Dynamic Uplink/Downlink Resource Management in Flexible Duplex-Enabled Wireless Networks

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Abstract—Flexible duplex is proposed to adapt to the channel and traffic asymmetry for future wireless networks [1]. In this paper, we propose two novel algorithms within the flexible duplex framework for joint uplink and downlink resource allocation in multi-cell scenario, named successive approximation of fixed point (SAFP) and resource muting for dominant interferer (RMDI), based on the awareness of interference coupling among wireless links. Numerical results show significant performance gain over the baseline system with fixed uplink/downlink resource configuration, and over the dynamic time division duplex (TDD) scheme that independently adapts the configuration to timevarying traffic volume in each cell. The proposed algorithms achieve two-fold increase when compared with the baseline scheme, measured by the worst-case quality of service satisfaction level, under a low level of traffic asymmetry. The gain is more significant when the traffic is highly asymmetric, as it achieves three-fold increase.

I. INTRODUCTION

Flexible duplex is one of the key technologies in fifth generation (5G) to optimize the resource utilization depending on traffic demand [1]. The main objective is to adapt to asymmetric uplink (UL) and downlink (DL) traffic with flexible resource allocation in the joint time-frequency domain, such that the distinction between TDD and frequency division duplex (FDD) is blurred, or completely removed.

Despite the advantage of adaptation to the dynamic traffic asymmetry, the drawback is the newly introduced inter-cell interference (ICI) between duplexing mode DL and UL, hereinafter referred as inter-mode interference (IMI). The DL-to-UL interference plays a more important role due to the large difference between DL and UL transmission power. Many works focus on physical layer design to overcome IMI. In [2], special kinds of radio frames with different ratio of UL/DL are introduced to FDD, and heuristic approach is proposed to find the most suitable one solely based on the traffic volume. A few studies target the problem of dynamic UL/DL resource configuration. In [3], the authors formulate a utility maximization problem to minimize the per-user difference between UL and DL rates; while in [4] the problem is formulated as a twosided stable matching game to optimize the average utility per user. Both works consider a single cell system where IMI does not play a role. However, in a multi-cell system the optimal UL/DL configuration depends not only on the traffic volume but also the interference coupling between all transmission links. Although very few studies provide solutions within the flexible duplex framework, similar problem exists in dynamic TDD. A popular solution is the cell-cluster-specific UL/DL

reconfiguration [5], but how to coordinate the clusters for intercluster IMI mitigation still remains a challenge.

In this paper, we optimize UL/DL resource configuration in multi-cell scenario, by recasting max-min fairness problem into a fixed point framework. Such framework is widely used for power control [6], [7] and load estimation [8], [9] for UL or DL systems independently. Our previous work [10] exploits the framework to tackle the joint UL/DL resource allocation and power control problem within flexible duplex, assuming that ICI is simply proportional to the load. This assumption, however, is valid only when each resource unit has the same chance to be allocated to UL or DL, which may result in high probability of generating IMI. We improved the model in this paper. The main contribution is summarized in below.

- A new interference model is defined, which allows to prioritize the positions of the resources for UL and DL transmission, to reduce the probability of generating IMI.
- We propose a novel algorithm SAFP to find algorithmic solution to optimize UL/DL resource configuration. Unlike the models in previous works [6], [8], [9], the new interference model is *nonlinear* and *nonmonotonic*.
- Further we enhance SAFP to RMDI by detecting sequentially the dominant interferer in the system, and muting the partial resource in neighboring cells to reduce ICI.
- We compare SAFP and RMDI numerically with two conventional schemes: a) fixed UL/DL configuration, and b) dynamic TDD that adapts UL/DL configuration solely based on traffic volume, and show a performance gain varying from two to three fold depending on the traffic asymmetry.

The rest of the paper is organized as follows. In Section II, the system model is described together with the correspondent notation. The problem statement is given in Section III. The proposed algorithms SAFP and RMDI are introduced in Section IV and V, respectively. Finally, in Section VI, the numerical results are presented.

II. SYSTEM MODEL

In this paper, we use the following definitions. The nonnegative and positive orthant in k dimensions are denoted by \mathbb{R}^k_+ and \mathbb{R}^k_{++} , respectively. Let $\mathbf{x} \leq \mathbf{y}$ denote the componentwise inequality between two vectors \mathbf{x} and \mathbf{y} . Let diag(\mathbf{x}) denote a diagonal matrix with the elements of \mathbf{x} on the main diagonal. For a function $\mathbf{f} : \mathbb{R}^k \to \mathbb{R}^k$, \mathbf{f}^n denotes the *n*-fold composition so that $\mathbf{f}^n = \mathbf{f} \circ \mathbf{f}^{n-1}$. The cardinality of set \mathcal{A} is

TABLE I: NOTATION SUMMARY

N	set of BSs with $ \mathcal{N} = N$
K	set of UEs with $ \mathcal{K} = K$
S	set of services with $ S = S$
W	set of MRUs with $ W = W$
$S^{(u)}(S^{(d)})$	set of UL (DL) services
S_n	set of services served by the <i>n</i> th BS
n_s	index of BS serving the sth service
Α	UE-to-service association matrix
В	BS-to-service association matrix
$\mathbf{B}^{(u)}$ ($\mathbf{B}^{(d)}$)	BS-to-UL (BS-to-DL) association matrix
$\delta_t(\delta_f)$	length of time duration (range of frequency) of an MRU
$W_t(W_f)$	number of smallest time (frequency) units in MRU set W
w	fraction of resource allocated to services
ν	cell load
$oldsymbol{ u}^{(\mathrm{u})}(oldsymbol{ u}^{(\mathrm{d})})$	cell load in UL (DL)
р	transmit power allocated to services
d	traffic demand of services
Н	channel gain matrix
V	link gain coupling matrix
ρ_s	per service QoS satisfaction level
ρ	worst-case QoS satisfaction level

denoted by $|\mathcal{A}|$. The positive part of a real function is defined by $[f(x)]^+ := \max\{0, f(x)\}$. The notation that will be used in this paper is summarized in Table I.

