

User-Centric Clustering and Power Control in Cell-Free Networks with Dynamic TDD

Matheus D. Carneiro, Samuel S. Silva, Igor M. Guerreiro, Yuri C. B. Silva and Victor F. Monteiro

Abstract—Dynamic time division duplex (D-TDD) in distributed multiple-input multiple-output (D-MIMO) networks allows for efficient management of asymmetric traffic demands but introduces cross link interference (CLI). This paper addresses these operational conflicts by analyzing the joint application of both user clustering and power control strategies. By first creating disjoint clusters and then relaxing constraints to allow multiple user equipment (UE) connections per access point (AP), the considered strategy promotes allocation fairness and improves overall quality of service (QoS). Additionally, we evaluate the impact of fractional power control (FPC) within this re-clustering framework. Results indicate that combining dynamic cooperation clustering (DCC) with fractional power control (FPC) not only improves packet delay and spectral efficiency (SE) for disadvantaged user equipment (UE) devices, but also drastically enhances the system's energy efficiency (EE) and mitigates CLI, which ultimately improves downlink (DL) performance.

Keywords—D-TDD, D-MIMO, Clustering, Power Control.

I. INTRODUCTION

In the context of mobile communication networks, distributed multiple-input multiple-output (D-MIMO) architecture, also known as cell-free, is better equipped to meet the requirements established for the next generation of communications, such as supporting a larger number of active user equipment (UE) devices and meeting their demands for higher data transmission rates and better signal coverage [1], [2]. These networks are mainly characterized by a large number of access points (APs) distributed throughout the coverage area and the use of centralized processing, which enables joint decoding and pre-processing.

Most studies on cell-free networks assume that these systems operate in traditional time division duplex (TDD) mode [1], meaning that all APs or UEs transmit in a single direction at a time, and transmission frames are generally configured in a fixed manner, with an equal division between uplink (UL) and downlink (DL). However, as the number of simultaneously connected devices has increased, traffic demands on these systems have grown in a heterogeneous manner. Thus, systems operating with this rigid configuration tend to experience a degradation in service quality and a reduced ability to serve a large number of UEs simultaneously.

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To address these challenges, the use of dynamic time division duplex (D-TDD) in communication systems has been studied as a possible solution to deal with the problems arising from the asymmetry in traffic demands, allowing a more efficient use of temporal resources [3]. The core principle remains the dynamic configuration of transmission frames to adapt to instantaneous traffic fluctuations. For example, in cellular architectures, frame configurations can be adjusted on a per-cell basis to satisfy the demands of associated UEs [4]. Conversely, in cell-free systems, transmission frames can be tailored for each user individually, considering specific constraints of the network deployment. In networks with half-duplex APs, which can only operate in one transmission mode at a time, a user-centric implementation is achievable via user-centric clustering[3]. This guarantees that each user is served by a disjoint or exclusive subset of APs, thereby mitigating potential operational conflicts inherent to D-TDD.

However, D-TDD introduces cross link interference (CLI): inter-AP-interference (IAI), where DL transmissions from APs interfere with the reception at APs serving UL UEs, and inter-UE-interference (IUI), caused by UL UEs and experienced at the receiving DL UEs. Thus, power control is a key technique not only for dealing with interference, but also for improving the energy efficiency (EE) of the system. Classic power control approaches can be used, such as fractional power control (FPC), which is a widely explored algorithm in the literature and has the objective of partially compensating for the large-scale fading (LSF) effect. For instance, [5] utilizes an FPC algorithm in a cellular scenario with D-TDD.

Previous works have analyzed user-centric clustering [6] and power allocation [7] in a D-TDD cell-free context, but as separate approaches and assuming single-antenna APs. In this work, we extend those studies to analyze the joint impact of both techniques, while also generalizing the scenario to support multi-antenna APs. Starting from an initial disjoint clustering algorithm, designed to ensure customized frame configurations for each user, we consider the use of dynamic cooperation clustering (DCC) to increase group sizes, while ensuring that the link direction restrictions are satisfied. Then, we evaluate the impact of an adapted FPC scheme in addition to DCC, analyzing system performance in terms of spectral/energy efficiency and packet delay metrics.

