Interference Mitigation via Power Optimization Schemes for Full-Duplex Networking

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***Abstract*—In this paper we study the interference mitigation problem based on power adjustment of the involved nodes, for a cellular communication system where base stations are empowered with full-duplex capability. A full-duplex base station, by definition, is capable of transmission and reception at the same time and frequency and hence can simultaneously establish a downlink and uplink communication, and potentially increase the spectral efficiency. In the first step, an overview of the system is given, where new sources of interference are discovered due to the full-duplex function at the base station. It is discussed that the coordination of the base stations via strong backhaul connection is essential to estimate and reduce the main parts of the interference signals. In the next step, we aim at mitigating the effects of the remaining interference paths via smart power adjustment at the involved communicating nodes. In this regard two strategies will be considered. Firstly, the transmit powers will be adjusted to maximize the provided rate to the users in a fair fashion, following a max-min approach. In the second approach, the power optimization is done in order to maximize the sum-rate in the network. The aforementioned strategies are then evaluated via numerical simulations.**

I. Introduction

The tempting idea of full-duplex (FD) communications, as the ability to establish two directions of communication at the same time and frequency, has been long considered to be practically infeasible due to the inherent self-interference. In theory, since each node is aware of its own transmitted signal, the interference from the loopback path can be estimated and suppressed. However, in practice this procedure is challenging due to the high strength of the self-interference channel, limited channel state information (CSI) precision, as well as the inaccuracies in the Rx and Tx chains (e.g., power amplifier non-linearity, oscillator phase noise, limited analog to digital convertor (ADC) and digital to analog convertor (DAC) precision). Recently, specialized cancellation techniques, i.e., [1]–[4] and [5], have provided an adequate level of isolation between Tx and Rx directions to facilitate a FD communication. A common idea of these approaches is the accurate attenuation of main interference components in RF (prior to down-conversion), so that the remaining self-interference can be correctly processed in the effective dynamic range of the ADC and further attenuated in the baseband (digital) domain. The reported result in [4] promises the suppression of self-interference down to the receiver noise floor throughout the bandwidth of 80 MHz. Hence investigating the possible gains and methodology of applying FD operation on the traditionally half-duplex (HD) scenarios is becoming more interesting. In this work we study the impact of a FD-empowered base station (BS) on the performance of the traditional cellular systems. The aforementioned scenario is particularly interesting for a FD update, as higher resource efficiency can be achieved while the end users remain compatible to their previous HD operation. Nevertheless, realizing a better resource efficiency is highly dependent on the smart interference mitigation schemes in order to tackle the new sources of interference, which are inherent to the FD operation [6]. Other than the well-known interference sources of the traditional cells, i.e., inter-cell uplink (UL) to BS and inter-cell base station to downlink (DL) interference, see Fig. 1, we recognize new sources of interference in a system with FD base station. Due to the simultaneous transmission and reception on the same channel at the base station on one hand, and the co-channel operation of the uplink and downlink in the same cell, we are additionally facing with i) the *self-interference* at each FD base station node, ii) the interference due to the simultaneous transmission and reception among adjacent base stations, i.e., *inter-BS interference*, iii) interference among the uplink and downlink directions in the same cell, i.e., *intra-cell UL-DL interference* and iv) interference among the uplink direction and the downlink direction at the adjacent cells, i.e., *inter-cell UL-DL interference*, see Fig. 2. As the methodology of dealing with the interference in traditional cells is well-known in the literature, there exists very little work on how to deal with the aforementioned interference sources in a similar FD system. In [7] multiple antenna techniques are studied in order to extend the multi-user MIMO scenarios with the FD operation at the base station, while assuming the loop-back self interference at the base station as the only existing interference in the system. Similar methods have been then extended in [8] by incorporating the intra-cell UL-DL interference, using a simplified model for the loopback self-interference at the base station. An interesting discussion on the theoretical gains and possible interference alignment schemes for such a system is been provided in [9], assuming the intra-cell UL-DL interference (type iii interference) as the only interference in the system. A more realistic picture of a cellular system with FD operation at the base station is discussed in [6] and few useful outlines are provided to obtain higher spectral efficiency, compared to a HD counterpart.

Contribution: In this work we present interference mitigation schemes via power adjustment on the involved nodes, where non of the major interference sources are ignored. Although the allocation of channels to the users plays an important role in managing the resulting interference, we assume a given channel allocation for each user and merely focus on the power optimization in this work. In this regard two strategies will be considered. Firstly, the transmit powers

ISBN 978-3-8007-3662-1

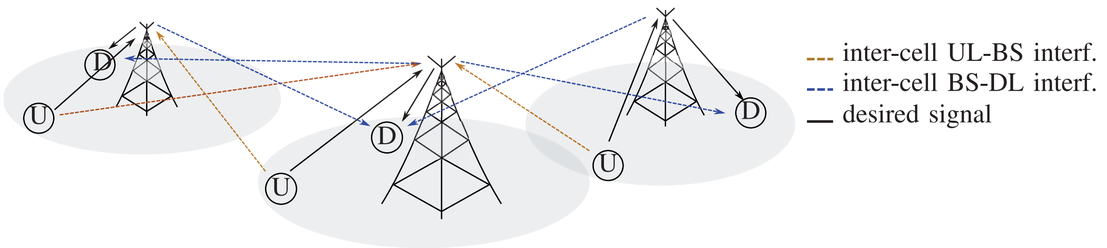

Fig. 1. Interference signals for cells with FD base station, similar to a traditional cell, i.e., with HD base station. Uplink and downlink nodes are sharing the same channel as the base station nodes are functioning in FD mode. Traditional interference sources still exit with the FD setup. Uplink and downlink users are represented by U and D, respectively.

