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Interference Management in Full-Duplex Cellular Networks with Partial Spectrum Overlap

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***Abstract*—Full-duplex (FD) communication is promoted to double the spectral efficiency when compared to the half-duplex (HD) counterpart. In the context of cellular networks, however, FD communication exacerbates the aggregate uplink and downlink interference, which diminishes the foreseen FD gains. This paper considers a flexible duplex system, denoted by α-duplex (α-D) system, wherein a fine-grained bandwidth control for each uplink/downlink channel pair in each base station (BS) is allowed, which also leads to partial spectrum overlap between the uplink and downlink channels. The paper addresses the resulting interference management problem by maximizing a network-wide rate-based utility function subject to uplink/downlink power constraints, so as to determine user-to-BS association, user-to-channel scheduling, the UL and DL transmit powers, and the fraction of spectrum overlap between UL and DL for every user, under the assumption that the number of available channels and users are equal. The paper solves such a non-convex mixed-integer optimization problem in an iterative way by decoupling the problem into several sub-problems. Particularly, the user-to-BS association problem is solved using a matching algorithm that is a generalization of the stable marriage problem. The scheduling problem is solved by iterative Hungarian algorithm. The power and spectrum overlap problem is solved by successive convex approximation. The proposed iterative strategy guarantees an efficient one-to-one user to BS and channel assignment. It further provides optimized flexible duplexing and power allocation schemes for all transceivers. Simulations results show appreciable gains when comparing the proposed solution to different schemes from the literature.**

***Index Terms*—α-duplex, full-Duplex communication, self-interference, cross-mode, intra-mode, interference management, power allocation, user scheduling.**

I. Overview

A. Introduction

Recent advances in transceivers design enable simultaneous transmission and reception on a common frequency channel, denoted by in-band full-duplex (FD) communication. FD communication eliminates the necessity for orthogonal transmission and reception and allows both to take place on the same time-frequency channel. Instead of splitting the spectrum between forward and reverse links, both links can simultaneously access the entire spectrum, which doubles the bandwidth (BW) available of each link. FD communication has other potential advantages in terms of latency, relaying, transmission secrecy, and frequency reuse [2]. Therefore, FD communication is expected to provide tangible improvements in terms of spectrum utilization as compared to the conventional half-duplex (HD) systems. In cellular networks, FD communication is envisioned to provide simultaneous improvement in uplink (UL) and downlink (DL) transmission rates.

In the context of cellular network, FD communication generates self-interference (SI) and cross-mode inter-cell interference, in addition to the traditional intra-mode inter-cell interference which exists in HD scheme. While SI is due to the interference from the transmitter of a network entity to its own receiver, cross-mode interference is the inter-cell interference from DL transmission in one cell to the UL transmission in another cell, and vice versa. As interference is a major performance limiting parameter in modern cellular networks [3], the induced interference by FD communication can diminish or even negate the FD foreseen gains, especially in the UL transmission [4]. Interference management is, therefore, crucial to truly assess the gains harvested by FD communication networks. This paper considers the interference management problem in FD enabled systems. The focus is on designing practical optimization strategies for UL and DL scheduling, base station (BS) assignment, power control and spectrum allocation, as a means to mitigate self-interference, cross-mode and intra-mode inter-cell interference.

The paper considers a multi-cell network where both users and BS are FD-enabled. Instead of following a rigid half-duplex/full-duplex binary decision for each user-BS link, the proposed interference management allows partial UL/DL channel overlap via fine-tuned bandwidth allocation. The paper assumes that the number of available channels and users are equal, which helps deriving efficient allocation algorithms. It then addresses the problem of maximizing a network-wide rate-based utility function subject to UL/DL power constraints, so as to determine user-to-BS association, user-to-channel scheduling, the UL and DL transmit powers, and the fraction of spectrum overlap between UL and DL for each user.

B. Related Work

This paper is related to the recent state-of-art on FD communication. While some works focus on self-interference cancellation (SIC) via multi-stage RF/analog/digital suppression

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techniques [2], [5], other works tackle cross-mode intra-cell and inter-cell interference mitigation to improve the efficiency of FD operation [6]–[13]. [1] Note that the SIC is performed locally within every network entity while the mitigation of cross-mode intra-cell and inter-cell interference is network-wide due to its interdependence through the whole network.

Cross-mode interference mitigation is achieved via network management mechanisms that take into account the high disparity between the UL and DL transmission powers [9], [17]. For instance, references [14]–[16] utilize joint UL/DL scheduling to maximize the sum-rate in a single FD BSs and multiple HD users scenario. References [18], [19] exploit MIMO precoding to maximize spectral and energy efficiencies in a single FD BS serving multiple FD users. The models in [14]–[16], [18], [19], however, do not account for the prominent effect of inter-cell interference.

Examples of interference mitigation in a multi-cell FD cellular network are further presented in [8], [13]. While the authors in [13] develop power control algorithms to manage inter-cell interference in a FD multi-cell scenario, the work in [8] addresses the problem via scheduling and coordination between nearby BSs. The authors of [20] design an algorithm maximizing the sum rate for a network where the BS are operating in FD and the users in HD. The algorithm allocates subcarrier to every user and perform power control using iterative water-filling. References [8], [13], [20], however, consider sum-rate maximization, and assume a model of fully overlapping UL/DL channels. As shown in [9], [17], considering sum-rate objective may hide intolerable deterioration in the UL performance due to cross-mode interference [9], [17]. Particularly, due to the UL/DL transmission power disparity, FD communication improves the DL rate on the expense of deteriorating the UL rate. Therefore, it becomes important to explicitly account for UL and DL performances when maximizing the overall network performance.

In [21], the authors consider a two layer FD-based cellular network and suggest a heuristic algorithm maximizing the total network utility. The algorithm optimally allocates transmit powers to users and chooses the transmission mode for every frequency resource block, i.e. the algorithm chooses between the following transmission modes: FD-FD, FD-HD, HD-HD, where the first and second words are the operating mode of, respectively, the BS and the user.

It is shown in [9] that UL gains can only be harvested via FD communication when the BS and user equipment (UE) powers are comparable. When the BSs and UEs have high power disparity, the work in [17] proposes the α-duplex(α-D) scheme instead, which strikes a good balance between UL and DL performance and, at the same time, exploits FD transceivers so as to harvest rate gains. Instead of enforcing an FD operation with fully overlapped channels, the α-D scheme enables flexible duplexing via partial UL/DL channel overlap. The overlap is controlled via the tunable design parameter $\alpha \in [0, 1]$, where $\alpha = 0$ and $\alpha = 1$ represent the HD and FD cases, respectively. The results in [17] show that the α-D scheme provides appreciable simultaneous improvement in the UL and DL rates when compared to both the HD and FD cases. However, [17], enforces the same α for all BSs, and does not optimize over the transmit power and user scheduling.

C. Contributions

Unlike the aforementioned literature, this paper considers a multi-cell multi-user FD cellular network and allows a flexible partial UL/DL channel overlap. The paper then addresses the interference management problem via BS association, user scheduling, power control, and fractional duplexing adaptation. The paper assumes that each BS in the network has a certain number of orthogonal channels available to simultaneously serve users. The channels are universally reused by all BSs. The total number of available channels and users are equal, so as to facilitate the derivation of heuristic scheduling policies [2]. It then addresses the problem of maximizing a network-wide rate-based utility function subject to UL/DL power constraints. The paper focuses on two network-wide utility functions, namely, the sum-rate and the sum-of-log rate. The sum-of-log rate utility function is especially of practical interest as the sum-rate optimization favors the DL on the expense of significant degradation in the UL rate. The logarithmic sum-rate formulation is therefore used to induce a relative fairness between UL and DL. One of the paper main contributions is to solve the above mixed-integer continuous optimization problem using a heuristic iterative algorithm which decouples the problem into two sub-problems. The first sub-problem consists of assigning users to BSs using a generalization of the stable marriage problem, which guarantees that the number of users assigned to every BS is equal to the number of available channels. The second sub-problem consists of alternating between the following sub-steps: 1) assigning channel to every user assigned to every BS by iteratively applying the Hungarian algorithm to cells in a sequential manner, while fixing the powers and α values, 2) optimizing the values of the UL and DL transmit powers and α for each user, by fixing the scheduling found in the first sub-step. Note that the system allows different α for each user. For the sum-of-log rate maximization problem, the paper particularly proposes a solution that relies on successive convex approximation of the original problem, which can be solved using efficient techniques from optimization theory.

The paper simulation results confirm the vulnerability of UL performance to the FD operation, and show the superiority of the proposed scheme when compared to FD and HD schemes with random scheduling and Voronoi cell based association. Both the sum-rate and the sum-of-log rate are considered in the simulations. While the sum-rate utility is the classical measure that characterizes the network throughput, the results of the paper show that the sum-of-log rate utility is more appropriate in FD cellular networks, as it guarantees a balanced UL and DL performance. For comparable BSs and UEs transmission powers, i.e., in small-cell environment, the suggested scheme

[1] The cross mode intra-cell interference problem appears when a FD BS serves multiple HD users [14]–[16].

[2] One possible way to deal with the situation of unequal number of users and subchannels is to add an additional admission control step that pre-determines the subset of users to be scheduled to the subchannels.

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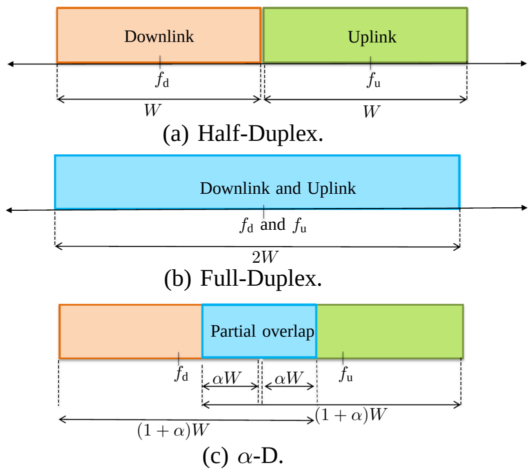

Fig. 1: An illustrative diagram showing α-D scheme.

provides around 100% gain in UL rate and 120% in DL rate as compared to conventional HD schemes with Voronoi user-to-BS association and random channel assignment[3]. For high disparity between UL and DL transmission power, i.e. macro-cell environment, the suggested scheme guarantees around 40% gain as compared to conventional schemes.

D. Paper Organization

The rest of this paper is organized as follows. The system model and problem formulation are presented in Section II. Section III details the suggested algorithm to solve the problem presented in Section II. Numerical results and discussion are presented in Section IV, before concluding the paper in Section V.