II. SYSTEM MODEL

In this work, we consider a cell-free multiple-input multiple-output (MIMO) network operating under D-TDD, which is composed of L APs and K UEs. The UEs are randomly

distributed across the coverage area, while the APs are deployed in a regular grid. The UEs are equipped with a single omnidirectional antenna, while the APs are equipped with an array of N antennas. The APs are connected to a single central processing unit (CPU) via fronthaul links and are subject to the half-duplex constraint, where transmission and reception cannot occur simultaneously.

The propagation channels—including UE-to-AP, UE-to-UE, and AP-to-AP links—follow a Rician distribution, consisting of line-of-sight (LOS) and diffuse components. The propagation channel $\mathbf{H}_{k,l} \in \mathbb{C}^{N_l \times N_r}$ between the k -th transmitter and the l -th receiver can be expressed as follows:

$$\mathbf{H}_{k,l} = \left[\sqrt{\frac{\bar{K}_{k,l}}{\bar{K}_{k,l} + 1}} \mathbf{A}_{k,l} + \sqrt{\frac{1}{\bar{K}_{k,l} + 1}} \mathbf{H}_{k,l}^\omega \right] \beta_{k,l}, \quad (1)$$

in which $\bar{K}_{k,l}$ denotes the Rician K-factor; $\mathbf{H}_{k,l}^\omega \sim \mathcal{CN}(\mathbf{0}, \mathbf{R}_{k,l})$ is the non line-of-sight (NLOS) component, modeled following a Rayleigh correlated distribution; $\mathbf{A}_{k,l} \in \mathbb{C}^{N_l \times N_r}$ is the steering matrix; $\beta_{k,l}$ is the LSF coefficient, which models the path loss (PL) and shadowing effects.

The LOS probability is inherent to all links in the system and depends on the position of the elements in the environment and their heights. The LOS probability can be defined by

$$\text{Prob}_{\text{LOS}}(d) = 0.5 - \min\left(0.5, 5e^{-0.156/d}\right) + \min\left(0.5, e^{-d/0.03}\right), \quad (2)$$

where d is the distance between the transmitter and the receiver in km. The determination of the PL effect, the generation of the shadowing effect, and the Rician K-factor depend directly on whether the channel is LOS or not. If the channel is LOS, $\bar{K} \sim \mathcal{N}(9, 5)$ dB; if not, $\bar{K}$ is equal to zero [8]. We consider that the link between two UEs has no direct path component, so $\bar{K}$ is always equal to zero.

The LSF coefficient $\beta_{k,l}$ is defined as:

$$\beta_{k,l} = 10^{\frac{PL_{k,l} + SH_{k,l}}{10}}, \quad (3)$$

where $SH_{k,l} \sim \mathcal{N}(0, \sigma_{sh}^2)$ and $PL_{k,l}$ represent the spatially correlated shadowing and PL gains in dB. The PL calculation is dependent on the type of link being modeled and the LOS conditions according to [9]; the value of σ_{sh}^2 depends solely on the LOS conditions. The calculation of the PL for all links and LOS conditions is implemented as in [9] and the shadowing generation is implemented as in [2].

After the channel estimates between UEs and APs have been calculated, the coefficients are used to configure the receive combiners and transmit precoders. To mitigate multi-user interference and cross-interference, the set of APs $\mathcal{A}_k$ serving UE k in UL applies a minimum mean square error (MMSE) combiner. On the other hand, to better direct the beams toward the UE i , each AP in set $\mathcal{A}_i$ applies a maximum ratio (MR) precoder. In addition, we denote the set of UEs in UL as $\mathcal{A}$ and the set of UEs in DL as $\mathcal{D}$.