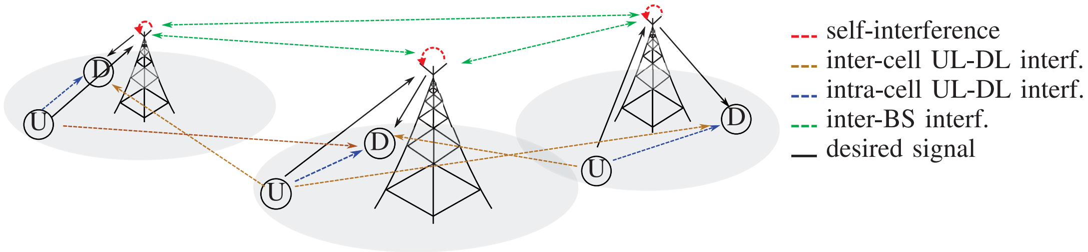

Fig. 2. Interference signals specific to the FD operation in the BS. Uplink and downlink nodes are sharing the same channel as the base station nodes are functioning in the FD mode. New sources of interference appear, due to FD operation. Uplink and downlink users are represented by U and D, respectively.

will be adjusted to maximize the provided rate to the users in a fair fashion. In the second approach, the power optimization is done for a greedy sum-rate maximization in the network. The aforementioned strategies are then evaluated via numerical simulations.

Paper organization: In this document, a detailed system description and mathematical model is presented in Section II. The proposed fair power optimization is then provided in Section III. The power adjustment, following the greedy sum rate maximization is presented in Section IV. Finally, numerical evaluation is performed in Section V. We conclude the paper in Section VI.

II. System Model

We investigate a cellular communication system in which L full-duplex and single antenna base stations are providing communication service to the users. We study the scenario where K single antenna uplink users, $U_1^{(l)} \cdots U_k^{(l)} \cdots U_K^{(l)}$, and K single antenna downlink users, $D_1^{(l)} \cdots D_k^{(l)} \cdots D_K^{(l)}$ are communicating with the BS node with index l, see Fig. 3. We assume that each user is assigned to a single sub-channel where the index k represents the sub-channel which is associated with the uplink user $U_k^{(l)}$ and the downlink user $D_k^{(l)}$. While DL and UL users with different sub-channel index do not make direct interference on each other, their operation is connected due to the nature of self-interference at the base station, which requires a joint power optimization of all users in a cell[1]. All users are assumed to operate in HD mode, where the UL and DL users with the same index, e.g., $U_k^{(l)}$ and $D_k^{(l)}$ are operating at the same sub-channel. For the base station with index l, we denote the uplink channel for $U_k^{(l)}$ as $h_{\text{ub},k}^{(l)} \in \mathbb{C}$, the downlink channel for $D_k^{(l)}$ as $h_{\text{bd},k}^{(l)} \in \mathbb{C}$, and the interference channel between $U_k^{(l)}$ and $D_k^{(l)}$ as $h_{\text{ud},k}^{(l)} \in \mathbb{C}$. The loopback self-interference sub-channel, coinciding with the function of $U_k^{(l)}$ at the base station is denoted as $h_{\text{bb},k}^{(l)} \in \mathbb{C}$, see Fig. 3. The BS to BS, BS to DL, UL to DL and UL to BS inter-cell interference channels are respectively denoted as $h_{\text{bb},k}^{(l_1,l_2)}, h_{\text{bd},k}^{(l_1,l_2)}, h_{\text{ud},k}^{(l_1,l_2)}, h_{\text{ub},k}^{(l_1,l_2)} \in \mathbb{C}$, where l_2 and l_1 represent the indexes of the cells corresponding to the origin and destination of the interference paths. We assume all sub-channels are frequency flat and the channel knowledge is available.

[1]Residual self-interference acts with a white nature [10], and after analog-domain cancellation, spreads over all sub-channels. E.g., a high-power transmission in a single sub-channel at BS, results in residual interference components at all sub-channels in the receiver side.

A. Communication schedule with FD base station

In a network with HD base stations, the operation of UL and DL users is usually separated via frequency division duplex (FDD) or time division duplex (TDD) schemes. As a result, e.g., in the TDD scheme, the communication from base station to $D_k^{(l)}$ will be only activated, after the uplink communication by $U_k^{(l)}$ is accomplished (two-phase communication). On the other hand, for a FD base station, the transmission from $U_k^{(l)}$ can be done simultaneous to the transmission to $D_k^{(l)}$. In the current work, we follow the similar two-phase communication as for the HD setup, with the exception that the uplink and downlink communications can be simultaneously active on the same sub-channel.

B. Uplink communication

In the uplink, the base station with index l receives the desired transmit signal from $U_k^{(l)}$ together with noise, the self-interference from its own transmit front-end, and the collective sources of interference from the adjacent cells, see Fig. 2:

$$y_{\mathrm{b},k,i}^{(l)} = h_{\mathrm{ub},k}^{(l)} \sqrt{P_{\mathrm{u},k,i}^{(l)}} s_{\mathrm{u},k,i}^{(l)} + \underbrace{h_{\mathrm{bb},k}^{(l)} \sqrt{P_{\mathrm{b},k,i}^{(l)}} s_{\mathrm{b},k,i}^{(l)}}_{\text{self-interf.}=:c_{k,i}^{(l)}} + \underbrace{\sum_{z \neq l} h_{\mathrm{bb},k}^{(l,z)} \sqrt{P_{\mathrm{b},k,i}^{(z)}} s_{\mathrm{b},k,i}^{(z)} + h_{\mathrm{ub},k}^{(l,z)} \sqrt{P_{\mathrm{u},k,i}^{(z)}} s_{\mathrm{u},k,i}^{(z)}}_{\text{collective inter-cell interf.}=:m_{\mathrm{b},k,i}^{(l)}} + n_{\mathrm{b},k,i}^{(l)}, \tag{1}$$