We consider an orthogonal frequency division multiplexing (OFDM)-based wireless network system, consisting of a set of base stations (BSs) $\mathcal{N} := \{n : n = 1, 2, ..., N\}$ and a set of user equipments (UEs) $\mathcal{K} := \{k : k = 1, 2, ..., K\}$. We assume that the network enables flexible duplex, where the resource in both frequency and time domains can be dynamically assigned to UL and DL. We define *minimum resource unit (MRU)* as the smallest time-frequency unit, that has a length of δ_t seconds in time domain and a range of δ_f Hz in frequency domain. We consider a set of MRUs, denoted by \mathcal{W} , consisting of W_t smallest time units and W_f smallest frequency units, and we have $W := |\mathcal{W}| = W_t \cdot W_f$.

We assume that K UEs generate a set of UL and DL services $S := S^{(u)} \cup S^{(d)}$ within the time duration of W MRUs (i.e., $W_t \delta_t$ seconds). Let the UE-to-service association matrix be denoted by $\mathbf{A} \in \{0,1\}^{K \times S}$, where $a_{k,s} = 1$ means that the *s*th service is generated by the *k*th UE, and 0 otherwise. Let $\mathbf{B} \in \{0,1\}^{N \times S}$ denote the BS-to-service association matrix. To differentiate UL and DL services, we further define BS-to-UL and BS-to-DL association matrices, denoted by $\mathbf{B}^{(u)} \in \{0,1\}^{N \times S}$ and $\mathbf{B}^{(d)} \in \{0,1\}^{N \times S}$, respectively. Let the set of services served by BS n be denoted by S_n and let the BS associated with service s be denoted by n_s .

Let $\mathbf{w} := [w_1, \ldots, w_S]^T \in [0, 1]^S$ be a vector collecting the fraction of resource allocated to all services $s \in S$. The *cell load*, defined as the fraction of occupied resource within a cell, is denoted by $\boldsymbol{\nu} = \mathbf{B}\mathbf{w} \in [0, 1]^N$. The cell load in UL and DL are denoted by $\boldsymbol{\nu}^{(u)} = \mathbf{B}^{(u)}\mathbf{w}$ and $\boldsymbol{\nu}^{(d)} = \mathbf{B}^{(d)}\mathbf{w}$ respectively, and we have $\boldsymbol{\nu} = \boldsymbol{\nu}^{(u)} + \boldsymbol{\nu}^{(d)}$. We collect the transmit power (in Watt) allocated to all services in a vector $\mathbf{p} := [p_1, \ldots, p_S]^T$.

A. Link Gain Coupling Matrix

We assume that average channel gains over W MRUs from each transmitter (TX) to each receiver (RX) are known,



Fig. 1: Example: Interference link gain.

collected in $\mathbf{H} := (h_{i,j}) \in \mathbb{R}_{++}^{(N+K)\times(N+K)}$. Note that the TXs and RXs include both UEs and BSs. Let $v_{l,s}$ denote the channel gain of the link between the TX of link l and the RX of link s. If l = s, $v_{l,s}$ is the channel gain of link s, otherwise if $l \neq s$, $v_{l,s}$ is the channel gain of the interference link caused by service l to s. We define *link gain coupling matrix* $\tilde{\mathbf{V}}$ as

$$\tilde{\mathbf{V}} := (\tilde{v}_{l,s}) \in \mathbb{R}^{S \times S}_{+}, \text{ with } \tilde{v}_{l,s} := v_{l,s}/v_{s,s}, \qquad (1)$$

where $\tilde{v}_{l,s}$ is the ratio between the interference link gain from service *l* to service *s* and the serving link gain of *s*.

An example is shown in Fig. 1, where we consider a system enabling downlink and uplink decoupling in 5G [11]. The interference caused by UL service 3 (link l_3) to DL service 1 (link l_1) has a link gain of $v_{3,1} = h_{3,4}$, i.e., the link gain between TX 3 (transmitter of l_3) and RX 4 (receiver of l_1). Given that the channel gain of l_1 is $h_{2,4}$, the interference coupling ratio is given by $\tilde{v}_{3,1} = h_{3,4}/h_{2,4}$.

Remark 1 (Incorporating different interference conditions). Without loss of generality, we can modify $\tilde{\mathbf{V}}$ to take into account different interference conditions. For example, to allow self-interference cancellation we can define $\tilde{v}_{s,s} := 0$ for every $s \in S$, while to allow zero intra-cell interference we have $\tilde{v}_{l,s} := 0$ if l and s are associated with the same BS.

