Joint User Scheduling and Transmit Direction Selection in 5G TDD Dense Small Cell Networks

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***Abstract*—This paper proposes a joint user scheduling and transmit direction selection procedure for dynamic TDD in 5G dense small cell networks, where the transmit direction (i.e. downlink (DL) or uplink (UL)) selected per small cell is dynamically optimized together with the user scheduling at every frame. We focus on the maximization of a general utility function that takes into account the DL/UL traffic asymmetries of each user and the interference conditions in the network. After relaxation of the integer variables that subsume the user scheduling and transmit direction selection, the problem is decomposed and efficiently solved in parallel at every frame. Simulation results show significant gains in DL and UL average rates for different traffic asymmetries, network densities, and user densities as compared to existing schemes for dynamic TDD.**

***Index Terms*—Dynamic TDD, small cell networks, 5G systems, user scheduling.**

I. Introduction

Dense small cell networks (SCNs) are considered a key technology for 5th generation (5G) systems as a result of their cost-effectiveness in boosting the spectral efficiency of cellular networks through densification and, hence, improved spatial reuse of the spectrum [1]. Small cells (SCs) have low power and a low cell size, such that the number of users that are expected to be served per SC is reduced. As a consequence, the amount of downlink (DL) and uplink (UL) traffic per cell can vary over space and time more drastically in dense SCNs than in conventional macrocell-based networks [2].

Differently from long term evolution (LTE) frequency division duplex (FDD) systems where the amount of band devoted for DL and UL is fixed and equally divided, LTE time division duplex (TDD) systems allow for asymmetric DL-UL allocations by providing seven different semi-statically configured UL-DL configurations [3]. The predefined UL-DL configurations differ in the switching points between a DL and a UL transmission within a frame, hence providing DL-UL allocation ratios that vary from 4:6 to 9:1 (DL:UL). Usually, the UL-DL configuration is the same for all cells and it is determined at the network level based on long-term traffic statistics, which might not match the instantaneous per-cell traffic asymmetries.

In this regard, the new emerging *dynamic TDD* technique [4][5] offers the possibility of a dynamic UL-DL reconfiguration to adapt the DL-UL allocation ratio to the instantaneous traffic asymmetry at each cell. This higher flexibility is specially suited for dense SCNs. As a downside, it introduces new types of interference in the system (i.e. DL-to-UL and UL-to-DL interferences). Under these conditions, interference management procedures are key enablers for dynamic TDD.

One may find works in the literature on dynamic TDD, which mainly focus on optimizing the UL-DL configuration ([2][6][7]) or the DL-to-UL switching point decision within a frame ([8][9][10]) per SC or per group of SCs, in many cases constrained to the frame patterns predefined in LTE TDD [5]. These works can be classified according to where and how such decision is taken. References like [2][6][7] consider a centralized and coordinated (i.e. *cluster-specific*) decision, where the deployed SCs are divided into isolated groups of SCs (or clusters) and the same UL-DL configuration is used within the cluster. This way, DL-to-UL and UL-to-DL interferences are not created inside the cluster but the flexibility of adapting to the per-SC traffic asymmetries is reduced. On the other hand, decentralized solutions are investigated in [8][9][10]. In [8], the decision on the DL-to-UL switching point is performed at each SC in coordination with the neighboring SCs thanks to the exchange of backhaul control plane messages (i.e. prices) that take into account the traffic asymmetry of the serving users but also how such decision affects to the users associated to neighboring SCs. In [10], decentralized and uncoordinated (i.e. *SC-specific*) solutions are evaluated, where each SC performs its own decision based on the traffic asymmetry of the serving users. [10] shows that SC-specific decisions are sufficient if interference mitigation techniques are used at reception. [6] also concludes that SC-specific decisions with coordinated scheduling and coordinated beamforming (CS/CB) achieve a better performance than cluster-specific decisions with CS/CB.

However, all these previous works on dynamic TDD keep the order of the transmit directions fixed (i.e. first DL and then UL). On the contrary, [11] shows the positive benefits in terms of interference reduction of optimizing also the order in which UL and DL transmissions are performed at each node. But the considered frame structure in [11] is equally partitioned between both transmit directions (DL and UL), such that traffic asymmetries cannot be incorporated.

In this sense, new short length frame structures are envisioned for 5G systems. A potential frame structure is presented in [12], and also in [13], where the data part on each frame is assigned only to one transmit direction and each cell can determine if is used either for DL or for UL. Such new frame structure is very powerful for scenarios where the traffic varies drastically (as SCNs) and, due to its short length and one transmit direction per frame, avoids interference variability within the frame. The key point is that, under such new frame structures envisioned for 5G systems, full exploitation of dynamic TDD is possible without resorting to one of the

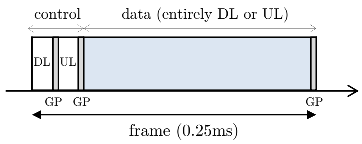

Fig. 1: Frame structure suggested for dynamic TDD [12].

predefined UL-DL configurations in LTE TDD or focusing on the DL-to-UL switching point decision. To that end, new interference management procedures being able to determine the transmit direction in a per-frame basis are needed.

