A Subcarrier and Power Allocation Algorithm for OFDMA Full-Duplex Systems

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***Abstract*—In this paper, we focus on subcarrier and power allocation for an orthogonal frequency division multiple access (OFDMA) full-duplex (FD) system. A three-step algorithm is proposed to maximize the sum-rate of the system subject to individual rate constraints at the uplink and downlink users, and transmit power constraints at the base station (BS) and uplink users. The steps are: 1) Subcarrier allocation that considers user target rate requirements, 2) residual subcarrier allocation that further increases the sum rate, and 3) power allocation based on iterative water-filling (IWF). Simulation results reveal that the proposed FD scheduling improves the sum-rate over the traditional half-duplex (HD) and round-robin (RR) scheduling significantly under the self-interference cancellation levels that has been recently achieved.**

***Index Terms*—Full-duplex, QoS, OFDMA, resource allocation, subcarrier and power allocation.**

I. INTRODUCTION

Next generation wireless communication systems dynamically schedule users, and allocate subcarriers and power among them in order to meet the quality of service (QoS) requirements of each user, and to utilize the limited resources efficiently. Subcarrier and power allocation in orthogonal frequency division multiple access (OFDMA) systems has been investigated for downlink channels in [1]-[2], and for uplink channels in [3]-[5].

Recently, full-duplex (FD) radio, which can receive and transmit concurrently on the same frequency, has been proposed as a promising technique to increase the spectral efficiency [6]-[11]. This is in contrast to the half-duplex (HD) communication, where each node receives and transmits on two orthogonal channels, and thus cannot utilize the resources efficiently, and cannot achieve the maximal spectral efficiency. The potential of high spectral efficiency of FD radios has recently attracted several research groups to study theoretical problems associated with FD systems, mostly on the physical layer [12]-[21].

The limiting factor on the performance of FD systems is the strong self-interference at the front-end of the receiver created by the signal leakage from the transmitter antennas of a FD node to its own receiver antennas. Promising results from experimental research that demonstrate the feasibility of FD transmission using the off-the-shelf hardware are available in [6]-[11]. However, due to imperfections of radio devices such as amplifier non-linearity, phase noise, and I/Q channel imbalance, the self-interference cannot be canceled completely in reality, resulting in residual self-interference. Moreover, in cellular networks, the difficulty in studying FD systems is increased further by the co-channel interference created by the uplink users to downlink users. FD radios have been extensively studied for various systems (multi-user, cellular networks, cognitive radios, relaying), and important progress has been made in performance evaluation (outage, diversity, sum-rate analysis, etc.) [12]-[21] and references therein.

FD technology has also been studied to mitigate the problems associated with medium access control (MAC) layer, such as hidden terminals, large delays, congestion [6], [22]. The scheduling issue on the MAC layer of the FD cellular networks, where a FD mode base station (BS) communicates with HD mode users, was considered in [23]-[24]. In particular, a sub-optimal scheduling algorithm to maximize the system throughput is proposed in [24], and a hybrid scheduler that can switch between FD and HD modes to maximize the system throughput as well as to ensure fairness is proposed in [23], but these works have not considered the power allocation and QoS requirements of each user.

In this paper, we present a scheduler that maximizes the sum-rate in a FD OFDMA small-cell system, where the BS and uplink users have power constraints; and all users have QoS requirements (predefined target rate). Similar to [5], a subcarrier and power allocation algorithm is proposed, which consists of three steps. In the first step, subcarriers are allocated only to users whose rates are below the QoS requirements. In the second step, the residual subcarriers, which have not been allocated in the first step are assigned to users to further increase the sum-rate. And finally, in the third step a power allocation is performed for all the sub-carriers using iterative water-filling (IWF) algorithm [25]. Unlike [1]-[5] where uplink or downlink scheduling is considered separately, here we consider FD transmission, in which uplink and downlink scheduling is performed simultaneously. And unlike [23]-[24], here we study subcarrier allocation as well as power and rate allocation of each user.