B. Quality of Service Metric

In [10] we assume that the probability that l causes ICI to s associated with a different BS is approximated by the fraction of its allocated resource w_l , which leads to

$$\Pr\{l \text{ interferes } s | n_l \neq n_s\} \approx w_l \text{ for } l, s \in \mathbb{S}.$$
(2)

The average signal-to-interference-plus-noise ratio $(SINR)^1$ of $s \in S$ is approximated by

$$\operatorname{SINR}_{s} \approx \frac{p_{s}}{\sum_{l \in \mathbb{S}} \tilde{v}_{l,s} p_{l} w_{l} + \frac{\sigma_{s}^{2}}{v_{s,s}}} = \frac{p_{s}}{\left[\tilde{\mathbf{V}}^{T} \operatorname{diag}(\mathbf{w})\mathbf{p} + \tilde{\boldsymbol{\sigma}}\right]_{s}},$$
(3)

where $\tilde{\boldsymbol{\sigma}} := [\sigma_1^2/v_{1,1}, \sigma_2^2/v_{2,2}, \dots, \sigma_S^2/v_{S,S}]^T$, σ_s^2 denotes the noise power in the receiver of s. Note that in (3) w_l serves as a probability. The interference condition is taken into account in $\tilde{v}_{l,s}$ as illustrated in Remark 1.

¹Note that $\tilde{v}_{l,s}$ is computed with average channel gain over W MRUs. Thus, (3) is the ratio between average received signal strength and average received interference, rather than the actual average SINR. Since we do not assume to know the distribution of the channel gain, here we use (3) to approximate the average SINR. However, the approximations (2) and (3) are only valid under the assumption that each MRU is considered to be "equal" for all the services to be allocated, namely, the position of resource is not specified for UL or DL. Unfortunately, such assumption results in a high probability of IMI. In the following we introduce an improved SINR model based on a simple UL/DL resource positioning strategy to reduce IMI.

Recall that conventional TDD or FDD specifies a set of resource for UL and DL respectively to prevent IMI. With flexible duplex, the challenge is to allow different resource partitioning between UL and DL in each cell, while limiting the probability of generating IMI. Let us take an example, cell m with UL load $\nu_m^{(u)}$ and cell n with DL load $\nu_n^{(d)}$ share same set of available resource. It is obvious that the minimum overlapping area between UL resource in cell m and DL resource in cell n is $\left[\nu_m^{(u)} + \nu_n^{(d)} - 1\right]^+$, which can be easily achieved by allocating the set of resource to UL traffic in cell m in some priority order while allocating the same set of resource to DL traffic in cell n in reverse order.

Given the aforementioned strategy, to derive the interference coupling matrix that incorporates the probability that a link causes ICI to another, we introduce a *reuse factor coupling matrix* C(w) depending on w. Let $x_s \in \{u, d\}$ denote the UL or DL traffic type of service $s \in S$, and recall that n_s denotes the serving BS of s, C(w) is defined as

$$\mathbf{C}(\mathbf{w}) := \mathbf{C} := (c_{l,s}) \in \mathbb{R}^{S \times S}_{+},$$

$$c_{l,s} := \begin{cases} \left[\left(\nu_{n_{l}}^{(x_{l})} + \nu_{n_{s}}^{(x_{s})} - 1 \right) / \nu_{n_{s}}^{(x_{s})} \right]^{+} & \text{if } x_{l} \neq x_{s} \\ \min \left\{ 1, \nu_{n_{l}}^{(x_{l})} / \nu_{n_{s}}^{(x_{s})} \right\} & \text{if } x_{l} = x_{s}, \end{cases}$$
(4)

where the load of cell n_s occupied by traffic type x_s is computed by $\nu_{n_s}^{(x_s)} := \left[\mathbf{B}^{(x_s)} \mathbf{w} \right]_{n_s}$. In general, $c_{l,s}$ is defined as the ratio of the overlapping area on the resource plane between the load of cell n_l serving traffic type x_l and the load of cell n_s serving traffic type x_s to the load of cell n_s serving traffic type x_l .

With C(w) in hand, given the power vector p, we can modify (3) and derive the SINR of service $s \in S$ as

$$\operatorname{SINR}_{s}(\mathbf{w}) \approx \frac{p_{s}}{\left[\left(\mathbf{C}(\mathbf{w}) \circ \tilde{\mathbf{V}}\right)^{T} \operatorname{diag}(\mathbf{p})\mathbf{w} + \tilde{\boldsymbol{\sigma}}\right]_{s}}, \quad (5)$$

where with a slight abuse of notation, $\mathbf{X} \circ \mathbf{Y}$ denotes the Hadamard (entrywise) product of matrices \mathbf{X} and \mathbf{Y} . Note that the first term in the denominator is the interference power received by service *s* divided by the channel gain of *s*, and it is equivalent to $\sum_{l} c_{l,s} w_{l} v_{l,s} p_{l} / v_{s,s}$, where $c_{l,s} \cdot w_{l}$ approximates the probability that service *l* causes interference to service *s*.

The maximum achievable number of bits for service $s \in S$ within the time span of resource set W is

$$\eta_s(\mathbf{w}) = \delta_t \delta_f W w_s \log \left(1 + \text{SINR}_s(\mathbf{w})\right), \tag{6}$$

where the unit of $\delta_t \delta_f$ is Hz·s/MRU, while Ww_s is the number of MRUs allocated to s.

