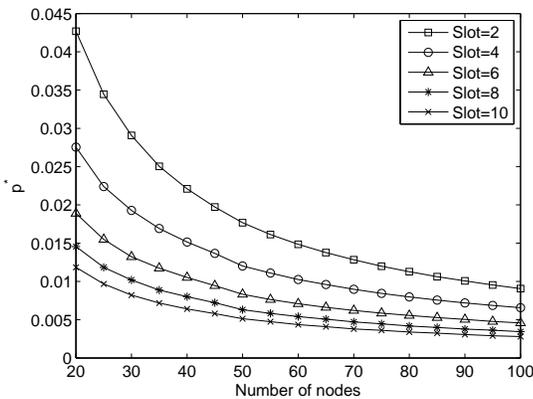
Fig. 3. Comparison between analysis and simulation.

Fig. 4. Optimal feedback probability p^* obtained through analysis. p^* decreases with the increase of N and K.

V. Performance Evaluation

A. Simulation Setting

Simulation parameters are configured according to the typical values of LTE systems [37]. We assume 10 MHz spectrum band and 50 subchannels, each with a bandwidth[6] of 180 kHz. For the path loss model, we use the Hata propagation model for urban environments where the path loss P_{loss} (dB) is calculated as in [37],

$$P_{loss}(d) = 69.55 + 26.16 \cdot \log f - 13.83 \cdot \log h_{BS} \\ - C_H(f) + (44.9 - 6.55 \cdot \log h_{BS}) \log d, \quad (22)$$

where d (km) denotes the distance between the transmitter and the receiver, f (MHz) is the center frequency, and h_{BS} (m) denotes the height of the BS. $C_H(f)$ is the antenna height correlation factor defined as,

$$C_H(f) = 0.8 + (1.1 \cdot \log f - 0.7) h_N - 1.56 \cdot \log f, \quad (23)$$

where h_N (m) is the height of the terminal node. The power budgets are set as $P_{BS} = 43$ (dBm) and $P_n = 24$ (dBm) for all uplink nodes. Other simulation parameters are summarized in Table 1.

---

[6]The basic scheduling unit in LTE systems is a resource block of 180 kHz.

We assume a time-slotted system and adopt the model of Rayleigh block fading channel in [7]. In a time slot, each channel gain includes location-dependent path loss and independent Rayleigh terms. We conduct simulation for 100 time slots and obtain the average result. For network topology, we configure the number of uplink nodes N to be the same as that of downlink nodes M. We consider two different topologies:

• Cell topology: Nodes are randomly distributed within a cell radius of r. Also, they are newly positioned at each time slot.
• Ring topology: Nodes are located at an equal distance d from the BS. As a result, all uplink and downlink channel gains have the same distribution. In addition, we assume that inter-node channel gains also have the same distribution.

For the full CSI scenario, we compare the following schemes:

• Downlink first allocation algorithm (D-First): Subcarriers are first assigned to downlink nodes.
• Uplink first allocation algorithm (U-First): Subcarriers are first assigned to uplink nodes.
• Baseline (BL): As a point of reference, we consider a simple combination of (half-duplex) uplink and downlink allocation schemes without considering inter-node interference. An optimal allocation algorithm [3] is used for the downlink while a near-optimal algorithm [6] is used for the uplink.
• Half-duplex (HD): Downlink and uplink transmissions switch over time slots using the algorithms [3] and [6], respectively.

According to CSI scenarios, we compare the following schemes:

• Full-duplex limited CSI (FD-LCSI): Proposed resource allocation scheme with limited CSI.
• Full-duplex full CSI (FD-FCSI): U-First scheme with full CSI.
• Half-duplex limited CSI (HD-LCSI): Half-duplex transmissions with limited CSI.

For FD-LCSI and HD-LCSI, we use the optimal feedback probability p^* obtained through the analysis.