We compare the performance of the proposed algorithm with the ones obtained through traditional HD time-division-duplexing, in which uplink and downlink transmissions are operated in alternating time-slots, and round-robin (RR) scheduling, which allocates the subcarriers sequentially to all uplink

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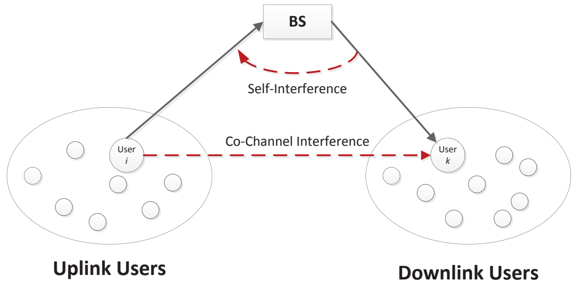

Fig. 1. The system model of the FD wireless network. The solid lines denote the desired signals, and the dashed lines denote the interference.

(downlink) users so that each uplink (downlink) user has an approximately equal number of subcarriers allocated. The simulation results show that the proposed FD scheduling can achieve significant improvement in terms of throughput over both RR and HD scheduling under the self-interference cancellation levels that have been achieved recently [7].

II. SYSTEM MODEL

We consider a single-cell single-input single-output (SISO) OFDMA system having a FD BS in the center with randomly distributed HD uplink and downlink users, and N subcarriers. Let us denote $\mathcal{I}^{UL}$, $\mathcal{K}^{DL}$ and $\mathcal{N}$ as the sets associated with uplink users, downlink users, and subcarriers, respectively.

As shown in Fig. 1, the BS simultaneously receives signal from one of its uplink user and transmits signal to one of its downlink user. The received signals at the uplink and downlink channels of the BS serving ith uplink user, $i \in \mathcal{I}^{UL}$ and kth downlink user, $k \in \mathcal{K}^{DL}$ on the nth subcarrier simultaneously are given, respectively, as

$$y^{UL}_{ik,n} = \sqrt{p^{UL}_{i,n}}h^{UL}_{i,n}s^{UL}_{i,n} + \sqrt{\frac{p^{DL}_{k,n}}{C_{SI}}}s^{DL}_{k,n} + w_{0,n}, \qquad (1)$$

$$y^{DL}_{ki,n} = \sqrt{p^{DL}_{k,n}}h^{DL}_{k,n}s^{DL}_{k,n} + \sqrt{p^{UL}_{i,n}}h_{ki,n}s^{UL}_{i,n} + w_{k,n}, \qquad (2)$$

where $p^{UL}_{i,n}$ and $p^{DL}_{k,n}$ denote the transmit power of the ith uplink user and the transmit power of the BS serving downlink user k on the nth subcarrier, respectively. $s^{UL}_{i,n}$ and $s^{DL}_{k,n}$ are the data streams of the ith uplink and kth downlink user with unit powers, respectively. $h^{UL}_{i,n}$ and $h^{DL}_{k,n}$ denote the channel from the ith uplink user to the BS and the channel from BS to the kth downlink user on the nth subcarrier, respectively. $h_{ki,n}$ denote the co-channel interference from the ith uplink user to the kth downlink user on the nth subcarrier. $w_{0,n}$ and $w_{k,n}$ denote the additive white Gaussian noise (AWGN) at the BS and kth downlink user on the nth subcarrier, respectively. In (1), C_{SI} denotes the self-interference cancellation value at the BS. In particular, $\frac{p^{DL}_{k,n}}{C_{SI}}$ represents the residual self-interference power at the BS on the nth subcarrier [23].