II. System Model and Problem Formulation

A. Network Model

Consider a single-tier cellular network served by B BSs. Every BS transmits signals over K orthogonal channels and can, therefore, serve K different users. For the case of unequal number of users and channels, additional admission control policy may be needed, but this falls outside the scope of the current paper. The users are assumed to be uniformly distributed in the coverage area of the B BSs. Let $\mathcal{B} = \{1, \ldots, B\}$, $\mathcal{K} = \{1, \ldots, K\}$ and $\mathcal{U} = \{1, \ldots, BK\}$ be, respectively, the set of BSs, transmission channels, and users. The channels are universally reused by all BSs. Each channel has $2W$ Hz of bandwidth, which is equally split into two non-overlapping channels. In the conventional HD operation, one channel is used for UL transmission and the other channel is used for DL transmission. However, for FD transceivers, each BS can extend the UL and DL channels bandwidths within the $2W$ available spectrum such that the UL and DL channels overlap. Particularly, we employ the α-D scheme, where the UL and DL channels can be extended from W Hz to $(1+\alpha)W$ Hz, such that an overlap of $2\alpha W$ exists between the UL and the DL channels, and the total occupied bandwidth for each channel remains $2W$. At one extreme, $\alpha = 0$ captures the HD scheme with W Hz for each of the UL and DL channels with zero UL/DL overlap. On the other extreme, $\alpha = 1$ captures the FD scheme with $2W$ Hz in each of the UL and DL channels with full UL/DL overlap. An illustrative figure for the α-D scheme is shown in Fig. 1. The overlap factor α not only affects the cross-mode inter-cell interference, but also introduces a change in the terms of conventional intra-mode inter-cell interference, as well as the SI. This paper explicitly considers the optimal interference management between cells by suitably adjusting the value of α and the transmission powers, which affects the cross-mode and intra-mode inter-cell interference, as well as the SI. Flexible spectrum allocation for the UL and DL channels is enabled in such a way that all users do not necessarily have equivalent overlap factor α. Such flexibility is induced by introducing the factor α_{bk}, which is defined as the overlap between the UL and DL spectrum for the k-th channel of the b-th BS.

Let the variables p, h, r, β, γ, and R denote, respectively, the transmit powers, channel power gains, distances between network elements, SIC factor signal-to-interference-plus-noise-ratios (SINRs), and transmission rates. All of the aforementioned variables come with superscripts, to denote the types of network elements (b for BS and u for user). Variables with single superscript denote a single network element. Variables with double superscript denote communicating network elements. The variables also have a subscript to indicate the index of the single network element (for p) or double subscript for communicating network elements (for r), followed by the channel number if the variable is channel dependent (h, γ, R, p). For instance, $p^{(\text{u})}_{bk}$ is the transmit power of the user scheduled at the k-th channel of the b-th BS, $p^{(\text{b})}_{bk}$ is the transmit power of the b-th BS on the k-th channel, $r^{(\text{bu})}_{bu}$ is the distance between the b-th BS and the u-th user, and $h^{(\text{ub})}_{ubk}$ the channel gain between the b-th BS and the u-th user on the k-th channel. The SIC factor $\beta \in [0, 1]$ such that $\beta = 0$ implies perfect SIC, and $\beta = 1$ implies there is no SIC. Fig. 2 shows an example of the considered network with two BSs (b and m), 4 users and 2 channels.

For the sake of analysis, let $\boldsymbol{p}^{(\text{b})}$, $\boldsymbol{p}^{(\text{u})}$ and $\boldsymbol{\alpha}$ be 3 distinct matrices of dimension $B \times K$. The (b, k)-th element of each of these 3 matrices correspond to the DL transmit power, the UL transmit power and the overlap between the UL and DL channels at the k-th channel of the b-th BS, respectively. Moreover, Let $\boldsymbol{p}^{(\text{b})}_k$, $\boldsymbol{p}^{(\text{u})}_k$ and $\boldsymbol{\alpha}_k$ be the k-th column of $\boldsymbol{p}^{(\text{b})}$, $\boldsymbol{p}^{(\text{u})}$ and $\boldsymbol{\alpha}$, respectively. Let $\boldsymbol{x}_k$ be the vector of length $3B$ containing the design parameters related to the k-th channel, i.e. $\boldsymbol{x}_k$ is a concatenation of $\boldsymbol{p}^{(\text{b})}_k$, $\boldsymbol{p}^{(\text{u})}_k$ and $\boldsymbol{\alpha}_k$.

In the rest of this paper, in the expressions of SINRs and rates, we consider an arbitrary test user u which is assumed to be assigned to the k-the channel of the b-th BS, denoted as the test BS. m is a generic index that denotes all BSs except the test BS. v is a generic index for the user assigned to the k-th channel of the m-th BS.

[3]The maximum rate gain from FD compared to HD in terms of rate is 100%, i.e. double. However, in this work, this limit is exceeded, thanks to the additional resource allocation schemes, i.e., the user-to-BS association and the scheduling policies.

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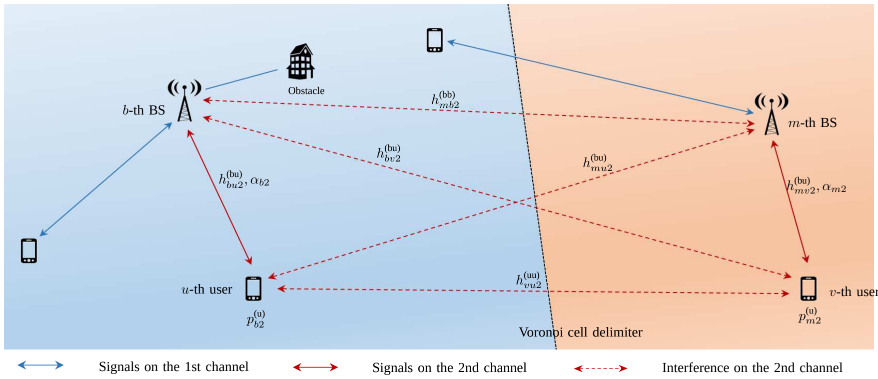
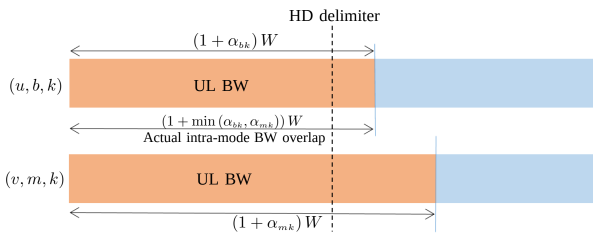
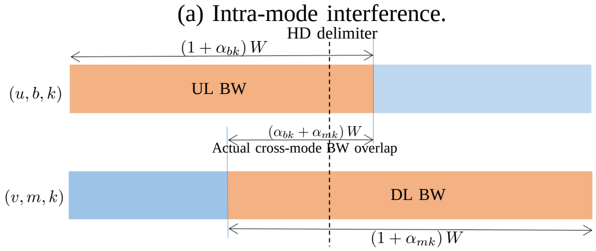


Fig. 2: The system model with 2 BSs (m and b), 4 users and 2 channels.



(a) Intra-mode interference.



(b) Cross-mode interference.

Fig. 3: Amount of overlapping BW between b-th and m-th BS for k-th channel.

B. Effective Interference and SINR Representation

Due to the variable bandwidth allocation and the flexible partial overlap between the UL and DL channels, different portions of the cross-mode, intra-mode, and SI powers leak through the receiver filter that operates on a given channel. For instance, Fig. 3 shows the amount of overlapping bandwidth of the UL transmission on the k-th channel of the b-th BS with the k-th channel of the m-th BS. Fig. 3a shows the amount of bandwidth overlap between UL at the b-th BS and UL at the m-th BS, on the k-th channel. This overlap results in the *effective intra-mode interference factor*, that is the fraction of intra-mode interference powers from m, leaking through the receiver filter of b at the k-th channel. In this case, assuming that the UL and DL transmissions are using identical unit-power rectangular pulse-shapes in the frequency domain, the effective intra-mode interference factor can be written as:

$$\mathcal{I}(\alpha_{bk},\alpha_{mk}) = \left| \int_0^{(1+\min(\alpha_{bk},\alpha_{mk}))W} \frac{1}{\sqrt{(1+\alpha_{bk})W}} \frac{1}{\sqrt{(1+\alpha_{mk})W}} dx \right|^2$$
$$= \frac{(1+\min(\alpha_{bk},\alpha_{mk}))^2}{(1+\alpha_{bk})(1+\alpha_{mk})} = \begin{cases} \frac{(1+\alpha_{bk})}{(1+\alpha_{mk})} & \alpha_{bk} < \alpha_{mk}, \\ 1 & \alpha_{bk} = \alpha_{mk}, \\ \frac{(1+\alpha_{mk})}{(1+\alpha_{bk})} & \alpha_{bk} > \alpha_{mk}. \end{cases} \quad (1)$$

Furthermore, Fig. 3b shows the amount of bandwidth overlapping between the UL at the b-th BS and the DL at the m-th BS on the k-th channel. Due to this overlap, a fraction of cross-mode interference power from m leaks through the receiver filter of b, which is in this paper denoted by *effective cross-mode interference factor*. In this case, again, assuming that the UL and DL transmissions are using identical unit-power rectangular pulse-shapes in the frequency domain, the effective cross-mode interference factor is given by:

$$\mathcal{C}(\alpha_{bk},\alpha_{mk}) = \left| \int_0^{(\alpha_{bk}+\alpha_{mk})W} \frac{1}{\sqrt{(1+\alpha_{bk})W}} \frac{1}{\sqrt{(1+\alpha_{mk})W}} dx \right|^2$$
$$= \frac{(\alpha_{bk}+\alpha_{mk})^2}{(1+\alpha_{bk})(1+\alpha_{mk})}. \quad (2)$$

The SI is a special case of cross-mode interference, i.e., it is the interference from one mode affecting another from the transmitter to the receiver of the same equipment. Therefore, the *effective SI factor* is given by:

$$\mathcal{C}_{\text{SI}}(\alpha_{bk}) = \frac{4\alpha_{bk}^2}{(1+\alpha_{bk})^2}. \quad (3)$$

