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Partial Joint Processing for Frequency Selective Channels

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***Abstract*—In this paper, we consider a static cluster of base stations where joint processing is allowed in the downlink. The partial joint processing scheme is a user-centric approach where subclusters or active sets of base stations are dynamically defined for each user in the cluster. In frequency selective channels, the definition of the subclusters or active set thresholding of base stations can be frequency adaptive (per resource block) or non-adaptive (averaged over all the resource blocks). Frequency adaptive thresholding improves the average sum-rate of the cluster, but at the cost of an increased user data interbase information exchange with respect to the non-adaptive frequency thresholding case. On the other hand, the channel state information available at the transmitter side to design the beamforming matrix is very limited and rank deficiency problems arise for low values of active set thresholding and users located close to the base station. To solve this problem, an algorithm is proposed that defines a cooperation area over the cluster where the partial joint processing scheme can be performed, frequency adaptive or non-adaptive, for a given active set threshold value.**

I. Introduction

Coordinated MultiPoint (CoMP) schemes have been identified as one of the key technologies for mitigating intercell interference in future broadband communication systems [1], [2]. Under this framework, both coordinated beamforming and/or user scheduling and the more advanced joint processing between Base Stations (BSs) are included. In joint processing CoMP, multiple BSs can collaborate on the transmission and reception of user data. Under the assumption of perfect channel knowledge, perfect synchronization among BSs and negligible delays, the theoretical gains with joint processing CoMP are substantially larger than with coordinated beamforming. How much of these gains are preserved under more realistic assumptions is still an open issue. On the other hand, these larger performance gains come at the cost of an increased overhead in the system, since the amount of information exchanged between BSs and the required feedback from the users increase. To reduce this overhead, clustering of BSs is proposed. These techniques arrange clusters of BSs that may remain *static* in time, or may *dynamically* adapt to the changing conditions of the channel. Moreover, based on where the clustering decision is carried out, these approaches are further divided into *network-centric* or *user-centric*.

In the previous work [3], the performance of three joint processing schemes for the downlink of a static cluster of BSs was characterized and compared over a flat fading Rayleigh channel. In the Centralized Joint Processing (CJP) approach, global channel state information (CSI) was available at the transmitter side, and the BSs within the cluster jointly performed the power allocation and the design of the linear beamformer [1], [2]. With the aim of decreasing both the required interbase information exchange and feedback from the users, a Partial Joint Processing (PJP) scheme was evaluated, where different stages of joint processing between the BSs in the cluster were defined based on a user-centric clustering algorithm. Finally, a Distributed Joint Processing (DJP) scheme where the power allocation and the beamformers were locally calculated at each BS was also considered. In this last case, a multibase scheduling algorithm was required in order to assign users to BSs.

In this paper, we consider the impact over these joint processing schemes of a more realistic frequency selective fading channel using the WINNER II Channel Model [4]. Specifically, the problem of how to perform the PJP scheme arises[1]. In the PJP scheme, each user in the cluster area is served by a user-centric *subcluster* or *active set* of BSs, which is defined based on an active set threshold value [3]. By doing this, the cluster becomes partially coordinated and different stages of joint processing are achieved. In the case of frequency selective channels, an OFDM-based approach can be considered where the active set thresholding is performed in every subcarrier or group of subcarriers, cf., Resource Block (RB) in 3GPP LTE [5]. This adaptive nature of forming the active set of BSs is referred in this paper as *frequency adaptive* thresholding. On the other hand, when the active set thresholding is performed over the entire channel without exploiting the frequency selectivity of the channel, we have *non-adaptive frequency* thresholding. With frequency adaptive thresholding, the subcluster of BSs transmitting to a user is defined within each RB. However, this implies that the subclusters of BSs for the user may change in each RB for a given time slot and that the benefit of the PJP scheme, i.e., the decreased amount of interbase information exchange, is no

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[1]Notice that a similar problem appears for the multibase scheduling technique required for the DJP scheme. However, in this paper, we focus on the PJP scheme.

