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On the Performance of Joint Processing Schemes over the Cluster Area

Carmen Botella*, Tommy Svensson*, Xiaodong Xu†, Hui Zhang†
*Signals and Systems, Chalmers University of Technology, Gothenburg, Sweden, {carmenb, tommy.svensson}@chalmers.se
†WTI Lab, Key Lab of UWC, Ministry of Education, Beijing University of Posts and Telecommunications, Beijing, China
{xuxiaodong, zhanghui}@mail.wtilabs.cn

Abstract*—In this paper, three joint processing schemes for the downlink are characterized and compared within a cluster of base stations. The motivation of this study is to analyze the performance of these schemes over the cluster area, as a first step towards designing an adaptive joint processing scheme supporting dynamic usage scenarios. Each one of the analyzed schemes, the centralized, partial and distributed joint processing approaches, requires a different amount of available channel knowledge at the transmitter side, inter-base information exchange and feedback from the users. In addition, these schemes show varying capabilities to serve the users depending on their location in the cluster area. Therefore, in a real scenario, an adaptive joint processing scheme encompassing the three schemes could be used by the cluster of base stations. Simulation results show that, assuming coherent transmission, the centralized joint processing scheme outperforms with 25% the partial joint processing scheme and with 50% the distributed joint processing approach in the cell edge when a backhaul-load *weighted average sum-rate per cell* metric is taken into account.

I. INTRODUCTION

Recently, joint processing between Base Stations (BSs), which is included in the more general framework of Coordinated MultiPoint (CoMP) transmission schemes, has been identified as one of the key techniques for mitigating inter-cell interference in future broadband communication systems [1], [2]. In this approach, a group of BSs acts as a single and distributed antenna array and hence, data to a single user is simultaneously transmitted from more than one BS.

From a practical point of view, one of the major drawbacks related to the implementation of joint processing, as the number of users and BSs increases, is the amount of feedback needed from the users and the large signaling overhead related to the inter-base information exchange. Therefore, the design of efficient algorithms and principles that could reduce these complexity requirements is of great interest in the field of joint processing. To achieve this goal, solutions that restrict the use of joint processing techniques to a limited number of BSs or areas of the system have been proposed. In these approaches, the network is typically divided into clusters of cells, and the joint processing schemes are implemented within the BSs included in each cluster. The cluster formation can be *static*, if the clusters remain fixed in time [3], [4], or *dynamic* [5], [6].

In this paper, we consider the downlink of a static cluster of BSs. Within the cluster, three schemes that result in several degrees of joint processing between BSs are characterized and compared:

- *Centralized Joint Processing (CJP).*
  In this scheme, global Channel State Information (CSI) is available at the transmitter side, and the BSs within the cluster jointly perform the power allocation and the design of the linear precoder [1], [2].
- *Partial Joint Processing (PJP).*
  This scheme defines different stages of joint processing between BSs. Joint processing degrees or stages are obtained arranging an *active set* or subset of BSs for each user in the cluster area. Hence, a user only receives its data from the subset of BSs included in its active set [7].
- *Distributed Joint Processing (DJP).*
  In the DJP approach, local CSI is available at each BS. Therefore, the power allocation and the precoders are locally calculated at each BS (*distributed*) but the user may receive its data from several BSs (*joint processing*), depending on its given channel conditions. In a first step, a multibase scheduling algorithm is required in order to assign users to BSs.

As we detail in sections II, III and IV, each one of the above schemes requires a different amount of available CSI at the BSs, inter-base information exchange and feedback from the users. In a real scenario, an adaptive joint processing scheme encompassing the CJP, PJP and DJP schemes could be used by the cluster of BSs. Then, based on the current users requirements (e.g., quality of service or service delay constraints) and the availability of the system resources (e.g., available transmit power or backhaul constraints due to the system load), the cluster of BSs may dynamically decide between the CJP, PJP and DJP schemes. On the other hand, the quality of service experienced by a user should preferably not be location dependent, that is, the joint processing scheme should provide a uniform performance over the cluster area. Thus, users location and mobility are other factors that should influence this decision. In section V, CJP, PJP and DJP schemes are characterized by means of simulations as a first step towards designing a scenario-adaptive joint processing

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scheme. To this end, *the probability of outage area*, *the average sum-rate per cell*, *the total transmitted power* in the system and the *backhaul and signaling requirements*, are the metrics considered for each one of the analyzed schemes.