where $i \in \{1, 2\}$ represents the index of the communication phase. $y_{\mathrm{b},k,i}^{(l)} \in \mathbb{C}$ is the baseband representation of the received signal at the base station at sub-channel k and i-th time slot, $P_{\mathrm{u},k,i}^{(l)} \in \mathbb{R}$ and $P_{\mathrm{b},k,i}^{(l)} \in \mathbb{R}$ represent the transmit power for the uplink user and the base station, and $s_{\mathrm{u},k,i}^{(l)} \in \mathbb{C}$ and $s_{\mathrm{b},k,i}^{(l)} \in \mathbb{C}$ represent the corresponding transmitted data symbols. We assume $\mathcal{E}\{s_{\mathrm{u},k,i}^{(l)} {s_{\mathrm{u},k,i}^{(l)}}^*\} = \mathcal{E}\{s_{\mathrm{b},k,i}^{(l)} {s_{\mathrm{b},k,i}^{(l)}}^*\} = 1$, where $\mathcal{E}\{\cdot\}$ represents the mathematical expectation. The zero-mean circularly symmetric complex Gaussian noise at the base station is represented as $n_{\mathrm{b},k,i}^{(l)} \in \mathbb{C}$ with variance $N_{\mathrm{b},k,i}^{(l)}$ and the combination of all coexisting interferences from the adjacent cells is represented as $m_{\mathrm{b},k,i}^{(l)} \in \mathbb{C}$. It is worth mentioning, that ideas for mitigating the interference for traditional (HD) cells have been proposed recently, exploiting the strong backhaul connection and synchronization among the base stations [11], [12]. A famous example of such methods is the coordinated multi-point (CoMP) transmission and reception which is standardized within 4G long term evolution advanced (LTE-A). These ideas are as well extendible for FD setup and can effectively reduce the effects of inter-cell interference components. Nevertheless, implementing such systems are costly and require coordination and joint processing with respect to the all active nodes, which results in a significant burden and latency. Furthermore they are not effective in dealing with the inter and intra-cell UL-DL interference signals, see Fig. 2, as these interference signals are not affected by the infrastructure nodes. Hence, in this work, we focus on a more general interference mitigation design, where the coordination among infrastructure nodes is only exploited to tackle the inter-BS interference signal, and does not implement a per-user coordination and processing.

1) Self-interference at BS: As the self-interference is been transmitted from the same node, it can be estimated and subtracted at the receiver side, in the ideal case. Nevertheless, due to the high-power nature of the self-interference signal, the baseband representation of the received signal in (4) can not be realized in the digital domain, due to the limited dynamic range of the receiver chain. As the result more specialized techniques have been developed to tackle the self-interference cancellation problem in different stages, i.e., in the analog domain, propagation domain and via digital processing methods [2]–[4]. The remaining self-interference has been modeled in [10], [13] based on system measurements and analysis [14], [15]. As it is shown, the residual interference components can be modeled as an additional noise component whose variance is dependent on the accuracy and the induced power of the involved chains. For the defined base station setup we have

$$\bar{c}_{k,i}^{(l)} \sim \mathcal{CN}\left(0, \beta_k^{(l)} \left| h_{\mathrm{bb},k}^{(l)} \right|^2 P_{\mathrm{tx},i}^{(l)} + \gamma_k^{(l)} P_{\mathrm{rx},i}^{(l)}\right) \sim \mathcal{CN}\left(0, \beta_k^{(l)} \left| h_{\mathrm{bb},k}^{(l)} \right|^2 \sum_k P_{\mathrm{b},k,i}^{(l)} + \gamma_k^{(l)} \sum_k P_{\mathrm{b},k,i}^{(l)} \left| h_{\mathrm{bb},k}^{(l)} \right|^2 \right) \tag{2}$$

where $P_{\mathrm{tx},i}^{(l)}$ and $P_{\mathrm{rx},i}^{(l)}$ are the collective power levels (in all sub-channels) at transmit and receive chains for the communication phase i, which are related to the variance of the residual self-interference signal via the coefficients $\beta_k^{(l)}, \gamma_k^{(l)} \in \mathbb{R}_+$, respectively. The baseband representation of the residual self-interference signal is denoted as $\bar{c}_{k,i}^{(l)}$. More elaborations on the used distortion model can be found in [10] and the references therein.

2) Inter-BS interference: Other than the interference from the own transmit front-end (self-interference), the interference from adjacent BS nodes is the most severe interference on the BS. On the other hand, we can benefit from the strong backhaul connection between BS nodes to communicate the transmit signal to the adjacent base stations. For the special case, where the channel between adjacent BS nodes is accurately known, the aforementioned interference can be estimated and subtracted in the digital domain. It is worth mentioning, that unlike the self-interference signal, there is no dynamic range challenge regarding the accurate digital domain processing as the interference signal is already attenuated via passing through the inter-BS channel. In this work we denote the remaining parts of the inter-cell interference for the sub-channel k at the base station with index l as

$$\bar{m}_{\mathrm{b},k,i}^{(l)} \sim \mathcal{CN}\left(0, M_{\mathrm{b},k,i}^{(l)}\right), \tag{3}$$

where $M_{\mathrm{b},k}^{(l)}$ is the variance of the defined residual interference, $\bar{m}_{\mathrm{b},k,i}^{(l)}$. It is worth mentioning that the Gaussian distribution assumption of the interference signals is not necessarily accurate and represents a worst-case approximation of the interference signal's statistics. The interference-reduced version of the received signal at the BS can be hence formulated as

$$\bar{y}_{\mathrm{b},k,i}^{(l)} = h_{\mathrm{ub},k}^{(l)} \sqrt{P_{\mathrm{u},k,i}^{(l)}} s_{\mathrm{u},k,i}^{(l)} + \bar{c}_{k,i}^{(l)} + \bar{m}_{\mathrm{b},k,i}^{(l)} + n_{\mathrm{b},k,i}^{(l)}, \tag{4}$$

where $\bar{c}_{k,i}^{(l)}$ and $\bar{m}_{\mathrm{b},k,i}^{(l)}$ respectively represent the interference-reduced version of the self-interference at the base station, and the collective interference from the adjacent cells.