In this paper we assume a frame structure for TDD systems similar to the one proposed in [12], and as shown in Fig. 1, where each SC can decide the transmit direction (DL or UL) at every frame. In this context, we propose a dynamic procedure for joint user scheduling and transmit direction selection (DUSTDS) in interfering multi-cell scenarios that works on a per-frame basis (see Fig. 2) by taking into account the traffic asymmetries and the instantaneous interference in the network. A general utility function is used, whereby the initial problem can be uncoupled through frames. Then, after relaxation of the integer variables that subsume the user scheduling and transmit direction selection, the problem per-frame is decomposed among SCs by using the interference cost concept and a direct solution is obtained such that the problem per-frame can be efficiently solved in parallel.

II. System Model

Consider a synchronized TDD dense SCN composed of a set of $\mathcal{N} \triangleq \{1,\dots,N\}$ SCs, each with a set of $\mathcal{I}_n \triangleq \{1,\dots,I_n\}$ associated users ($n=1,\dots,N$). Let i_n denote the i-th user associated to the n-th SC ($i_n = 1,\dots,I_n$). The total set of users in the system is denoted by $\mathcal{I} = \bigcup_{n\in\mathcal{N}} \mathcal{I}_n$. Subindexes $\{i_n, j_m, l_k\}$ and $\{n, m, k\}$ are used through the paper to denote users and SCs, respectively. An example is shown in Fig. 2 for $|\mathcal{N}| = 3$ SCs and $|\mathcal{I}| = 5$ users ($|\mathcal{I}_1| = 2$, $|\mathcal{I}_2| = 2$, $|\mathcal{I}_3| = 1$).

The frame structure in [12] is assumed. Control and data planes are separated in time, as shown in Fig. 1. A short guard period (GP) is inserted between every switch of the transmit direction. The data part is entirely devoted either for UL or for DL transmission, and the transmit direction in the data part (i.e. DL or UL) can vary at every frame and every SC. Through the paper, let index d denote the transmit direction: $d = D$ refers to DL and $d = U$ denotes UL transmission.

For the ease of presentation, it is assumed that all SCs have the same available power for DL, p^D, and all users have the same available power for UL, p^U.

Let us assume that channel state information (CSI) of all users remain constant over a set of frames $\mathcal{S} \triangleq \{1,\dots,S\}$. CSI is assumed to be known at a central node that controls the N SCs and will perform the optimization of user scheduling and transmit direction selection per frame.

The optimization variables that denote the user scheduling and transmit direction selection are $\{x^d_{i_n,s}\}_{\forall i_n,n,s,d}$, which take value 1 if the i_n-th user and d-th transmit direction are selected at the n-th SC in the s-th frame or 0 otherwise.

Assuming that interference is treated as Gaussian noise, the rates that are achievable in DL and UL transmissions,

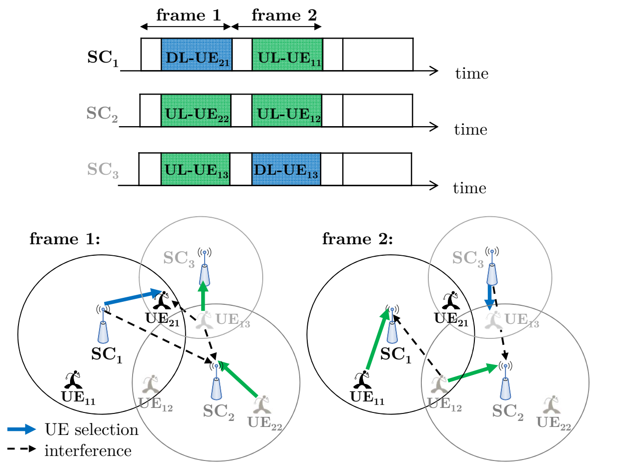

Fig. 2: Dynamic TDD in SCNs. At each frame every SC schedules one user in one transmit direction (DL or UL). An example of the user scheduling and transmit direction selection is shown for frame 1 and frame 2.