Using (1) and (2), the uplink and downlink instantaneous rates of the FD system serving ith uplink user, $i \in \mathcal{I}^{UL}$ and kth downlink user, $k \in \mathcal{K}^{DL}$ on the nth subcarrier simultaneously are given, respectively, as

$$R^{DL}_{ki,n} = \log_2\left(1 + \frac{p^{DL}_{k,n}\left|h^{DL}_{k,n}\right|^2}{N_{k,n} + p^{UL}_{i,n}\left|h_{ki,n}\right|^2}\right), \qquad (3)$$

$$R^{UL}_{ik,n} = \log_2\left(1 + \frac{p^{UL}_{i,n}\left|h^{UL}_{i,n}\right|^2}{N_{0,n} + \frac{p^{DL}_{k,n}}{C_{SI}}}\right), \; i \in \mathcal{I}^{UL}, \; k \in \mathcal{K}^{DL}, (4)$$

where $N_{0,n}$ and $N_{k,n}$ denote the noise power at the BS and kth downlink user on the nth subcarrier, respectively.

The optimal scheduling algorithm to maximize the sum-rate of the FD system is formulated as

$$\max_{\mathbf{W},\, \mathbf{P}^{UL},\, \mathbf{P}^{DL}} \sum_{n=1}^{N}\sum_{i\in\mathcal{I}^{UL}}\sum_{k\in\mathcal{K}^{DL}} w_{nik}\left(R^{UL}_{ik,n} + R^{DL}_{ki,n}\right) \qquad (5)$$

$$\text{s.t.} \quad \sum_{n=1}^{N}\sum_{k\in\mathcal{K}^{DL}} p^{DL}_{k,n} \le P_T, \qquad (6)$$

$$\sum_{n=1}^{N} p^{UL}_{i,n} \le P_i, \; i \in \mathcal{I}^{UL}, \qquad (7)$$

$$\sum_{n=1}^{N}\sum_{k\in\mathcal{K}^{DL}} w_{nik}R^{UL}_{ik,n} \ge R^{UL}_t, \; i \in \mathcal{I}^{UL}, (8)$$

$$\sum_{n=1}^{N}\sum_{i\in\mathcal{I}^{UL}} w_{nik}R^{DL}_{ki,n} \ge R^{DL}_t, k \in \mathcal{K}^{DL}, (9)$$

$$\sum_{i\in\mathcal{I}^{UL}}\sum_{k\in\mathcal{K}^{DL}} w_{nik} = 1, \; n = 1, \ldots, N, \; (10)$$

$$p^{DL}_{k,n} \ge 0, \; k \in \mathcal{K}^{DL}, \; n = 1, \ldots, N, \qquad (11)$$

$$p^{UL}_{i,n} \ge 0, \; i \in \mathcal{I}^{UL}, \; n = 1, \ldots, N, \qquad (12)$$

where P_T and P_i are the transmit power constraints at the BS and ith uplink user, respectively. R^{UL}_t and R^{DL}_t are the minimum required target rates at the uplink and downlink users, respectively. When a user experiences deep fading, its instantaneous achievable rate becomes extremely low, and thus its QoS requirement may not be satisfied. The minimum required target rate constraints in (8) and (9) try to achieve certain instantaneous rate for each user to guarantee the fairness among different users [5], [26]. w_{nik} is an indicator variable which is equal to 1 if subcarrier n is allocated to ith uplink user and kth downlink user. The design variables $\mathbf{W}$, $\mathbf{P}^{UL}$, and $\mathbf{P}^{DL}$ are matrices obtained by stacking all w_{nik}, $p^{UL}_{i,n}$, and $p^{DL}_{k,n}$, respectively. The constraint in (10) ensures that each subcarrier can be allocated to at most one uplink and one downlink user. The optimization problem (5)-(12) is a combinatorial problem due to the indicator variable w_{nik}, which requires high-complexity algorithms and exhaustive search to solve [24]. Therefore, in the next section, similar to [1]-[5], [23]-[24], we introduce a heuristic subcarrier and power allocation algorithm to solve the problem (5)-(12). The joint allocation problem is proven to be generally NP-hard [27], [28]. The problem considered in this paper can be seen as a generalization of the problems considered in [27], [28], and thus is also NP-hard. The NP-hardness result makes the development of the heuristics algorithm natural, since there are no algorithms which can solve the problem in polynomial time.