C. Downlink communication

In the downlink, the data symbols are transmitted from the BS, and degraded by the noise, the intra-cell UL-DL interference, and interference signals from adjacent cells:

$$y_{\mathrm{d},k,i}^{(l)} = h_{\mathrm{bd},k}^{(l)} \sqrt{P_{\mathrm{b},k,i}^{(l)}} s_{\mathrm{b},k,i}^{(l)} + \underbrace{h_{\mathrm{ud},k}^{(l)} \sqrt{P_{\mathrm{u},k,i}^{(l)}} s_{\mathrm{u},k,i}^{(l)}}_{\text{UL-DL interf.}} + \underbrace{\sum_{z \neq l} h_{\mathrm{bd},k}^{(l,z)} \sqrt{P_{\mathrm{b},k,i}^{(z)}} s_{\mathrm{b},k,i}^{(z)} + h_{\mathrm{ud},k,i}^{(l,z)} \sqrt{P_{\mathrm{u},k,i}^{(z)}} s_{\mathrm{u},k,i}^{(z)}}_{\text{collective inter-cell interf.}=:m_{\mathrm{d},k,i}^{(l)}} + n_{\mathrm{d},k,i}^{(l)}, \tag{5}$$

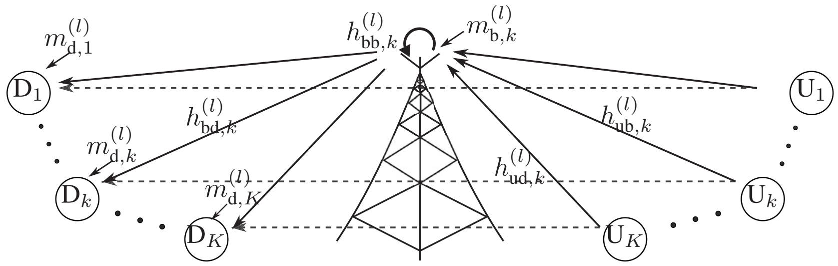

Fig. 3. The defined signal model for the cell with index l. K uplink users, $U_1 \cdots U_K$ and K downlink users, $D_1 \cdots D_K$ are communicating with BS where the nodes with same index are using the same channel (FD operation at BS). Dashed arrows represent the intra-cell UL-DL interference (type iii interference), and the tilted arrows represent the collective interference signals from the adjacent cells.

where $m_{\text{d},k,i}^{(l)} \sim \mathcal{CN}\left(0, M_{\text{d},k,i}^{(l)}\right)$ represents the interference from adjacent cells including inter-cell UL-DL and inter-cell BS-DL interference, see Figs. 1,2. Please note that similar to the UL case, the Gaussian distribution assumption of the interference signal is not necessarily accurate and represents a worst-case approximation of the interference signal's statistics. The following parts of this paper are dedicated to study how an appropriate power adjustment scheme on the communicating nodes can be beneficial to enhance the communication quality for the network.

III. Transmit Power adjustment with fair rate maximazation

It is clear that a smart power adjustment can mitigate the destructive effects of the defined interference components. In an extreme case, where the FD-inherent sources of interference are dominant, we can turn the FD system into the corresponding HD setup by separating the UL and DL communications in the defined consecutive communication phases, i.e., $i = 1$ and $i = 2$. In this section, we are aiming at providing an optimization strategy on the power of the communicating nodes, where the delivered communication rate is enhanced for all of the communicating users. In order to obtain a quality metric of the system we formulate

$$R_{\text{u},k}^{(l)} = \sum_{i \in \{1,2\}} \log_2 \left(1 + \frac{P_{\text{u},k,i}^{(l)} \left| h_{\text{ub},k}^{(l)} \right|^2}{N_{\text{b},k,i}^{(l)} + M_{\text{b},k,i}^{(l)} + C_{\text{b},k,i}^{(l)}} \right), \quad (6)$$

$$R_{\text{d},k}^{(l)} = \sum_{i \in \{1,2\}} \log_2 \left(1 + \frac{P_{\text{b},k,i}^{(l)} \left| h_{\text{bd},k}^{(l)} \right|^2}{N_{\text{d},k,i}^{(l)} + M_{\text{d},k,i}^{(l)} + P_{\text{u},k,i}^{(l)} \left| h_{\text{ud},k}^{(l)} \right|^2} \right), \quad (7)$$

where $C_{\text{b},k,i}^{(l)} := \beta_k^{(l)} \left| h_{\text{bb},k}^{(l)} \right|^2 \sum_k P_{\text{b},k,i}^{(l)} + \gamma_k^{(l)} \sum_k P_{\text{b},k,i}^{(l)} \left| h_{\text{bb},k}^{(l)} \right|^2$, is the indication of the residual self-interference intensity (2), and $R_{\text{u},k}^{(l)}$ and $R_{\text{d},k}^{(l)}$ are the achievable communication rates in the UL-BS and in the BS-DL directions, respectively. The collective inter-cell interference power can be inferred from (1), (3) and (5) as