respectively, for the i_n-th user in the s-th frame, $r^D_{i_n,s}$, $r^U_{i_n,s}$, are given by:

$$r^D_{i_n,s} = \log_2\left(1 + \frac{p^D g_{n,i_n}}{\gamma^D_{i_n,s}}\right) \tag{1}$$

$$\gamma^D_{i_n,s} = \sigma^2_{i_n} + \sum_{m\neq n}\sum_{j_m\in\mathcal{I}_m}\left(x^D_{j_m,s}p^D g_{m,i_n} + x^U_{j_m,s}p^U g_{j_m,i_n}\right) \tag{2}$$

$$r^U_{i_n,s} = \log_2\left(1 + \frac{p^U g_{i_n,n}}{\gamma^U_{i_n,s}}\right) \tag{3}$$

$$\gamma^U_{i_n,s} = \sigma^2_n + \sum_{m\neq n}\sum_{j_m\in\mathcal{I}_m}\left(x^D_{j_m,s}p^D g_{m,n} + x^U_{j_m,s}p^U g_{j_m,n}\right) \tag{4}$$

being $\gamma^D_{i_n,s}$ the noise-plus-interference power received in DL at the i_n-th user when the n-th SC transmits in the s-th frame, $\gamma^U_{i_n,s}$ the noise-plus-interference power received in UL at the n-th SC when the i_n-th user transmits in the s-th frame, $\sigma^2_{i_n}$ the noise power at the i_n-th user, σ^2_n the noise power at the n-th SC, and $g_{y,z}$ the channel gain (including pathloss and shadowing) between the y-th terminal and the z-th terminal (where y and z indexes can denote either a SC (e.g. n) or a user (e.g. i_n)). As it can be observed in (2)-(4), interferences received in DL and UL depend on the user and transmit direction selected at neighbor SCs in the s-th frame.

III. Problem Formulation

The problem for joint user scheduling and transmit direction selection is formulated by following the maximization of a general utility function that takes into account the traffic asymmetries and interference conditions in the network under the constraint that at most one user in one transmit direction is selected at each SC in every frame:

$$\underset{\{x^d_{i_n,s}\}_{\forall i_n,n,s,d}}{\text{maximize}} \sum_{n\in\mathcal{N}}\sum_{i_n\in\mathcal{I}_n}\left(a_{i_n}u\big(\bar{R}^D_{i_n}\big) + (1-a_{i_n})u\big(\bar{R}^U_{i_n}\big)\right) \tag{5}$$

$$\text{subject to}\quad \begin{cases} x^D_{i_n,s}, x^U_{i_n,s} \in \{0,1\} & \forall i_n, n, s \\ \sum_{i_n\in\mathcal{I}_n}\left(x^D_{i_n,s} + x^U_{i_n,s}\right) \leq 1 & \forall n, s \end{cases}$$

where $0 \leq a_{i_n} \leq 1$ is related to the DL-UL data traffic asymmetry of the i_n-th user [8], $u(z)$ is a continuous function on the interval $z \in [0, \infty)$, and $\bar{R}^d_{i_n}$ is the average rate of the i_n-th user in the d-th transmit direction ($d = \{D, U\}$) over the set of frames $\mathcal{S}$:

$$\bar{R}^d_{i_n} = \frac{1}{S} \sum_{s \in \mathcal{S}} x^d_{i_n,s} r^d_{i_n,s} \tag{6}$$

being $r^d_{i_n,s}$ the achievable rate of the i_n-th user and d-th transmit direction in the s-th frame shown in (1)-(3).

Note that problem in (5) involves integer variables. To deal with them, we define a relaxed version of the problem in (5) where the variables $\{x^d_{i_n,s}\}_{\forall i_n,n,s,d}$ are continuous within the interval $[0, 1]$, i.e. the first constraint in (5) is replaced by: $0 \le x^D_{i_n,s} \le 1$, $0 \le x^U_{i_n,s} \le 1$, $\forall i_n, n, s$.

Problem in (5) can be decoupled per frame, see [14]. Therefore, by joining the decoupling among frames and the relaxation of variables $\{x^d_{i_n,s}\}$, the relaxed version of the problem in (5) to be solved at the s-th frame is:

$$\begin{aligned} \underset{\{x^d_{i_n,s}\}_{\forall i_n,n,d}}{\text{maximize}} \sum_{n \in \mathcal{N}} \sum_{i_n \in \mathcal{I}_n} \Big(& a_{i_n} \mu^D_{i_n,s} x^D_{i_n,s} r^D_{i_n,s} \\ & + (1 - a_{i_n}) \mu^U_{i_n,s} x^U_{i_n,s} r^U_{i_n,s} \Big) \end{aligned} \tag{7}$$

$$\text{subject to} \begin{cases} 0 \le x^D_{i_n,s}, x^U_{i_n,s} \le 1 & \forall i_n, n \\ \sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} + x^U_{i_n,s} \right) \le 1 & \forall n \end{cases}$$

where $\mu^d_{i_n,s}$ is a fixed weight associated to the i_n-th user and d-th transmit direction in the s-th frame that depends on the function $u(z)$ adopted for problem in (5) [14]. The relaxed problem per frame in (7) is non-convex due to interference (see (1)-(3)). Even though, Section IV proposes an efficient procedure to solve (7) that strongly reduces the computational complexity as compared to an exhaustive search solution[1].