The MMSE combiner applied by the set of APs $\mathcal{A}_k$ is

$$\mathbf{v}_k = p_k \left(\sum_{i \in \mathcal{U}} p_i \mathbf{\Psi}_{i, \mathcal{A}_k} + \sum_{j \in \mathcal{D}} \sum_{l \in \mathcal{A}_j} \mathbf{Q}_{\mathcal{A}_k, l} \right)^{-1} \hat{\mathbf{h}}_{k, \mathcal{A}_k}, \quad (4)$$

in which $\mathbf{\Psi}_{i, \mathcal{A}_k} = (\mathbf{h}_{i, \mathcal{A}_k} \mathbf{h}_{i, \mathcal{A}_k}^H + \mathbf{C}_i)$ is the multi-user interference component, with $\mathbf{h}_{i, \mathcal{A}_k}$ being the collective channel between the UE i and all APs in $\mathcal{A}_k$, and $\mathbf{C}_i = \text{diag}(\mathbf{C}_{i,1}, \dots, \mathbf{C}_{i,|\mathcal{A}_k|})$ is the diagonal matrix of the channel estimation error correlation, as in [1]; $\mathbf{Q}_{l, \mathcal{A}_k}$ represents the inter-AP interference component, which can be expressed as:

$$\mathbf{Q}_{l, \mathcal{A}_k} = \mathbf{G}_{l, \mathcal{A}_k} \mathbf{p}_{l,j} \mathbf{p}_{l,j}^H \mathbf{G}_{l, \mathcal{A}_k}^H, \quad (5)$$

where $\mathbf{G}_{l, \mathcal{A}_k} \in \mathbb{C}^{N|\mathcal{A}_k| \times N}$ denotes the collective channel matrix from interfering AP l to AP cluster $\mathcal{A}_k$, and $\mathbf{p}_{l,j} \in \mathbb{C}^N$ is the DL precoder that the interfering AP l uses to transmit to UE j .

Next, we present the signal and spectral efficiency (SE) expressions for a cell-free network employing D-TDD. As a result of the dynamic switching between transmission directions, the interference levels vary and the SEs of all UEs need to be recalculated constantly. We denote the set of UEs actively transmitting in UL and DL during a given time slot n as $\mathcal{U}$ and $\mathcal{D}$. The signal received by the set of APs serving UE k in UL can be expressed as:

$$\mathbf{y}_{\mathcal{A}_k} = \sqrt{p_k} \mathbf{h}_{k, \mathcal{A}_k} x_k + \gamma_{\mathcal{A}_k}, \quad (6)$$

in which $\mathbf{h}_{k, \mathcal{A}_k} \in \mathbb{C}^{N|\mathcal{A}_k|}$ is the collective channel vector to UE k from all APs in $\mathcal{A}_k$; $p_k \in \mathbb{R}$ and x_k are the transmit power and the symbol of the k -th UE, respectively. The first term of (6) is the desired signal and the second one, γ , is the sum of the interference and noise and is given by:

$$\gamma_{\mathcal{A}_k} = \sum_{\substack{i \in \mathcal{U} \\ i \neq k}} \sqrt{p_i} \mathbf{h}_{i, \mathcal{A}_k} x_i + \sum_{\substack{j \in \mathcal{D} \\ j \neq k}} \sum_{l \in \mathcal{A}_j} \mathbf{G}_{l, \mathcal{A}_k} \mathbf{p}_{l,j} + \mathbf{n}_{\mathcal{A}_k},$$

where $\mathbf{h}_{i, \mathcal{A}_k} \in \mathbb{C}^{N|\mathcal{A}_k|}$ is the collective channel vector between the i -th interfering UE and all APs in $\mathcal{A}_k$; $p_i \in \mathbb{R}$ and $x_i \in \mathbb{C}$ are the transmission power and symbol from the i -th UE; $\mathbf{G}_{l, \mathcal{A}_k} \in \mathbb{C}^{N|\mathcal{A}_k| \times N}$ is the collective channel between the DL AP l and the AP cluster $\mathcal{A}_k$, $\mathbf{p}_{l,j} \in \mathbb{C}^N$ is the DL precoder that AP l uses to transmit to the j -th UE and $\mathbf{n}_{\mathcal{A}_k} \in \mathbb{C}^N$ is the receiving noise. The SE of the UL UE k is given by:

$$R_k^{\text{ul}} = \log_2(1 + \text{SINR}_k^{\text{ul}}), \quad (7)$$

where SINR_k can be calculated as:

$$\text{SINR}_k^{\text{ul}} = \frac{p_k |\mathbf{v}_k^H \mathbf{h}_{k, \mathcal{A}_k} x_k|^2}{|\mathbf{v}_k^H \gamma_{\mathcal{A}_k}|^2}. \quad (8)$$

The signal received by the k -th UE in DL is given by:

$$y_k = \sum_{a \in \mathcal{A}_k} \mathbf{h}_{a, k}^H \mathbf{p}_{a, k} s_k + \psi_k, \quad (9)$$

where the first term is the superposition of the desired signals, with $\mathbf{h}_{a, k} \in \mathbb{C}^N$ and $\mathbf{p}_{a, k} \in \mathbb{C}^N$ being the channel vector and the precoder between the k -th UE and the AP a , which belongs to $\mathcal{A}_k$, and ψ_k is the sum of interference and noise:

$$\psi_k = \sum_{\substack{i \in \mathcal{D} \\ i \neq k}} \sum_{l \in \mathcal{A}_i} \mathbf{h}_{l, k}^H \mathbf{p}_{l, i} s_i + \sum_{j \in \mathcal{U}} \sqrt{p_j} h_{j, k} s_j + n_k, \quad (10)$$

in which the first term is the DL multi-user interference and the second one is the inter UE interference component, with

$\mathbf{h}_{l,k} \in \mathbb{C}^N$ being the channel between the DL AP l and the victim UE k , $h_{j,k} \in \mathbb{C}$ is the channel for the link between the j -th and the k -th UEs and $n_k \in \mathbb{C}$ is the DL receiving noise. The SE of the DL UE k is given by:

$$R_k^{\text{dl}} = \log_2 (1 + \text{SINR}_k^{\text{dl}}), \quad (11)$$

where $\text{SINR}_k^{\text{dl}}$ can be computed as:

$$\text{SINR}_k^{\text{dl}} = \frac{|\mathbf{h}_{k,\mathcal{A}_k}^H \mathbf{p}_{\mathcal{A}_k} s_k|^2}{|\psi_k|^2}. \quad (12)$$

To evaluate the system performance, the per-user EE is defined as the ratio of the achieved spectral efficiency to the consumed transmit power. For the UL, the EE of the k -th UE is given by:

$$\text{EE}_k^{\text{ul}} = \frac{R_k^{\text{ul}}}{p_k}. \quad (13)$$

For the DL, the EE accounts for the total power allocated to the k -th UE by its serving AP cluster, $\mathcal{A}_k$:

$$\text{EE}_k^{\text{dl}} = \frac{R_k^{\text{dl}}}{\sum_{l \in \mathcal{A}_k} p_{l,k}}, \quad (14)$$

where $p_{l,k}$ is the DL transmit power allocated by the l -th AP to the k -th UE.

III. POWER CONTROL ALGORITHM

To mitigate the CLI and improve the EE, we adopt a widely explored approach to set the power levels of the UEs in UL, the FPC. For comparison purposes, we adopt the max power (MP) as a baseline, in which each UE transmits with the maximum power as $p_k = P_{\max} \forall k \in \{1, \dots, K\}$ in UL mode.

