Interference Management in Full-Duplex Wireless Cellular Networks via Fractional Programming

(Invited Paper)

Kaiming Shen and Wei Yu
Electrical and Computer Engineering Department
University of Toronto, ON M5S 3G4, Canada
Email: {kshen,weiyu}@ece.utoronto.ca

***Abstract*—Mutual interference is a key obstacle in the realistic adoption of full-duplex (FD) technique in future wireless cellular networks. Interference is a much more pressing problem for FD system than for the conventional half-duplex (HD) system, because FD allows the same time-frequency resource to be used for both uplink and downlink, thus possibly creating myriad interference between multiple transmissions throughout the network. Without proper interference control, FD may not even outperform HD in a multicell setup. The main objective of this paper is to show that coordinated scheduling and power control enables wireless cellular networks to reap significant system-level performance improvement due to FD. Toward this end, this paper utilizes fractional programming to derive a sequence of convex reformulations that allow distributed and efficient iterative optimization. Numerical results suggest that the proposed system-level interference management can provide 30-40% rate gain for an optimized FD multicell network as compared to optimized HD.**

I. Introduction

Full-duplex (FD) transmission, whose history can be traced back to the early radar system in 1940s [1], revives in these years as a potential technique to raise spectral efficiency for the future wireless cellular networks. This is due mainly to the recent progress in analog and digital echo cancellation which now allows self-interference suppression of up to 110dB [2]. A line of recent works [1]–[6] have verified the success of FD technique in nearly doubling spectral efficiency for an isolated end-to-end wireless link.

Real-world wireless systems, however, never consist of just a single link. When multiple transmission links are densely present in the same geographical area, as can often occur in urban cellular networks, the aggressive exploitation of time-frequency resources in FD would also bring in myriad *inter-link* interference, which can easily negate the benefits of using FD. This work aims to show that a careful control of interference pattern by coordinating the link schedules and transmit powers is capable of regaining in part the loss due to interference. Toward this goal, the paper formulates a network utility maximization problem involving mixed integer optimization (for user scheduling) and nonconvex optimization (for power control), and proceeds to show that this problem can be transformed to a *fractional program* to facilitate its distributed and efficient solution.

Prior works on interference mitigation for FD are mostly based on heuristics. For instance, [7] proposes an opportunistic way of selecting between FD and half-duplex (HD) modes; [8] employs a heuristic penalty term to render the resource allocation interference-aware; [9] proposes to schedule the users geographically far apart so as to avoid strong interference. Other existing works, e.g., [10] and [11], focus on the single-cell scenario, and find the optimal schedule and power settings under some particular conditions.

Our paper distinguishes from the prior works with two aspects. First, we take a system level perspective by considering the maximization of the overall network utility of the average user rates in the long run, rather than a one-shot objective such as sum of instantaneous rates. Second, we treat the problem from a rigorous optimization perspective; the proposed algorithm is more reliable and significantly outperforms the benchmarks.

II. System Model

Consider a wireless multicell network in which the BSs and the user terminals are deployed with one transmit antenna and one receive antenna each. Let $\mathcal{B}$ be the set of BSs in the network; let $\mathcal{K}_i$ be the set of users that are associated with BS i. The users are scheduled within each cell on a slot-to-slot basis in the time domain. At time slot t, in cell i, denote the index of the user scheduled in uplink as $u_i[t]$ and denote the index of the user scheduled in downlink as $d_i[t]$; denote the uplink transmit power spectral density (PSD) of the scheduled user u_i as $p^{\text{ul}}_{u_i}[t]$ and denote the downlink transmit PSD of the BS i as $p^{\text{dl}}_i[t]$. For convenience, the total frequency bandwidth is normalized to 1, and the channels are assumed to be flat-fading across the band. The BS-to-BS, the user-to-BS, the BS-to-user, and the user-to-user channel strengths are denoted as $G^{\text{bb}}_{q_1,q_2}$, $G^{\text{bu}}_{q_1,q_2}$, $G^{\text{ub}}_{q_1,q_2}$, and $G^{\text{uu}}_{q_1,q_2}$, respectively where q_1 and q_2 are respectively the receiver and transmitter indices. Denote the additive white Gaussian background noise PSD level as σ^2. We assume that only the BSs are capable of transmitting and receiving signals in the same time-frequency resource block in FD mode, but not the user terminals; this is a common assumption in the literature [8], [9], [11].