Using the effective intra-mode, cross-mode and SI interference factor defined in (1), (2) and (3), the UL SINR on the k-th channel of the b-th BS can be written as follows:

$$\gamma^{(\text{u})}_{bk}(\boldsymbol{x}_k) = \frac{S^{(\text{u})}_{bk}(\boldsymbol{x}_k)}{\tilde{S}^{(b)}_{bk}(\boldsymbol{x}_k) + I^{(\text{bb})}_{bk}(\boldsymbol{x}_k) + I^{(\text{ub})}_{bk}(\boldsymbol{x}_k) + N^{(\text{b})}_{bk}(\boldsymbol{x}_k)}, \quad (4)$$

where $S^{(\text{u})}_{bk}$ is the UL useful signal. As previously mentioned, let the u-th user be the user scheduled at the k-th channel of

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the b-th BS. $S^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k)$ can therefore be written as:

$$S^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k) = p^{(\mathrm{u})}_{bk} h^{(\mathrm{ub})}_{ubk} l(r^{(\mathrm{ub})}_{ub}), \tag{5}$$

where $l(r)$ is the function that models both the signal power attenuation with distance r and the channel shadowing effect. In the denominator of (4), $\tilde{S}^{(b)}_{b}$ is the SI power received at the receiver of the b-th BS on the k-th channel from its transmitter:

$$\tilde{S}^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k) = \frac{4\beta^{(\mathrm{b})}_{bk} p^{(\mathrm{b})}_{bk} \alpha^2_{bk}}{(1+\alpha_{bk})^2}. \tag{6}$$

$I^{(\mathrm{bb})}_{bk}(\boldsymbol{x})$ is the interference received by the b-th BS from all other BSs on the k-th channel. Assuming that the v-th user is scheduled at the k-th channel of the m-th BS, $I^{(\mathrm{bb})}_{bk}(\boldsymbol{x})$ can be written as:

$$I^{(\mathrm{bb})}_{bk}(\boldsymbol{x}_k) = \sum_{\substack{m\in\mathcal{B}\\ m\neq b}} \frac{p^{(\mathrm{b})}_{mk} h^{(\mathrm{bb})}_{mbk} l(r^{(\mathrm{bb})}_{mb})(\alpha_{bk}+\alpha_{mk})^2}{(1+\alpha_{bk})(1+\alpha_{mk})}, \tag{7}$$

$I^{(\mathrm{ub})}_{bk}$ is the interference received by the b-th BS from all other users on the k-th channel, and can be written as:

$$I^{(\mathrm{ub})}_{bk}(\boldsymbol{x}_k) = \sum_{\substack{v\in\mathcal{U}\\ v\neq u\\ \alpha_{bk}\leq\alpha_{mk}}} p^{(\mathrm{u})}_{k} h^{(\mathrm{ub})}_{vbk} l(r^{(\mathrm{ub})}_{vb}) \frac{(1+\alpha_{bk})}{(1+\alpha_{mk})} + \sum_{\substack{v\in\mathcal{U}\\ v\neq u\\ \alpha_{bk}>\alpha_{mk}}} p^{(\mathrm{u})}_{mk} h^{(\mathrm{ub})}_{vbk} l(r^{(\mathrm{ub})}_{vb}) \frac{(1+\alpha_{mk})}{(1+\alpha_{bk})}. \tag{8}$$

$N^{(\mathrm{b})}_{bk}$ is the noise power at the receiver of the k-th channel of the b-th BS.

Similarly, the expression of the DL SINR on the k-th channel of the b-th BS is:

$$\gamma^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k) = \frac{S^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k)}{\tilde{S}^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k) + I^{(\mathrm{uu})}_{bk}(\boldsymbol{x}_k) + I^{(\mathrm{bu})}_{bk}(\boldsymbol{x}_k) + N^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k)}, \tag{9}$$

where $S^{(\mathrm{b})}_{bk}$ is the DL useful signal which is defined as follows:

$$S^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k) = p^{(\mathrm{b})}_{bk} h^{(\mathrm{bu})}_{buk} l(r^{(\mathrm{bu})}_{bu}). \tag{10}$$

$\tilde{S}^{(\mathrm{u})}_{bk}$ is the SI power received at the receiver of the user from its transmitter:

$$\tilde{S}^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k) = \frac{4\beta^{(\mathrm{u})}_{bk} p^{(\mathrm{u})}_{bk} \alpha^2_{bk}}{(1+\alpha_{bk})^2} \tag{11}$$

$I^{(\mathrm{uu})}_{bk}(\boldsymbol{x}_k)$ is the interference received by user u coming from all other users on channel k:

$$I^{(\mathrm{uu})}_{bk}(\boldsymbol{x}_k) = \sum_{\substack{v\in\mathcal{U}\\ v\neq u}} \frac{p^{(\mathrm{u})}_{vk} h^{(\mathrm{uu})}_{uvk} l(r^{(\mathrm{uu})}_{uv})(\alpha_{bk}+\alpha_{mk})^2}{(1+\alpha_{bk})(1+\alpha_{mk})}, \tag{12}$$

and $I^{(\mathrm{bu})}_{bk}$ is the interference received by user u coming from all other BSs on channel k:

$$I^{(\mathrm{bu})}_{bk}(\boldsymbol{x}_k) = \sum_{\substack{m\in\mathcal{B}\\ m\neq b\\ \alpha_{bk}\leq\alpha_{mk}}} p^{(\mathrm{b})}_{mk} h^{(\mathrm{bu})}_{muk} l(r^{(\mathrm{bu})}_{mu}) \frac{(1+\alpha_{bk})}{(1+\alpha_{mk})} + \sum_{\substack{m\in\mathcal{B}\\ m\neq b\\ \alpha_{bk}>\alpha_{mk}}} p^{(\mathrm{b})}_{mk} h^{(\mathrm{bu})}_{muk} l(r^{(\mathrm{bu})}_{mu}) \frac{(1+\alpha_{mk})}{(1+\alpha_{bk})}, \tag{13}$$

$N^{(\mathrm{u})}_{bk}$ is the noise power at the receiver of the k-th the user served by the k-th channel of the b-th BS. The noise powers $N^{(\mathrm{b})}_{bk}$ and $N^{(\mathrm{u})}_{bk}$ can be explicitly written as follows: $N^{(\chi)}_{bk}(\boldsymbol{x}_k) = (1+\alpha_{bk})\, N_\chi B$ with $\chi \in \{\mathrm{u,b}\}$, where N_χ is the thermal noise level at the receiver of type χ. The first term in the denominator of (4) and (9) is the cross-mode interference, which is the aggregate cross-mode interference power multiplied by the effective cross-mode interference factor given in (2). The second term is the intra-mode interference, which is the aggregate intra-mode interference power multiplied by the effective intra-mode interference factor given in (1). Note that the expressions of SINRs for channel k depend only on $\boldsymbol{x}_k$.

Using the expressions of the SINRs, the UL and DL achievable rates for the user served by the k-th channel of the b-th BS are respectively:

$$R^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k) = (1+\alpha_{bk}) B \log(1+\gamma^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k)), \text{ and} \tag{14}$$

$$R^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k) = (1+\alpha_{bk}) B \log(1+\gamma^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k)). \tag{15}$$

C. Problem Formulation

This paper considers the problem of maximizing a rate-based utility function subject to power constraints, bandwidth-limited rectangular pulse shapes and one-to-one UE to channel assignment. In other words, the aim is to optimally assign every user to one BS and one channel, determine the UL and DL power levels to serve every user, as well as to find the spectrum overlap between UL and DL for every user. The assignment problem is reduced to the determination of an optimal mapping $u = \mathcal{M}(b,k)$ for $u \in \{1,\ldots,BK\}$, where (b,k) denotes the k-th channel of the b-th BS.

Let f_{ubk} be the benefit from assigning user u to the k-th channel of BS b. As mentioned earlier, all rates on channel k depend only on the design vector $\boldsymbol{x}_k$. As the considered utility function f_{ubk} is a function of the rate of transmission, it is, therefore, a function of $\boldsymbol{x}_k$ only. Let a_{ubk} be a binary variable such that $a_{ubk} = 1$ if the user u is assigned to the k-th channel of the b-th BS, and zero otherwise. This paper considers the following network-wide optimization problem:

$$\max_{\substack{p^{(\mathrm{u})}_{bk},\, p^{(\mathrm{b})}_{bk},\, \alpha_{bk},\, a_{ubk}\\ \forall(u,b,k)\in(\mathcal{U}\times\mathcal{B}\times\mathcal{K})}} \sum_{u,b,k} f_{ubk}(\boldsymbol{x}_k) a_{ubk} \quad \text{where } \boldsymbol{x}_k = [\boldsymbol{p}^{(\mathrm{u})}_k; \boldsymbol{p}^{(\mathrm{b})}_k; \boldsymbol{\alpha}_k], \tag{16a}$$

$$\text{s.t.}\quad 0 \leq p^{(\mathrm{u})}_{bk} \leq p^{(\mathrm{u})}_{\mathrm{max}}, \quad \forall(u,b,k)\in(\mathcal{U}\times\mathcal{B}\times\mathcal{K}), \tag{16b}$$

$$p^{(\mathrm{b})}_{\mathrm{min}} \leq p^{(\mathrm{b})}_{bk} \leq p^{(\mathrm{b})}_{\mathrm{max}} \quad \forall(u,b,k)\in(\mathcal{U}\times\mathcal{B}\times\mathcal{K}), \tag{16c}$$

$$\boldsymbol{0} \leq \boldsymbol{\alpha} \leq \boldsymbol{1}, \tag{16d}$$

$$a_{ubk} \in \{0,1\}\ \forall(u,b,k)\in(\mathcal{U}\times\mathcal{B}\times\mathcal{K}), \tag{16e}$$

$$\sum_{k,b} a_{ubk} = 1 \quad \forall u\in\mathcal{U} \tag{16f}$$

$$\sum_{u} a_{ubk} = 1 \quad \forall(b,k)\in(\mathcal{B}\times\mathcal{K}) \tag{16g}$$

where the optimization is over the assignment variables a_{ubk} for $(u,b,k) \in (\mathcal{U}\times\mathcal{B}\times\mathcal{K})$, all transmit powers in the matrices $\boldsymbol{p}^{(\mathrm{u})}$ and $\boldsymbol{p}^{(\mathrm{u})}$, and the spectrum overlap fraction in the matrix $\boldsymbol{\alpha}$ for all users, and where $p^{(\mathrm{u})}_{\max}$ is the maximum transmit power of the UEs, and $p^{(\mathrm{b})}_{\min}$ and $p^{(\mathrm{b})}_{\max}$ are respectively the minimum and maximum transmit power of every BS at every channel. The constraint (16d) is the range of values that the fraction of overlap between UL and DL spectrum can take. As mentioned before, the minimum and maximum value of α_{bk} are, respectively, 0 (HD communication) and 1 (FD communication). The assignment variables a_{ubk} are binary variables (16e). In (16a), a_{ubk} serves as a binary switch: f_{ubk} contributes to the network utility only if $a_{ubk} = 1$, i.e., if the user u is assigned to the k-th channel of the b-th BS. The constraints defined in (16f) and (16g) constrain the assignment to be one-to-one, i.e., only one channel is assigned to user u (16f), and only one user is assigned to channel k of BS b (16g). The minimum transmit power constraint in (16c) guarantees a minimum signal to noise ratio for cell edge users. Therefore, this minimum transmit power is inevitably higher for larger cell areas. Note that the maximum transmit power affordable by users equipment is generally small compared to the one for BSs $\left(p^{(\mathrm{u})}_{\max} \ll p^{(\mathrm{b})}_{\max}\right)$.