II. CENTRALIZED JOINT PROCESSING (CJP)

We assume a cluster of K BSs, each one equipped with N_t antennas, where M single-antenna users are using a particular orthogonal dimension[1]. When joint processing between BSs is allowed, the data to each user is simultaneously transmitted from multiple BSs. In this case, a total of $K \cdot N_t$ antennas transmit coordinately in the cluster, where $K \cdot N_t \geq M$. In this paper, we assume that the joint processing between BSs is implemented by means of a joint linear precoding design and power allocation. Then, the received signals at the M users can be expressed by means of a vector $\mathbf{y}$, of size $[M \times 1]$, as[2]:

$$\mathbf{y} = \mathbf{H}\mathbf{W}\sqrt{\mathbf{P}}\mathbf{x} + \mathbf{n}. \tag{1}$$

In the above expression, the matrix $\mathbf{H}$ of size $[M \times KN_t]$ includes the channel vectors of the system:

$$\mathbf{H} = \left[\begin{array}{ccc} \mathbf{h}_1^T & \ldots & \mathbf{h}_M^T \end{array}\right]^T, \tag{2}$$

where $\mathbf{h}_m \in \mathbb{C}^{1 \times KN_t}$ stands for the channel between the mth user and the K BSs. In the transmitter side, the joint processing is reflected in the choice of the $\mathbf{W}$ and $\sqrt{\mathbf{P}}$ matrices. The precoding matrix $\mathbf{W}$ of size $[KN_t \times M]$ contains the precoders designed for each of the users:

$$\mathbf{W} = \left[\begin{array}{ccc} \mathbf{w}_1 & \cdots & \mathbf{w}_M \end{array}\right], \tag{3}$$

where $\mathbf{w}_m \in \mathbb{C}^{KN_t \times 1}$ is the precoder for the mth user. In this case, precoding matrix $\mathbf{W}$ is obtained using a zero-forcing (ZF) approach, that is, $\mathbf{HW} = \mathbf{I}_{[M \times M]}$, where $\mathbf{I}_{[M \times M]}$ is an identity matrix of size $[M \times M]$. Since $K \cdot N_t \geq M$, the ZF matrix is the pseudo-inverse of the channel matrix:

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

The power allocation matrix $\sqrt{\mathbf{P}}$ is a diagonal matrix of size $[M \times M]$. In this paper, we assume that the maximum available transmit power at each BS is restricted to a P_{max} value. For simplicity, equal user power allocation is performed. We use the expression for matrix $\sqrt{\mathbf{P}}$ as given in [8]:

$$\sqrt{\mathbf{P}} = \left\{ \min_{k=1,\ldots,K} \sqrt{\frac{P_{max}}{||\mathbf{W}^{(k)}||_F^2}} \right\} \cdot \mathbf{I}_{[M \times M]}, \tag{5}$$

where $\mathbf{W}^{(k)}$ are the rows of matrix $\mathbf{W}$ related to the kth BS. It should be pointed out that this power allocation is suboptimal, since it typically results in only one BS meeting the maximum transmitted power requirement with equality, and hence, the remaining $K-1$ BSs transmit below the P_{max} value. Finally, vector $\mathbf{x}$ of size $[M \times 1]$ includes the precoded information symbols and $\mathbf{n}$ is the receiver noise with variance σ^2, which is spatially temporally white and is also uncorrelated with the signals.