Considering the FPC scheme from [10], its objective is to partially compensate for the PL effect according to a compensation factor α and a multiplicative constant P_0 . Thus, the transmit power of a UE k is given by $p_k = \min(P_{\max}, P_0 \zeta_k^{-\alpha})$, in which ζ_k considers the LSF coefficients and the steering vector of APs associated with each UE k as follows:

$$\zeta_k = \sqrt{\sum_{a \in \mathcal{A}_k} \text{tr} \left(\frac{\beta_{k,a}}{\bar{K}_{k,a} + 1} [\bar{K}_{k,a} \mathbf{A}_{k,a} \mathbf{A}_{k,a}^H + \mathbf{I}_{N_L}] \right)}. \quad (15)$$

Note that the power allocation rule based on (15) aims to maintain a target performance level for each UE (scaled by P_0) while reducing overall energy expenditure. Consequently, it does not explicitly account for interference terms, other than implicitly capping the individual transmit power at $P_{\max}$.

IV. CLUSTERING STRATEGY IN D-TDD

In this work, we adopt a primary clustering strategy designed to accommodate the specific traffic configurations of individual UEs according to [3]. To ensure that service is tailored to their needs, we enforce a constraint where each AP connects only to UEs operating in the same transmission mode. Initially, we allocate a fixed and equal number of APs to each UE based on LSF to form disjoint clusters. Under this initial allocation, UEs with the highest LSF coefficients are

assigned to the best available APs. Thus, some UEs may be relegated to APs with comparatively lower channel gains.

To address this limitation and enhance overall system performance, we consider a reallocation algorithm similar to the one in [6], which allows UEs with poor channel gains to be served by APs with better links, provided those APs are already serving other UEs in the same transmission direction. This process, termed "re-clustering", is inherently dynamic due to the variability of traffic and transmission directions. However, it remains computationally feasible in practice because frame configurations are defined in advance, allowing the CPU to compute the dynamic AP allocation prior to transmission.

We implement this re-clustering by adapting the DCC, a widely studied algorithm in D-MIMO architecture. While the DCC in [1] was originally designed for static TDD scenarios, which do not require initial disjoint clustering, we adapt it here to function as a re-clustering approach.

This algorithm re-allocates the APs to each UE based on signal-to-noise ratio (SNR). The first step of this approach is identifying, for each UE k , the AP in the initial cluster with the best SNR and defining it as the master AP with $\text{SNR}_{\text{master}}$. Then, we evaluate all APs that are not currently in the cluster and allocate those that satisfy the condition $\text{SNR}_a - \text{SNR}_{\text{master}} \geq \delta$, $\forall a \in \{1, \dots, L\} \setminus \mathcal{A}_k$ in UL mode, with both SNR values in dB. The threshold δ determines how restrictive the algorithm can be in adding a new AP.

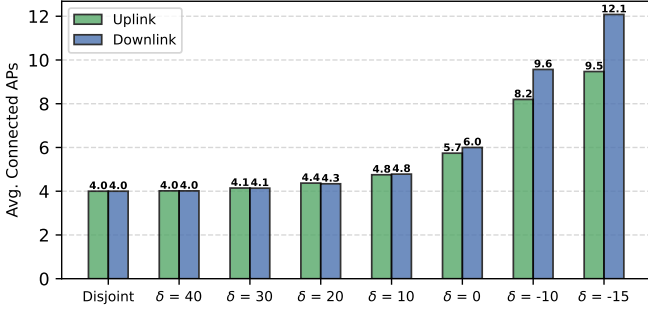
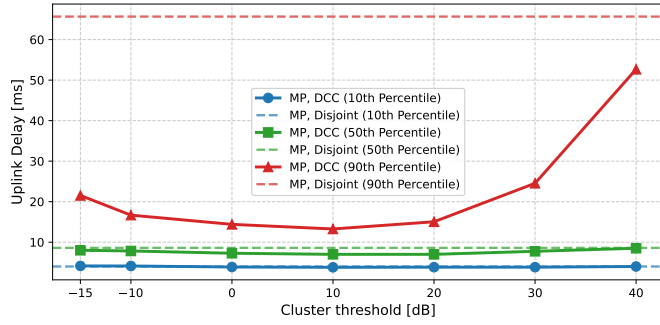
V. SIMULATION RESULTS

The simulated cell-free network with D-TDD consists of $K = 25$ UEs and $L = 100$ APs, with $N = 4$, distributed over a coverage area of 1.2 km². MMSE combining is considered for UL receive beamforming and MR processing is considered for DL transmit beamforming. The total AP power is divided equally among the streams of the UEs it serves. Additional simulation parameters can be found in Table I.