The problem defined in (16) is a non-convex mixed-integer optimization problem, which is hard to solve in general. Solving only the assignment problem by searching over all possible combination requires $(BK)!$ permutations, which is computationally infeasible for any reasonably sized network. Moreover, in our case, even with fixed powers $\boldsymbol{p}^{(\mathrm{u})}$, $\boldsymbol{p}^{(\mathrm{u})}$ and fixed $\boldsymbol{\alpha}$, the scheduling is not a simple assignment problem. The benefit from assigning one user to a BS and a channel depends on the assignment of the other users in the network. This is due to the interference terms involved in the expression of the rate. In other words, the benefit from assigning a user to a BS and a channel can not be trivially represented using matrix mappings, which makes applying classical assignment solution such as auction algorithm, stable marriage algorithm, Hungarian, simplex network etc., difficult. To the best of our knowledge, this kind of assignment problem has not been visited yet in the literature. Towards this end, this paper suggests a practical, heuristic algorithm in the next section so as to overcome the problem of inter-dependency between utilities, and efficiently allocate the powers and the UL/DL channel overlap for all users.

In concise terms, the paper solves the assignment problem, the power control and the spectrum overlap allocation. Such optimization is decoupled in 2 major steps: 1) assign every user to one BS; 2) alternating between the following substeps, 2-i) assign a channel to serve every user within every BS using the powers and $\boldsymbol{\alpha}$ obtained from the second sub-step, 2-ii) find the optimized transmit powers (UL and DL) and the spectrum overlap fraction α for all users in the network, assuming the scheduling found from 2-i) . The simulations results in the later section show that such heuristic algorithm provides appreciable gain as compared to conventional schemes.

D. Utility Function Choice

The power control step of the optimization problem (16) particularly depends on the choice of the utility function. If the utility function is the sum of the rates at every receiver, the benefit from assigning user u to the k-th channel of the b-th BS can be written as follows:

$$f_{ubk}(\boldsymbol{x}_k) = R^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k) + R^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k). \tag{17}$$

However, in case there is a high disparity between UL and DL transmission powers, the UL rate might be negligible compared to the DL rate. Therefore, the maximization of the sum of rates may lead to a maximization of the DL rate only, while neglecting the UL rate terms. The higher the DL transmission power is, the lower the UL rate becomes, due to the stronger interference from DL transmission. In other words, the DL rate may have more important contribution to the utility function, which makes the effect of the UL-to-DL interference almost negligible. Therefore, the sum-rate maximization often tends to assign higher values of α and high DL power, which induces an overwhelming interference for the UL transmission that degrades the UL rate.

To enforce a balanced UL and DL operation and give higher weights to the vulnerable UL rate, we adopt the sum log-rate as utility function. In this case, the benefit from assigning user u to the k-th channel of BS b becomes:

$$f_{ubk}(\boldsymbol{x}_k) = \log\left(R^{(\mathrm{u})}_{bk}(\boldsymbol{x}_k)\right) + \log\left(R^{(\mathrm{b})}_{bk}(\boldsymbol{x}_k)\right). \tag{18}$$

As shown later in the simulations section (cf. Figs. 6 and 7), the sum of log rate optimization along with the α-D scheme harvests appreciable FD rate gains and, at the same time, maintains a reasonably balanced UL/DL operation.

III. Algorithm Description

This section proposes a solution to solve the difficult optimization problem presented in (16). The proposed algorithm requires an central processing unit that is aware of the network parameters. First, the algorithm assigns K users to every BS in part III-A. Then, it alternates between the channel allocation and the resource allocation as follows: First, for a fixed resource allocation (powers and spectrum overlap between UL and DL for all users), assign a channel to every user in III-B. Second, using the optimized scheduling found in the first step, find the best resource allocation in III-C. Finally, assuming the resource allocation found in the second step, perform again the channel allocation, and iterate. The section now presents the algorithm steps in details.

A. User-to-BS association

In practical wireless systems, the users are assigned to BSs based on the quality or the power of the received signal [22]. The measurement of the quality or the power of received signal considers path loss, shadowing and fading. In the context of this paper, user to BS association denotes the strategy of matching BK users to B BSs, where every BS serves K users, in such a way that all BK users are served. There are many algorithms performing many-to-many assignment in the literature [23]. The paper proposes solving such a problem using a matching algorithm that is a generalization of the stable marriage problem, based on the Deferred Acceptance

Algorithms[4] for its simplicity to implement, and because it gives satisfactory results. The algorithm guarantees that there is no user u and a BS b such that both of the following statements are true [24]:

- u is unmatched or would prefer to go to b instead of the BS it is currently matched with.
- b has a free slot or would prefer u over one of the users currently served by one of its channels.

To apply such algorithm, first of all, every user ranks all the BSs. Every BS then ranks all the users. At this stage, the algorithm relies on the pathloss and shadowing between the user and the BS, since the channel coefficient due to fading depends on the assigned transmission channel, which is yet to be determined.

The algorithm begins with an attempt to match a user to the BS that is the most preferred within the user's rank order list. If the user cannot be matched to that first choice BS, an attempt is made to place the user into the second choice BS, and so on. Such process goes on until the user obtains a tentative match. There are two possible outcomes of a tentative match:

1) If the BS has a free channel (not assigned), then the tentative match succeeds.
2) If the BS does not have a free channel, but the user is ranked better than any of the other users who are already tentatively matched to the BS, then the user who has the worst ranking is removed to make room for a tentative match with the more preferred user.

Note that every match is tentative until the end of the algorithm (i.e., until all users are matched with a BS), because every matched user can be removed anytime, if another user with better ranking attempts to match with that BS.

Let $\boldsymbol{\rho}_u$ and $\boldsymbol{\rho}_b$ be 2 vectors containing, respectively, the indices of all BSs, ranked in order of preferences for user u, and the indices of all users, ranked in order of preferences for BS b. Let $\mathcal{A}_o$ be a $(B \times K)$ matrix, where the b-th row of $\mathcal{A}_o$ contains the indices of the users tentatively matched with the b-th BS. A concise description of this first step is given in Algorithm 1 and Algorithm 2 described in the sequel.

Algorithm 1 Assign users to BS

```
input : ρ_u, ρ_b ∀u ∈ U,  ∀b ∈ B
for every user u unmatched do
    while u does not have a tentative match do
        Tentatively match u to the most preferred BS in ρ_u by
        calling Algorithm 2 with ρ_u, ρ_b, A_o  if succeed then
            Continue with other users
        else
            Remove b from ρ_u.
        end
    end
end
return A_o
```

Algorithm 2 Tentative match u to b

```
input : ρ_u, ρ_b, A_o
if b has an unfilled channel, i.e., the b-th row of A_o has less
than K elements then
    1- match u with b, i.e, add u to the b-th row of A_o
    2- return succeed
else
    if u is more preferred by b than another user who already
    is tentatively matched to b then
        1- remove the less preferred user from the b-th row of
        A_o then add u
        2- return succeed
    else
        return fail
    end
end
```

B. Channel Allocation to Users

The previous step assigns K users to every BS. This second step consists of assigning channels to users, for fixed UL and DL transmissions powers and fixed α for all users. For every BS with K channels and K users, assign a channel to every user. The aim of this step is to exploit multi-user diversity in the user scheduling so as to minimize cross-mode and intra-mode inter-cell interference. Although the channel allocation step performs a one-to-one assignment of the K channels at each BS to its K associated users, we cannot directly apply a one-to-one matching algorithm. This is because the utilities at the BSs are inter-dependent due to the interference effect. In other words, the benefit from the channel assignment for a given BS depends on the decision of the other BSs. To overcome such inter-dependence of utilities, this paper suggests an iterative one-to-one assignment algorithm.

Let $\mathcal{A}_i$ be the assignment matrix of K rows and B columns at the i-th iteration of the proposed algorithm. The (k, b) element of $\mathcal{A}_i$ contains the index of the user assigned to the k-th channel of the b-th BS. At each iteration of the proposed method, the algorithm sequentially performs the channel assignment for all BSs via the updated assignment matrix. More specifically, for every cell (BS) under consideration, the algorithm applies a one-to-one assignment (K to K assignment) to allocate channels to the users associated to that BS, while assuming that the others BSs have the assignment defined in $\mathcal{A}_i$. There are several combinatorial optimization algorithms that solve the one-to-one assignment problem in polynomial time, e.g., see [23] and references therein. In this paper, we choose to use Hungarian algorithm[5] [25] for its

[4]This algorithm is introduced by Gale and Shapley in 1962. It is used by NRMP (National Resident Matching Program) to match medical school students with residency programs, i.e. hospitals. In our case, the applicants are the users, and the residency programs are the BSs, where every BS has K slots.

[5]The Hungarian algorithm is a combinatorial optimization algorithm that solves the one-to-one assignment problems in a polynomial time. To assign K objects to K elements, the Hungarian algorithm relies on forming a $K \times K$ matrix called cost matrix, where the (i, j)th element of the matrix is the cost of assigning object i to element$j$. The algorithm guarantees that every element in the row is assigned to an element in the column in such a way that the total cost is minimized (in our case, the total utility maximized). The Hungarian algorithm guarantees that every user in the cell under consideration is assigned to a subchannel in such a way that the total utility in that cell is maximized.

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relative ease.