Assuming that the nonzero traffic demands $\mathbf{d} := (d_1, \ldots, d_S)^T \in \mathbb{R}^S_{++}$ is known, where d_s is defined as

number of required bits of s during the time span of W, we introduce *per service quality of service (QoS) satisfaction level*, written as

$$\rho_s(\mathbf{w}) = \eta_s(\mathbf{w})/d_s, \ s \in \mathcal{S}. \tag{7}$$

III. PROBLEM FORMULATION

The objective is to partition the resource set W in each cell $n \in \mathbb{N}$ into three subsets: resource for UL, resource for DL, and blanked resource², respectively, to maximize *the worst-case QoS satisfaction level*, defined as

$$\rho(\mathbf{w}) := \min_{s \in \mathcal{S}} \rho_s(\mathbf{w}). \tag{8}$$

All demands of the services are feasible, when $\rho(\mathbf{w}) \ge 1$.

We formulate the problem in Problem 1, where (9a) and (9b) imply the objective of maximizing the worst-case QoS satisfaction level ρ^* , and (9c) is the per-cell load constraint. **Problem 1**

$$\max_{\mathbf{v}\in\mathbb{R}^{K}_{+},\rho\in\mathbb{R}_{+}}\rho\tag{9a}$$

s.t.
$$\mathbf{w} \ge \rho \mathbf{f}(\mathbf{w}),$$
 (9b)

$$g(\mathbf{w}) := \|\mathbf{B}\mathbf{w}\|_{\infty} \le 1, \tag{9c}$$

where the vector-valued function f is defined by

$$\mathbf{f}: \mathbb{R}^{S}_{+} \to \mathbb{R}^{S}_{++}: \mathbf{w} \mapsto \left[f_{1}(\mathbf{w}), \dots, f_{S}(\mathbf{w})\right]^{T}, \qquad (10a)$$

where
$$f_s(\mathbf{w}) := \frac{a_s}{\delta_t \delta_f W \log(1 + \text{SINR}_s(\mathbf{w}))}$$
. (10b)

In [10], we show that with conventional model of SINR (3), Problem 1 is equivalent to solve a nonlinear system of equations such that $\mathbf{w} = \rho \mathbf{f}(\mathbf{w})$, $g(\mathbf{w}) = 1$ and that ρ is maximized. It is worth mentioning that, with the modified models of interference coupling (4) and SINR (5), Problem 1 is a multi-variate nonconvex optimization problem. Moreover, the constraint (9b) is neither convex nor continuously differentiable, and Problem 1 is not necessarily equivalent to the nonlinear system of equations.

In Section IV we provide algorithmic solution to Problem 1, denoted by \mathbf{w}^* . The per-cell fraction of resource to allocated to UL and DL are then obtained as $\boldsymbol{\nu}^{(u),*} = \mathbf{B}^{(u)}\mathbf{w}^*$ and $\boldsymbol{\nu}^{(d),*} = \mathbf{B}^{(d)}\mathbf{w}^*$, respectively. If $\rho^* := \rho(\mathbf{w}^*) \ge 1$, all demands are feasible. However, if $\rho^* < 1$, the solution to Problem 1 is not a good operating point, since the demands of all services are infeasible. In other words, all users are unsatisfied. Therefore, a further question arises: *how can we transform the desired demands in Problem 1 from infeasible to feasible?* One of the factors causing infeasible demand is the bottleneck services. In Section V we modify Problem 1 by dedicating partial resources for bottleneck services, while muting them for others, and develop an algorithm with heuristic strategies.

²Under certain conditions, enhanced interference mitigation can be achieved by muting partial resources in some cells. However, it is also possible that the optimal solution returns an empty set of the blanked resource.

Remark 2 (New challenge due to complex interference coupling). Problem 1 is formulated along similar lines to our previous work [10, Problem 2a]. However, in [10], the received interference in SINR (3) is an affine function of \mathbf{w} , which further leads to some nice properties of f (as shown in Lemma 1). In this paper, because we introduce more complex interference coupling (4) and the resulting modified SINR model (5), the desired properties of f do not exist, which brings new challenge with developing efficient algorithmic solution.

IV. SUCCESSIVE APPROXIMATION OF FIXED POINT

In this section, we first provide background information about the mathematical tool to solve the problem. Then, we propose a novel efficient algorithm SAFP to find a feasible point of w with good, if not optimal, objective value of ρ^* .

A. Background Information and Previous Results

With the conventional SINR model in (3), **f** defined in (10)has the following property.

Lemma 1 ([10, Lemma 1]). With SINR defined in (3), f : $\mathbb{R}^S_+ \to \mathbb{R}^S_{++}$ is a standard interference function (SIF) (see Appendix A for definition).

Knowing that **f** is SIF, and that $g : \mathbb{R}^{S}_{++} \to \mathbb{R}_{++}$ in (9c) is a monotonic norm, we encounter the same type of problem as [10, Problem 2a]. The following proposition is provided based on the previous result [10, Theorem 1], which gives rise to an algorithmic solution to Problem 1 with conventional SINR model based on the fixed point iteration scheme.