The long-term system-level objective is to maximize a proportional fairness utility function of the network. Let $\bar{R}^{\text{ul}}_k$ and $\bar{R}^{\text{dl}}_k$ be the long-term average rates of user k respectively in the uplink and the downlink. The log-utility objective is

$$\text{utility } = \alpha^{\text{ul}} \sum_{i\in\mathcal{B}} \sum_{k\in\mathcal{K}_i} \log(\bar{R}_k^{\text{ul}}) + \alpha^{\text{dl}} \sum_{i\in\mathcal{B}} \sum_{k\in\mathcal{K}_i} \log(\bar{R}_k^{\text{dl}}) \quad (1)$$

where the factors α^{ul} and α^{dl} account for the priorities of uplink and downlink data streams.

To make the optimization over the user schedules and the PSDs tractable, we optimize the incremental change in log-utility in each time slot t, which is approximated as a weighted sum of instantaneous rates:

$$f_o[t] = \sum_{i\in\mathcal{B}} w_{u_i}^{\text{ul}}[t] R_{u_i}^{\text{ul}}[t] + \sum_{i\in\mathcal{B}} w_{d_i}^{\text{dl}}[t] R_{d_i}^{\text{dl}}[t], \quad (2)$$

where the weights are determined by

$$w_k^{\text{ul}}[t+1] = \frac{\alpha^{\text{ul}}}{\bar{R}_k^{\text{ul}}[t]} \text{ and } w_k^{\text{dl}}[t+1] = \frac{\alpha^{\text{dl}}}{\bar{R}_k^{\text{dl}}[t]}, \quad (3)$$

i.e., in proportion to the inverse of the uplink and the downlink average rates evaluated for user k up until time t. In the remainder of this paper, we drop the time index t for brevity.

The instantaneous uplink and downlink rates $R_{u_i}^{\text{ul}}$ and $R_{d_i}^{\text{dl}}$ in an FD multicell network are computed as follows. For uplink, introduce a factor $0 \le \varphi \le 1$ as the fraction of residual echo after self-interference cancellation (e.g., $\varphi = 0$ in the perfect cancellation case). The uplink rate is expressed as

$$R_{u_i}^{\text{ul}} = \log\left(1 + \frac{G_{i,u_i}^{\text{bu}} p_{u_i}^{\text{ul}}}{\sum\limits_{j\ne i} G_{i,u_j}^{\text{bu}} p_{u_j}^{\text{ul}} + \sum\limits_{j\ne i} G_{i,j}^{\text{bb}} p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2}\right). \quad (4)$$

In the denominator of the SINR term in the above expression, i.e., $\sum_{j\ne i} G_{i,u_j}^{\text{bu}} p_{u_j}^{\text{ul}} + \sum_{j\ne i} G_{i,j}^{\text{bb}} p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2$, the first term accounts for the uplink signal interference coming from the other scheduled uplink users, the second term accounts for the downlink signal interference coming from all the BSs in the nearby cells, and the third term accounts for self interference.

In the downlink, the instantaneous data rate is computed as

$$R_{d_i}^{\text{dl}} = \log\left(1 + \frac{G_{d_i,i}^{\text{ub}} p_i^{\text{dl}}}{\sum_j G_{d_i,u_j}^{\text{uu}} p_{u_j}^{\text{ul}} + \sum_{j\ne i} G_{d_i,j}^{\text{ub}} p_j^{\text{dl}} + \sigma^2}\right). \quad (5)$$

In the denominator of the SINR term in the above expression, i.e., $\sum_j G_{d_i,u_j}^{\text{uu}} p_{u_j}^{\text{ul}} + \sum_{j\ne i} G_{d_i,j}^{\text{ub}} p_j^{\text{dl}} + \sigma^2$, the first term accounts for the interference due to the uplink users, while the second term accounts for the interference due to the nearby BSs.

With the system model as characterized above, we can formulate a coordinated scheduling and power optimization problem for maximizing the FD network utility as follows:

$$\begin{aligned} &\text{maximize} && f_o(\mathbf{u}, \mathbf{d}, \mathbf{p}^{\text{ul}}, \mathbf{p}^{\text{dl}}) && \text{(6a)}\\ &\text{subject to} && u_i, d_i \in \mathcal{K}_i && \text{(6b)}\\ &&& 0 \le p_{u_i}^{\text{ul}} \le P_{\max}^{\text{ul}} && \text{(6c)}\\ &&& 0 \le p_i^{\text{dl}} \le P_{\max}^{\text{dl}} && \text{(6d)} \end{aligned}$$

where $P_{\max}^{\text{ul}}$ and $P_{\max}^{\text{dl}}$ are the maximum transmit PSD constraints in the uplink and the downlink, respectively.