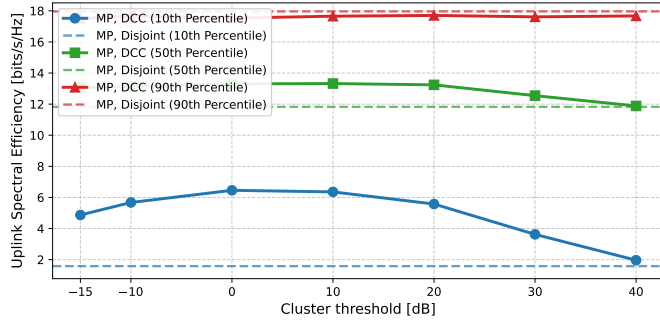
TABLE I
SIMULATION PARAMETERS

Parameter	Value
Carrier frequency	$f_c = 2$ GHz
Equipment height (AP, UE)	11.5, 1.5 m
Number of pilots	$\tau_p = 10$
Coherence block length	$\tau_c = 200$
Max transmit power (UL, DL)	0.1 W, 0.2 W
FPC P_0 and α	-10 dBm and 0.5
Noise power density	-174 dBm/Hz
Shadowing variance (LOS, NLOS)	4, 8.2
Slot duration	1 ms
UL and DL packets size	50 bytes
Packet arrival interval	(UL, DL)
UL-heavy	(8,16) ms
DL-heavy	(16,8) ms
Symmetric	(12,12) ms

The packet traffic system is based on a discrete-time queuing model, with packet arrivals modeled by a Poisson process, with queuing and dequeuing occurring exclusively at the start and end of each time slot. In addition, the average packet inter-arrival time varies according to individual user demands, being shorter for traffic directions with higher demand. Packet delay is defined as the number of slots required for a given packet


 Fig. 1. Average number of APs connected to each UE for varied δ values.


(a) UL delays at the 10th, 50th, and 90th percentiles.



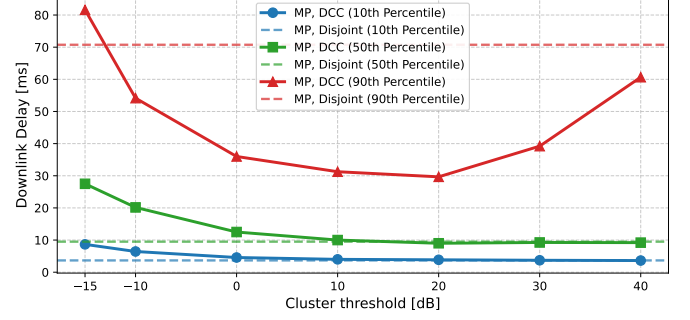
(b) UL SE at the 10th, 50th, and 90th percentiles.

 Fig. 2. Impact of the DCC threshold (δ) on UL performance metrics.

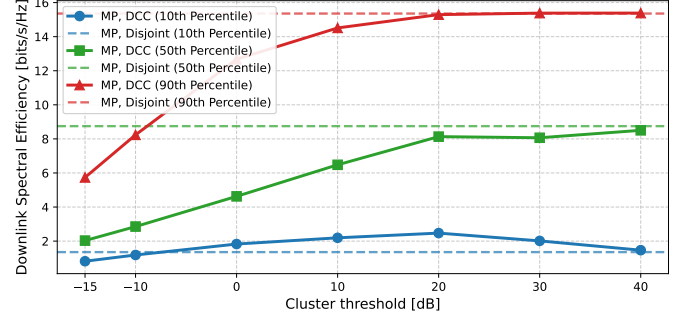
to be fully transmitted, covering the interval from the moment it enters the queue until it departs.