Proposition 1. Suppose SINR is modeled with (3), and

f: ℝ^S₊ → ℝ^S₊₊ is SIF,
g: ℝ^S₊₊ → ℝ₊₊ is monotonic, and homogeneous with degree 1 (i.e., g(α**x**) = αg(**x**) for all α > 0)

There exists a unique solution to Problem 1, denoted by $\{\mathbf{w}^*, \rho^*\}$, where \mathbf{w}^* can be obtained by performing the following fixed point iteration:

$$\mathbf{w}^{(t+1)} = \frac{\mathbf{f}\left(\mathbf{w}^{(t)}\right)}{g \circ \mathbf{f}\left(\mathbf{w}^{(t)}\right)}, t \in \mathbb{N},$$
(11)

where with a slight abuse of notation, $g \circ \mathbf{f}$ denotes the composition of functions q and f. The iteration in (11) converges to \mathbf{w}^* , and we have $\rho^* = 1/q \circ \mathbf{f}(\mathbf{w}^*)$ and $q(\mathbf{w}^*) = 1$.

Proof. The proof is omitted here since it uses our previous result [10, Theorem 1] and is along the same lines as [10, Proposition 1].

B. Successive Approximation of Fixed Point

Proposition 1 provides an algorithmic solution to Problem 1 with SINR (3), by utilizing the properties of SIF. Unfortunately, with the modified SINR in (5), f is not SIF because the coupling matrix C(w) depends on w in a non-monotonic and non-differentiable manner. However, it is easy to show that by replacing C(w) in (5) with some approximation C' := C(w')computed with fixed w', the SINR in (5) falls into the same class as (3), and the approximated problem can be solved by Proposition 1 with $f(\mathbf{w})$ replaced by $f_{\mathbf{C}'}(\mathbf{w}) := f(\mathbf{w}, \mathbf{C}(\mathbf{w}'))$.

Therefore, our essential, natural idea is to efficiently compute a suboptimal solution of Problem 1 by solving a sequence of (simpler) max-min fairness subproblems whereby the noncontractive mapping f is replaced by suitable contraction approximation $f_{C'}$. These subproblems can be solved with Proposition 1.

More specifically, the proposed SAFP algorithm consists in solving a sequence of approximations of Problem 1 in the form

$$\max_{\mathbf{v}\in\mathbb{R}^{K}_{+},\rho\in\mathbb{R}_{+}}\rho; \text{ s.t. } \mathbf{w} \ge \rho \mathbf{f}_{\mathbf{C}'}(\mathbf{w}); \ g(\mathbf{w}) \le 1,$$
(12)

where $f_{C'}(w)$ represents approximation of f(w) at the current iterate w'. The unique solution to (12) can be obtained by the fixed point iteration (11), with C(w) replaced by C(w').

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Unfortunately, due to the complexity of C(w), the convergence of SAFP to a limit point cannot be guaranteed, since multiple fixed points can exist in the system where the inequality sign in (9b) is replaced by the equality sign. Different initial values of $\hat{\mathbf{w}}$ may lead to different fixed points. Moreover, the solution to the system of nonlinear equations may not be the optimal solution to the original problem of maximizing the minimum, due to the nonmonotonicity of the mapping **f** when including **C** into the interference model. Thus, we design the searching algorithm to guarantee the utility increase with initial values of $\{\rho^*, \mathbf{w}^*\}$, maximum number of random initiation $N_{\rm max}$, and algorithm stopping criterion depending on the maximum number of iterations N_{iter} and the distance threshold ϵ , illustrated as below.

- The algorithm runs for $N_{\rm max}$ times, each with a different random initialization of $\hat{\mathbf{w}}$ and the corresponding $\mathbf{C}(\hat{\mathbf{w}})$.
- For each initialization $\hat{\mathbf{w}}_n$, $n = 1, 2, \dots, N_{\max}$, we iteratively perform the fixed point iteration in (11) with $\mathbf{f}(\mathbf{w})$ replaced by $\mathbf{f}_{\hat{\mathbf{C}}_n}(\mathbf{w})$ where $\hat{\mathbf{C}}_n := \mathbf{C}(\hat{\mathbf{w}}_n)$. The iteration stops if the number of iterations exceeds N_{iter} or the distance yields $\|\mathbf{w}' - \mathbf{w}\| \le \epsilon$ and returns the solution $\{\mathbf{w}', \rho'\}$ with respect to the *n*th random initialization. The solution is updated with $\mathbf{w}^* \leftarrow \mathbf{w}'$, $\rho^* \leftarrow \rho'$ if $\rho' > \rho^*$. The proposed SAFP algorithm is summarized in Algorithm 1.

Although the convergence of SAFP to a global optimum cannot be guaranteed and heuristics are introduced, numerical results in Section VI (e.g., Fig. 2b) show that each random initialization converges to a fixed point, and with limited number of initializations, the algorithm finds a suboptimal, if not optimal, solution among multiple fixed points.

V. RESOURCE MUTING FOR DOMINANT INTERFERER

The proposed SAFP finds a feasible point of w^* with suboptimal, if not optimal, objective value of ρ^* . If $\rho^* \ge 1$, the obtained \mathbf{w}^* provides fairness on the services, and the demands of all services are feasible. However, if $\rho^* < 1$, \mathbf{w}^* is not a good operating point since the traffic demands of all services are infeasible. Therefore, in this section we focus the following question: how can we transform the desired demands in Problem 1 from infeasible to feasible?