B. Simulation Results: Full CSI

We first provide the simulation results obtained in the ring topology. Fig. 5(a) shows the sum-rate of each scheme for various d values when $N = 50$. D-First and U-First show a similar performance and outperform the baseline scheme. As shown in Figs. 5(b) and 5(c), U-First gives priority to the uplink traffic and achieves a higher uplink rate than D-First, while D-First operates in the opposite way. Although the baseline scheme achieves the highest uplink rate, its downlink rate becomes significantly low due to the excessive inter-node interference. Their performance gains over the baseline scheme decrease with the distance because the inter-node interference diminishes.
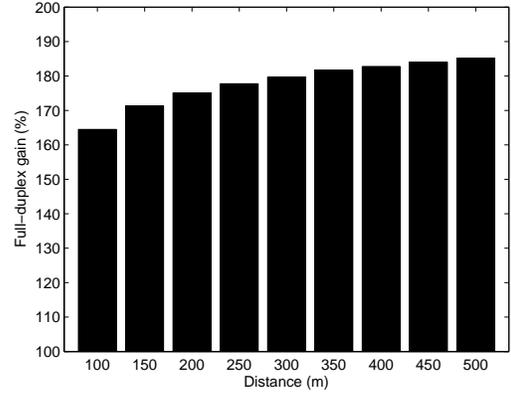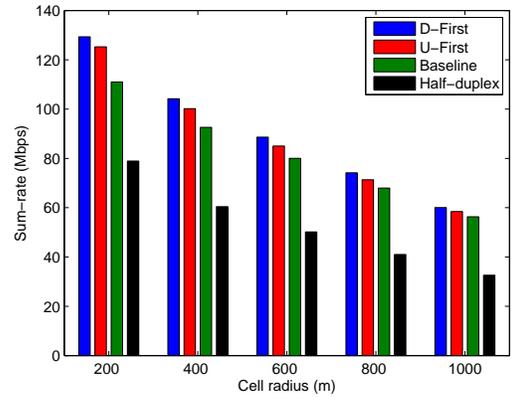
Fig. 6 depicts the full-duplex gain as a function of d. The full-duplex gain increases with the distance, and ranges from 164% ($d = 100$ m) to 185% ($d = 500$ m). As explained in Section III-D, this is because the ratio of interference to noise shrinks with the distance. This indicates that the full-duplex technology will bring large gain in large-size cells with sparse user distribution, e.g., rural areas.

We next show the simulation results obtained in the cell topology. Fig. 7 shows the sum-rate of each scheme for various r's. The results are similar to those obtained in the ring topology except that D-First achieves a larger sum-rate than U-First. In
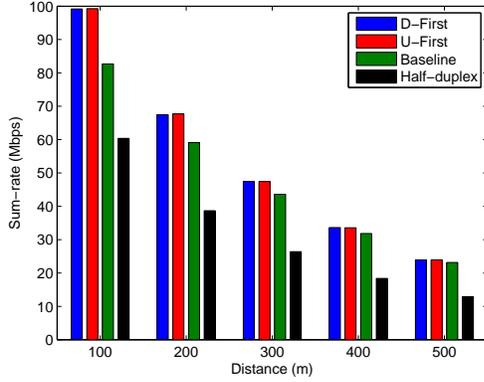
(a) Sum-rate R
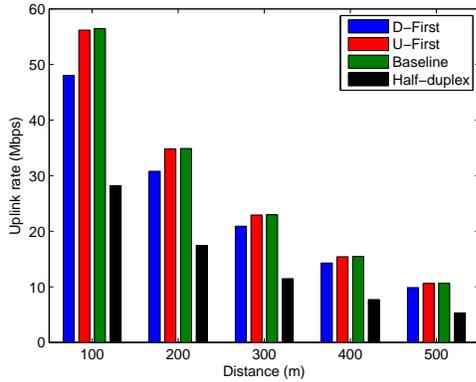
(b) Uplink rate R^u
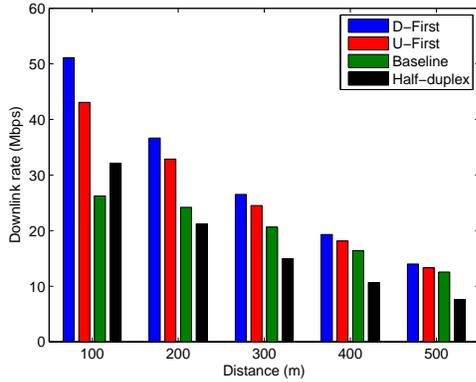
(c) Downlink rate R^d

Fig. 5. Performance comparison in the ring topology ($N = 50$).

Fig. 6. Full-duplex gain as a function of the distance d.

Fig. 7. Performance comparison in the cell topology ($N = 50$).