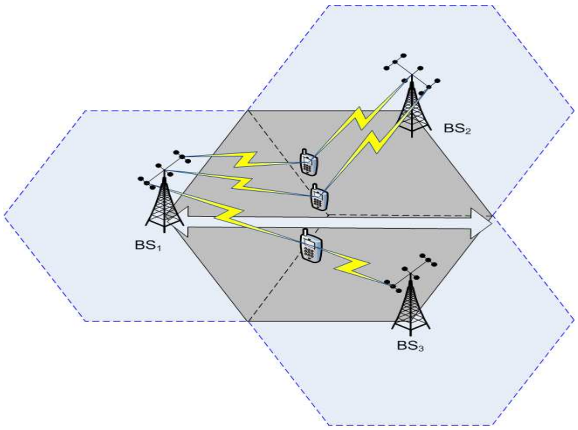

Figure 1. Cluster Layout. The shadowed hexagon is the cluster area under consideration. The dotted lines are the cell-edge regions.

longer possible, since all the user data needs to be available in each BS. In recent approaches involving clustering of sectors or BSs in frequency selective channels, this problem is solved by performing user grouping in a first step [6], and then allocating each group of users to a given RB. However, we are interested in the case where all the users are allocated to all the available RBs in each time slot, so that it is possible to take advantage of the frequency selectivity of the channel.

The outline of the paper is as follows. The system model for the CJP scheme is discussed in section II. The frequency adaptive and non-adaptive frequency thresholding for the PJP scheme are discussed in section III. As stated in [3], the PJP scheme introduces multiuser interference, since less CSI is available at the BSs for the design of the linear beamformer. In the scenario considered in the paper, the multiuser interference can even cancel the potential gains of the PJP scheme when the user is located close to the BS. Therefore, an algorithm is proposed in this section to define a cooperation area where the PJP scheme can be performed for a given active set threshold value. The simulation results are presented in section IV, and the contribution is concluded in section V.

II. System Model

Consider the downlink of a cellular system with a given number of static clusters of BSs. Each static cluster is formed by K BSs with N_T antennas each, and M single antenna users (see Figure 1). The BSs within the cluster can cause intracluster interference due to overloading or loss of orthogonality in any dimension, and the transmissions from BSs outside this set give rise to intercluster interference.

In the worst case interference scenario and under a fairness assumption, the M users are allocated in all the RBs. In this case, the joint processing between BSs is implemented by joint linear beamforming and power allocation being applied in the frequency domain in every RB. Hence, the discrete-time received signal at the M users, $\mathbf{y} \in \mathbb{C}^{M\times 1}$, in a given RB of the ith cluster can be expressed as[2]

$$\mathbf{y} = \mathbf{H}_i \mathbf{W}_i \sqrt{\mathbf{P}_i}\mathbf{x} + \mathbf{z}_{i'} + \mathbf{n}, \tag{1}$$

where $\mathbf{H}_i \in \mathbb{C}^{M\times KN_T}$ is the channel matrix, $\mathbf{W}_i \in \mathbb{C}^{KN_T\times M}$ is the beamforming matrix and $\sqrt{\mathbf{P}_i} \in \mathbb{R}^{M\times M}$ is the power allocation matrix. The transmitted symbols $\mathbf{x} \in \mathbb{C}^{M\times 1}$ are normalized to unit power and $\mathbf{z}_{i'}$ models the intercluster interference from all the $i' \neq i$ clusters. The receiver noise $\mathbf{n}$ is spatially and temporally white, with a variance σ^2, and is uncorrelated with the signals. The channel matrix $\mathbf{H}_i$ is of the form

$$\mathbf{H}_i = [\mathbf{h}_{i,1}^T \mathbf{h}_{i,2}^T \ldots \mathbf{h}_{i,M}^T]^T, \tag{2}$$

where $\mathbf{h}_{i,m} \in \mathbb{C}^{1\times KN_T}$ is the channel from the mth user to all the BSs in the cluster. The beamforming matrix $\mathbf{W}_i$ is