Algorithm 1: SAFP algorithm for resource partitioning

input : $i \leftarrow 1$, $N_{\text{max}} > 1$, $N_{\text{iter}} > 1$, $\epsilon > 0$, $\rho^* \leftarrow 0$, $\mathbf{w}^* \gets \mathbf{0}$ **output:** $\{w^*, \rho^*\}$ while $i \leq N_{max}$ do random initialization of \mathbf{w}' ; $\mathbf{C}' \leftarrow \mathbf{C}(\mathbf{w}')$; $j \leftarrow 0, \mathbf{w} \leftarrow \mathbf{0};$ $\Delta^{(j)} \leftarrow \|\mathbf{w}' - \mathbf{w}\|_{\infty}; \ \mathbf{w}^{(j)} \leftarrow \mathbf{w}';$ while $j \leq N_{iter}$ or $\Delta^{(j)} \geq \epsilon$ do % solving approximated subproblem with C'; while $\|\mathbf{w}' - \mathbf{w}\|_{\infty} \ge \epsilon$ do $\mathbf{w} \leftarrow \mathbf{w}';$ $\mathbf{w}' \leftarrow \mathbf{f}_{\mathbf{C}'}(\mathbf{w})/g \circ \mathbf{f}_{\mathbf{C}'}(\mathbf{w});$ % Update C with optimized \mathbf{w}' ; $\mathbf{w}^{(j+1)} \leftarrow \mathbf{w}'$; $\mathbf{C}^{(j+1)} = \mathbf{C}' \leftarrow \mathbf{C}(\mathbf{w}') ;$ $\Delta^{(j+1)} \leftarrow \|\mathbf{w}^{(j+1)} - \mathbf{w}^{(j)}\|_{\infty};$ $j \leftarrow j + 1;$ $\rho' = \rho'(\mathbf{w}') \leftarrow \min_{s \in \mathcal{S}} w'_s / f_{\mathbf{C}',s}(\mathbf{w}');$ % update the solution if ρ' exceeds the stored value; if $\rho' > \rho^*$ then $\rho^* \leftarrow \rho';$ $\mathbf{w}^* \leftarrow \mathbf{w}';$ $i \leftarrow i + 1;$

In [12], the authors propose a removal selection criterion for an infeasible DL power control problem, that removes sequentially the bottleneck services until the demands for all the remaining services are feasible. However, is there a method of further increasing ρ^* without removal of services? Motivated by coordinated muting using almost blank subframe (ABS) for time domain intercell interference coordination introduced in [13], we are interested in exploring the tradeoff between resource utilization and interference reduction by introducing the resource muting in flexible duplex.

A. Modified Load Constraints Incorporating Resource Muting

The key concept is to sequentially reserve some resource in a cell for the dominant interferer, while muting them in the cells strongly impacted by the interferer. To this end, we rank the services based on the interference level that they generate to others, given by

$$I_{s}(\mathbf{w}) := \left(\mathbf{c}_{s}' \tilde{\mathbf{v}}_{s}'^{T}\right) p_{s} w_{s}, \text{ for } s \in \mathbb{S},$$
(13)

where $\mathbf{c}'_s := \operatorname{row}_s \mathbf{C}(\mathbf{w})$ denotes the *s*th row of $\mathbf{C}(\mathbf{w})$, and $\tilde{\mathbf{v}}'_s := \operatorname{row}_s \tilde{\mathbf{V}}$ denotes the *s*th row of $\tilde{\mathbf{V}}$.

Moreover, to prevent the waste of resource, we select the strongly affected cells to mute their resource. The set of cells to mute the resource reserved for s is selected by

$$\mathcal{M}_s := \{ m \in \mathcal{N} \setminus \{ n_s \} : J_{s,m}(\mathbf{w}) \ge \alpha \},$$
(14)

where α is a threshold and $J_{s,m}(\mathbf{w})$ is the interference generated from service s to a cell $m \neq n_s$, defined as

$$J_{s,m}(\mathbf{w}) := \left[\mathbf{B} \left(\mathbf{c}'_s \circ \tilde{\mathbf{v}}'_s \right)^T \right]_m p_s w_s.$$
(15)

If a set of dominant interferens \overline{S} is chosen, and for each $s \in \overline{S}$ a subset of the cells \mathcal{M}_s is selected to mute resource w_s , then, in each cell we have the load constraint

$$g'_{m}(\mathbf{w}) := \sum_{s \in \overline{\mathbb{S}}} \mathbb{1}_{\{m \in \mathcal{M}_{s}\}} w_{s} + \sum_{l \in \mathcal{S}_{m}} w_{l} \le 1, \text{ for } m \in \mathcal{N}, \text{ (16)}$$

where $\mathbb{1}_{\{\cdot\}}$ is the indication function, the first term is the total amount of resource to be muted in cell m, and the second term is the amount of available resource for services in m.

Since $g'_m(\mathbf{w}) \leq 1$ needs to be held for every $m \in \mathbb{N}$, the load constraint can be rewritten as

$$g'(\mathbf{w}) := \max_{m \in \mathcal{N}} g'_m(\mathbf{w}) \le 1.$$
(17)

Note that without the muting scheme, i.e., if $\overline{S} = \emptyset$, the first term in (16) is zero and (17) is equivalent to the per-cell load constraints in (9c).