U-First, a few of uplink nodes close to the BS use most of the subchannels due to their large channel gains. In contrast, the uplink subchannel assignment in D-First is relatively fair because an uplink node with a large channel gain will not be scheduled if the interference to the already scheduled downlink node is higher than a threshold value. As a result, the uplink power allocated for each subchannel in D-First is larger than that in U-First, which leads to the performance gap.

Fig. 8 depicts the impact of N on the performance. The cell radius r is set to 500 m and we vary N from 20 to 100. For $N = 10$, our schemes and the baseline scheme show a similar

performance. This is because the inter-node interference is weak in sparse node distribution. As the node density increases, our scheme outperforms the baseline scheme with a gain of 13%.

Fig. 9 shows the FD gain of D-First over HD as a function of N. According to the increase of N, the gain decreases due to the growing interference (for instance, from 180% ($N = 10$) to 170% ($N = 100$)), as explained in Section III-D. This result implies that the benefit from full-duplex is limited in urban areas with dense user population.

Lastly, we investigate the impact of imperfect interference cancellation. We introduce residual self-interference σ by increasing the noise power. According to [13], the noise power after cancellation is increased by at most 1 dB over the receiver noise floor when the transmission power ranges from 5 dBm to 20 dBm. In other words, after the self-interference cancellation, the residual self-interference remains at the same level regardless of the transmission power.

Based on this, we increase the noise power by σ dB to account for residual self-interference. Fig. 10 shows the sum-rate of each scheme for various σ values in the ring topology when $d = 200$ m. The sum-rates of all the schemes except HD decrease with σ due to the increased noise power. Also, the full-duplex gain decreases from 175% ($\sigma = 0$) to 129% ($\sigma = 10$). This indicates that the performance of full-duplex transmission heavily degrades when a substantial amount of residual self-
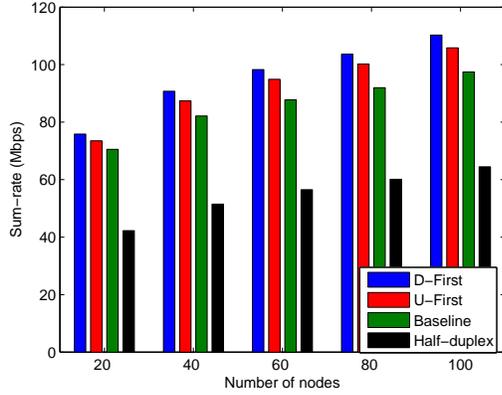
Fig. 8. Impact of the number of nodes on the performance. The performance gain of our schemes over the baseline scheme increases with more nodes.
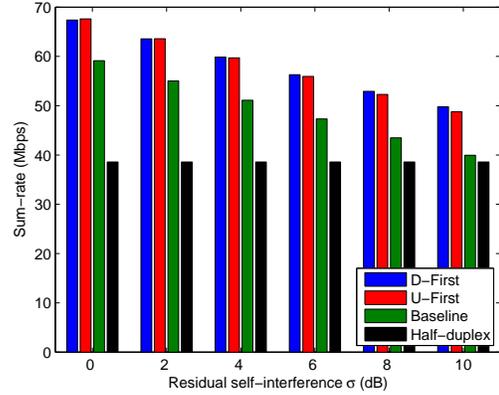

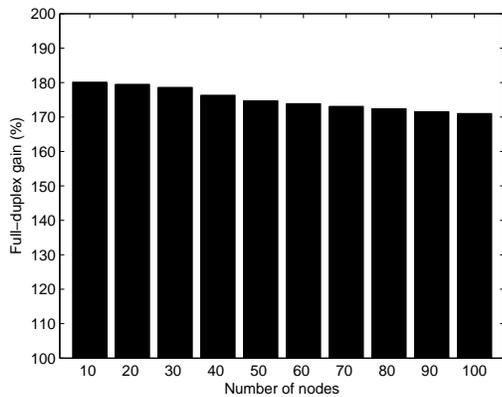Fig. 10. Impact of residual self-interference σ on the performance.
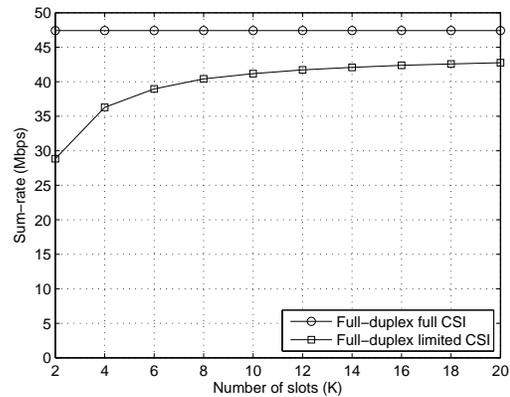

Fig. 9. Full-duplex gain as a function of N.