$$\mathbf{W}_i = [\mathbf{w}_{i,1}\, \mathbf{w}_{i,2}\, \ldots\, \mathbf{w}_{i,M}], \tag{3}$$

where $\mathbf{w}_{i,m} \in \mathbb{C}^{KN_T\times 1}$ is the beamformer for the mth user. Considering the CSI from all the BSs in the ith cluster being available in the central unit for joint processing (CJP), the multiuser interference is canceled with a zero-forcing beamforming design, taking the pseudoinverse of $\mathbf{H}_i$

$$\mathbf{W}_i = \mathbf{H}_i^H (\mathbf{H}_i \mathbf{H}_i^H)^{-1}. \tag{4}$$

The intracluster interference is completely removed, i.e., $\mathbf{H}_i\mathbf{W}_i = \mathbf{I}_M$, where $\mathbf{I}_M \in \mathbb{R}^{M\times M}$ is an identity matrix, when $KN_T \geqslant M$ for the entire cluster [7]. At every BS, the maximum transmit power is restricted to P_{max}. Then, the power allocation matrix based on equal user power allocation [8] becomes

$$\sqrt{\mathbf{P}_i} = \left\{ \underset{k=1,\ldots,K}{min} \sqrt{\frac{P_{max}}{||\mathbf{W}_i^k||_F^2}} \right\} \cdot \mathbf{I}_M, \tag{5}$$

where $\mathbf{W}_i^k$ are the rows of the matrix $\mathbf{W}_i$ related to the kth BS. This power allocation is suboptimal, since it typically results in only one of the BSs meeting the maximum transmitted power requirement with equality, and hence, the remaining BSs transmit below the P_{max} value.

Assuming that the intercluster interference is effectively removed, the Signal to Interference Noise Ratio (SINR) at the mth user is

$$\text{SINR}_m = \frac{||\mathbf{h}_{i,m}\mathbf{w}_{i,m}||^2 p_{i,m}}{\sum\limits_{\substack{j=1\\ j\neq m}}^{M} ||\mathbf{h}_{i,m}\mathbf{w}_{i,j}||^2 p_{i,j} + \sigma^2}, \tag{6}$$

[2]Notation: Boldface upper-case letters denote matrices, boldface lowercase letters denote vectors and italics denote scalars. Superscripts $(\cdot)^H$, $(\cdot)^T$ and $(\cdot)^{-1}$ stand for conjugate transpose, transpose and matrix inversion operations, respectively. We use $\mathbb{R}^{M\times N}$ and $\mathbb{C}^{M\times N}$ to denote the set of $M \times N$ real and complex matrices, respectively. $\mathbf{X}_{(i,j)}$ refers to the (i,j)th element of $\mathbf{X}$, whereas $\mathbf{X}_{(:,j)}$ and $\mathbf{X}_{(j,:)}$ indicate its jth column and jth row, respectively. The Frobenius norm of a matrix is denoted by $||\cdot||_F$. Finally, $\mathbb{E}\{\cdot\}$ denotes mathematical expectation.

where $p_{i,m} = \left(\sqrt{\mathbf{P}}_{i(m,m)}\right)^2$. Assuming coherent combining at the receivers, the average sum-rate per cell achieved in the cluster area for a given RB becomes

$$SR_{RB} = \frac{1}{K}\mathbb{E}_H\left\{\sum_{m=1}^{M}\log_2\left(1+\mathrm{SINR}_m\right)\right\}. \tag{7}$$