To perform Hungarian algorithm, a $K \times K$ utility matrix, called $\mathcal{U}_b^{(i)}$, is constructed. The element (u, k) of this matrix is the benefit from assigning user u to channel k of BS b. In our case, at the i-th iteration, the benefit is defined $f_{ubk}^{(i)}(\boldsymbol{x}_k)$ given in (18). The value of $f_{ubk}^{(i)}(\boldsymbol{x}_k)$ is evaluated using the assignment defined in $\mathcal{A}_i$. The Hungarian algorithm guarantees that every user in the cell under consideration is assigned to a subchannel in such a way that the total utility in that cell is maximized. The b-th row of $\mathcal{A}_i$ is updated after the allocation within the b-th BS. The algorithm stops when the value of the utility function is stable, i.e., its value evaluated with the current assignment matrix $\mathcal{A}_i$ is the same as the one obtained with the previous assignment matrix $\mathcal{A}_{i-1}$. In other words, the algorithm stops when the $\mathcal{A}_i$ is equal to $\mathcal{A}_{i-1}$, or when $\mathcal{A}_i$ and $\mathcal{A}_{i-1}$ yield the same utility value. A description of this step is given in Algorithm 3.

Algorithm 3 Channel Assignment

```
input : A_o, p^(b), p^(u) and α
i = 0;
Evaluate Σ_{b,k} f_{ubk}^{(o)}(x_k) ;
do
    i = i + 1;
    A_i = A_{i-1}
    for b ← 1 to b do
        1- Construct the utility matrix U_b^{(i)} using A_i.
        2- Apply Hungarian algorithm to find the optimal
           assignment from U_b.
        3- Update the b-th row of A_i with the result.
    end
    Evaluate Σ_{b,k} f_{bk}^{(i)}(x_k);
while Σ_{b,k} f_{ubk}^{(i-1)}(x_k) ≤ Σ_{b,k} f_{ubk}^{(i)}(x_k);
A = A_i;
return A
```

C. Power Control and Spectrum Overlap Allocation

Given the scheduling obtained in the previous step, this part now proposes the subsequent step to determine the powers and UL/DL spectrum overlap. First, write the contribution of every channel to the utility function as follows:

$$\mathcal{F}_k = \sum_b f_{ubk}, \tag{19}$$

where f_{ubk} is defined in (18). Therefore, maximizing the total utility is equivalent to separately maximizing the contribution of every channel to the total utility. This is because the total utility is just the summation of the contribution from all independent channels, i.e.:

$$\sum_k \mathcal{F}_k. \tag{20}$$

In other words, at this stage (within every iteration, and for fixed scheduling), solve the following optimization problem for every k:

$$\max_{\boldsymbol{x}_k} \quad \mathcal{F}_k = \sum_b f_{ubk}(\boldsymbol{x}_k), \tag{21a}$$

$$\text{s.t.} \quad \mathbf{0} \leq \boldsymbol{p}_{\boldsymbol{k}}^{(\text{u})} \leq \boldsymbol{p}_{\max}^{(\text{u})}, \tag{21b}$$

$$\boldsymbol{p}_{\min}^{(\text{b})} \leq \boldsymbol{p}_k^{(\text{b})} \leq \boldsymbol{p}_{\max}, \tag{21c}$$

$$\mathbf{0} \leq \boldsymbol{\alpha}_k \leq \mathbf{1}, \tag{21d}$$

where the optimization is over $\boldsymbol{x}_k \in \mathbb{R}^{3N}$, which is the vector containing the design variables corresponding to the k-th channel, i.e., a concatenation of k-th column of $\boldsymbol{p}^{(\text{b})}$, $\boldsymbol{p}^{(\text{u})}$ and $\boldsymbol{\alpha}$ as mentioned in Section II-A.

For every k, and for both objective functions (17) and (18), the optimization problem (21) is a non-convex optimization problem due the coupled interference terms in the SINR expressions (4) and (9). Moreover, the problem has a difference of convex (d.c.) function structure, which is known to be NP-hard in general [26]. This paper, however, argues that the objective function defined in (18) is more convenient for FD cellular networks. Therefore, for this objective function, the paper proposes an algorithm that overcomes the d.c. structure of the problem by means of iteratively relaxing it to a convex optimization problem that can be solved in a polynomial time (e.g., the interior point method [27]). Such approach particularly follows from the ability of transforming the sum-log rate maximization in (18) into a sequence of relaxed convex problems as shown in the following proposition.

Proposition 1. *The non-convex utility function in* (21a) *when using* (18) *is approximated with two convex functions, according to the range of SINRs, as given in* (22).

Those two convex functions iteratively depend on the optimizer of the approximated problem in the previous iteration. In (22), $\boldsymbol{x}_k^{[j-1]}$ *is defined as the solution of the problem at the* $(j-1)$*-th iteration.* $L_{bk}^{(\mathcal{X})}$ *is defined as follows:*

$$L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k) = \log\left(\tilde{S}_{bk}^{\mathcal{X}\overline{\mathcal{X}}}(\boldsymbol{x}_k) + I_{bk}^{(\overline{\mathcal{X}\mathcal{X}})}(\boldsymbol{x}_k) + I_{bk}^{(\mathcal{X}\overline{\mathcal{X}})}(\boldsymbol{x}_k) + N_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right). \tag{23}$$

$\widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\right)$ *is the first order Taylor expansion of* $L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)$ *at* $\boldsymbol{x}_k^{[j-1]}$*:*

$$\widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\right) = L_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k^{[j-1]}\right) + \left(\nabla L_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k^{[j-1]}\right)\right)^T \left(\boldsymbol{x}_k - \boldsymbol{x}_k^{[j-1]}\right) \tag{24}$$

Finally,

$$v_{bk}^{(\mathcal{X})} = \frac{y_o}{1 + y_o}, \quad \textit{and} \tag{25}$$

$$w_{bk}^{(\mathcal{X})} = \log(1 + y_o) - \frac{y_o}{1 + y_o}\log(y_o). \tag{26}$$

Note that the interior point method [27] is used to solve the power and α *allocation for the sum-of-rate objective function in the simulations section of the paper.*

Details of the above proposition proof are given in **Appendix A**. A brief description of the algorithm used to solve the proposed convex relaxation is shown in Algorithm 4 table.

It is worth noting that since the approximated optimization problem is convex at each iteration, convex optimization algorithms can be implemented to adequately obtain the optimal

$$\mathcal{F}_k^{[j]}\Big(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\Big) = \sum_{n=1}^{N} 2\log((1+\alpha_{bk})B) + \\ \sum_{n=1}^{N} \sum_{\mathcal{X}=\{\text{b,u}\}} \begin{cases} \log\left(v_{bk}^{(\mathcal{X})}\left(\log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - \widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\right)\right) + w_{bk}^{(\mathcal{X})}\right) & \text{if } \gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k^{[j-1]}) \geq 1, \\ \log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - \widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\right) & \text{if } \gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k^{[j-1]}) < 1. \end{cases} \quad (22)$$

Algorithm 4 Optimization of the design parameters for channel k

input : k-th column of $\mathcal{A}$
Choose a feasible starting point $\boldsymbol{x}_k = \boldsymbol{x}_k^{[o]}$ (for example, FD with maximum powers).
Set the maximum iteration number J
$j = 1$;
while $\|\nabla\mathcal{F}_k^{[j]}\Big(\boldsymbol{x}_k^{[j-1]}\Big)\| \geq \epsilon$ *or* $j \leq J$ **do**
  1- Find $v_{bk}^{(\mathcal{X})}$ and $w_{bk}^{(\mathcal{X})}$ using (29) with $y_o = \gamma_{bk}^{(\mathcal{X})}\Big(\boldsymbol{x}_k^{[j-1]}\Big)$
  2- Solve the convex approximation of (21) using $\widetilde{\mathcal{F}}^{[k]}\Big(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\Big)$ as objective function in order to find $\boldsymbol{x}_k^{[j]}$
  3- $j = j+1$
end
return $\boldsymbol{x}_k$

solution at each iteration. The solution for the convex relaxed problem is, however, a suboptimal solution for the original non-convex problem with the utility in (21a). Nevertheless, the simulations results in next section show the appreciable performance improvement of the proposed algorithm as compared to HD and FD schemes for different network environments.

Algorithm 5 Overall Algorithm

1- Construct $\boldsymbol{\rho}_u\ \forall u \in \mathcal{U}$, $\boldsymbol{\rho}_b\ \forall\ b \in \mathcal{B}$
2- Assign users to BSs, call Algorithm 1:
  Input: $\boldsymbol{\rho}_u\ \forall u \in \mathcal{U}$, $\boldsymbol{\rho}_b\ \forall b \in \mathcal{B}$,
  Output: $\mathcal{A}_o$
3- Set maximum number of iteration N, $n = 1$;
while $n \leq N$ ***and*** $\sum_{b,k} f_{ubk}^{(n-1)}(\boldsymbol{x}_k) \leq \sum_{b,k} f_{ubk}^{(n)}(\boldsymbol{x}_k)$ **do**
  - **for** $k \leftarrow 1$ **to** K **do**
    Allocate powers and spectrum overlap for all users using the k-th channel, call Algorithm 4 using $\mathcal{A}_o$:
      Input: k-th column of $\mathcal{A}$
      Output: Optimal solution of the relaxed problem $\boldsymbol{x}_k$
  end
  - Construct the matrices $\boldsymbol{p}^{(\text{b})}$, $\boldsymbol{p}^{(\text{u})}$ and $\boldsymbol{\alpha}$ with $\boldsymbol{x}_k$'s.
  - Find the best channel assignment matching the powers and $\boldsymbol{\alpha}$, call Algorithm 3:
    - Input: $\mathcal{A}_o$, $\boldsymbol{p}^{(\text{b})}$, $\boldsymbol{p}^{(\text{u})}$ and $\boldsymbol{\alpha}$.
    - Output: $\mathcal{A}$
  - Set $\mathcal{A}_o = \mathcal{A}$;
  - Set $n = n+1$;
end

D. Overall Algorithm

A concise description of the overall iterative algorithm, including all parts described in the previous subsections, is presented in Algorithm 5. The stopping criteria of the iterative algorithm is when the value of the utility function is no longer increasing. Note that the implementation steps of the algorithm requires in practice a centralized processing unit that is aware of the network parameters involved in the resource allocation process.