$$M_{\text{b},k,i}^{(l)} = \sum_{z \neq l} \left| h_{\text{ub},k}^{(l,z)} \right|^2 P_{\text{u},k,i}^{(z)}, \quad (8)$$

$$M_{\text{d},k,i}^{(l)} = \sum_{z \neq l} \left| h_{\text{bd},k}^{(l,z)} \right|^2 P_{\text{b},k,i}^{(z)} + \left| h_{\text{ud},k}^{(l,z)} \right|^2 P_{\text{u},k,i}^{(z)}, \quad (9)$$

assuming that different information sources are mutually independent and zero-mean. In order to incorporate the individual requirements of each communicating user we define the weights: $\mu_{\text{u},k}^{(l)}, \mu_{\text{d},k}^{(l)} \in \mathbb{R}^+$, which represent the quality demand for each link. The corresponding optimization strategy is then formulated as

$$\begin{aligned} \max_{P_{\text{b},k,i}^{(l)}, P_{\text{u},k,i}^{(l)} \in \mathbb{R}^+} \quad & \min_{k,l} \ \min\left(R_{\text{u},k}^{(l)} / \mu_{\text{u},k}^{(l)},\ R_{\text{d},k}^{(l)} / \mu_{\text{d},k}^{(l)} \right) \\ \text{s.t.} \quad & \sum_k P_{\text{b},k,i}^{(l)} \leq P_{\text{b-max}}^{(l)}, \ \ \forall l, i, \\ & P_{\text{u},k,i}^{(l)} \leq P_{\text{u-max},k}^{(l)}, \ \ \forall k, l, i, \end{aligned} \quad (10)$$

where $P_{\text{b-max}}^{(l)}$ and $P_{\text{u-max},k}^{(l)}$ represent the maximum allowed transmit power from the base station and the users, respectively. The quantities $R_{\text{u},k}^{(l)} / \mu_{\text{u},k}^{(l)}$ and $R_{\text{d},k}^{(l)} / \mu_{\text{d},k}^{(l)}$ are the normalized rates in the uplink and downlink directions to the user's rate demand. It can be observed that the defined problem (10) can be reformulated into the equivalent form

$$\begin{aligned} \max_{P_{\text{b},k,i}^{(l)}, P_{\text{u},k,i}^{(l)} \in \mathbb{R}^+} \quad & \epsilon \\ \text{s.t.} \quad & R_{\text{u},k}^{(l)} / \mu_{\text{u},k}^{(l)} \geq \epsilon, \ R_{\text{d},k}^{(l)} / \mu_{\text{d},k}^{(l)} \geq \epsilon, \ \forall k, l, \\ & \sum_k P_{\text{b},k,i}^{(l)} \leq P_{\text{b-max}}^{(l)}, \ \ \forall l, i, \\ & P_{\text{u},k}^{(l)} \leq P_{\text{u-max},k}^{(l)}, \ \ \forall k, l, i, \end{aligned} \quad (11)$$

where ϵ is the feasible normalized rate which holds for all of the communication links. Due to the mathematical structure of the sum rate for uplink (6) and for downlink (7), our optimization problem (11) does not exhibit a convex structure with no obvious analytical solution. As the result, we apply a sequential convex optimization framework, see [16], where an approximated version of (11) is optimized in each step. For a known set of power values: $\check{P}_{\text{b},k,i}^{(l)}, \check{P}_{\text{u},k,i}^{(l)}, \ \forall i, l, k$, we can linearly approximate the sum rate in (6) and (7) as

$$\begin{aligned} R_{\text{u},k}^{(l)} \sim \check{R}_{\text{u},k}^{(l)} + \sum_{d_1} \sum_{d_2} \sum_{d_3} \Big(& \lambda_{d_1,d_2,d_3}^{\text{b},k,l} \left(P_{\text{b},d_2,d_3}^{(l)} - \check{P}_{\text{b},d_2,d_3}^{(l)} \right) \\ & + \lambda_{d_1,d_2,d_3}^{\text{u},k,l} \left(P_{\text{u},d_2,d_3}^{(d_1)} - \check{P}_{\text{u},d_2,d_3}^{(d_1)} \right) \Big), \end{aligned} \quad (12)$$

$$\begin{aligned} R_{\text{d},k}^{(l)} \sim \check{R}_{\text{d},k}^{(l)} + \sum_{d_1} \sum_{d_2} \sum_{d_3} \Big(& \tau_{d_1,d_2,d_3}^{\text{b},k,l} \left(P_{\text{b},d_2,d_3}^{(l)} - \check{P}_{\text{b},d_2,d_3}^{(l)} \right) \\ & + \tau_{d_1,d_2,d_3}^{\text{u},k,l} \left(P_{\text{u},d_2,d_3}^{(d_1)} - \check{P}_{\text{u},d_2,d_3}^{(d_1)} \right) \Big), \end{aligned} \quad (13)$$