III. Partial Joint Processing

The PJP algorithm is a threshold based window approach, where those BSs within the cluster whose links with the user fall within this window are included in the active set of the user and are allowed to cooperate. This window is a threshold level that is given by the cluster to the user. The user takes its best channel as its reference or serving BS link and sorts the links with the remaining BSs in the cluster relative to this reference link. This ordering is based on the channel strength or energy of the frequency selective channel, $\mathbf{h}_{i,m}(\tau;t)$ for the mth user, where τ is the tap delay in that time instant t. The PJP algorithm is a particular case of CJP and it asymptotically reaches the CJP performance when the active set threshold goes to infinity. Those BS links which fall within this given threshold are made active and those that fall outside this threshold are marked inactive. These active and inactive links are represented by '1' and '0', respectively, forming a *non-adaptive frequency* thresholding matrix, $\mathbf{T}^{NA} \in \{0,1\}$ of size $[M \times K]$. Notice that $\mathbf{T}^{NA}_{(m,k)} = 1$ means that the link between the BS k in the cluster and the user m is active. In the non-adaptive frequency case, the active set thresholding is performed over an average of all the RBs. This active set of BSs is used in all the RBs but the user needs to feed back the CSI of these active links per RB.

With a realistic wideband channel, one can exploit the frequency selectivity by performing the active set thresholding in every RB. In this paper, this adaptive thresholding approach is called *frequency adaptive* thresholding. The frequency adaptive thresholding approach defines a $\mathbf{T}^{FA}$ matrix in each RB. As a drawback, the active set of BSs may change in each RB. The backhauling load is increased, since the user data needs to be available in all the BSs of the cluster.

As we later show in the simulation results, frequency adaptive thresholding does improve the average sum-rate per cell per RB compared to the non-adaptive frequency thresholding, but at the cost of an increased user data exchange over the backhaul. With the PJP scheme, there is very limited CSI available for designing the beamformer, specially when the user is close to the BS and the active set threshold value is low. This motivates us to develop a partial zero-forcing beamformer based on the proposal in [9].

A. Partial Zero-Forcing Beamforming

The partial zero-forcing beamformer is derived in this section for both frequency adaptive and non-adaptive frequency thresholding approaches. The partial zero-forcing technique proposed in [9] is based on the definition of a useful matrix and interference matrices that modify the channel matrix to obtain useful and interference channel matrices. In our case, $\mathbf{T}^{NA}$ and $\mathbf{T}^{FA}$ active link matrices are the basis for defining them. For a given time instant t, and considering the ath RB of the M users in the ith cluster, the useful channel matrix $\mathbf{U}_x \in \mathbb{C}^{M\times KN_T}$ is defined as

$$\mathbf{U}_x = \left[\mathbf{T}^x \otimes \mathbf{1}_{N_T}\right] \odot \mathbf{H}_i(f_a;t), \tag{8}$$

where $\otimes$ is the Kronecker product, $\mathbf{1}_{N_T}$ is an all ones N_T row vector and $\odot$ is the element-wise multiplication operation. x represents either TA or NA and f_a is the center frequency of the ath RB.

Using the active link matrices $\mathbf{T}^{NA}$ and $\mathbf{T}^{FA}$, one can construct the matrices of the interference caused due to the transmission to the mth user in the cluster, $\mathbf{T}^{NA}_{m,Int}$ and $\mathbf{T}^{FA}_{m,Int}$, respectively. The rules for building the interference matrices for the mth user are that the data destined to the user only affects those users that share the transmitting BS. Such links that cause interference are marked '1'. Conversely, the inactive links for this user obviously do not cause interference to other users and also, the active links do not cause interference to itself. Hence, such links are marked '0'. The interference matrices try to remove the interference generated due to the transmission to a user by explicitly forcing this interference to zero. Therefore, the interference channel matrix $\mathbf{V}_{x,m} \in \mathbb{C}^{M\times KN_T}$ introduced by the transmission to the mth user in the ith cluster in the ath RB can be written as

$$\mathbf{V}_{x,m} = \left[\mathbf{T}^x_{m,Int} \otimes \mathbf{1}_{N_T}\right] \odot \mathbf{H}_i(f_a;t). \tag{9}$$