One of the evaluation metrics under consideration is the average sum-rate per cell, which assuming coherent multibase reception can be expressed as:

$$C = \frac{1}{K} E_H \left[\sum_{m=1}^{M} \log_2(1 + \text{SINR}_m) \right], \tag{6}$$

where the Signal to Interference plus Noise Ratio (SINR) for the mth user is given by the following expression:

$$\text{SINR}_m = \frac{||\mathbf{h}_m \mathbf{w}_m||^2 p_m}{\sum_{i=1, i \neq m}^{M} ||\mathbf{h}_m \mathbf{w}_i||^2 p_i + \sigma^2}, \tag{7}$$

with $p_m = (\sqrt{\mathbf{P}}_{(m,m)})^2$.

Assuming that global CSI is available, this approach is regarded as a *centralized* joint processing scheme since it requires a central unit to perform the linear precoding design and the power allocation. This central unit can be an additional network element associated to the cluster of BSs, or one of the BSs of the cluster can act as a central unit. In this scenario, each user needs to feedback the estimated CSI related to all the BSs in the cluster, $\hat{\mathbf{h}}_m$ (2), to its primary BS, which can be defined as the one that provides the highest channel gain. Then, the inter-base station exchange allows to gather in the central unit the global CSI and the user data, in order to perform the joint processing. However, some work has been done in order to constrain the inter-base exchange through the backhaul or to avoid modifications of the network [9].

III. PARTIAL JOINT PROCESSING (PJP)

The motivation for the Partial Joint Processing (PJP) scheme comes from the fact that the backhaul overhead related to exchanging the user data between the BSs is higher than the required for exchanging the channel coefficients, under low to moderate Doppler assumptions [6] or unless the channel conditions change really fast. In the PJP case, the user only receives its data from the BSs included in its *active set*. Therefore, the amount of user data that needs to be exchanged between BSs and/or the central unit is reduced. From the system point of view, three benefits are provided: feedback reduction (users only feed back channels with an acceptable quality), lower inter-base information exchange (user data is only needed in the BSs included in its active set) and transmit power saving (power is saved from poor quality channels). However, the PJP scheme introduces multi-user interference in the system, since less CSI is available at the central unit to design the linear precoding matrix (4).

In order to define the active set of BSs for a given user, the user estimates the average gain of the received channels, one from each BS, and defines its reference link or strongest

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[1] Note that in a multicarrier system, multiple sets of M users can be served in parallel in orthogonal dimensions.

[2] **Notation**: boldface upper-case letters denote matrices, boldface lower-case 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 $\mathbb{C}^{m \times n}$ to denote the set of $m \times n$ complex matrices. $\mathbf{X}_{(i,j)}$ 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 $|| \cdot ||_F$. The sets are indicated by calligraphic letters and $|\mathcal{M}|$ denotes the cardinality of the set $\mathcal{M}$. Finally, $E[\cdot]$ denotes mathematical expectation.

channel, associated to a given BS. Then, the user compares the channel gains related to the remaining BSs with the reference link, and includes these BSs in its active set only if their channel gains are above a relative threshold, with respect to the strongest channel. By doing so, BSs related to poor quality channels do not transmit to the user and the cluster becomes partially coordinated. The threshold value is specified by the cluster, and different degrees or stages of joint processing can be obtained by modifying its value [7].

As stated before, the PJP scheme introduces a certain level of multi-user interference in the system due to the limited CSI available at the central unit. This multi-user interference contribution can be defined by analyzing the expression of the signal received by one user. Assume that $\mathcal{BS}_m$ is the active set of BSs that give service to the mth user, whereas $\mathcal{M}_k$ is the set of users that are served by the kth BS. Note that the cardinality of any $\mathcal{BS}_m$ is such that $1 \leq |\mathcal{BS}_m| \leq K$, whereas the cardinality of any $\mathcal{M}_k$ ranges between $0 \leq |\mathcal{M}_k| \leq M$. Hence, for the mth user, the received signal can be expressed as a sum of the signal of interest (8), multi-user interference ((9), (10)) and noise:

$$\begin{aligned} y_m &= \sum_{k \in \mathcal{BS}_m} \mathbf{H}^{(k)}_{(m,:)} \mathbf{W}^{(k)}_{(:,m)} \sqrt{p^{(k)}_m}\, x_m && (8) \\ &+ \sum_{k \in \mathcal{BS}_m} \sum_{i=1, i \neq m}^{\mathcal{M}_k} \mathbf{H}^{(k)}_{(m,:)} \mathbf{W}^{(k)}_{(:,i)} \sqrt{p^{(k)}_i}\, x_i && (9) \\ &+ \sum_{j \in \overline{\mathcal{BS}}_m} \sum_{i=1}^{\mathcal{M}_j} \mathbf{H}^{(j)}_{(m,:)} \mathbf{W}^{(j)}_{(:,i)} \sqrt{p^{(j)}_i}\, x_i && (10) \\ &+ n_m, && (11) \end{aligned}$$

where $\overline{\mathcal{BS}}_m$ is the complement set of $\mathcal{BS}_m$. $\mathbf{H}^{(k)}_{(m,:)}$ stands for the mth row of the $[M \times N_t]$ matrix $\mathbf{H}^{(k)}$, which is formed with the columns of matrix $\mathbf{H}$ related to the kth BS (the same applies for $\mathbf{W}^{(k)}_{(:,m)}$). Similarly, $p^{(k)}_m$ is the power allocated to the mth user from the kth BS. In the above expression, it is assumed that the channel coefficients included in the multi-user interference term (10) cannot be estimated by the mth user, since those BSs are not included in $\mathcal{BS}_m$. Therefore, this term represents the multi-user interference contribution that remains in the system when the PJP scheme is implemented by the cluster of BSs.

IV. DISTRIBUTED JOINT PROCESSING (DJP)

The Distributed Joint Processing (DJP) scheme assumes a local per-base station design of the linear precoding matrix and power allocation, since only local CSI is available at each BS. Hence, the cardinality of the set of spatially separated users that can be served by each BS in the cluster is reduced to N_t. Under this constraint, the problem of assigning users to BSs under a joint processing assumption arises. This multibase scheduling problem has been previously considered in [10], where low-complexity algorithms have been proposed in order to optimize a given objective function.

In this paper, the multibase scheduling problem is solved as follows: $\mathcal{M}_k$ includes the set of N_t users with the highest channel gain with respect to the kth BS. This approach is similar to the active set procedure of the PJP scheme. However, the decision process of determining which BS transmits to each user is now centered in the BS or transmitter side, that is, it can be regarded as a *cluster-centric* approach, whereas the active set procedure can be classified as a *user-centric* one. As shown in [10], the solution for the multibase scheduling problem typically results in different degrees or stages of joint processing in the cluster depending on the distribution of the users over the cluster area and the system parameters, i.e., each of the M users can be served by a number of BSs that ranges from zero to K, that is, $0 \leq |\mathcal{BS}_m| \leq K, \forall m$. Hence, the DJP scheme implies that a certain number of users in the cluster may remain without service and then, some sort of fairness mechanism would be additionally required. However, this can be easily solved by exploiting the subcarrier allocation in the case of multicarrier systems.

The signal received by one user can still be modeled with the expression (8)-(11), where the linear precoding matrix $\mathbf{W}^{(k)}$ is the pseudo-inverse of the channel matrix $\mathbf{H}^{(k)}$ and the power allocation is performed equally dividing the maximum available transmit power P_{max} into the N_t users.

Regarding the signaling aspects, each BS only needs local CSI in order to design the linear precoding matrix and the power allocation. However, in a first step, global CSI is required to perform the multibase scheduling mechanism. Depending on the system requirements or specifications, this process can be carried out by a central unit (external or related to one of the BSs in the cluster), or can be performed using a decentralized approach [10]. On the other hand, the backhaul overhead is significantly reduced in the DJP scheme, since the user data is only needed in the BSs that transmit to the user.