TABLE I
PROPOSED SCHEDULING ALGORITHM

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Initialization: $\mathcal{S}_i^{UL} = \phi,\ \mathcal{S}_k^{DL} = \phi,\ \bar{n} = 0$
                $\mathcal{U}^{UL} = \mathcal{I}^{UL}$, and $\mathcal{U}^{DL} = \mathcal{K}^{DL}$.
Step 1: Initial subcarrier allocation.
while $\mathcal{U}^{UL}$ or $\mathcal{U}^{DL}$ or $\mathcal{N}$ is not empty
  1) $\bar{n} = \bar{n} + 1,\ \tilde{\mathcal{S}}_i^{UL} = \mathcal{S}_i^{UL} \bigcup \bar{n},\ \tilde{\mathcal{S}}_k^{DL} = \mathcal{S}_k^{DL} \bigcup \bar{n}.$
  2) $\Delta_{ik} = R_i^{UL}\left(\tilde{\mathcal{S}}_i^{UL}\right) + R_k^{DL}\left(\tilde{\mathcal{S}}_k^{DL}\right) - R_i^{UL}\left(\mathcal{S}_i^{UL}\right)$
         $- R_k^{DL}\left(\mathcal{S}_k^{DL}\right),\ i \in \mathcal{U}^{UL},\ k \in \mathcal{U}^{DL}.$
  3) $(i^*, k^*) = \arg\max_{i \in \mathcal{U}^{UL},\ k \in \mathcal{U}^{DL}} \Delta_{ik}.$
  4) $w_{\bar{n} i^* k^*} = 1,\ \mathcal{S}_{i^*}^{UL} = \mathcal{S}_{i^*}^{UL} \bigcup \bar{n},\ \mathcal{S}_{k^*}^{DL} = \mathcal{S}_{k^*}^{DL} \bigcup \bar{n}.$
  5) Update $R_{i^*}\left(\mathcal{S}_{i^*}^{UL}\right)$ and $R_{k^*}\left(\mathcal{S}_{k^*}^{DL}\right)$.
  6) if $R_{i^*}\left(\mathcal{S}_{i^*}^{UL}\right) \geq R_t^{UL}, \mathcal{U}^{UL}/\{i^*\}$ end if
  7) if $R_{k^*}\left(\mathcal{S}_{k^*}^{DL}\right) \geq R_t^{DL}, \mathcal{U}^{DL}/\{k^*\}$ end if
  8) $\mathcal{N} = \mathcal{N}/\{\bar{n}\}.$
end loop
Step 2: Residual subcarrier allocation.
  Residual subcarrier allocation is almost the same as Step 1.
  The only difference is that line 3 must be replaced by:
if $\mathcal{U}^{UL} = \phi$ and $\mathcal{U}^{DL} \neq \phi$
  9) $(i^*, k^*) = \arg\max_{i \in \mathcal{I}^{UL},\ k \in \mathcal{U}^{DL}} \Delta_{ik}.$
else if $\mathcal{U}^{DL} = \phi$ and $\mathcal{U}^{UL} \neq \phi$
  10) $(i^*, k^*) = \arg\max_{i \in \mathcal{U}^{UL},\ k \in \mathcal{K}^{DL}} \Delta_{ik}.$
else
  11) $(i^*, k^*) = \arg\max_{i \in \mathcal{I}^{UL},\ k \in \mathcal{K}^{DL}} \Delta_{ik}.$
end if
Step 3: Sequential Iterative Water-Filling.
for $l = 1$ : Max-iteration
  for $m \in \left(\mathcal{I}^{UL} \bigcup \mathcal{K}^{DL}\right)$
    if $m \in \mathcal{I}^{UL}$
      12) $p_{m,n}^{UL} = \left[\mu_m - \frac{N_{0,n} + \frac{p_{\bar{m},n}^{DL}}{C_{SI}}}{\left|h_{m,n}^{UL}\right|^2}\right]^+, \sum_{n \in \mathcal{S}_m^{UL}} p_{m,n}^{UL} = P_m,$
    else
      13) $p_{m,n}^{DL} = \left[\mu_m - \frac{N_{m,n} + p_{\bar{m},n}^{UL}\left|h_{m\bar{m},n}\right|^2}{\left|h_{m,n}^{DL}\right|^2}\right]^+,$
          $\sum_{n \in \mathcal{S}_m^{DL}} p_{m,n}^{DL} = \frac{\left|\mathcal{S}_m^{DL}\right| P_T}{N}.$
    end if
  end loop
end loop
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III. PROPOSED SCHEDULING ALGORITHM