B. Design of Heuristic Algorithm

It is obvious that the modified g' is also monotonic and homogeneous with degree 1, which enables leverage of Proposition 1 to solve the modified Problem 1, with $g(\mathbf{w})$ replaced by $g'(\mathbf{w})$ to incorporate the resource reservation and muting strategy.

Compared to the solution to the original Problem 1, resource muting may not necessarily improve the desired utility ρ , because muting of w_s in cell $m \in \mathcal{M}_s$ may lead to waste of resource. Therefore, we develop a heuristic algorithm RMDI to guarantee a utility that is no less than the ρ derived in Algorithm 1. The Algorithm is described briefly in the following steps.

- 1. Derive $\mathbf{w}^{(0)} = \mathbf{w}^*$ to Problem 1 with Algorithm 1 and compute the corresponding $\rho^{(0)} = \rho^*$.
- 2. Compute $I_s(\mathbf{w}^*)$ and rank the services based on I_s . Let q_s denote the rank of s, e.g., the maximum interferer $\hat{s} := \arg \max_s I_s$ has a rank of $q_{\hat{s}} = 1$. Set k = 1.
- 3. Add the service with highest rank into $\bar{S}^{(k)}$, e. g., $\bar{S}^{(k)} = \{s : q_s \leq k\}$.
- 4. Solve modified Problem 1 with $\bar{S}^{(k)}$ using Algorithm 1 (with g replaced by g'), derive $\mathbf{w}^{(k)}$ and $\rho^{(k)}$.
- 5. If $\rho^{(k)} \ge \rho^{(k-1)}$, increment k and go back to Step 3; otherwise stop the algorithm.
- 6. Obtain solution $\mathbf{w}^{\star} = \mathbf{w}^{(k-1)}$.

VI. NUMERICAL RESULTS

In this section, we analyze the performance of the proposed algorithms SAFP and RMDI, by considering the asymmetry of UL and DL traffic in two-cell scenario. The distance between the two BSs is 2 km. The transmit power of BS and UE are 43 and 22 dBm respectively and all the other simulation parameters mainly related to channel gain can be found in [14, Tab. A2.1.1-2]. We define the minimum time unit δ_t as 0.5 ms and the minimum frequency unit δ_f as 15 kHz. Further we have $W_t = 20$ and $W_f = 300$, i. e., a resource plane that spans a time duration of 0.01 seconds and frequency of 5 MHz (including the guard band). We defined a fixed total traffic demand $\Lambda = \sum_s d_s = 50$ kbits within $W_t \delta_t = 0.01$ seconds, which implies a total serving data rate of 5 Mbit/s. The total traffic can be asymmetrically distributed between the two cells with different ratios among $\mathcal{T}_{inter} := \{1/9, 2/8, 3/7, \dots, 9/1, 10/0\}$. Within each cell, the traffic can be asymmetrically distributed between UL and DL traffic with ratios among $\mathcal{T}_{intra} := \{1/9, 2/8, 3/7, \dots, 9/1\}$. UEs with either UL or DL traffic are generated with uniform distribution within the intersection of two balls with radius 2 km, and with BS 1 and 2 as their centers respectively, to analyze the scenario of high inter-cell interference. Without loss of generality, we can place one UL and one DL service in each cell with the traffic demand computed by the traffic ratio mentioned above.

1) Algorithm convergence of SAFP. Let us first examine the convergence of Algorithm 1, and compare it with Algorithm "FP" that is summarized in Proposition 1 with conventional SINR model (3). The parameters are set as $N_{\text{max}} = 30$, $N_{\rm iter} = 1000, \ \epsilon = 10^{-4}$. In Fig. 2a we show the convergence of the SAFP with one particular initialization of \mathbf{w}' and $\mathbf{C}(\mathbf{w}')$ and compare it with FP. The magenta circle indicates the starting point with an updated $\mathbf{C}(\mathbf{w}^{(j)})$, and the green dashed line shows that with each fixed $\mathbf{C}(\mathbf{w}^{(j)})$, by performing fixed point iteration, ρ monotonically increases and converges to the fixed point with respect to $C(w^{(j)})$. Note that the green dashed line is not the "actual" utility ρ , since it is computed with updated $\mathbf{w}^{(i)}$ and the approximation $C(\mathbf{w}^{(j-1)})$. Therefore, we plot the red line to show the convergence of the actual utility at each step of updating C, computed with $\mathbf{w}^{(j)}$ and $\mathbf{C}(\mathbf{w}^{(j)})$. By comparing the red curve and the blue curve (convergence of FP algorithm), we observe a significant increase of utility ρ by using SAFP. This is because, comparing with FP that randomly places the UL and DL resource, SAFP is based on an improved interference model, where ICI only appears in the intersection of the sets of allocated MRUs between different cells. Fig. 2b illustrates that with each random initialization of \mathbf{w}' , the proposed SAFP converges to a fixed point. The example shows that 30 initializations converge to two different fixed points with utilities 4.35 and 1.19 respectively. \mathbf{w}^* corresponding to higher utility is chosen as the final solution.

2) *Performance comparison*. We compare the performance of SAFP and RMDI to the performance of the other three protocols, described in below.