Assuming that the iterative partial zero-forcing algorithm proposed in [9] converges, the partial zero-forcing beamformer $\mathbf{W}^x_i \in \mathbb{C}^{KN_T\times M}$ is given by

$$\mathbf{W}^x_i = \mathbf{U}^H_x \cdot \left(\mathbf{G}_x + \overline{diag}(\mathbf{R}_x)\right)^{-1}, \tag{10}$$

where $\overline{diag}(\cdot)$ are the off-diagonal elements of the matrix. The matrix $\mathbf{G}_x \in \mathbb{R}^{M\times M}$ is the channel energy scaling matrix given as $\mathbf{G}_x = diag(\mathbf{U}_x\mathbf{U}^H_x)\cdot\mathbf{I}_M$, where $diag(\cdot)$ are the diagonal elements of the matrix. The channel correlation matrix $\mathbf{R}_x \in \mathbb{C}^{M\times M}$ is given as

$$\mathbf{R}_x = \left(\mathbf{V}_{x,1}\mathbf{U}^H_{x(1,:)}\ldots\mathbf{V}_{x,M}\mathbf{U}^H_{x(M,:)}\right). \tag{11}$$

The partial zero-forcing beamformer can only be used when the scaled channel correlation matrix $\mathbf{Q}_x = \left[\mathbf{G}_x + \overline{diag}(\mathbf{R}_x)\right]$ is invertible. As we show in the simulation results, this condition is not always fulfilled, specially for low values of the active set threshold and users located close to a BS. Hence, we propose an algorithm to define a *cooperation area* for a given active set threshold value such that the frequency adaptive or non-adaptive PJP scheme can be performed.

B. Algorithm for Cooperation Area Definition

The algorithm for the definition of the cooperation area is based on the rank of the channel correlation matrix $\mathbf{Q}_x$.

Algorithm 1 Definition of cooperation area for PJP

1: **while** M users in the cluster area **do**
2: Users report CSI based on active set threshold
3: **if** $rank(\mathbf{Q}_x) = M$ **then**
4: Full rank, users in cooperation area
5: Use PJP, $\mathbf{W}_i^x = \mathbf{U}_x^H \cdot \left(\mathbf{G}_x + \overline{diag}(\mathbf{R}_x)\right)^{-1}$
6: **else**
7: Rank deficient, users not in cooperation area
8: **if** active set threshold < 40 dB* **then**
9: Increase the active set threshold, go to step 2
10: **else**
11: Use CJP or DJP schemes
12: **end if**
13: **end if**
14: **end while**

* An active set threshold value of 40dB results in all the BSs being active, i.e., CJP.

IV. Simulation Results

Consider a cluster of three BSs with three antennas each, spaced 4λ apart, and a cell radius of $R = 500$ m. $M = 6$ single antenna users are dropped at 8 predefined positions on the cluster layout (see the arrow in Figure 1), along a uniform distribution forming an ellipse around each position. The major and minor axis of the ellipse are $(2\triangle x, 2\triangle y)$, where $\triangle x \leq \frac{R}{16}$, $\triangle y \leq \frac{h/2}{16}$ and h is the height of the hexagon or cluster. A realistic frequency selective channel is simulated using the WINNER II channel model [4] (scenario B1, urban micro-cell, non-line of sight). 500 independent channel realizations in each predefined position are evaluated at 2GHz center frequency. The signal-to-noise ratio at the cell-edge (reference value for one user located at the cell-edge) is fixed to 15 dB. A 256-point Fast Fourier Transform is used, and one RB corresponds to one subcarrier.

Figure 2 shows the average sum-rate per cell per RB for the CJP, DJP and the PJP scheme with active set threshold values of 5, 10 and 20 dB, for the non-adaptive frequency thresholding approach. The 2 BSs case is a particular case of the PJP scheme, where always the best 2 BSs are transmitting to each user. The performance of the schemes is similar to [3]. Figure 3 shows the gain in the average sum-rate per cell per RB that can be achieved for the PJP scheme with frequency adaptive thresholding, i.e., $G_{SR}[\%] = \frac{SR^{FA} - SR^{NA}}{SR^{NA}}$. This gain depends on the scenario, e.g., for the PJP-5dB case, the maximum gain in the B1 scenario due to frequency adaptive thresholding is ~3%, while ~25% is observed in case of scenario C1 (suburban macro-cell). It should also be pointed out that for high values of the active set threshold, PJP-20dB, there is no appreciable gain in the average sum-rate per cell per RB, since the partial zero-forcing beamformer cannot effectively remove the multiuser interference. The results for the DJP scheme confirm that the multibase scheduling technique presents a similar problem to the active set thresholding of the PJP scheme.