ISBN 978-3-8007-3662-1

where $d_1 \in \{1, \cdots, L\}, d_2 \in \{1, \cdots, K\}$ and $d_3 \in \{1, 2\}$ respectively represent the index of the cell, the subchannel, and the communication phase for the corresponding transmission power. In order to ensure the validity of the above approximation, we define a trust region [16] for the power values as

$$\check{P}^{(l)}_{\text{u},k,i} - \delta^{(l)}_{\text{u},k,i} \leq P^{(l)}_{\text{u},k,i} \leq \check{P}^{(l)}_{\text{u},k,i} + \delta^{(l)}_{\text{u},k,i}, \tag{14}$$

$$\check{P}^{(l)}_{\text{d},k,i} - \delta^{(l)}_{\text{d},k,i} \leq P^{(l)}_{\text{d},k,i} \leq \check{P}^{(l)}_{\text{d},k,i} + \delta^{(l)}_{\text{d},k,i}, \tag{15}$$

which will add up to the problem (11) in each iteration as additional affine constraints. It is worth mentioning that the above formulation (12), is the first-order Taylor series approximation of the sum rate function in the uplink, at the point $\check{P}^{(l)}_{\text{b},k,i}, \check{P}^{(l)}_{\text{u},k,i}, \ \forall i, l, k$. The coefficients $\lambda^{\text{u},k,l}_{d_1,d_2,d_3}$ and $\lambda^{\text{b},k,l}_{d_1,d_2,d_3}$ can be hence calculated as

$$\lambda^{\text{b},k,l}_{d_1,d_2,d_3} := \begin{cases} \frac{-\left(\gamma^{(l)}_k + \beta^{(l)}_k\right)\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}h^{(l)}_{\text{bb},k}\right|^2}{\ln(2)\times\Pi^{(l)}_{\text{b},k,i}\left(\Pi^{(l)}_{k,i}+\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}\right|^2\right)} & d_1 = l, \ d_2 = k, \\ 0 & d_1 \neq l, \ d_2 = k, \\ \frac{-\left(\gamma^{(l)}_k\left|h^{(l)}_{\text{bb},d_2}\right|^2 + \beta^{(l)}_k\left|h^{(l)}_{\text{bb},k}\right|^2\right)\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}\right|^2}{\ln(2)\times\Pi^{(l)}_{k,i}\left(\Pi^{(l)}_{k,i}+\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}\right|^2\right)} & d_1 = l, \ d_2 \neq k, \\ 0 & d_1 \neq l, \ d_2 \neq k, \end{cases} \tag{16}$$

and

$$\lambda^{\text{u},k,l}_{d_1,d_2,d_3} := \begin{cases} \frac{1}{\ln(2)} \times \frac{\left|h^{(l)}_{\text{ub},k}\right|^2}{\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}\right|^2 + \Pi_{k,i}(l)} & d_1 = l, \ d_2 = k, \\ \frac{1}{\ln(2)} \times \frac{-\left|h^{(l,d_1)}_{\text{ub},k}h^{(l)}_{\text{ub},k}\right|^2\check{P}^{(l)}_{\text{u},k,i}}{\Pi^{(l)}_{k,i}\left(\Pi^{(l)}_{k,i}+\check{P}^{(l)}_{\text{u},k,i}\left|h^{(l)}_{\text{ub},k}\right|^2\right)} & d_1 \neq l, \ d_2 = k, \\ 0 & d_1 = l, \ d_2 \neq k, \\ 0 & d_1 \neq l, \ d_2 \neq k, \end{cases} \tag{17}$$

where $\Pi^{(l)}_{k,i}$ is the resulting value of the term $N^{(l)}_{\text{b},k,i} + M^{(l)}_{\text{b},k,i} + C^{(l)}_{\text{b},k,i}$ for a given set of the power values $\check{P}^{(l)}_{\text{b},k,i}, \check{P}^{(l)}_{\text{u},k,i}, \ \forall i, l, k$. Following the same procedure, the coefficients of the rate approximation in the downlink (7) can be derived as

$$\tau^{\text{b},k,l}_{d_1,d_2,d_3} := \begin{cases} \frac{1}{\ln(2)} \times \frac{\left|h^{(l)}_{\text{bd},k}\right|^2}{\check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{bd},k}\right|^2 + \Phi^{(l)}_{k,i}} & d_1 = l, \ d_2 = k, \\ \frac{1}{\ln(2)} \times \frac{-\left|h^{(l,d_1)}_{\text{bd},k}h^{(l)}_{\text{bd},k}\right|^2\check{P}^{(l)}_{\text{b},k,i}}{\Phi^{(l)}_{k,i}\left(\Pi^{(l)}_{k,i}+\check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{bd},k}\right|^2\right)} & d_1 \neq l, \ d_2 = k, \\ 0 & d_1 = l, \ d_2 \neq k, \\ 0 & d_1 \neq l, \ d_2 \neq k, \end{cases} \tag{18}$$

end

$$\tau^{\text{u},k,l}_{d_1,d_2,d_3} := \begin{cases} \frac{-\check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{bd},k}h^{(l)}_{\text{ud},k}\right|^2}{\ln(2)\Phi^{(l)}_{\text{b},k,i}\left(\Phi^{(l)}_{\text{b},k,i}+\check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{bd},k}\right|^2\right)} & d_1 = l, \ d_2 = k, \\ \frac{-\left|h^{(l,d_1)}_{\text{bd},k}h^{(l,d_1)}_{\text{ud},k}\right|^2\check{P}^{(l)}_{\text{b},k,i}}{\ln(2)\Phi^{(l)}_{\text{b},k,i}\left(\Pi^{(l)}_{\text{b},k,i}+\check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{bd},k}\right|^2\right)} & d_1 \neq l, \ d_2 = k, \\ 0 & d_1 = l, \ d_2 \neq k, \\ 0 & d_1 \neq l, \ d_2 \neq k, \end{cases} \tag{19}$$

where $\Phi^{(l)}_{k,i}$ is the resulting value of the term $N^{(l)}_{\text{b},k,i} + M^{(l)}_{\text{b},k,i} + \check{P}^{(l)}_{\text{b},k,i}\left|h^{(l)}_{\text{ud},k}\right|^2$ for a given set of power values $\check{P}^{(l)}_{\text{b},k,i}, \check{P}^{(l)}_{\text{u},k,i}, \ \forall i, l, k$. As the result of the Taylor series substitution, in each step, the problem in (11) is converted into a linear program. The optimal power values can be hence obtained in polynomial time, using known convex solvers, e.g, SeDuMi [16]. The obtained power values in each step, will be used as the approximation point for the next iteration. This procedure is continued until the resulting power values do not change, within a required accuracy. Algorithm 1 provides detailed description of the proposed solution steps.