The above optimization involves integer variables (u_i, d_i) as well as continuous variables (p_j^{dl}, $p_{u_i}^{\text{ul}}$); the problem is still nonconvex even when the integer variables are fixed. Therefore, directly solving such a problem is quite difficult.

III. Approach

The main idea of our approach is to apply the fractional programming technique [12] to decouple the denominator and numerator of the SINR term. The resulting reformulation is linear over the integer variables and also concave over the continuous variables; an efficient optimization then follows.

A. Fractional Programming Transform

Our fractional programming approach relies on the following two theorems, which are proposed in a previous work [12].

Theorem 1 (*Weighted Sum Log-Ratios*)**.** Given a nonempty constraint set $\mathcal{X}$, as well as weight $w_k \ge 0$, numerator function $A_k(\mathbf{x}) \ge 0$ and denominator function $B_k(\mathbf{x}) > 0$ for $k = 1, \ldots, K$, the weighted sum log-ratios problem

$$\underset{\mathbf{x}\in\mathcal{X}}{\text{maximize}} \quad \sum_{k=1}^{K} w_k \log\left(1 + \frac{A_k(\mathbf{x})}{B_k(\mathbf{x})}\right) \quad (7)$$

is equivalent to

$$\underset{\mathbf{x}\in\mathcal{X},\boldsymbol{\gamma}\succeq\mathbf{0}}{\text{maximize}} \quad \sum_{k=1}^{K} w_k \left(\log(1+\gamma_k) - \gamma_k + \frac{(1+\gamma_k)A_k(\mathbf{x})}{A_k(\mathbf{x}) + B_k(\mathbf{x})}\right) \quad (8)$$

where γ_k is an auxiliary variable introduced for each ratio.

Theorem 2 (*Weighted Sum Ratios*)**.** Given the same $\mathcal{X}$, w_k, $A_k(\mathbf{x})$, and $B_k(\mathbf{x})$ as assumed in Theorem 1, the weighted sum ratios problem

$$\underset{\mathbf{x}\in\mathcal{X}}{\text{maximize}} \quad \sum_{k=1}^{K} w_k \frac{A_k(\mathbf{x})}{B_k(\mathbf{x})} \quad (9)$$

is equivalent to

$$\underset{\mathbf{x}\in\mathcal{X},\mathbf{y}}{\text{maximize}} \quad \sum_{k=1}^{K} w_k \left(2y_k\sqrt{A_k(\mathbf{x})} - y_k^2 B_k(\mathbf{x})\right) \quad (10)$$

where y_k is an auxiliary variable introduced for each ratio.

Going back to our problem (6), applying Theorem 1 allows us to recast the original objective function f_o to f_r as displayed in (11) at the bottom of the next page, where γ_i^{ul} and γ_i^{dl} correspond to the uplink and downlink SINRs in cell i, respectively.

Observe that f_r is a concave function of $\boldsymbol{\gamma}$ when the other variables are held fixed. Thus, by setting $\nabla_{\boldsymbol{\gamma}} f_r = \mathbf{0}$, we obtain the optimal $\boldsymbol{\gamma}$ explicitly as

$$(\gamma_i^{\text{ul}})^* = \frac{G_{i,u_i}^{\text{bu}} p_{u_i}^{\text{ul}}}{\sum_{j\ne i} G_{i,u_j}^{\text{bu}} p_{u_j}^{\text{ul}} + \sum_{j\ne i} G_{i,j}^{\text{bb}} p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2} \quad \text{(12a)}$$

$$(\gamma_i^{\text{dl}})^* = \frac{G_{d_i,i}^{\text{ub}} p_i^{\text{dl}}}{\sum_j G_{d_i,u_j}^{\text{uu}} p_{u_j}^{\text{ul}} + \sum_{j\ne i} G_{d_i,j}^{\text{ub}} p_j^{\text{dl}} + \sigma^2}. \quad \text{(12b)}$$

We remark that the solutions of $\boldsymbol{\gamma}$ can be interpreted as the uplink/downlink SINRs in the network.

Further, we decouple the numerator and denominator for the weighted sum ratios of f_r by using Theorem 2; the resulting new objective function f_q is shown in (13) at the bottom of the page. Then, solving the original problem (6) amounts to maximizing f_q over the primal variables $(\mathbf{u}, \mathbf{d}, \mathbf{p})$ as well as the auxiliary variables $(\boldsymbol{\gamma}, \mathbf{y})$. With $\boldsymbol{\gamma}$ optimally updated by (12) in an iterative fashion, it remains to optimize the rest variables in f_q.