After optimization at every frame, the weights per user and per transmit direction, $\mu^d_{i_n,s+1}$, have to be updated. This provides a dynamic allocation, as the user scheduling and transmit direction selection at the s-th frame will impact on the weights used for the subsequent frame (s+1).

For example, in case a proportional fair criterion [15] was used, the function $u(z)$ for problem in (5) would be: $u(z) = \log(z)$ and the weights per user and transmit direction, $\mu^d_{i_n,s+1}$, in (7) would be updated at every frame as:

$$\mu^d_{i_n,s+1} = \frac{1}{\bar{R}^d_{i_n,s}} \tag{8}$$

being $\bar{R}^d_{i_n,s}$ the average rate of the i_n-th user in the d-th transmit direction up to frame s, which is computed over the time window S as a moving average:

$$\bar{R}^d_{i_n,s} = (1 - \alpha) \bar{R}^d_{i_n,s-1} + \alpha x^d_{i_n,s} r^d_{i_n,s} \tag{9}$$

where $\alpha = 1/S$.

Note however that the formulation of problem in (5) allows accommodating general utility functions corresponding to different traffic types and quality-of-service requirements (as best effort, non-real-time, and real-time services) while only the design of the weights per user and per transmit direction, $\mu^d_{i_n,s}$, in (7) turns out to be affected [14].

[1]The complexity of an exhaustive search to optimally solving (7) would scale as $(2I_n + 1)^N$, which is impractical for medium/high N and/or I_n.

IV. Joint User Scheduling and Transmit Direction Selection

In this section we propose an algorithm to solve the relaxed problem per frame in (7) and hence obtaining the user scheduling and transmit direction selection for each SC. To do so we use the interference cost concept (see [16]), whereby problem in (7) is decomposed into as many subproblems as SCs and the solution is obtained by solving them iteratively.

To simplify notation, let us define the equivalent weight per user and per transmit direction for the s-th frame (see (7)):

$$\tilde{\mu}^D_{i_n,s} = a_{i_n} \mu^D_{i_n,s}, \quad \tilde{\mu}^U_{i_n,s} = (1 - a_{i_n}) \mu^U_{i_n,s} \tag{10}$$

Let us introduce the cost [16] related to the impact on the neighboring SCs/users of selecting the i_n-th user and d-th transmit direction at the n-th SC in the s-th frame:

$$\pi^D_{i_n,s} = - \sum_{\substack{m \neq n \\ j_m \in \mathcal{I}_m}} \left(\tilde{\mu}^D_{j_m,s} x^D_{j_m,s} \frac{\delta r^D_{j_m,s}}{\delta x^D_{i_n,s}} + \tilde{\mu}^U_{j_m,s} x^U_{j_m,s} \frac{\delta r^U_{j_m,s}}{\delta x^D_{i_n,s}} \right) \tag{11}$$

$$\pi^U_{i_n,s} = - \sum_{\substack{m \neq n \\ j_m \in \mathcal{I}_m}} \left(\tilde{\mu}^D_{j_m,s} x^D_{j_m,s} \frac{\delta r^D_{j_m,s}}{\delta x^U_{i_n,s}} + \tilde{\mu}^U_{j_m,s} x^U_{j_m,s} \frac{\delta r^U_{j_m,s}}{\delta x^U_{i_n,s}} \right) \tag{12}$$

As an example, the derivatives $\frac{\delta r^D_{j_m,s}}{\delta x^D_{i_n,s}}$ and $\frac{\delta r^D_{j_m,s}}{\delta x^U_{i_n,s}}$ are:

$$\frac{\delta r^D_{j_m,s}}{\delta x^D_{i_n,s}} = \frac{-\left(p^D g_{j_m,n}\right)\left(p^D g_{j_m,m}\right)}{\ln(2)\left(1 + \frac{p^D g_{j_m,m}}{\gamma^D_{j_m,s}}\right)(\gamma^D_{j_m,s})^2} \tag{13}$$

$$\frac{\delta r^D_{j_m,s}}{\delta x^U_{i_n,s}} = \frac{-\left(p^U g_{j_m,i_n}\right)\left(p^D g_{j_m,m}\right)}{\ln(2)\left(1 + \frac{p^D g_{j_m,m}}{\gamma^D_{j_m,s}}\right)(\gamma^D_{j_m,s})^2} \tag{14}$$

The remaining derivatives $\Big(\frac{\delta r^U_{j_m,s}}{\delta x^D_{i_n,s}}$ and $\frac{\delta r^U_{j_m,s}}{\delta x^U_{i_n,s}}\Big)$ can be similarly obtained, but are omitted for brevity.