It is shown in the simulation results, Sec. IV, that the suggested algorithm converges after a few iterations for both utility functions introduced in Sec. II-D. As for its complexity, it is shown in [28] that the complexity (i.e., the total number of arithmetic operations required to reach an optimal solution) of stable marriage problem (SMP) is in the order of the square of the number of agents. More specifically, in our case, the time to run Algorithm 1 is $\mathcal{O}((BK)^2)$. Each main iteration of the interior point method (IPM) has a worse case complexity which is a polynomial function of the problem size [29], i.e., each time the algorithm runs one of the inner loops of Algorithm 4, the total number of arithmetic operations needed is in the order of $\mathcal{O}((B)^3)$. Finally, reference [30] shows that the complexity of the Hungarian method is in the order of $\mathcal{O}(K^3)$, where K is the number of agents. In this paper, K is the number of subcarriers. Table I displays the complexity of each algorithm and the corresponding number of repetitions in Algorithm 5. M is the number of iterations needed for Algorithm 3 convergence, and N is the number of iterations of the outer loop in Algorithm 5.

Algorithm	Complexity	Repetitions
SMP	$\mathcal{O}((BK)^2)$	1
Hungarian method	$\mathcal{O}(K^3)$	NMB
IPM	$\mathcal{O}((B)^3)$	NKJ

TABLE I: Complexity of each algorithm and the number of repetitions needed in the overall Algorithm 5.

The computational complexity of the overall algorithm, therefore, becomes:

$$\mathcal{O}((BK)^2) + N\left(KJ\mathcal{O}((B)^3) + MB\mathcal{O}(K^3)\right). \quad (27)$$

The overall algorithm, therefore, has a polynomial computational complexity.

IV. Numerical Results

A. Benchmark Schemes and Simulation Setup

In this section, different schemes are compared to the proposed interference management scheme. Since this pro-

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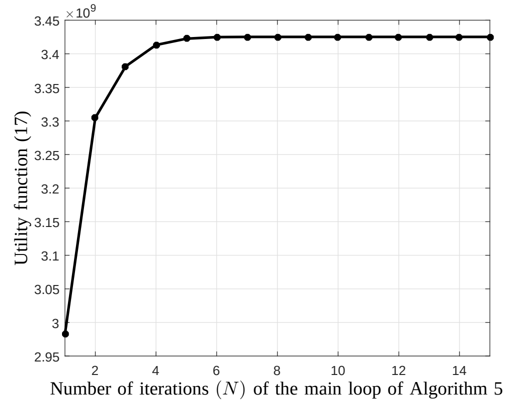
posed algorithm performs scheduling, power and α control, the benchmark schemes are divided in two categories: 1) the benchmark schemes designated to evaluate the performance of the scheduling part of the suggested algorithm, 2) the benchmark schemes assessing the performance of the power control and spectrum overlap allocation technique.

1) Scheduling Benchmark Schemes: The random assignment is the first considered scheduling benchmark scheme, which allows the users to be randomly assigned to BSs and channels. The second scheduling benchmark scheme is the Voronoi cell association, i.e., the users are assigned to the closest BSs. Within every cell, the channels are randomly assigned to users. This implies that if a BS has more users in its Voronoi cell than the available channels, some of the users are not served. The last benchmark scheme is the exhaustive search. For this scheme, the algorithm compares all the possible assignments (there are $BK!$ of them) and chooses the one that yields the highest utility function value.

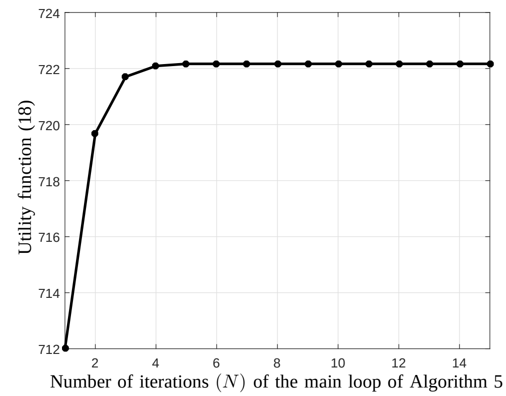
2) Power and α Allocation Benchmark Schemes: In this scenario, the performance of the optimized α-D is compared to the performance of HD ($\alpha = 0$ for all users) and FD ($\alpha = 1$ for all users) schemes. For these schemes, the users and BSs are assumed to be communicating with maximum powers.

Four test environments are used in the simulation results, where the types of the environments and their respective simulation parameters are taken from 3GPP standard in [31] and are shown in Table II. The parameters for the path-loss model in Table II are defined as follows; r is the propagation distance in meters, f_c is the carrier frequency in GHz and d is the average building height (we take $d = 5$ m). The thermal noise level is the same at all receivers $N_{(\text{u})} = N_{(\text{b})} = -174$ dBm/Hz.

In each simulation run, B BSs are deployed with the inter site distance (ISD) corresponding to each environment. Unless specifically stated otherwise, B is equal to 9. Then, BK users are randomly dropped inside the network. The disparity between UL and DL transmit power is specified through $\delta = p^{(\text{b})}_{\text{min}}/p^{(\text{u})}_{\text{max}}$. In Fig. 5, 6 and 9, δ is gradually increased by modification of $p^{(\text{b})}_{\text{min}}$. $p^{(\text{b})}$ varies in a range of 10 dB (i.e. $p^{(\text{b})}_{\text{max}} = p^{(\text{b})}_{\text{min}}{+}10$ dB).The SIC factor β is assumed to be perfect unless stated otherwise.



(a) Sum rate maximization.



(b) Sum of log rate maximization.

Fig. 4: Variation of the utility function according to the number of iteration of the main loop (N) of Algorithm 5.

B. Simulation Results

1) Algorithm Convergence: Fig. 4a and Fig. 4b show the variations of the utility function with the number of iterations in the main loop of algorithm 5, for the two objective functions introduced in Sec. II-D, i.e., the sum of rate and the sum of log rate. As the figures show, the algorithm converges in few iterations for both objective functions. It is worth mentioning that Algorithm 5 does not converge to the true optimal solution. Instead, it give a sub-optimal solution, based on a heuristic method, that is efficient and yields to tangible performance gains as illustrated in the following set of simulation results.

2) Gain from the Proposed Scheduling: In order to bring out the importance and efficiency of the proposed scheduling algorithm, in Fig. 5, we consider our proposed algorithm (cf. Algorithm 5), and replace the scheduling part by one of the benchmark scheduling algorithms presented in IV-A1. In other words, in Fig. 5, we consider the α-D scheme with optimized power and α but with different scheduling techniques. The variation of the value of the utility function according to the disparity between the UL and DL powers is shown. The power disparity here is measured by the difference between the DL (BS) minimum power and the UL (user) maximum power in dB. The exhaustive search gives the best value of the utility function followed by the suggested scheduling algorithm, then the Voronoi assignment, and finally the random scheduling. The value of the utility function obtained from our suggested scheduling algorithm is much higher than the one obtained from random and Voronoi scheduling. Moreover, it is comparable to the one obtained from exhaustive search. This result is satisfying considering that the suggested algorithm is much simpler to compute as compared to the exhaustive search.

3) Comparison of the Two Utility Functions: Fig. 6 is shown to support the choice of utility function as explained in II-D. We consider 3 schemes: 1) our suggested scheme, denoted by α-D in the figure, 2) the FD scheme with the suggested scheduling algorithm, where $\boldsymbol{\alpha}$ is fixed to $\mathbf{1}$ and all transceivers transmit with maximum power, and 3) a baseline scheme which considers the HD scheme ($\alpha = 0$ for all users) where the scheduling is based on Voronoi delimitation

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Environment	ISD(m)	f_c(GHz)	$2B$(MHz)	$p^{(\mathrm{u})}_{\max}$(dBm)	Pathloss model (dB)
Indor hotspot	60	3.4	40	21	$16.9\log_{10}(r)+32.8+20\log_{10}(f_c)$
Urban micro-cell	200	2.5	20	24	$36.7\log_{10}(r)+22.7+26\log_{10}(f_c)$
Urban macro-cell	500	2	20	24	$22.0\log_{10}(r)+32.8+20\log_{10}(f_c)$
Rural macro-cell	1732	0.8	20	24	$20\log_{10}(40\pi d f_c/3)+\min(0.03h^{1.72},10)\log_{10}(d)$ $-\min(0.044d^{1.72},14.77)+0.002\log_{10}(d)d$

TABLE II: Network parameters for different environment

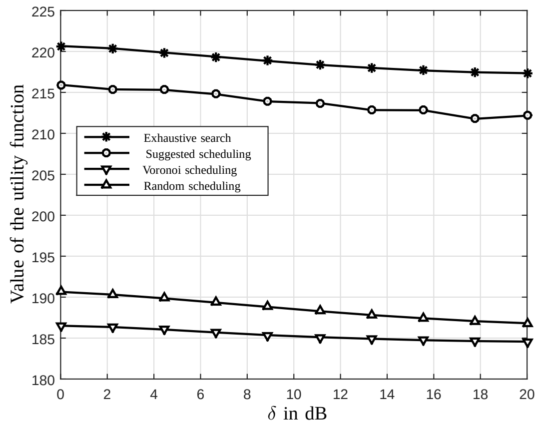
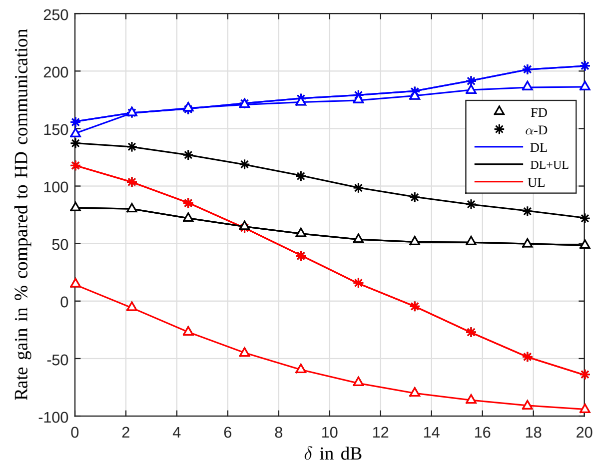
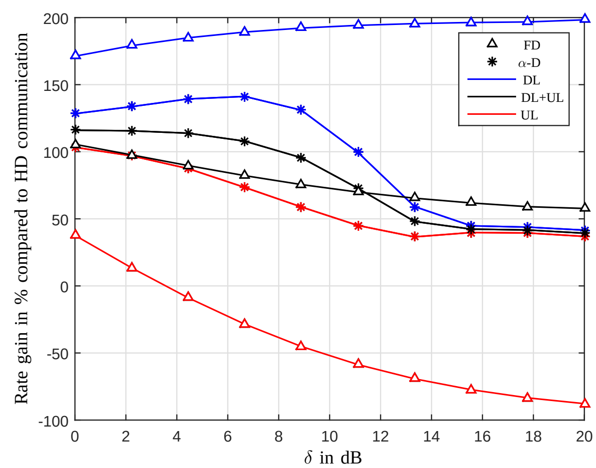


Fig. 5: Variation of the utility function for α-D with optimized α and power, using different scheduling algorithms, $B=2, K=3$ for micro urban environment.