First, we analyze the effect of the re-clustering DCC algorithm on the system performance. For this analysis, we present curves of delay and SE in both UL and DL according to the adopted threshold $\delta \in \{-15, -10, 0, 10, 20, 30, 40\}$ dB and a disjoint clustering baseline. Here we consider the MP for performing the power control.

In this setup, Figure 1 presents the average number of APs connected to each UE in both UL and DL. The first bars show the case in which no re-clustering is performed and the APs are allocated equally among the UEs; the following ones show the cases with DCC in the descending order of δ . From the results we can see that as δ increases, the algorithm re-allocates fewer APs to each UE. The case with $\delta = 40$ dB presents the same average value of APs reallocated as the disjoint one. As for $\delta = -15$ dB, the re-clustering is the least restrictive, adding more than 5 APs, for UL mode, and more than 8 APs, for DL mode, on average.



(a) DL delays at the 10th, 50th, and 90th percentiles.



(b) DL SE at the 10th, 50th, and 90th percentiles.

 Fig. 3. Impact of the DCC threshold (δ) on DL performance metrics.

Figure 2a illustrates the delay values at the 10th, 50th and 90th percentiles varying with different thresholds, as well as the disjoint baselines. Here we can clearly see that, from $\delta = -15$ dB, the delay keeps decreasing until it reaches a minimum point at $\delta = 10$ dB and then starts increasing. This is more noticeable at the 90th percentile, indicating that in UL, DCC is more sensitive to the threshold, particularly for the UE with the worst delay performance.

Figure 2b illustrates the 10th, 50th, and 90th percentiles of the UL SE as a function of δ , alongside the disjoint baselines. Note that for the 90th and 50th percentile, the impact of δ is marginal, as these UEs already enjoy strong channel conditions. In contrast, the 10th percentile shows a significant sensitivity to the threshold; the SE increases until it reaches a maximum between $\delta = 0$ dB and $\delta = 10$ dB. Beyond this range, performance declines toward the disjoint baseline as δ becomes more restrictive. Clearly, the gains provided by DCC at the lower SE percentiles translate directly to improvements at the higher delay percentiles. This occurs because the initial disjoint clustering prioritizes UEs with superior channel conditions, while disadvantaged UEs are initially assigned to APs with lower gains. Reducing the value of δ allows these UEs to be reallocated to higher quality APs, promoting greater spatial uniformity throughout the system.

Transitioning to the DL analysis, Figure 3a illustrates the 10th, 50th, and 90th percentiles of the DL delay as a function of δ , alongside the disjoint baselines. For the 10th and the 50th percentiles, the delay decreases as δ increases until eventually converging to the disjoint baseline starting at $\delta = 10$ dB. For the 90th percentile, the delay decreases until a minimum value at $\delta = 20$ dB before increasing again. By associating more UEs to a specific AP for lower values of δ , the DL transmission