A. Decomposition and solution

Problem in (7) can be decomposed into N subproblems (one per SC) assuming that the variables belonging to other SCs are fixed [16], i.e. fixed costs ($\pi^D_{i_n,s}, \pi^U_{i_n,s}$, see definition in (11)-(12)) and fixed DL/UL interferences ($\gamma^D_{i_n,s}, \gamma^U_{i_n,s}$, see (2)-(4)). DL/UL interferences impact on the achievable rates in (1)-(3), so once DL/UL interferences are fixed then the achievable rates in (1)-(3) are also determined. The subproblem corresponding to the n-th SC for fixed costs and DL/UL interferences is:

$$\begin{aligned} \underset{\{x^d_{i_n,s}\}_{\forall i_n \in \mathcal{I}_n,d}}{\text{maximize}} & \sum_{i_n \in \mathcal{I}_n} \left(\tilde{\mu}^D_{i_n,s} x^D_{i_n,s} r^D_{i_n,s} + \tilde{\mu}^U_{i_n,s} x^U_{i_n,s} r^U_{i_n,s} \right) \\ & - \sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} \pi^D_{i_n,s} + x^U_{i_n,s} \pi^U_{i_n,s} \right) \end{aligned} \tag{15}$$

$$\text{subject to} \begin{cases} 0 \le x^D_{i_n,s}, x^U_{i_n,s} \le 1 & \forall i_n \in \mathcal{I}_n \\ \sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} + x^U_{i_n,s} \right) \le 1 \end{cases}$$

As at most one user in one transmit direction is scheduled per-SC and the costs and the DL/UL interferences have been fixed, the solution to subproblem in (15) can be easily obtained: it corresponds either to select the user $i_n \in \mathcal{I}_n$ and the transmit direction $d \in \{D, U\}$ at the n-th SC providing a larger value of $\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}$ if $\max_{\{i_n,d\}} \left(\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}\right) > 0$ or to select none in case that $\max_{\{i_n,d\}} \left(\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}\right) \leq 0$ (see objective function in (15)). That is:

$$\begin{aligned}
&\text{if } \max_{\{i_n,d\}} \left(\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}\right) > 0 \\
&\qquad (i_n^*, d^*) = \arg\max_{\{i_n,d\}} \left(\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}\right) \\
&\qquad x^d_{i_n,s} = \begin{cases} 1 & \text{if } i_n = i_n^* \text{ and } d = d^*, \\ 0 & \text{otherwise} \end{cases} \qquad (16) \\
&\text{elseif } \max_{\{i_n,d\}} \left(\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}\right) \leq 0 \\
&\qquad x^d_{i_n,s} = 0 \quad \forall i_n, d \qquad (17)
\end{aligned}$$

Although the integer variables $\{x^d_{i_n,s}\}$ were relaxed, the solution in (16)-(17) always provides integer values for $\{x^d_{i_n,s}\}$. Therefore, the first constraint of problem in (5) is satisfied at any point in the optimization.

Subproblem in (15) with fixed costs and DL/UL interferences has to be solved (through (16)-(17)) for all SCs simultaneously. Then, the costs in (11)-(12) and the DL/UL interferences in (2)-(4) (which impact the achievable rates in (1)-(3)) have to be updated, and said procedure should be iterated until a stop condition.

Let us remark that the solution in (16)-(17) provides an 'on-off' solution for SCs, as it allows that at a given frame a specific SC does not select any user either in UL or in DL. This comes from the last constraint imposed to problem in (5) (and, consequently, to problem in (15)). In case said constraint was included with equality such that at every frame one user is scheduled at each SCs, i.e. $\sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} + x^U_{i_n,s}\right)$=1, then the optimal solution to subproblem in (15) would correspond to selecting the $i_n \in \mathcal{I}_n$ and the transmit direction $d \in \{D, U\}$ at the n-th SC providing a larger value of $\tilde{\mu}^d_{i_n,s} r^d_{i_n,s} - \pi^d_{i_n,s}$ (see (15)). Both options are evaluated in Section V.

B. Algorithm

Algorithm 1 details the procedure to solve problem in (7) in parallel (for all SCs) at frame s, by solving subproblem in (15) iteratively for all SCs. It starts from an initialization of the user scheduling and transmit direction selection $\{x^d_{i_n,s}\}$ (line 1). A suitable initialization is to select (for each n-th SC) the user (i_n^*) and transmit direction (d^*) with largest $\tilde{\mu}^d_{i_n,s} r^d_{i_n,s}$ (no cost) using the achievable rates in (1)-(3) as a function of the useful signal power (no interference). Then, the iterative algorithm is performed in which: *i*) the costs in (11)-(12) and the achievable rates in (1)-(3) are computed (lines 3-4), and *ii*) the optimization in (16)-(17) is performed simultaneously for all SCs to get the user scheduling and transmit direction selection $\{x^d_{i_n,s}\}$ (line 5). The procedure is iterated until a stop condition (i.e. convergence is reached or maximum number of iterations is achieved) and it provides $\{x^d_{i_n,s}\}$ as output.