The proposed algorithm has three steps. In the initial subcarrier allocation, subcarriers are sequentially assigned to two users (one downlink and one uplink) whose rates are below the target rate and will increase the sum-rate on this subcarrier the most with this additional assignment. This step ends when the rates of all uplink or downlink users reach the target rate, or when all the subcarriers are assigned. At this stage, to reduce the computation complexity and to make the problem tractable, the transmit power of each user is assumed to be equally distributed over the assigned subcarriers.

In the residual subcarrier allocation step, the rest of the subcarriers, which are not allocated in the first step are assigned to users to further increase the sum-rate. If all uplink (downlink) users reach the target rate in the first step, then in the residual subcarrier allocation step, the uplink (downlink) users are chosen among all the uplink (downlink) users, and downlink (uplink) users are chosen among the users which have not reached the target rate. If both uplink and downlink users reach the target rate, and there are still available subcarriers, then the downlink and uplink users are chosen among all users.

After the subcarriers are assigned, power allocation based on the IWF [25] is performed in the last step. In particular, each uplink (downlink) user applies the single-user water-filling algorithm given that the interference from the downlink (uplink) users over the assigned subcarriers are fixed. Note that in [1]-[5], traditional water-filling algorithm is applied, since each subcarrier is allocated to only one user, but here the IWF algorithm is used, since subcarriers are shared among two users.

Let us denote $\mathcal{S}_i^{UL}$ and $\mathcal{S}_k^{DL}$ as the subcarrier set assigned to ith uplink user and kth downlink user, respectively. Moreover, $\mathcal{U}^{UL}$ and $\mathcal{U}^{DL}$ denote the indices of uplink and downlink users whose rates are below target rate, respectively. Defining the uplink and dowlink rates under equal power allocation among subcarriers, respectively, as

$$R_i^{UL}\left(\mathcal{S}_i^{UL}\right) = \sum_{n \in \mathcal{S}_i^{UL}} \log_2\left(1 + \frac{P_i\left|h_{i,n}^{UL}\right|^2}{\left|\mathcal{S}_i^{UL}\right|\left(N_{0,n} + \frac{P_T/N}{C_{SI}}\right)}\right) \quad (13)$$

$$R_k^{DL}\left(\mathcal{S}_k^{DL}\right) = \sum_{n \in \mathcal{S}_k^{DL}} \log_2\left(1 + \frac{P_T/N\left|h_{k,n}^{DL}\right|^2}{N_{k,n} + \frac{P_j}{\left|\mathcal{S}_j^{UL}\right|}\left|h_{kj,n}\right|^2}\right) \quad (14)$$

where $|\mathcal{S}|$ denotes the cardinality of the set $\mathcal{S}$, the detailed algorithm is given in Table I. In Table I, $[x]^+$ denotes $[x]^+ = \max\{x, 0\}$.

A. Complexity

The complexity of the proposed algorithm is calculated as follows. Assume that during Step 1 and Step 2, N_1 and N_2 subcarriers are allocated to users, respectively, i.e., $N_1 + N_2 = N$. Since line 3 in the proposed algorithm is executed $\left|\mathcal{U}^{UL}\right|\left|\mathcal{U}^{DL}\right|$ and at most $\left|\mathcal{I}^{UL}\right|\left|\mathcal{K}^{DL}\right|$ times for Step 1 and Step 2, respectively, the complexity of subcarrier allocation is $\mathcal{O}\left(N_1\left|\mathcal{U}^{UL}\right|\left|\mathcal{U}^{DL}\right| + N_2\left|\mathcal{I}^{UL}\right|\left|\mathcal{K}^{DL}\right|\right) \leq \mathcal{O}\left((N_1 + N_2)\left|\mathcal{I}^{UL}\right|\left|\mathcal{K}^{DL}\right|\right) = \mathcal{O}\left(N\left|\mathcal{I}^{UL}\right|\left|\mathcal{K}^{DL}\right|\right)$. Since the single user water-filling algorithm has a complexity of $\mathcal{O}\left(N\log(N)\right)$, each iteration of the IWF algorithm in Step 3 has an $\mathcal{O}\left(\left(\left|\mathcal{I}^{UL}\right| + \left|\mathcal{K}^{DL}\right|\right)N\log(N)\right)$ complexity.