V. NUMERICAL RESULTS

We consider a cluster of $K = 3$ BSs, each one equipped with an array of $N_t = 3$ antennas, and M single-antenna users. The objective of the simulations is to characterize and compare the performance of the CJP, PJP and DJP schemes over the cluster area, see Fig. 1, as a first step towards designing an adaptive joint processing scheme. The cluster radius and height are $R = 500$ and $h = 433$ meters, respectively. The channel vector between the mth user and the kth BS is modeled as $\mathbf{h}_{mk} = \mathbf{h}'_{mk}\sqrt{\gamma_s \gamma_p}$, where the shadow fading is a random variable described by a log-normal distribution, $\gamma_s \sim \mathcal{N}(0, 8\,\mathrm{dB})$, the pathloss follows the 3GPP Long Term Evolution (LTE) model, $\gamma_p(dB) = 148.1 + 37.6 \log_{10}(r_{mk})$, and $\mathbf{h}'_{mk}$ includes the small-scale fading coefficients, which are i.i.d. complex Gaussian values according to $\mathcal{CN}(0, 1)$.

In the simulations, a grid of possible locations is defined over the cluster area. Then, the M users are uniformly placed over a small area around one location in the grid ($[x \pm \Delta x, y \pm \Delta y]$, with $\Delta x \leq R/16$ and $\Delta y \leq h/16$) and several metrics are evaluated and averaged over 500 independent channel realizations for the CJP, PJP and DJP schemes. This procedure is repeated for each position of the grid, until covering the cluster area. System SNR values

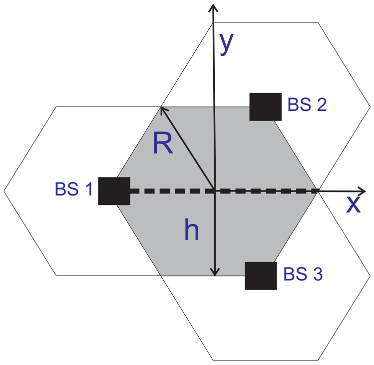

Fig. 1. The cluster area under consideration is the shadowed area close to the cell-edge of each cell.

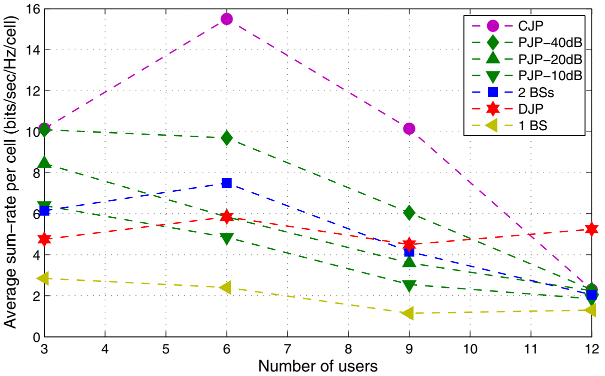

Fig. 2. Average sum-rate per cell for a 5% probability of outage area. Results are shown for $M = 3,\ 6,\ 9$ and 12 users and a system SNR of 15 dB.

ranging from 0 to 15 dB are also simulated (reference value for one user located at the cell-edge), but due to space constraints, simulation results are only provided for interference-limited scenarios (system SNR of 15 dB).

Fig. 2 compares the average sum-rate per cell achieved by the different schemes for a 5% *probability of outage area* [11] in an interference-limited scenario[3]. 'PJP-10dB', 'PJP-20dB' and 'PJP-40dB' plots stand for the results of the PJP scheme when active set threshold values of 10, 20 or 40 dB are simulated, respectively. For comparison purposes, results for the conventional single-base station transmission scheme, '1BS', are also included as a base-line. Results labeled with '2BSs' are obtained when each user receives its data from 2 BSs. It should be noticed that this is a particular case of the PJP scheme.