(a) Sum rate maximization.



(b) Sum of log rate maximization.

Fig. 6: Variation of the gain (%) in rate compared to the same baseline scheme, according to the disparity between UL and DL transmit powers (δ) for micro urban environment.

and random channel assignment, and both users and BSs transmit with maximum transmit power. The figure depicts the variation of the gains in percentage brought by the α-D and FD schemes compared to the baseline scheme (HD), for UL rate, DL rate, and sum of UL and DL rates. Particularly, the figure shows the variations of each gain as a function of the disparity between the UL and DL powers, in which the power disparity is measured by the difference between the DL (BS) minimum power and the UL (user) maximum power in dB. The considered utility functions in Fig. 6a and Fig. 6b are, respectively, the sum of rate (17) and the sum of log of rate (18). The figures confirm the fairness introduced by the log-sum rate utility along with the α duplex scheme, especially in case of high disparity between transmit powers $\left(p^{(\mathrm{b})}_{\min}-p^{(\mathrm{u})}_{\max}\geq 10\mathrm{dB}\right)$. The figure also shows that the FD is always the best scheme for DL transmission for both utilities, and the gain enhances as the minimum DL transmit power increases. This comes at the cost of degrading the UL performance as the DL power increases, due to the strong interference from other BSs. For low BS transmit power, the FD communication can still yield small gains in UL rate compared to HD: 75% from sum rate maximization and 58% from log-sum rate maximization, while gaining respectively 197% and 110% in DL. For high DL transmit power, FD remains advantageous for DL transmission, but the UL is highly deteriorated. At this point, the sum of log rate utility fails to prevent the degradation in the UL rate due to the inflexible spectrum allocation.

The balancing between UL and DL, introduced by the fairness-aware utility, is more evident in α-D scheme in which the vector $\boldsymbol{\alpha}$ is also an optimization variable. For low power disparity, $\boldsymbol{\alpha}$ is chosen such that both UL and DL benefit from the partial overlap of spectrum. As the disparity increases, the generated DL interference gets stronger. However, thanks to the choice of utility function, in Fig. 6b, the scheme never gets to choose a value of $\boldsymbol{\alpha}$ that deteriorates the UL transmission. Therefore, for high disparity between UL and

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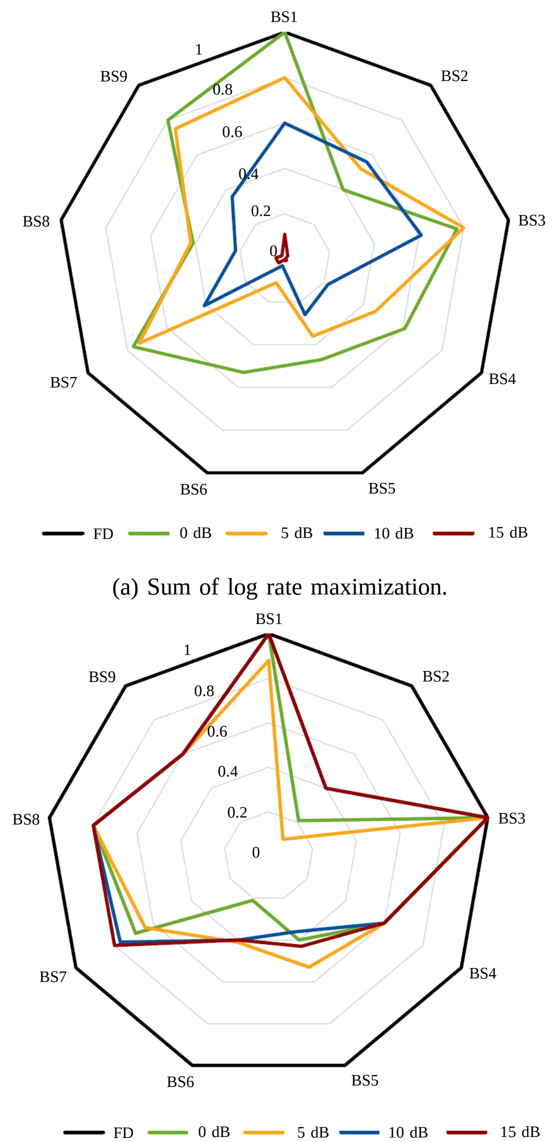
DL transmit power $\left(p_{\min}^{(b)} - p_{\max}^{(u)} \geq 12 \text{ dB}\right)$, the gain from α-D becomes constant. As a matter of fact, with the optimization of sum of logarithm of rates, α-D never deteriorates any of the performance metrics shown in Fig. 6b (UL rate, DL rate and sum of rates). This is not the case when the utility function is the sum of all rates. As we can see in Fig. 6a, for high power disparity, the optimization problem opts for higher $\boldsymbol{\alpha}$, in order to boost the DL transmission, thereby generating strong interference that shadows the users' signals and hence damaging the UL transmission.

Finally, Fig. 6 shows that managing the interference generated by FD communication through scheduling only is not enough. Adding the control of the transmission power and the amount of overlap between UL and DL spectrum grants better results.

4) Optimal value of α: The selection of $\boldsymbol{\alpha}$ as a function of the optimization utility and the UL/DL power disparity can be observed and explained clearly using Fig. 7. The figure shows the optimal $\boldsymbol{\alpha}$ opted by every BS for different levels of disparity between UL and DL power. For the sum of log rates optimization, Fig. 7a shows that the chosen $\boldsymbol{\alpha}$ is high when the disparity level is low, because the UL has sufficient power to compensate for the interference from the other BSs. As the disparity increases, the system becomes more conservative and selects smaller $\boldsymbol{\alpha}$ to protect the UL rate, and tends to $\mathbf{0}$ at 15 dB (HD communication). On the other hand, for sum rate optimization, Fig. 7b shows that the system is always aggressive and chooses a high value of $\boldsymbol{\alpha}$ independently from the level of disparity between UL and DL powers, which explains the high degradation in the UL rate in the case of sum of rates utility.

5) Effect of SIC: Fig. 8 depicts the effect of the imperfection of SIC to the network performance. The figure shows the variation of the UL and DL rate according to the SIC factor β. Note that higher value of β means more SI power leaked from the transmitter to the receiver of every equipment. Therefore, as expected, the UL and DL rate are degrading with the increase of β. The degradation of the rates is more highlighted when the disparity between UL and DL transmit powers is low (i.e., when $\delta = p_{\min}^{(b)} - p_{\max}^{(u)}$ becomes 0dB). This happens for two reasons. First, in case of low disparity, the algorithm chooses large overlap between the UL and DL spectrum as the cross-mode and intra-mode interference power is manageable. This leads to high SI power as the SI is an increasing function of the amount of spectrum overlap. Therefore, poor SIC has more eminent effect on the performance metrics. Second, in low disparity, both UL and DL powers are relatively low, and so the useful signal may get shadowed by the SI power.

6) Comparison to Different Schemes: In Fig. 9, we compare our suggested scheme to different schemes obtained from the combination of the schemes presented in IV-A. The variation of the utility function, the DL rate and the UL rate are respectively shown in Fig. 9a, Fig. 9b and Fig. 9c as a function of the disparity between the maximum users transmit power and the minimum BSs transmit power. In Fig. 9a, it can be seen that the scheme with the suggested scheduling algorithm always provides the highest value of the utility function. In fact, using the suggested scheduling algorithm, both HD and FD with fixed powers perform better than the schemes using others scheduling algorithms, even when these schemes perform the power and α optimization steps. This is not always the case for UL and DL rate. However, considering the same resource allocation technique (i.e. optimized α-D or FD or HD), the one with the suggested scheduling algorithm yields always the best UL and DL rates.



(a) Sum of log rate maximization.

(b) Sum rate maximization.

Fig. 7: Chart showing the optimal value of $\boldsymbol{\alpha}$ for different levels of UL and DL power disparity for micro urban environment.

Fig. 9b shows that using FD under maximum transmit power combined with the suggested scheduling algorithm is the most beneficial. The DL rate increases as the minimum DL transmit power grows. This shows again the indifference of DL transmission to interference thanks to its strong transmission power. The figure also shows that FD with maximum power is the best for the other scheduling algorithm in terms of

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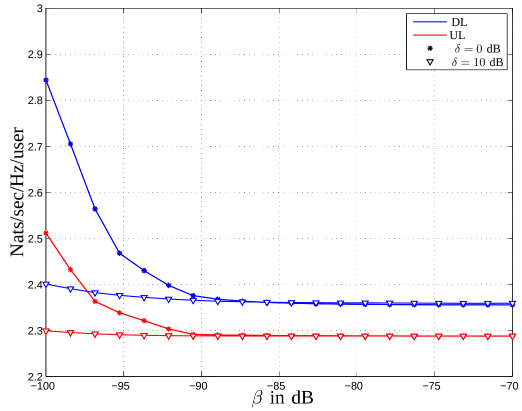


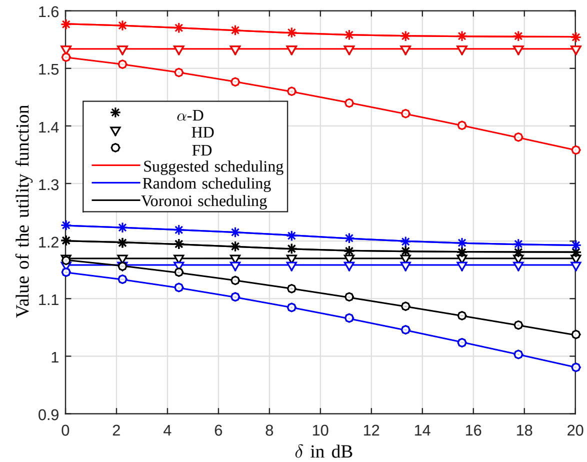
Fig. 8: Variation of the UL and DL rate according to the level of SIC in dB for different level of power disparity, $B = 9, K = 3$ for micro urban environment.

DL rate as well. On the contrary, for UL transmission, FD with maximum transmit power is the least favorable as shown in Fig. 9c. Furthermore, as the BS transmission power gets stronger, the loss generated by the interference gets worse. The figure also shows that similar conclusions can be drawn for all scheduling algorithms.