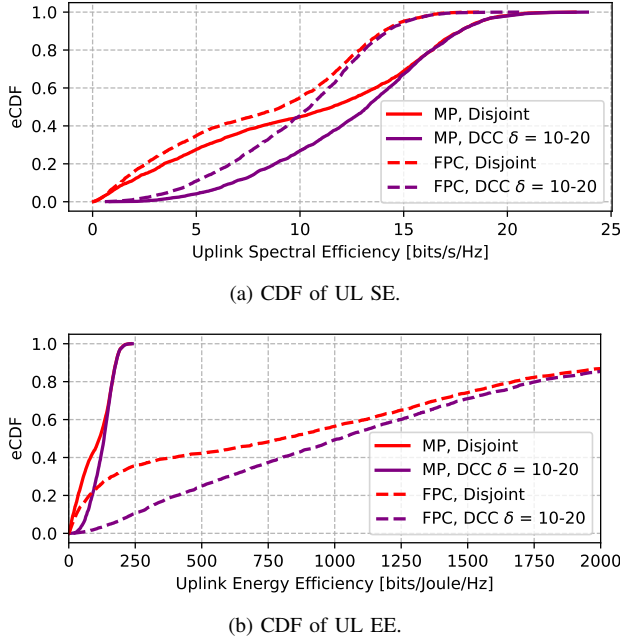


Fig. 4. Comparison of power control and clustering schemes on UL.

experiences amplified interference and power splitting, which consequently increases the transmission delay. As δ becomes more restrictive, this excessive interference is mitigated.

Figure 3b illustrates the 10th, 50th, and 90th percentiles of the DL SE as a function of δ , also including the disjoint baseline. As the threshold increases, the 50th and 90th values increase until they tend to the disjoint baseline, starting from $\delta = 40$ dB at the 50th and $\delta = 20$ dB at the 90th. For the 10th percentile it rises until the maximum point at $\delta = 20$ dB and starts to decrease again.

These findings suggest that the best DCC thresholds are: $\delta = 10$ dB for the UL and $\delta = 20$ dB for the DL, as they yield the best overall performance across the analyzed metrics.

Next, we analyze the effect of the re-clustering algorithm DCC and the power control algorithm FPC on the system performance. For this analysis, we present the SE and EE curves in UL direction (as DL is not significantly affected by FPC) across four setups: i) MP with disjoint clustering; ii) MP with DCC; iii) FPC with disjoint clustering; iv) FPC with DCC. As previously established, for DCC we set the thresholds as $\delta = 10$ dB for UL and $\delta = 20$ dB for DL. For FPC, we use the multiplicative constant as $P_0 = -10$ dBm and the compensation factor as $\alpha = 0.5$.

Figure 4a illustrates the empirical cumulative distribution function (eCDF) of UL SE for this setup. Comparing the clustering schemes, we can also see a behavior consistent with our initial findings. Regarding power control strategies within each clustering scheme, the MP outperforms the FPC across all percentiles. This occurs because FPC does not explicitly incorporate interference mitigation and thus, reduces its own power level in relation to MP in order to guarantee a sufficient performance, which decreases the data transmission rates. However, the case with FPC and DCC is better than the case with MP and disjoint clustering at lower percentiles, with the opposite happening at higher percentiles.

Figure 4b illustrates the eCDF of UL EE for this setup. For

UL EE, the comparison between the clustering schemes is the same as SE, in which DCC outperforms the disjoint clustering, especially for lower percentiles. Regarding the power control schemes, it is evident that FPC provides better EE than MP. It happens because in FPC, the power levels cannot exceed the maximum power and usually have lower values. Hence, a decrease in the denominator of (13) is more significant than a decrease in the numerator when comparing to MP, which highly improves the ratio.

VI. CONCLUSIONS

In this work, we evaluated the joint effects of dynamic re-clustering (DCC) and power control (FPC) on packet delay, SE, and EE in a D-TDD D-MIMO network with multi-antenna APs against disjoint clustering and MP baselines. Under specific thresholds, DCC improves SE and reduces packet delay in both links. In the UL, DCC outperforms the disjoint baseline in all cases, primarily benefiting disadvantaged UEs by allowing service from higher-quality APs outside their initial clusters. In the DL, DCC only outperforms the baseline within specific threshold ranges. Highly permissive settings introduce excessive interference from additional AP allocations, which, while assisting disadvantaged UEs, degrades performance for UEs with strong channel conditions, especially in the DL. Regarding the joint analysis, MP outperforms FPC in UL SE across most percentiles, except for disadvantaged UEs, where FPC with DCC yields better SE than MP with disjoint clustering. Conversely, FPC vastly outperforms MP in terms of EE across all configurations, making it attractive for energy optimization.

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