From Fig. 2, it can be seen that the CJP scheme clearly outperforms the remaining schemes, but this gain comes at the cost of a higher required amount of backhaul exchange and feedback from the users. The PJP scheme defines a trade-off between the required amount of backhaul exchange and feedback from the users and the achieved average sum-rate per cell, that is, its performance improves as the joint processing degree between BSs or the threshold value increases. Moreover, the transmitted power per base station of the PJP scheme also depends on the threshold value, e.g., when $M = 3$ users are located in each position of the grid, and a threshold value of 10 dB is set in the system, in average, a 14.14 % of the *total transmitted power* in the system is saved when compared to the CJP and DJP schemes. This value decreases to 5.74 % when the threshold value is set to 20 dB. Therefore, the threshold value arises as a key parameter in order to dynamically adapt in time both the required amount of backhaul exchange and feedback from the users and the total transmitted power in the cluster area. On the other hand, both the performance of the CJP and PJP schemes (including the '2BSs' case) decreases as the system becomes spatially overloaded, that is, when $K \cdot N_t \leq M$. This is due to the design of the linear precoding as a ZF beamformer, and the suboptimal power allocation performed by the cluster (see expression (5)). The performance of the DJP scheme remains almost constant as the number of users increases, since in this case, the number of users that each BS can serve is spatially constrained to N_t. Hence, some users may remain without being served.

In Fig. 3, the *average sum-rate per cell* obtained by the different joint processing schemes is plotted when moving from BS 1 along the dashed line in Fig. 1. In this case, $M = 6$ users are placed in each position of the grid, which is the value that maximizes the performance of the CJP scheme in Fig. 2. When comparing the curves of the PJP scheme with the '2BSs' scheme results, we can conclude that by allowing a different number of BSs to transmit to each user, depending on the user channel conditions, we can also improve the average sum-rate per cell, since we are increasing the flexibility of our system. Comparing now the results of Fig. 2 for $M = 6$ users and Fig. 3, it can be seen that the '2BSs' and DJP transmission schemes achieve a better performance with respect to the 'PJP-10dB' in terms of the average sum-rate per cell for a given probability of outage area metric. This illustrates that the suitability of a given scheme also depends on the metric under consideration and motivates further research on this direction.

In the CJP scheme, the amount of backhaul exchange and feedback from the users remains fixed regardless of the location of the users in the cluster area. In the case of the DJP scheme, when the M users are placed in a certain location of the grid, they may be served by a number of BSs that ranges from zero (in the case of users being in outage due to the spatial limitation to N_t in the design of the beamformers) to $K = 3$. Notice that the number of BSs serving to a user is also position-dependent. Due to space constraints, Table I shows the *average* number of users per grid point in outage or served by up to $K = 3$ BSs over the cluster area. This metric gives a rough estimation of the amount of backhauling that is required in order to exchange the user data towards the BSs once the multibase scheduling step is finished.

In a real scenario, the best approach would be to define an adaptive joint processing scheme encompassing the CJP, PJP and DJP schemes. To this end, we need to compare the

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[3] A 5% probability of outage area metric indicates that the average sum-rate per cell is below a given value only in a 5% of the locations in the cluster area.

TABLE I

DJP SCHEME: AVERAGE NUMBER OF USERS PER GRID POINT IN OUTAGE, OR SERVED BY 1, 2 OR 3 BSS, RESPECTIVELY. THE EQUIVALENT PROBABILITY WITH RESPECT TO THE TOTAL NUMBER OF USERS IS GIVEN BETWEEN BRACKETS