B. Joint User Scheduling and Power Control

When all the other variables are fixed, f_q turns out to be a concave function of $\mathbf{y}$, so the solution for $\mathbf{y}$ can be found in closed form by solving $\nabla_{\mathbf{y}} f_q = \mathbf{0}$, that is

$$(y_i^{\text{ul}})^* = \frac{\sqrt{w_i^{\text{ul}}(1+\gamma_i^{\text{ul}})G_{i,u_i}^{\text{bu}}p_{u_i}^{\text{ul}}}}{\sum_j G_{i,u_j}^{\text{bu}}p_{u_j}^{\text{ul}} + \sum_{j\neq i} G_{i,j}^{\text{bb}}p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2} \quad (14a)$$

$$(y_i^{\text{dl}})^* = \frac{\sqrt{w_{d_i}^{\text{dl}}(1+\gamma_i^{\text{dl}})G_{d_i,i}^{\text{ub}}p_i^{\text{dl}}}}{\sum_j G_{d_i,u_j}^{\text{uu}}p_{u_j}^{\text{ul}} + \sum_{j\neq i} G_{d_i,j}^{\text{ub}}p_j^{\text{dl}} + \sigma^2}. \quad (14b)$$

To optimize downlink power, we set $\nabla_{\mathbf{p}^{\text{dl}}} f_q = \mathbf{0}$ for each BS i to obtain the optimal downlink transmit PSD

$$(p_i^{\text{dl}})^* = \min \left\{ P_{\max}^{\text{ul}}, \left(\frac{y_i^{\text{dl}}\sqrt{w_{d_i}^{\text{dl}}(1+\gamma_i^{\text{dl}})G_{d_i,i}^{\text{ub}}}}{\sum\limits_j (y_j^{\text{dl}})^2 G_{d_j,i}^{\text{ub}} + \sum\limits_{j\neq i}(y_j^{\text{ul}})^2 G_{j,i}^{\text{bb}} + (y_i^{\text{ul}})^2\varphi} \right)^2 \right\}. \quad (15)$$

The optimal downlink schedule decision $\mathbf{d}$ can be obtained by recognizing that the f_q expression is of the form

$$f_q = \sum_{i\in\mathcal{B}} \xi_{d_i}^{\text{dl}} + \text{const} \quad (16)$$

where "const" refers to a constant term when all the variables excluding $\mathbf{d}$ are held fixed, and the parameter ξ_k^{dl} can be predetermined for every user k associated with BS i as follows:

$$\xi_k^{\text{dl}} = w_k^{\text{dl}}\log(1+\gamma_i^{\text{dl}}) - w_k^{\text{dl}}\gamma_i^{\text{dl}} + 2y_i^{\text{dl}}\sqrt{w_k^{\text{dl}}(1+\gamma_i^{\text{dl}})G_{k,i}^{\text{ub}}p_i^{\text{dl}}} - (y_i^{\text{dl}})^2\left(\sum_j G_{k,u_j}^{\text{uu}}p_{u_j}^{\text{ul}} + \sum_j G_{k,j}^{\text{ub}}p_j^{\text{dl}}\right). \quad (17)$$

Note that ξ_k^{dl} can be intuitively interpreted as a utility minus a cost, with its first three terms being the utility and the last term being the interference cost. The downlink scheduling decision now amounts to choosing the optimal downlink user that maximizes the utility-minus-cost value in each cell, i.e.,

$$d_i^* = \begin{cases} \arg\max\limits_{k\in\mathcal{K}_i} \xi_k^{\text{dl}}, & \text{if} \max\limits_{k\in\mathcal{K}_i}\{\xi_k^{\text{dl}}\} > 0 \\ \varnothing, & \text{otherwise} \end{cases} \quad (18)$$

where $\varnothing$ refers to the decision of not scheduling any user.