- *FIX:* Fixed ratio and same position of the UL and DL resource in different cell. IMI does not exist due to the orthogonal frequency band for UL and DL. The amounts of the UL and DL resource are fixed to be the same.
- *dTDD:* Adaptive UL and DL resource proportional to the traffic volume in each cell independently.
- *FP*: Proposed algorithm in [10] (summarized in Proposition 1) that solves Problem 1 with old SINR model (3).

To compare the performance of protocols FIX, dTDD, FP, SAFP, and RMDI under different traffic asymmetry, we define a measure *inter-cell traffic distance*, given by $D_{m,n} := \|\vartheta_n - \vartheta_n\|$

 $\boldsymbol{\vartheta}_{m} \|$, where $\boldsymbol{\vartheta}_{n} := \left[\vartheta_{n}^{(\mathrm{u})}, \vartheta_{n}^{(\mathrm{d})} \right]^{T}$ characterizes the UL and DL traffic distribution in cell n, and $\vartheta_{n}^{(x)} := \left[\mathbf{B}^{(x)} \mathbf{d} \right]_{n} / \Lambda$, $n = 1, 2, x \in \{\mathrm{u}, \mathrm{d}\}$ denotes the fraction of the total traffic Λ that traffic of type x in cell n accounts for, such that $\sum_{n \in \mathbb{N}} \sum_{\mathrm{x} \in \{\mathrm{u},\mathrm{d}\}} \vartheta_{n}^{(\mathrm{x})} = 1$. For example, if $\vartheta_{1} = \vartheta_{2} = [0.25, 0.25]^{T}$, we have $D_{1,2} = 0$.

Fig. 3a and 3b show the cumulative distribution function (CDF) of utility ρ derived by applying the five protocols under low and high inter-cell traffic distance, respectively. The CDF is derived from 1000 simulation run times, each with different user locations and channel propagation, for every combination of the inter-cell traffic distribution ratio in set T_{inter} and intracell traffic distribution ratio in set T_{inter} and intracell traffic distribution ratio is set T_{inter} , while with $D_{1,2} > 0.5$ as high inter-cell traffic distance.

Both Fig. 3a and 3b show that CDF $F_d^{\rm (dTDD)}(1) > 0.95$ for dTDD, implying that service outage probability, i.e., the probability that at least one service cannot be served with satisfied QoS requirement, is above 95%. The performance is worse than protocol FIX with $F_d^{(\text{FIX})}(1) > 0.45$. This is because although UL/DL resource splitting is adapted to the traffic volume, the full occupation of the resource may cause severe IMI to some services. Such observation encourages the application of our proposed algorithms, which are able to reduce the interference coupling among services. By comparing FP, SAFP and RMDI, we show that FP further decreases the outage probability to below 20%, and SAFP and RMDI significantly outperform FP, with the outage probability for low traffic distance below 10%. Among the three, RMDI provides the best performance of the utility distribution. By comparing Fig. 3a and 3b, we observe that SAFP and RMDI provides even higher performance gain under high traffic asymmetry.

3) Performance gain depending on traffic asymmetry. To analvze the performance gain depending on the traffic asymmetry, we average the utility obtained from 1000 simulation run times for $D_{1,2}$ falling into the intervals [0, 0.16), [0.16, 0.32), [0.32, 0.48), [0.48, 0.64), [0.64, 0.80), [0.80, 1], respectively. Let us consider FIX as the baseline. Fig. 3c shows that the performance of FIX decreases with the traffic asymmetry, and the average utility is below 1 (infeasible QoS target) when traffic distance $D_{1,2} > 0.6$. Although dTDD adaptively splits the UL/DL resource, the full occupation of the resource causes severe IMI, leading to the worst performance. On the other hand, FP reduces interference coupling among services, and provides 25% gain when traffic asymmetry is low, and almost 2-fold gain when the asymmetry is ultra high. The proposed SAFP incorporates interference coupling with UL/DL resource localization, which improves the gain to 2-fold when the traffic asymmetry is low while 2.7-fold when asymmetry is high. The enhanced version RMDI further improves the gain by muting partial resource for interference cancellation. The gain is more significant when the traffic is highly asymmetric, achieving 3.2-fold increase when $D_{1,2} \ge 0.64$.



(b) Examination of the random initialization. An example: With 30 randomly initialized $\hat{\mathbf{w}}$, SAFP converges to two local optima with $\rho^*(1) = 4.35$ and $\rho^*(2) = 1.19$.

Fig. 2: Examination of SAFP.

APPENDIX A

Definition 1. A vector function $\mathbf{f} : \mathbb{R}^k_+ \to \mathbb{R}^k_{++}$ is a standard interference function (SIF) if the following axioms hold:

- 1. (Monotonicity) $\mathbf{x} \leq \mathbf{y}$ implies $\mathbf{f}(\mathbf{x}) \leq \mathbf{f}(\mathbf{y})$
- 2. (Scalability) for each $\alpha > 1$, $\alpha \mathbf{f}(\mathbf{x}) > \mathbf{f}(\alpha \mathbf{x})$

In Definition 1 we drop positivity from its original definition [6] because it is a consequence of the other two properties [15].

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(a) Utility CDF under low inter-cell traffic distance.



(b) Utility CDF under high inter-cell traffic distance.



(c) Average utility under different inter-cell traffic distance.

Fig. 3: Performance comparison among protocols.

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