Algorithm 1 is executed in a central node provided that CSI of all links is available. Otherwise, it could be performed in a distributed manner at each SC if CSI from each SC towards all users was available at each SC and information exchange was used iteratively among SCs to get the costs $\pi^d_{i_n,s}$ in (11)-(12).

Algorithm 1 Procedure to solve the problem per-frame in (7) in parallel for all SCs in a given frame s

initialize $\{x^d_{i_n,s}\}$, $\forall i_n, n, d$
repeat
- compute costs $\pi^d_{i_n,s}$ in (11)-(12), $\forall i_n, n, d$, for given $\{x^d_{i_n,s}\}$
- compute achievable rates $r^d_{i_n,s}$ in (1)-(3), $\forall i_n, n, d$, for given $\{x^d_{i_n,s}\}$
- for each n-th SC (all in parallel): perform (16)-(17) to determine user scheduling and transmit direction selection, i.e. $\{x^d_{i_n,s}\}, \forall i_n, d$.
until stop condition
output: $\{x^d_{i_n,s}\}, \forall i_n, n, d$

Algorithm 2 DUSTDS: Dynamic joint User Scheduling and Transmit Direction Selection (to solve problem in (5))

1: **for** $s = 1, ..., S$ **do**
2: *# Selection of user scheduling and transmit direction:*
3: - **Algorithm 1** to select $\{x^d_{i_n,s}\}$, $\forall i_n, n, d$
4: *# Update dynamic variables:*
5: - compute achievable rates $r^d_{i_n,s}$ in (1)-(3), $\forall i_n, n, d$, with the selected $\{x^d_{i_n,s}\}$
6: - update weights $\tilde{\mu}^d_{i_n,s+1}$ in (10), $\forall i_n, n, d$
7: **end for**

Note that the proposed Algorithm 1 can also be used to determine the user scheduling even if the transmit direction per SC is fixed at frame s, simply by not optimizing the values $x^d_{i_n,s}$ of transmit directions not allowed at SCs.

Convergence of Algorithm 1 with parallel optimizations (see line 5) might not be obtained as the objective function of problem in (7) might oscillate when the costs are updated. Convergence is guaranteed either by performing sequential optimizations (i.e. line 5 is performed for a single arbitrarily chosen SC) or by performing parallel optimizations but including a memory in the costs (for instance, through the use of a low pass filter, as it is done in [17]).

Complexity of Algorithm 1 scales lineally with the number of iterations (which is set to 20 for simulations in Section V). In contrast, complexity of an exhaustive search to optimally solving problem in (7) would scale exponentially: in case the number of users per SC was equal for all SCs, it would scale as $(2I_n + 1)^N$ (i.e. each SC has $2I_n + 1$ possible solutions, corresponding to selecting every associated user either in DL or in UL and to the solution in which none is selected), which is impractical when N and/or I_n increase[2]. Thus, Algorithm 1 provides a non-optimal but low complexity solution.

Finally, Algorithm 2 includes the dynamic user scheduling and transmit direction selection (DUSTDS) to solve problem in (5). At every frame s, Algorithm 1 is executed to design the final $\{x^d_{i_n,s}\}$ (line 3) and, then, the weights $\tilde{\mu}^d_{i_n,s+1}$ to be used in the subsequent frame (s+1) are updated (line 6). In case a proportional fair criterion was used, line 6 would consist on updating the average rates $\bar{R}^d_{i_n,s}$ as in (9), $\forall i_n, n, d$, and then updating the weights $\tilde{\mu}^d_{i_n,s+1}$ in (10) with (8).

[2]For example, in a fixed deployment with $N = 6$ and $I_n = 4$, more than 500.000 possible solutions would need to be checked at every frame.

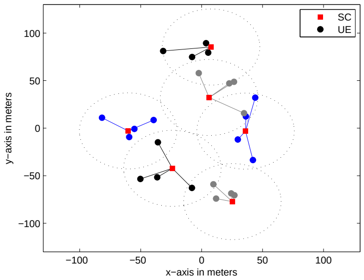

Fig. 3: Example of network deployment used for simulations with $N = 6$ SCs, each with $I_n = 4$ associated users.

V. Simulation Results

The scenario consists of a dense synchronized TDD deployment of N SCs randomly placed within an area of 100 m radius with a minimum distance of 40 m among them. I_n users are randomly placed around each n-th SC in a concentric 40 m radius circle. A deployment example is shown in Fig. 3 for $N = 6$ and $I_n = 4, \forall n$. All SCs/users operate on the same carrier frequency at 2 GHz with 10 MHz bandwidth. Path loss and shadowing models follow specifications in [5] for multi-cell pico scenario. The antenna patterns are omnidirectional. Transmit power is 24 dBm at SCs and 23 dBm at users. Noise spectral density is -174 dBm/Hz. For simulation purposes the same traffic asymmetry (a_{i_n}) is used for all users, $\forall i_n, \forall n$, and the same number of users per SC (I_n) is deployed, $\forall n$.