A similar set of optimizations can be done in the uplink. Assuming that user k is scheduled for uplink transmission by its associated BS i, the optimal uplink transmit PSD of user k is found by solving $\partial f_q/\partial p_{u_i}^{\text{ul}} = 0$ with u_i set to k, i.e.,

$$(p_k^{\text{ul}})^* = \min\left\{ P_{\max}^{\text{ul}}, \left(\frac{y_i^{\text{ul}}\sqrt{w_k^{\text{ul}}(1+\gamma_i^{\text{ul}})G_{i,k}^{\text{bu}}}}{\sum_j (y_j^{\text{dl}})^2 G_{d_j,k}^{\text{uu}} + \sum_j (y_j^{\text{ul}})^2 G_{j,k}^{\text{bu}}} \right)^2 \right\}. \quad (19)$$

For the uplink schedule decision, we recognize that the f_q expression is of the form

$$f_q = \sum_{i\in\mathcal{B}} \xi_{u_i}^{\text{ul}} + \text{const} \quad (20)$$

where "const" is a constant term when all the variables excluding $\mathbf{u}$ are held fixed, and the parameter ξ_k^{ul} is evaluated for every user k associated with BS i as below:

$$\xi_k^{\text{ul}} = w_k^{\text{ul}}\log(1+\gamma_i^{\text{ul}}) - w_k^{\text{ul}}\gamma_i^{\text{ul}} + 2y_i^{\text{ul}}\sqrt{w_k^{\text{ul}}(1+\gamma_i^{\text{ul}})G_{i,k}^{\text{bu}}p_k^{\text{ul}}} - \sum_j (y_j^{\text{ul}})^2 G_{j,k}^{\text{bu}}p_k^{\text{ul}} - \sum_j (y_j^{\text{dl}})^2 G_{d_j,k}^{\text{uu}}p_k^{\text{ul}}. \quad (21)$$

$$f_r(\mathbf{u},\mathbf{d},\mathbf{p}^{\text{ul}},\mathbf{p}^{\text{dl}},\boldsymbol{\gamma}^{\text{ul}},\boldsymbol{\gamma}^{\text{dl}}) = \sum_{i\in\mathcal{B}} w_{u_i}^{\text{ul}}\log(1+\gamma_i^{\text{ul}}) - \sum_{i\in\mathcal{B}} w_{u_i}^{\text{ul}}\gamma_i^{\text{ul}} + \sum_{i\in\mathcal{B}} \frac{w_{u_i}^{\text{ul}}(1+\gamma_i^{\text{ul}})G_{i,u_i}^{\text{bu}}p_{u_i}^{\text{ul}}}{\sum_j G_{i,u_j}^{\text{bu}}p_{u_j}^{\text{ul}} + \sum_{j\neq i}G_{i,j}^{\text{bb}}p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2} + \sum_{i\in\mathcal{B}} w_{d_i}^{\text{dl}}\log(1+\gamma_i^{\text{dl}}) - \sum_{i\in\mathcal{B}} w_{d_i}^{\text{dl}}\gamma_i^{\text{dl}} + \sum_{i\in\mathcal{B}} \frac{w_{d_i}^{\text{dl}}(1+\gamma_i^{\text{dl}})G_{d_i,i}^{\text{ub}}p_i^{\text{dl}}}{\sum_j G_{d_i,u_j}^{\text{uu}}p_{u_j}^{\text{ul}} + \sum_j G_{d_i,j}^{\text{ub}}p_j^{\text{dl}} + \sigma^2} \quad (11)$$

$$f_q(\mathbf{u},\mathbf{d},\mathbf{p}^{\text{ul}},\mathbf{p}^{\text{dl}},\boldsymbol{\gamma}^{\text{ul}},\boldsymbol{\gamma}^{\text{dl}},\mathbf{y}^{\text{ul}},\mathbf{y}^{\text{dl}}) = \sum_{i\in\mathcal{B}} \Bigg[w_{u_i}^{\text{ul}}\log(1+\gamma_i^{\text{ul}}) - w_{u_i}^{\text{ul}}\gamma_i^{\text{ul}} + 2y_i^{\text{ul}}\sqrt{w_{u_i}^{\text{ul}}(1+\gamma_i^{\text{ul}})G_{i,u_i}^{\text{bu}}p_{u_i}^{\text{ul}}} - (y_i^{\text{ul}})^2\left(\sum_j G_{i,u_j}^{\text{bu}}p_{u_j}^{\text{ul}} + \sum_{j\neq i}G_{i,j}^{\text{bb}}p_j^{\text{dl}} + \varphi p_i^{\text{dl}} + \sigma^2\right) + w_{d_i}^{\text{dl}}\log(1+\gamma_i^{\text{dl}}) - w_{d_i}^{\text{dl}}\gamma_i^{\text{dl}} + 2y_i^{\text{dl}}\sqrt{w_{d_i}^{\text{dl}}(1+\gamma_i^{\text{dl}})G_{d_i,i}^{\text{ub}}p_i^{\text{dl}}} - (y_i^{\text{dl}})^2\left(\sum_j G_{d_i,u_j}^{\text{uu}}p_{u_j}^{\text{ul}} + \sum_j G_{d_i,j}^{\text{ub}}p_j^{\text{dl}} + \sigma^2\right)\Bigg] \quad (13)$$