	Outage	**1 BS**	**2 BSs**	**3 BSs**
$M = 6$	0.74 (12%)	2.25 (38%)	2.27 (38%)	0.74 (12%)
$M = 9$	2.65 (29%)	4.03 (45%)	2.00 (22%)	0.32 (4%)
$M = 12$	5.05 (42%)	5.10 (43%)	1.67 (13%)	0.18 (2%)

schemes taking into account both the performance of each scheme and its complexity requirements. Assuming that the backhaul overhead related to exchanging the user data between the BSs is higher than the required for exchanging the channel coefficients for low mobility users [6], we define a *weighted average sum-rate per cell* metric. This metric is obtained by dividing the average sum-rate per cell by a rough estimate of the required amount of backhaul exchange and feedback from the users, which in this case is the average number of BSs that transmit to a user in each scheme. For the CJP, DJP, '2BSs' and '1BS' schemes, this value remains fixed regardless of the location of the users in the cluster area: $3BSs/user$, $1.5BSs/user$ $(M/(K \cdot N_t))$, $2BSs/user$ and $1BSs/user$, respectively, for $M = 6$ users. However, for the PJP scheme, it depends both on the active set threshold value and on the user position over the cluster area. Fig. 4 shows the weighted average sum-rate per cell of the different schemes, obtained from the results of Fig. 3. Consider the $\text{Distance} = R$ point as a reference, i.e., the cell edge. At this point, schemes with low degrees of joint processing between BSs (DJP, '2BSs' and 'PJP-10dB') do not achieve any gain with respect to the '1BS' case once the complexity requirements are also considered in the metric of evaluation. The CJP scheme outperforms with 25% the 'PJP-20dB' scheme ($2.7BSs/user$) and with 50% the DJP approach.

VI. CONCLUSION

In this paper, three joint processing schemes, the centralized, partial and distributed joint processing approaches, have been analyzed under different metrics over the cluster area. This study confirms that the suitability of a given scheme mainly depends on the metric under consideration. Hence, a *weighted average sum-rate per cell* metric has been defined to take into account both the performance and the complexity of the schemes. Under this metric, and taking into account the cell edge performance as reference point, the centralized joint processing scheme outperforms with 25% the partial joint processing scheme and with 50% the distributed joint processing approach.

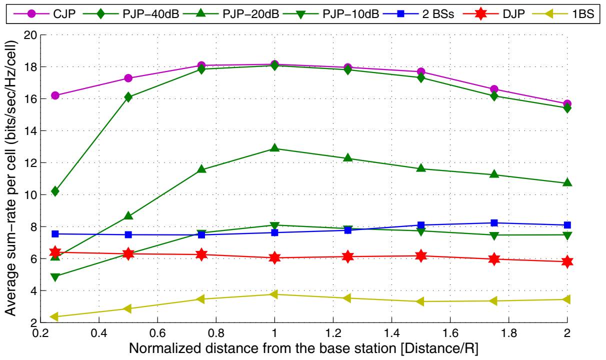

Fig. 3. Average sum-rate per cell versus normalized distance [Distance/R] when moving from BS 1 along the dashed line in Fig. 1. Results are shown for $M = 6$ users and a system SNR of 15 dB.

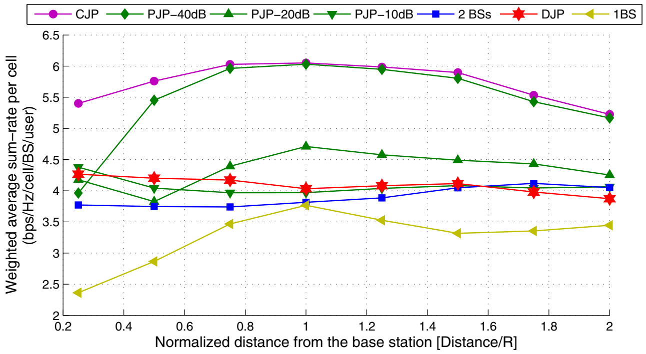

Fig. 4. Weighted average sum-rate per cell versus normalized distance [Distance/R] when moving from BS 1 along the dashed line in Fig. 1. Results are shown for $M = 6$ users and a system SNR of 15 dB.

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