IV. SIMULATION RESULTS

In this section, we compare the proposed FD scheduling algorithm with the traditional HD and RR scheduling algo-

TABLE II
SIMULATION PARAMETERS

Parameter	**Settings**
Cell Radius	40m
Number of subcarriers	$N = 1024$
$[\|\mathcal{I}^{UL}\|, \|\mathcal{K}^{DL}\|]$	$[10, \ 10]$
Bandwidth	10MHz
Maximum BS Power	$P_T = 24$dBm
Maximum user Power	$P_i = 23$dBm
Thermal Noise Density	-174dBm/Hz
Noise Figure	BS: 13dB, User: 9dB
Path Loss (dB) between BS and users (d in km)	LOS: $103.8 + 20.9 \log_{10} d$ NLOS: $145.4 + 37.5 \log_{10} d$
Path Loss (dB) between users (d in km)	LOS: $98.45 + 20 \log_{10} d, \ d \leq 50$m NLOS: $175.78 + 40\log_{10} d, \ d > 50$m
Shadowing Standard Deviation	LOS: 3dB, NLOS: 4dB
Rate Target	$R_t^{DL} = 4$Mbps, $R_t^{UL} = 2$Mbps

TABLE III
AVERAGE RATE GAIN OF FULL-DUPLEX UPLINK SYSTEM OVER HALF-DUPLEX UPLINK SYSTEM

C_{SI}	85dB	90dB	100dB	110dB	120dB	130dB
	0.86%	11%	39%	61%	75%	78%

rithms under the 3GPP LTE specifications for small cell deployments [29]. We consider a small cell scenario, since small cells which provide improved cellular coverage is considered to be suitable for deployment of full-duplex technology due to low transmit powers, short transmission distances and low mobility [21], [23]. A single hexagonal cell having a BS in the center with randomly distributed 10 uplink and 10 downlink users is studied. The channel between BS and users are assumed to experience the path loss model for line-of-sight (LOS) and non-line-of-sight (NLOS) communications depending on the probability

$$\begin{aligned} P_{\text{LOS}} &= 0.5 - \min(0.5, 5\exp(-0.156/d)) \\ &\quad + \min(0.5, 5\exp(-d/0.03)), \end{aligned} \tag{15}$$

where d is the distance between BS and users in km. Without loss of generality, power constraints of uplink users are assumed to be equal, i.e $P_i = P, \ i \in \mathcal{I}^{UL}$. Detailed simulation parameters adopted from [29] are shown in the Table II. The channel gain from the BS to ith uplink user on the nth subcarrier is given by $h_{i,n}^{UL} = \sqrt{\kappa_{i,n}^{UL}} \tilde{h}_{i,n}^{UL}$, where $\tilde{h}_{i,n}^{UL}$ denotes the small scale fading following a complex Gaussian distribution with zero mean and unit variance, and $\kappa_{i,n}^{UL} = 10^{(-\mathrm{X}/10)}$, $X \in \{\text{LOS}, \text{NLOS}\}$ represents the large scale fading consisting of path loss and shadowing, where LOS and NLOS are calculated from a specific path loss model given in Table II. The channel between BS and downlink users, and between uplink and downlink users are defined similarly.

In Fig. 2, the distribution of average FD (FD uplink rate plus FD downlink rate), HD uplink, and HD downlink rates over 500 drops are shown under various self-interference cancellation levels. It is seen that the self-interference needs to canceled at least 80dB so that FD system achieves higher sum-rate than HD system. FD system has a significantly higher throughput than HD systems at 110dB self-interference cancellation, which has been recently achieved in [7].