At the cluster center and for normalized distances from the BS_1 between 1.2 and 2, the average number of active links serving a user with frequency adaptive thresholding is lesser than with non-adaptive frequency thresholding. This is due to the fact that frequency adaptive thresholding is more sensitive to the threshold values as it quickly adapts to the frequency changes in every RB. The relative average number of active links, $R[\%] = \frac{\mathbf{T}^{FA} - \mathbf{T}^{NA}}{\mathbf{T}^{NA}}$, is illustrated in Table I. The negative values imply that with frequency adaptive thresholding, in average less CSI is fed back to the BSs. Notice that with frequency adaptive thresholding the user data invariably needs to be available at all the BSs, since the active set typically change along the RBs in a given time slot.

Rank deficiency problems of the scaled channel correlation matrix are more prominent close to BS_1 and for low values of the active set threshold, as shown in Figure 4 for the frequency adaptive case. This agrees with the results presented in [3], where the PJP with low values of the active set threshold did not achieve any gain with respect to the conventional single-BS case once the complexity requirements were taken into account. Applying the Algorithm 1 over the results in Figure 4, a *cooperation area* is defined for each value of the active

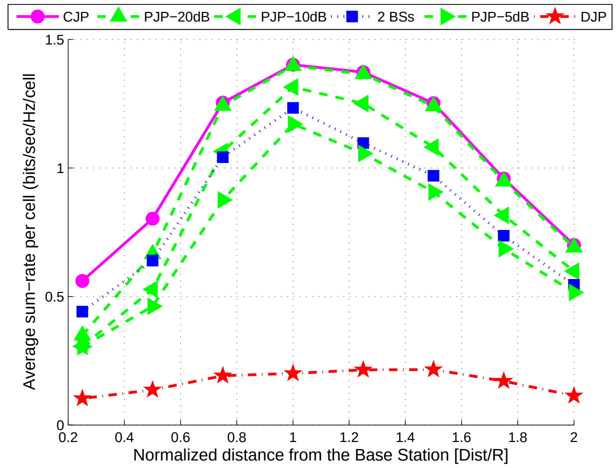

Figure 2. Average Sum-Rate per cell per RB vs. normalized distance from BS_1 when non-adaptive frequency thresholding is considered.

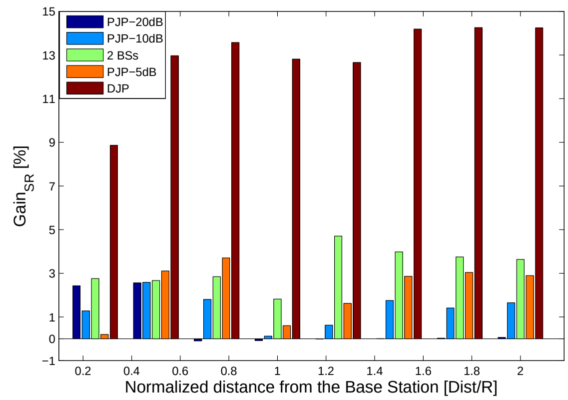

Figure 3. Percentage gain in average sum-rate per cell per RB due to frequency adaptive thresholding over non-adaptive frequency thresholding vs. normalized distance from BS_1.