Similar to the downlink case, this uplink scheduling parameter also has a utility-minus-cost interpretation. The optimal uplink schedule decision can be determined in a distributed fashion across all the cells as follows:

$$u_i^* = \begin{cases} \arg\max_{k \in \mathcal{K}_i} \xi_k^{\text{ul}}, \text{ if } \max_{k \in \mathcal{K}_i} \{\xi_k^{\text{ul}}\} > 0 \\ \varnothing, \text{ otherwise.} \end{cases} \tag{22}$$

Combining the above optimization steps gives rise to the following coordinated algorithm:

Algorithm 1 User scheduling and power control for FD

Initialization: Initialize all the variables to feasible values.
repeat
1) Update γ^{ul} and γ^{dl} by (12);
2) Update $\mathbf{y}^{\text{ul}}$ and $\mathbf{y}^{\text{dl}}$ by (14);
3) Update $\mathbf{p}^{\text{dl}}$ by (15) and then $\mathbf{d}$ by (18);
4) Update $\mathbf{p}^{\text{ul}}$ by (19) and then $\mathbf{u}$ by (22);

until Convergence

Algorithm 1 is guaranteed to converge, with the sum weighted rate objective f_o nondecreasing after each iteration. In particular, for fixed $\mathbf{u}$ and $\mathbf{d}$, the final $\mathbf{p}^{\text{ul}}$ and $\mathbf{p}^{\text{dl}}$ after convergence are locally optimal in terms of f_o. Unlike the heuristics in [7]–[9], our proposed algorithm does not require parameter tuning and therefore is easier to implement.

IV. Simulation Results

We now illustrate the effectiveness of the proposed algorithm. Consider a cellular topology of 7 wrapped-around hexagonal cells, with one pico-BS located at the centre of each cell. The BS-to-BS distance is 0.4km. The same 40MHz-wide frequency band is fully used in every cell. There are a total of 105 users uniformly distributed within the network. Every user is associated with the BS with the strongest channel. Following [1], we set the maximum transmit PSD to be -55dBm/Hz for both the pico-BSs and the users (corresponding to a maximum transmit power of 21dBm), and set the background noise PSD to be -176dBm/Hz. The channel path-loss model is $128.1 + 37.6\log_{10}(d) + \tau$ (in dB), where d (in km) refers to the distance between the two terminals of the channel, and τ is a Gaussian random variable with 8dB standard deviation accounting for shadowing. Equal priorities are assigned to the uplink and the downlink utilities with $\alpha^{\text{ul}} = \alpha^{\text{dl}} = 1$.

The following methods serve as benchmarks:

- *FD baseline*: Users are scheduled by a round-robin policy in both uplink and downlink; all the terminals transmit at maximum PSD.
- *HD baseline*: FDD mode is adopted with equal amount of bandwidth for uplink and downlink; users are scheduled by a round-robin policy in both uplink and downlink; all the terminals transmit at maximum PSD.

Fig. 1 and 2 shows the cumulative distribution of the uplink and downlink user rates achieved with coordinated user scheduling and power optimization for both HD and FD and with either perfect echo cancellation or 110dB cancellation, as compared to the baselines. Observe that the performance of the FD baseline is in fact worse than HD baseline, illustrating the fact that due to the excessive interference FD may even be harmful as compared to HD with no interference management. The proposed coordinated algorithm significantly improves the user throughput for both HD and FD baslines, but the improvement is much more significant for FD.

The figure also shows the case with perfect self-interference cancellation. Some further gain is observed but the performance improvement of FD as compared to HD does not approach a factor of 2 even with perfect cancellation.