IV. Transmit Power adjustment with Greedy rate maximazation

In this part, we define an optimization strategy in order to study the performance of the FD-capable network, in terms of sum rate. The transmit power optimization will be done at the involved nodes in order to maximize the total communication rate in the network. Similar to the last part, we normalize the resulting rate for each path to the individual rate requirements, given as constants $\mu^{(l)}_{\text{u},k}, \mu^{(l)}_{\text{d},k} \in \mathbb{R}^+$. The corresponding optimization problem can be then formulated as

$$\begin{aligned} \max_{P^{(l)}_{\text{b},k,i}, P^{(l)}_{\text{u},k,i} \in \mathbb{R}^+} \quad & \sum_l \sum_k R^{(l)}_{\text{u},k}/\mu^{(l)}_{\text{u},k} + R^{(l)}_{\text{d},k}/\mu^{(l)}_{\text{d},k} \\ \text{s.t.} \quad & \sum_k P^{(l)}_{\text{b},k,i} \leq P^{(l)}_{\text{b-max}}, \ \forall l, i, \\ & P^{(l)}_{\text{u},k} \leq P^{(l)}_{\text{u-max},k}, \ \forall k, l, i, \end{aligned} \tag{20}$$

where $R^{(l)}_{\text{u},k}$ and $R^{(l)}_{\text{d},k}$ are defined in (6) and (7). It is worth mentioning that the above optimization strategy, is ignorant regarding the satisfaction of the individual node requirements. Instead, the sum of the provided communication rate in the network is optimized, in a greedy fashion. Due to the nature of the rate functions, (20) is a jointly non convex optimization problem, with no obvious analytical solution. Hence, similar to the last part, we resort to the iterative convex optimization framework based on the Taylor expansion of the rate functions in each iteration. Algorithm 1 provides detailed description of the applied procedure.

ISBN 978-3-8007-3662-1

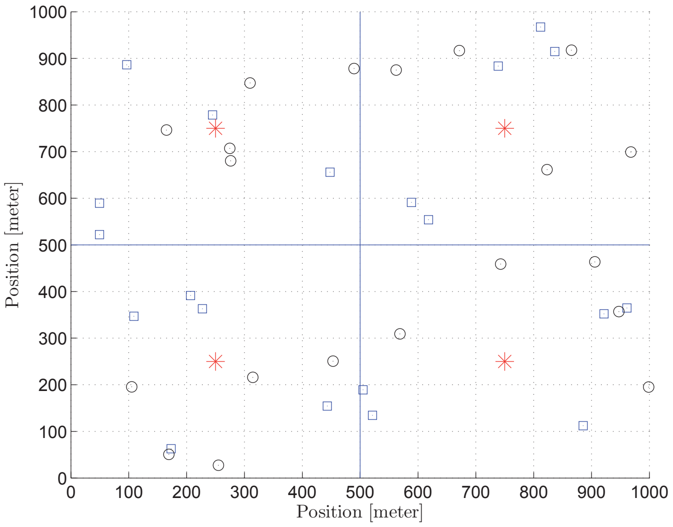

Fig. 4. Simulated locations of the base stations (red stars), the uplink users (blue squares), and downlink users (black circles). The nodes are randomly distributed in a square area of 1 km^2. Each node, belongs to the cell which is associated with the closest base station.

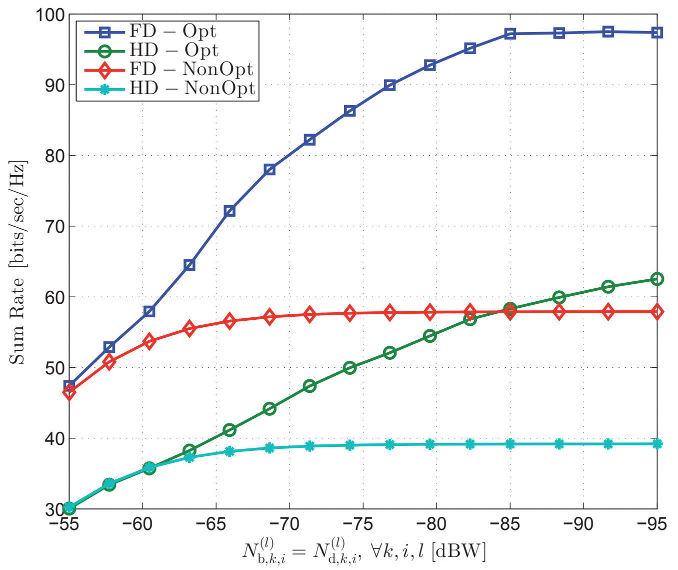

Fig. 5. Network sum rate with respect to the noise level at the base station and users. Optimal power adjustment becomes increasingly gainful for high SNR region.

TABLE I. THE USED VALUES FOR SYSTEM PARAMETERS.