A proportional fair criterion for problem in (5) is used, i.e. $u(z) = \log(z)$, such that the weights per user and transmit direction in (7), $\mu^D_{i_n,s}$, $\mu^U_{i_n,s}$, are updated as shown in (8).

We evaluate the proposed DUSTDS when:

- it is imposed that all SCs select a user at every frame (i.e. equality constraint $\sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} + x^U_{i_n,s}\right)$=1 for problem in (7)) ('DUSTDS' in figures), and
- the 'on-off' option of SCs is allowed (i.e. inequality constraint $\sum_{i_n \in \mathcal{I}_n} \left(x^D_{i_n,s} + x^U_{i_n,s}\right) \leq 1$ for problem in (7)) (denoted by 'DUSTDS on-off' in figures).

As *baseline scheme* we use a SC-specific TDD scheme with coordinated scheduling [5][6] ('Dynamic TDD CS' in figures), where the transmit direction per SC is set according to the traffic asymmetries of the associated users (e.g. if $a_{i_n} = 0.7$ then 7 frames are used for DL and 3 frames are used for UL) and the user scheduling is optimized in a coordinated manner among SCs at every frame. Recall that, as stated in the introduction, SC-specific decisions combined with interference coordination techniques achieve the best performance among existing dynamic TDD schemes [6][10]. The performance of the baseline scheme when 'on-off' of SCs is allowed is labeled as 'Dynamic TDD CS on-off'.

A. Averaged results

In this section we show results averaged over 100 random deployments for different traffic asymmetries (a_{i_n}), network densities (N) and user densities (I_n). 'Dynamic TDD CS' and 'DUSTDS' are evaluated in terms of the mean of the average rates in DL and UL (i.e. $\bar{R}^d_{i_n}$ in (6)).

First, Fig. 4 displays the mean of $\bar{R}^D_{i_n}$ and $\bar{R}^U_{i_n}$, separately, versus a_{i_n} (traffic asymmetry) for $N = 6$, $I_n = 4$, $\forall n$, and $S = 100$. As it is expected, when a_{i_n} increases (i.e. the amount of DL traffic increases as compared to the amount of UL traffic), DL average rates increase and UL average rates decrease both with 'DUSTDS' and 'Dynamic TDD CS'. The gains from the 'on-off' options in both schemes are appreciable in terms of DL and UL average rates for all a_{i_n}.

It can be observed in Fig. 4 that UL average rates are similar with 'Dynamic TDD CS' and 'DUSTDS', while DL average rates are significantly improved with the proposed 'DUSTDS' for all asymmetry conditions. This is because in the baseline scheme ('Dynamic TDD CS'), when UL is chosen at all SCs then detrimental interferences can be avoided with a proper user scheduling in UL but when DL is selected at all SCs then DL interferences cannot be controlled (interfering nodes are SCs) and is the same independently of the user scheduling for DL (unless neighbor SCs turn off which also degrades the average rate). For that reason, DL average rates are more benefited than UL average rates from the optimization of the transmit direction in SISO systems, as 'DUSTDS' allows reverting the transmit direction when it is required to avoid an interference situation without imposing SCs to turn off.

Second, Fig. 5 shows the mean of $\bar{R}^D_{i_n}$ and $\bar{R}^U_{i_n}$, separately, versus N (number of SCs per area) for $I_n = 4, \forall n$, $S = 100$, and $a_{i_n} = 0.7, \forall i_n, n$. As N increases, the average rates per-user in DL and UL decrease because the density of the network increases and more interference appears. Both DL and UL average rates are improved with the proposed 'DUSTDS' and the average rate gains are larger in DL than in UL. Further, as the network density increases (i.e. as N increases), the relative average rate gains in DL increase because the denser is the network the more important the optimization of the transmit direction for enhancing DL transmissions is.

Third, Fig. 6 depicts the mean of $\bar{R}^D_{i_n}$ and $\bar{R}^U_{i_n}$, separately, versus I_n (number of users per SC) for $N = 6$, $S = 100$, and $a_{i_n} = 0.7, \forall i_n, n$. As I_n increases, the average rates per-user in DL and UL decrease because there are more users to be scheduled in the network which results in a lower number of frames devoted per user. For low I_n, significant gains are obtained both in DL and UL average rates with 'DUSTDS'. As I_n increases, the relative average rate gains in UL decrease due to the fact that 'Dynamic TDD CS' has more flexibility to select the proper user at each SC not interfering neighbor SCs and the gain obtained by reverting the transmit direction is not much important for UL.