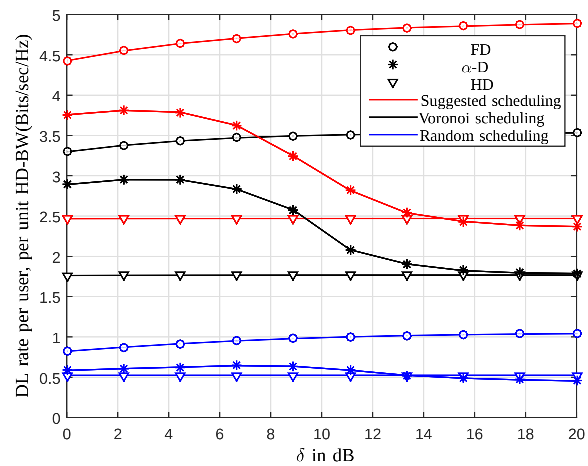
To recap, the balance introduced by the proposed scheme is evident from Fig. 9. The α-D scheme always grants the best overall utility function value while maintaining a balanced UL and DL rates.

7) Performance of the suggested scheme for Different Network Environments: Finally, Fig. 10 shows the gain harvested from the proposed algorithm for maximizing the sum of log rate under different network environments. The figure also shows the performance of the conventional baseline HD scheme that assumes $\alpha = 0$, maximum power allocation, Voronoi-based user to BS association, and random channel to user assignment. Fig. 10 further shows the performance of the FD scheme with $\alpha = 1$, maximum power allocation, but utilizing the scheduling algorithm proposed in this paper. The results are presented under four different environments: indoor, urban microcells, urban macrocells, and rural environments.

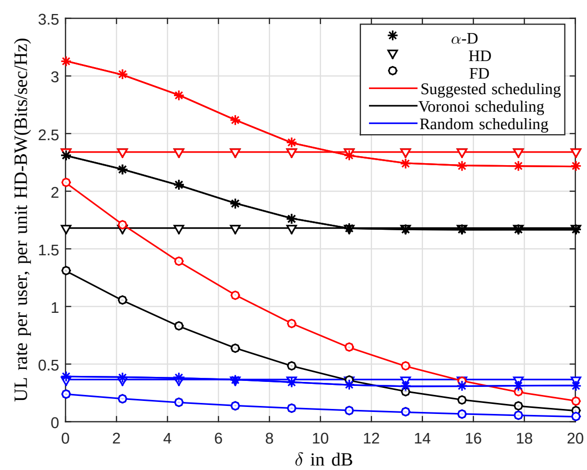
The figure shows that the maximum-power-FD with the suggested scheduling algorithm offers significant rate improvement for the DL transmission (up to 188% of gain). Such scheme, however, significantly degrades the UL transmission for all environments as expected (down to -88%). The figure particularly emphasizes the superiority of our proposed α-D scheme when compared to the FD scheme as it always improves the UL rate without sacrificing the DL FD rate gains, for all considered environments. The presented results underline again the importance of power control and UL/DL spectrum partial overlap, in addition to sensitivity to the scheduling policy. As we can see, scheduling combined with FD is beneficial only for DL but deteriorates the UL transmission. To summarize, the α-D improves both UL and DL for all environment schemes and gives a comparable DL rate improvement compared to the FD scenario. Hence, the UL rate is not only protected, but rather improved without significantly decreasing the harvested DL rate gain from FD.



(a) Utility.



(b) DL.



(c) UL.

Fig. 9: Comparison of the suggested scheme to different schemes for sum of log-rate maximization. $N = 9, \quad K = 5$ for micro urban environment..

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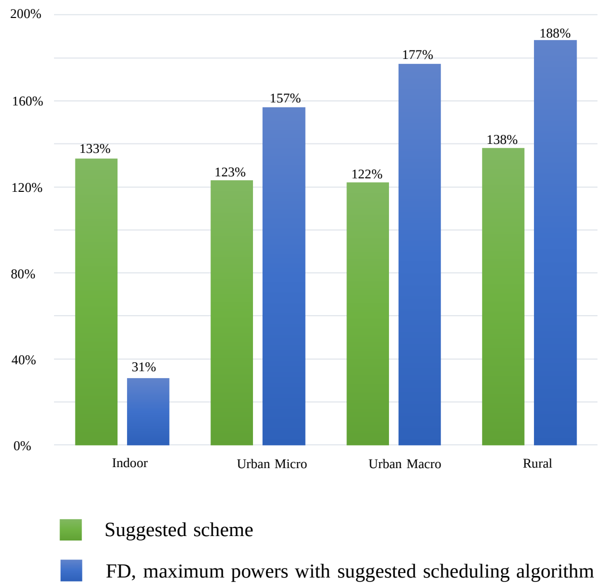
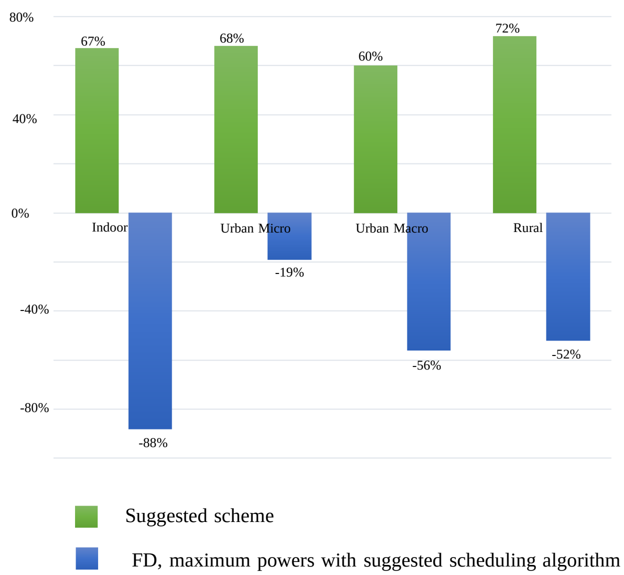


(a) DL.



(b) UL.

Fig. 10: Chart showing the gain from FD/α-D compared to HD communication for different network environments, for sum of log-rate maximization ($p^{(\mathrm{b})}_{\mathrm{min}}/p^{(\mathrm{u})}_{\mathrm{max}}$=5 dB).

V. Conclusion

This paper considers a duplex system, denoted by α-D system, wherein a fine-grained bandwidth control for each UL/DL channel pair in each BS is allowed. The paper proposes an interference management scheme through user-to-BS association, scheduling, power allocation and control of the amount of overlap between UL and DL spectrum. The problem of maximizing a rate-based utility function, subject to power constraints and bandwidth-limited rectangular pulse shapes, is considered. The paper proposes solving such a difficult problem by a heuristic algorithm that decouples the non-convex mixed-integer formulated optimization problem into simpler subproblems. The algorithm, first, matches users to BSs, then alternates between channel assignment and power/α allocations. The results confirm the superiority of the suggested algorithm compared to different benchmarks. From one side, FD communication is advantageous for DL rate on the expense of significant deterioration on the UL rate. On the other side, HD underutilizes the available spectrum. In contrast to the FD and HD schemes, the proposed α-D scheme harvests tangible network rate gains while maintaining the balance between the UL and DL rates.

Appendix A
Proof of Proposition 1

1) High SINR regime: For $\gamma_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k^{[j-1]}\right) \geq 1$, use the following lower bound [32]:

$$\log(1+y) \geq v \log y + w. \tag{28}$$

This bound is tight at $y = y_o$ when the approximation constants are chosen as

$$v = \frac{y_o}{1+y_o}, \qquad \text{and} \qquad w = \log(1+y_o) - \frac{y_o}{1+y_o}\log(y_o) \tag{29}$$

By properly choosing the constants of the above bound for every $\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)$, we get:

$$\begin{aligned} &\log\left(\log\left(1+\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right)\right) \simeq \log\left(v_{bk}^{(\mathcal{X})}\log\left(\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) + w_{bk}^{(\mathcal{X})}\right) \\ &\simeq \log\left(v_{bk}^{(\mathcal{X})}\left(\log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) + w_{bk}^{(\mathcal{X})}\right) \end{aligned} \tag{30}$$

where

$$L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k) = \log\left(\tilde{S}_{bk}^{(b)}(\boldsymbol{x}_k) + I_{bk}^{(\overline{\mathcal{X}}\mathcal{X})}(\boldsymbol{x}_k) + I_{bk}^{(\mathcal{X}\overline{\mathcal{X}})}(\boldsymbol{x}_k) + N_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right). \tag{31}$$

Using first order Taylor series expansion at $\boldsymbol{x}_k^{[j-1]}$ (optimal value of $\boldsymbol{x}_k$ at previous iteration), $L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)$ can be approximated as in (24). Combining (24) with (30), the utility function can be approximated as follows

$$\begin{aligned} \widetilde{\mathcal{F}}(\boldsymbol{x}_k) = &\sum_{i=1}^{N} 2\log\left((1+\alpha_{bk})B\right) + \\ &\sum_{i=1}^{N}\sum_{\mathcal{X}=\{\mathrm{b,u}\}} \log\left(v_{bk}^{(\mathcal{X})}\left(\log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - \widetilde{L}_{bk}^{(\mathcal{X})}\left(\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[k-1]}\right)\right) + w_{bk}^{(\mathcal{X})}\right). \end{aligned} \tag{32}$$

The first term is concave, since it is the summation of the logarithm of linear functions. As for the second term, every term of the summation is the logarithm of a concave function: $S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)$ is concave in $(\boldsymbol{x})$, and $\tilde{L}_{bk}^{(\mathcal{X})}\left(\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[k-1]}\right)\right.$ is a linear function of $(\boldsymbol{x}_k)$.

2) Low SINR regime: For low SINR, $\gamma_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k^{[j-1]}\right) < 1$,

$$\log\left(1+\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) \simeq \gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k). \tag{33}$$

Therefore

$$\log\left(\log\left(1+\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right)\right) \simeq \log\left(\gamma_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right), \tag{34}$$

$$= \log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - L_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k), \tag{35}$$

$$\simeq \log\left(S_{bk}^{(\mathcal{X})}(\boldsymbol{x}_k)\right) - \widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[k-1]}\right) \tag{36}$$

where $\widetilde{L}_{bk}^{(\mathcal{X})}\left(\boldsymbol{x}_k, \boldsymbol{x}_k^{[j-1]}\right)$ is given in (24).

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