Fig. 11. Performance comparison of full CSI and limited CSI schemes for various K values.

interference exists after cancellation.

C. Simulation Results: Limited CSI

We first compare the performance of FD-FCSI and FD-LCSI. Fig. 11 shows the sum-rate of FD-LCSI as a function of K (number of slots) when $N = 50$ and $d = 300$ m. With the increase of K, the sum-rate of FD-LCSI increases from 28.8 Mbps for $K = 2$ to 42.8 Mbps for $K = 20$. When $K = 20$, FD-LCSI achieves about 90% of the sum-rate of FD-FCSI. The performance improvement is clearly observed when K is increased from a small value, and for $K > 10$, the improvement ratio becomes marginal. Considering this, an appropriate number of slots needs to be recommended to achieve high performance without causing a large feedback overhead.

We next compare the performance of FD-LCSI and HD-LCSI to see the full-duplex gain in practical limited CSI scenarios. Fig. 12(a) shows the sum-rate of each scheme when $N = 50$ and $d = 300$ m. As expected, the sum-rates of both schemes grow with K due to the increasing feedback opportunity. Fig. 12(a) depicts the full-duplex gain as a function of K, and Fig. 12(b) shows that the full-duplex gain over half-duplex remains almost the same as 172% regardless of K and N. This implies that the proposed scheme can bring performance gain under various scenarios.

VI. Conclusion

In-band wireless full-duplex has emerged as a promising solution to alleviating the spectrum crunch problem. To fully exploit the full-duplex technology, it is of great importance to design a resource allocation algorithm considering inter-node interference. In this paper, we have tackled the radio resource allocation problem in a single-cell full-duplex OFDMA network which consists of one full-duplex base station and multiple half-duplex legacy mobile nodes.

We have considered two different cases of full and limited CSIs, and propose a scheme for each case. In the former case, we have proved that the problem is NP-hard, and designed sequential resource allocation algorithms. In the latter case, we have proposed a channel measurement and feedback scheme where downlink nodes measure inter-node interference with low complexity. Through simulation, we have confirmed that our algorithms perform better than existing algorithms oblivious to the interference, and identified the full-duplex gain in practical scenarios.

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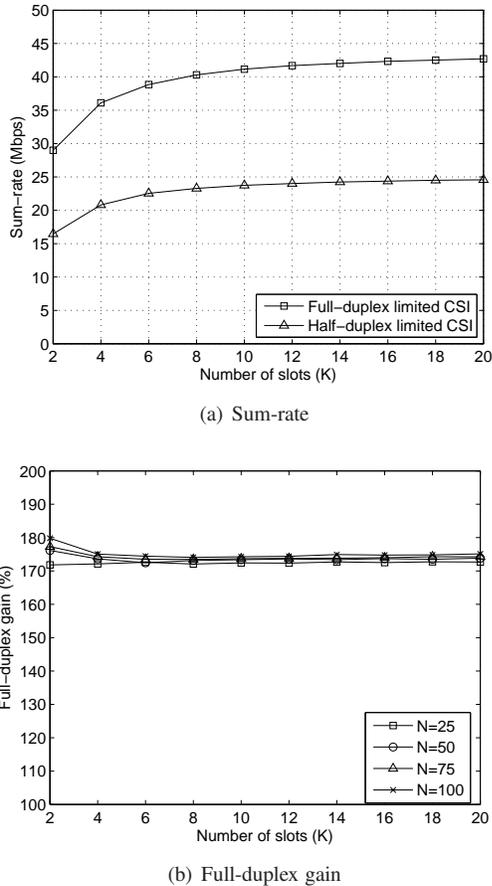
(a) Sum-rate

(b) Full-duplex gain

Fig. 12. Performance comparison of full-duplex and half-duplex under limited CSI.

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