B. Comparison with exhaustive search

Finally, let us compare the proposed 'DUSTDS' performed through Algorithm 1 with the exhaustive search solution that optimally solves (7) but involves larger complexity (see complexity considerations in Section IV-B). We show results averaged over 100 random deployments for a specific configuration where $N = 6$, $I_n = 2$, $\forall n$, $S = 100$, and $a_{i_n} = 0.3, \forall i_n, n$. Table I depicts the mean of the objective function (f_{obj}) of problem in (5), the mean of the average rates in DL and UL, and the 5%-ile of the average rates in DL and UL, for the 'on-off' option. It can be observed that 'DUSTDS exhaustive' provides the best solution with larger average rates than the proposed 'DUSTDS Alg1' and the baseline 'Dynamic TDD CS'. Although 'DUSTDS Alg1' already outperforms

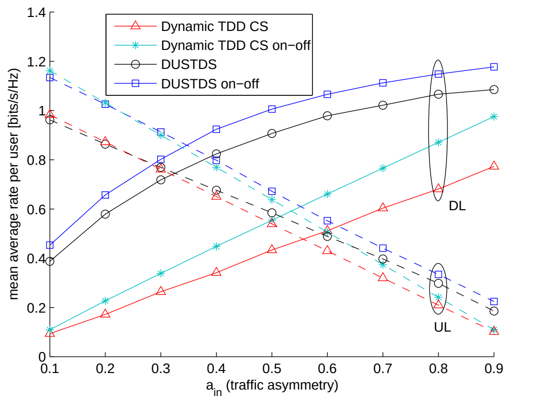

Fig. 4: Mean average per-user rate (in bits/s/Hz) in DL and UL vs. a_{i_n}. $N = 6, I_n = 4, S = 100$.

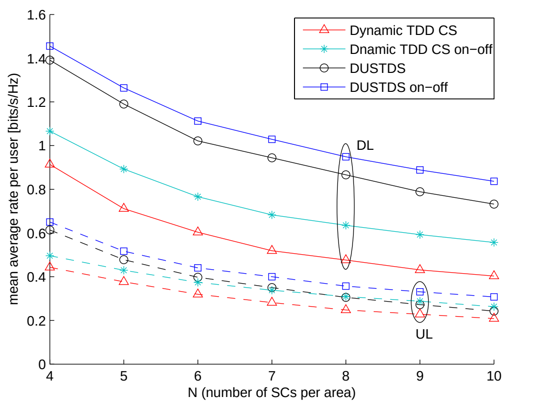

Fig. 5: Mean average per-user rate (in bits/s/Hz) in DL and UL vs. N. $I_n = 4, S = 100, a_{i_n} = 0.7$.

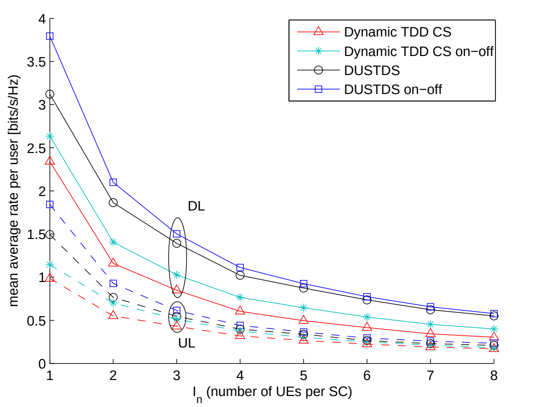

Fig. 6: Mean average per-user rate (in bits/s/Hz) in DL and UL vs. I_n. $N = 6, S = 100, a_{i_n} = 0.7$.

'Dynamic TDD CS', we conclude from Table I that still larger gains could be obtained through the joint optimization of the conventional allocation policies and the transmit direction selection through more complex algorithms.

TABLE I: PERFORMANCE FOR $N = 6, I_n = 2, S = 100, a_{i_n} = 0.3$.

	f_{obj}	$\bar{R}^D_{i_n}$ mean	$\bar{R}^U_{i_n}$ mean	$\bar{R}^D_{i_n}$ 5%ile	$\bar{R}^U_{i_n}$ 5%ile
Dynamic TDD CS	0.54	0.70	1.87	0.09	0.44
DUSTDS Alg1	4.17	1.49	1.90	0.26	0.50
DUSTDS exhaustive	7.50	1.54	2.26	0.75	1.16

VI. Conclusions

This paper presents a dynamic procedure for joint user scheduling and transmit direction selection in 5G TDD dense small cell networks. Differently from previous works, the transmit direction is optimized at each frame jointly with the user scheduling, hence providing high adaptability to the traffic asymmetries and allowing to control the interference conditions. Simulation results show significant gains in DL and UL average rates (being more important in DL average rates) for different traffic asymmetries and network/user densities as compared to existing schemes for dynamic TDD.

VII. Acknowledgments

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