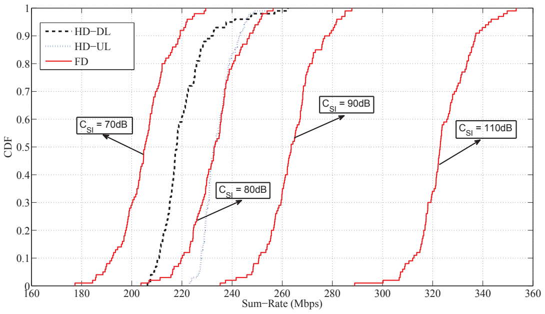

Fig. 2. Average sum-rate comparison of FD and HD systems under iterative water-filling.

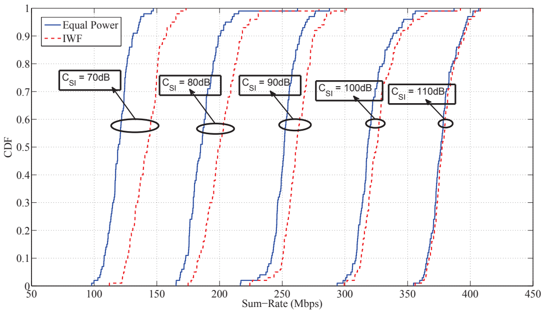

Fig. 3. Uplink sum-rate comparison of FD systems under equal power allocation and iterative water-filling.

Since self-interference, i.e., C_{SI} only affects the uplink rate, in Table III, we show the average gain of FD uplink channel over HD uplink channel. Note that we also observe 23% average gain in the downlink channel.

In Fig. 3, we show the distribution of the average FD uplink rate under equal power allocation and IWF algorithms. It is seen that at high self-interference cancellation values, they give similar performance. There are two reasons: First, it is well known that at high signal-to-interference-to-noise ratio (SINR), the performance gain of water-filling algorithm vanishes [30]. Secondly, a user is assigned only to subcarriers with good channel conditions. And since variations among the channel gains of subcarriers assigned to each user are small, water-filling algorithm results in near-flat power allocation.

In Fig. 4, the FD system is compared to full-duplex Round-Robin (FD-RR) scheduling to demonstrate the importance of intelligent scheduling. It is seen that even at 130dB self-interference cancellation, FD-RR system can still not achieve the performance of the HD systems. The reason is that FD-RR does not require the knowledge of channel state information (CSI), and allocates the subcarriers sequentially to all uplink

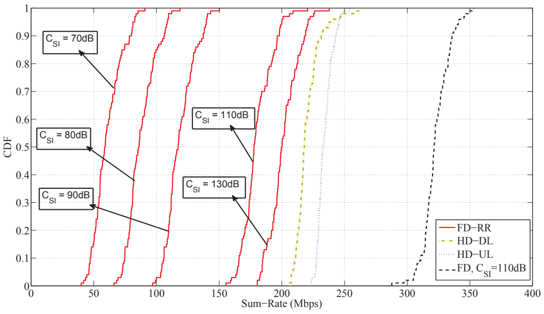

Fig. 4. Average sum-rate comparison of FD and FD-RR systems under equal power allocation.

(downlink) users so that each uplink (downlink) user has an approximately equal number of subcarriers allocated. Therefore, it does not exploit multiuser diversity.

V. Conclusion

In this paper, we have proposed a three step subcarrier and power allocation algorithm to maximize the system throughput for the OFDMA FD system. In particular, the subcarriers are first allocated to uplink and downlink users with power being fixed, and then power allocation is performed using IWF algorithm with subcarriers being fixed. The simulation results show that the proposed algorithm for the FD system performs similar to the HD scheduling around 85dB self-interference cancellation, and outperforms both HD and FD-RR significantly in terms of throughput under feasible self-interference cancellation levels, i.e. 110dB.

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