Fig. 3 compares the network log-utility of FD and HD schemes with or without coordinated optimization as functions of self-interference reduction capability of FD. It is shown that the proposed FD coordinated scheme can provide utility benefits even with modest echo cancellation capability of 100dB, while the FD baseline performs no better than the HD even at perfect cancellation, because of the inter-link interference induced by FD. These results indicate that interference control

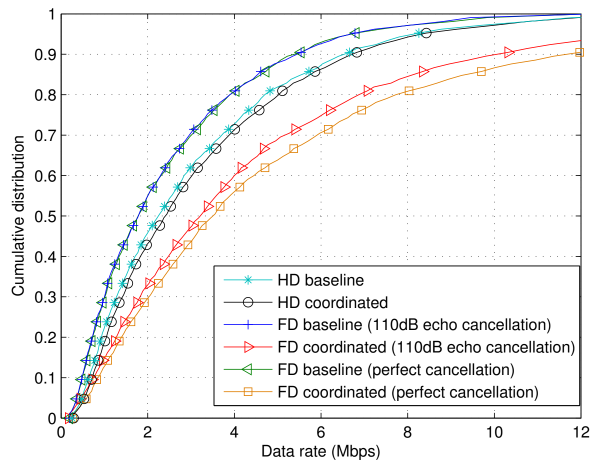

Fig. 1: Cumulative distribution of uplink user rates: FD vs HD

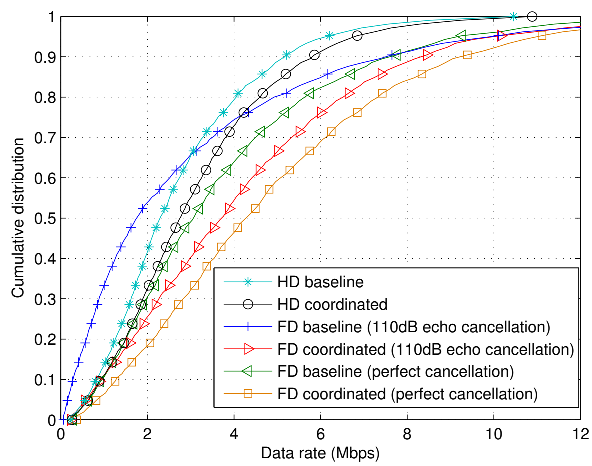

Fig. 2: Cumulative distribution of downlink user rates: FD vs HD

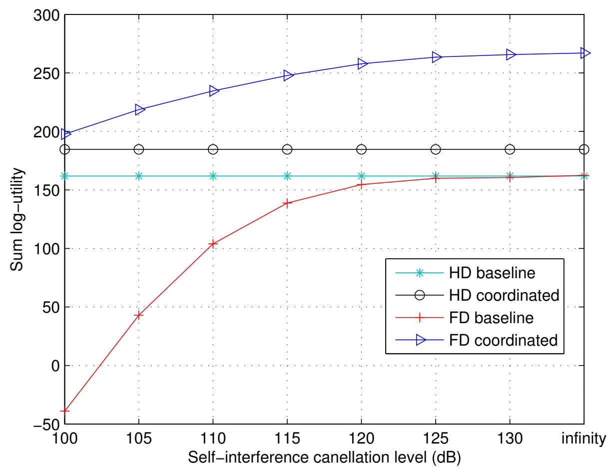

Fig. 3: Network utility of FD vs HD at varying cancellation levels

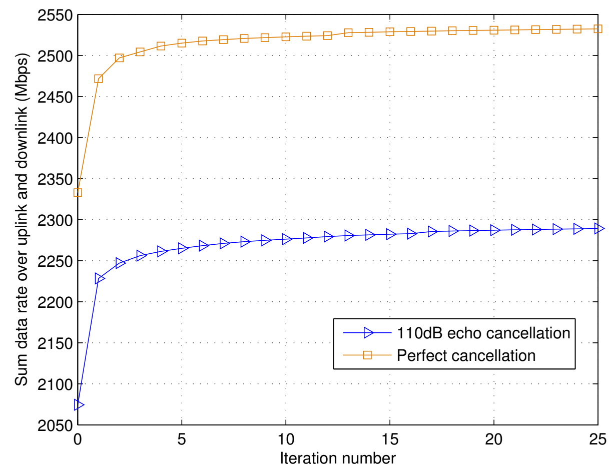

Fig. 5: Convergence of overall network throughput by Algorithm 1

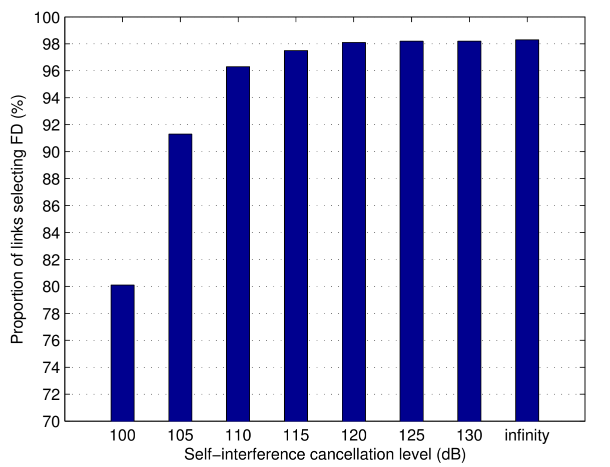

Fig. 4: Proportion of links selecting FD in Algorithm 1

with the proposed FP technique can effectively alleviate the negative effects from imperfect self-interference cancellation and from inter-link interference due to FD.