Parameter	Value
K	5
L	4
N	-50 dBm
$\gamma_k^{(l)}, k, l$	$1e-8$
$\beta_k^{(l)}, k, l$	$1e-8$
Path-loss exponent	2
$P_{\max}$	0 dBW

Algorithm 1 Sequential convex optimization procedure for (11) and (20). $\delta_{\mathrm{b},k}^{(l)} = 0.01\check{P}_{\mathrm{b},k}^{(l)}$, $\delta_{\mathrm{u},k}^{(l)} = 0.01\check{P}_{\mathrm{u},k}^{(l)}$ and $\xi = 1e-5 \times \sum_{k,l} \check{P}_{\mathrm{b},k}^{(l)} + \check{P}_{\mathrm{u},k}^{(l)}$.

```
P̌_{b,k}^{(l)}, P̌_{u,k}^{(l)} ∈ ℝ⁺, ∀l, k ← random initialization
while 1 do % infinite loop
    λ^b, λ^u, τ^b, τ^u, ∀d1, d2, d3, k, l, i ← see (16) − (19)   % calculate Taylor series
    P*_{b,k}^{(l)}, P*_{u,k}^{(l)}, ∀k, l ← Solve linearized (11) or (20).
    if (Σ_{k,l} |P̌_{b,k}^{(l)} − P*_{b,k}^{(l)}| + |P̌_{u,k}^{(l)} − P*_{u,k}^{(l)}| ≤ ξ) then
        stop! % stability check
    end if
    P̌_{b,k}^{(l)}, P̌_{u,k}^{(l)} ← P*_{b,k}^{(l)}, P*_{u,k}^{(l)} % update power with the solution
end while
```

V. SIMULATION RESULTS

In this part we simulate the defined system, with FD operation at the base stations. We simulate a network with 4 base stations and 40 users, which are randomly located in the area of 1 km^2. Each user, at a certain time and frequency either receives the DL or UL communication service (HD mobile stations) where the base stations are providing the simultaneous UL and DL connections in the same sub channel (FD base stastions). Each node, belongs to the cell which is associated with the closest base station. The channels are assumed to follow the Rayleigh distribution with the variance proportional to the path loss, calculated from the location of the each node. The location of the base stations and the UL and DL users are depicted in Fig. 4.

The simulative comparison is done between two major setups: the scenario where the base station is allowed to operate in FD, which enables the simultaneous service to the DL and UL, and the corresponding HD base station setup, where the UL and DL process are separated in the consecutive time slots, i.e., $i = 1$ and $i = 2$. For both cases, the setup with optimized transmit power values, i.e., 'FD-Opt' and 'HD-Opt' is compared to the case where the maximum allowed power is used at all nodes, with no optimization process, i.e., 'FD-NonOpt' and 'HD-NonOpt'. In Fig. 5, the resulting system sum rate is depicted with respect to the value of the noise power, where $N = N_{\mathrm{b},k,i}^{(l)} = N_{\mathrm{d},k,i}^{(l)},\ \forall k,i,l$ and $P_{\max} := P_{\text{u-max},k}^{(l)} = P_{\text{b-max}}^{(l)}/K,\ \forall k,l$. Unless stated otherwise, the values in the Table 1 are used as our system parameters. It is clear that while a FD setup with optimized power values enhances the achievable sum rate, a smart power adjustment is essential for such an enhancement, particularly in high SNR region. In order to evaluate the effect of the system dynamic range, Fig. 6 depicts the sensitivity of the FD system performance to the self-interference cancellation accuracy. As expected, the system performance suffers when the dynamic range decreases at the FD base stations.

VI. CONCLUSION

Since the interference signal is originally a desired signal in a different part of the system, a cooperative and smart power control is a gainful strategy. In particular, for the defined system where the performance suffers due to the new sources of interference, the smart power optimization at the users provides a trade-off between the traditional cells and the new full duplex setup. It is clear that in the highly interference-sensitive setup, the solution converges to the HD system, where all the co-channel transmissions are disabled to avoid the

ISBN 978-3-8007-3662-1

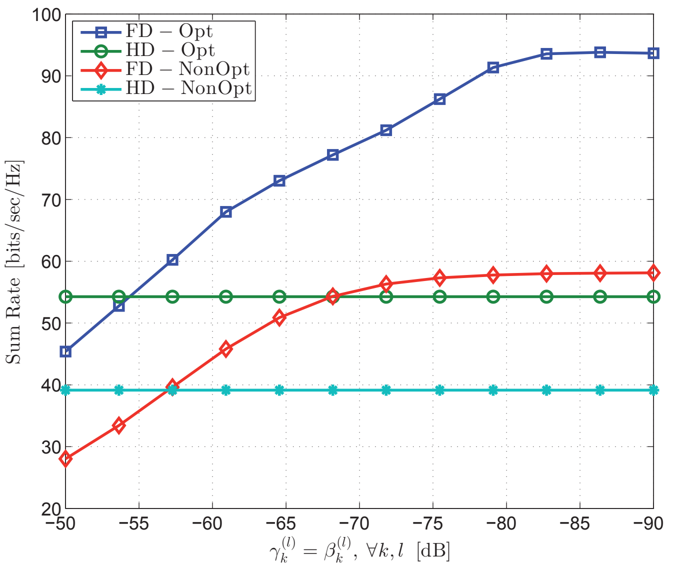

Fig. 6. Network sum rate with respect to the dynamic range, i.e., self interference cancellation capability at the base station. HD setup is not affected by the value of dynamic range. At high dynamic range region, even a non-optimal FD power adjustment setup outperforms the HD network performance for the simulated noise level (low SNR region).

interference. On the other hand, for a noise-dominant system, or a system where interfering channels are attenuated due to a smart channel assignment, significant gains will be achieved by enabling both communication directions. In this work we have studied and proposed a power adjustment-based interference mitigation for a cellular communication system where the base stations are empowered with FD capability. The simulated system shows the gains of the proposed methods compared to the system with HD base stations.

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