Table I
RELATIVE AVERAGE NUMBER OF ACTIVE LINKS OF FREQUENCY ADAPTIVE THRESHOLDING VERSUS NON-ADAPTIVE FREQUENCY THRESHOLDING

PJP-threshold	5dB	10dB	20dB	40dB
[Dist/R = 1]*	−4.84%	−3.56%	−0.81%	∼ 0%
[Dist/R = 1.2 to 2]*	−4.16%	−2.27%	−1.57%	−0.01%
[Dist/R = 0.2 to 0.8]*	0.89%	0.46%	−0.72%	−0.82%

*Average values along the normalized distance from BS_1

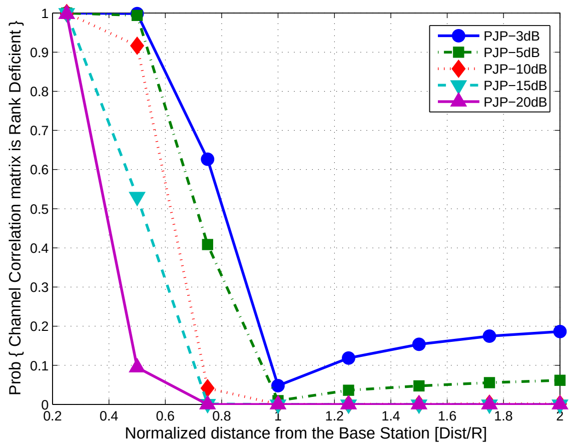

Figure 4. Rank deficiency of the scaled channel correlation matrix, $\mathbf{Q}_x$ is more prominent for users close to BS_1 and in the case of low values of the active set threshold. Results are shown for PJP schemes with frequency adaptive thresholding.

threshold, i.e., the PJP transmission is only allowed for that threshold value when the user is located in the cooperation area. When the outcome of the algorithm is that PJP is not feasible for any active set threshold value, the central unit switches to CJP or DJP schemes. It should be pointed out that for the same value of the active set threshold, the cooperation area due to frequency adaptive thresholding is smaller compared to non-adaptive frequency thresholding. Figure 5 shows the distribution of the average number of BSs transmitting to a user for the PJP-10dB. In this case, the cooperation area corresponds to more than 1.8 BSs transmitting to a user in average. On the other hand, the definition of the cooperation area identifies the cluster-edge users [10], where the use of intercluster coordination techniques is required in a multicluster layout.

V. CONCLUSION

In a frequency selective channel, partial joint processing with frequency adaptive thresholding improves the average sum-rate up to 25% for a suburban macro-cell scenario. This gain comes at the cost of an increased user data exchange with respect to the non-adaptive frequency thresholding case. However, on an average less channel state information is fed back to the base stations. On the other hand, the channel state information available at the transmitter side to design the beamforming matrix is very limited and rank deficiency problems arise for low values of the active set thresholding and for users located close to the base station. To solve this problem, an algorithm is proposed that defines a cooperation area over the cluster, where the partial joint processing scheme can be performed via frequency adaptive or non-adaptive frequency thresholding for a given active set threshold value. A hybrid two-step thresholding, combining the frequency adaptive and non-adaptive approaches, can reduce the backhaul cost with some performance degradation. This will be studied as part of our future work.

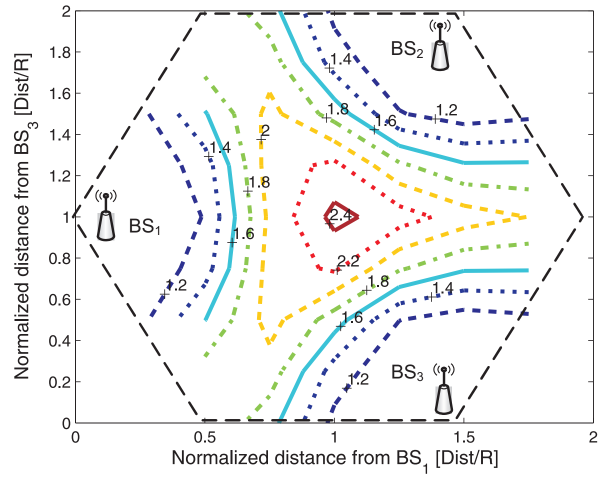

Figure 5. Distribution over the cluster area of the average number of BSs transmitting to one user for the PJP-10dB with frequency adaptive thresholding.

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