The optimization approach proposed in this paper is implicitly capable of switching between FD and HD, since the power optimization are included in the overall framework. Fig. 4 shows the percentage of links that use FD in the optimized solution as function of the self-interference cancellation capability. At 110dB echo cancellation, almost 96% of the links use FD, while with lower echo cancellation capability, the Algorithm 1 is able to adaptively choose between FD and HD modes. Finally, Fig. 5 shows that the proposed optimization algorithm has a fast convergence, reaching over 90% of the sum rate improvement after only 5 iterations.

V. Conclusion

This paper proposes an interference-aware user scheduling and power control algorithm for the FD wireless multicell networks. Fractional programming techniques are introduced to reformulate the original problem in a form where the integer and continuous variables can be efficiently optimized in an iterative fashion. The results of this paper show that interference management is crucial in an FD cellular network; with proper interference management, FD can improve user throughput of a multicell network by about 30-40% as compared to HD.

References

[1] A. Sabharwal, P. Schniter, D. Guo, D. W. Bliss, S. Rangarajan, and R. Wichman, "In-band full-duplex wireless: Challenges and opportunities," *IEEE J. Sel. Areas Commun.*, vol. 32, no. 9, pp. 1637–1652, Sept. 2014.

[2] J. I. Choi, M. Jain, K. Srinivasan, P. Levis, and S. Katti, "Achieving single channel, full duplex wireless communication," in *Proc. ACM MobiCom*, 2010, pp. 1–12.

[3] E. Aryafar, M. Khojastepour, K. Sundaresan, S. Rangarajan, and M. Chiang, "MIDU: Enabling MIMO full duplex," in *Proc. ACM MobiCom*, 2012, pp. 257–268.

[4] E. Everett, A. Sahai, and A. Sabharwal, "Passive self-interference suppression for full-duplex infrastructure nodes," *IEEE Trans. Wireless Commun.*, vol. 13, no. 2, pp. 680–694, Feb. 2014.

[5] A. C. Cirik, R. Wang, and Y. Hua, "Weighted-sum-rate maximization for bi-directional full-duplex MIMO systems," in *Asilomar Conf. Signals, Syst., Comput.*, Oct. 2013, pp. 1632–1636.

[6] Z. Zhang, X. Chai, K. Long, A. V. Vasilakos, and L. Hanzo, "Full duplex techniques for 5G networks: Self-interference cancellation, protocol design, and relay selection," *IEEE Commun. Mag.*, vol. 53, no. 5, pp. 128–137, May 2015.

[7] T. Riihonen, S. Werner, and R. Wichman, "Hybrid full-duplex/half-duplex relaying with transmit power adaptation," *IEEE Trans. Wireless Commun.*, vol. 10, no. 9, pp. 3074–3085, Sept. 2011.

[8] B. Di, S. Bayat, L. Song, and Y. Li, "Radio resource allocation for full-duplex OFDMA networks using matching theory," in *IEEE Conf. Comput. Commun. (INFOCOM) Workshops*, Oct. 2014, pp. 197–198.

[9] M. Duarte, A. Feki, and S. Valentin, "A matching game for decoupled uplink-downlink user association in full-duplex small cell networks," in *IEEE Int. Conf. Commun. (ICC)*, May 2016.

[10] H. Ju and R. Zhang, "Optimal resource allocation in full-duplex wireless-powered communication network," *IEEE Trans. Commun.*, vol. 62, no. 10, pp. 3528–3540, Oct. 2014.

[11] G. C. Alexandropoulos, M. Kountouris, and I. Atzeni, "User scheduling and optimal power allocation for full-duplex cellular networks," in *IEEE Workshop Signal Process. Advances Wireless Commun. (SPAWC)*, July 2016.

[12] K. Shen and W. Yu, "Fractional programming for communication systems, Part II: Scheduling," *Preprint*, 2017.