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Scheduling-Assisted Joint Processing for CoMP in the Framework of the WINNER+ Project

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Abstract: The goal of this paper is to present the main achievements reached within the WINNER+ project concerning, in particular, clustering as a way to improve the feasibility of joint processing schemes as enablers of coordinated multipoint solutions. Three different approaches are presented. First, a single and static cluster of base stations is considered. In this case, a user-centric partial joint processing scheme is proposed to reduce with respect to a fully centralized approach both the inter-base information exchange and feedback from the users. Second, a dynamic and network-centric clustering approach is presented. It is shown that substantial gains can be obtained with respect to a static clustering scenario when a central unit jointly creates the clusters of collaborating base stations, schedules the users in these clusters and calculates the beamforming coefficients and the power allocation. Finally, a dynamic clustering technique is combined with multi-antenna receivers. In addition, a concept for a scalable channel state information feedback is also presented.

Keywords: CoMP, WINNER+, LTE-Advanced, joint processing, user grouping, dynamic clustering, coordinated scheduling

1. Introduction

Recently, joint transmission or joint processing between base stations (BSs) has been identified as one of the key techniques for mitigating inter-cell interference in future broadband communication systems [1]. 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. In the 3GPP standardization activities concerning LTE-Advanced (LTE-A), joint processing techniques are included in the more general framework of coordinated multipoint (CoMP) transmission schemes [2]. A first real-time implementation of distributed CoMP in the cellular downlink is reported in [3].

From a practical point of view, one of the major drawbacks related to joint processing is its higher complexity, i.e., increasing backhaul and signaling overhead. To reduce these complexity requirements, *clustering* solutions that restrict joint processing techniques to a limited number of BSs have been proposed. In these approaches, the network is statically or dynamically divided into clusters of cells [4–6]. Moreover, the cluster formation may be performed and optimized by a central entity (*network-centric*), or in a per-user way (*user-centric*).

In this paper, we present the main achievements reached in WINNER+ activity on joint processing for CoMP. First, a single and static cluster of BSs is considered. In this case, a user-centric partial joint processing (PJP) scheme is proposed to reduce with respect to a fully centralized approach both the inter-base information exchange and feedback from the users. Further, we demonstrate that the performance varies over the cluster area. In a second step, we focus on a multi-cluster level and a dynamic and network-centric clustering approach including issues of user scheduling is presented. In this approach, substantial gains are obtained with respect to a static clustering scenario. Finally, a dynamic clustering technique is combined with multi-antenna receivers. In addition, a concept for a scalable channel state information (CSI) feedback is presented.

2. System Model

We consider a cellular OFDM downlink where a center site is surrounded by multiple tiers of sites. We assume each site to be partitioned into three 120° sectors, i.e. a set $\mathcal{L}$ consisting of $L = |\mathcal{L}|$ sectors in total. Each sector constitute a cell, and frequency resources are fully reused in all L cells. Each cell is controlled by a BS. When joint processing between BSs is allowed, the data to each user is simultaneously transmitted from multiple BSs. In order to mitigate the overhead related to joint processing techniques, BSs are grouped into subsets or *clusters*. In this paper, we assume that BSs are grouped in subsets of $N = \lceil \frac{L}{K} \rceil$ clusters, where $\mathcal{K}$ represents the set of cells included in the given cluster and $K = |\mathcal{K}|$ denotes its maximum dimension. Joint processing is only allowed between BSs belonging to the same cluster, whereas BSs belonging to different clusters are not coordinated. We also assume that the clusters are disjoint, i.e. a given BS cannot belong to more than one cluster. Hence, in the ith cluster, there are K BSs, each one equipped with N_T transmit antennas, and a set of $\mathcal{M}_{all}$ multi-antenna users using a particular resource in time, frequency and spatial domain. Further, we assume a scheduling instance, which selects a specific set of active users $\mathcal{M} \subset \mathcal{M}_{all}$ inside of this cluster, with $M = |\mathcal{M}|$ being the number of active users. In particular, the subset $\mathcal{M}_k$ combines those users experiencing highest channel gain to the kth BS. The downlink multiple-input multiple-output (MIMO)-OFDM transmission system is described on a per sub-carrier basis

$$\mathbf{y} = \mathbf{H}_i \mathbf{C}_i \sqrt{\mathbf{P}_i} \mathbf{x} + \mathbf{n} \ , \tag{1}$$

where $\mathbf{H}_i$ is the $MN_R \times KN_T$ channel matrix, $\mathbf{C}_i$ is the $KN_T \times KN_T$ pre-coding matrix and $\mathbf{P}_i$ is the power allocation matrix; $\mathbf{x}$ denotes the $KN_T \times 1$ vector of transmit symbols; $\mathbf{y}$ and $\mathbf{n}$ denote the $MN_R \times 1$ vectors of the received signals and of the additive white Gaussian noise (AWGN) samples, respectively, with covariance $\mathrm{E}[\mathbf{n}\mathbf{n}^H] = \sigma^2 \mathbf{I}$. $E[.]$ is the expectation operator.

When joint processing is allowed in the cluster, a total of $K \cdot N_T$ antennas transmit coordinately to each user, where $K \cdot N_T \geq M \cdot N_R$. Under the assumption of $N_R > 1$ and a sufficiently large set of users, i.e. $|\mathcal{M}_{all}| > KN_T$, multi-user eigenmode transmission (MET) using a single data stream per user was shown to achieve a near-optimum performance [7]. In this paper, we assume that the joint processing between BSs is implemented by means of a joint linear precoding design $\mathbf{C}_i$ and power allocation $\mathbf{P}_i$ with a single spatial stream per user. In particular, the $KN_T \times M$ precoding matrix $\mathbf{C}_i = [\mathbf{b}_{i,1} \cdots \mathbf{b}_{i,M}]$ contains the precoders $\mathbf{b}_{i,m}$ designed for each of the users in $\mathcal{M}$.

For further analysis, we assume the ith cluster is surrounded by $L - K$ BSs evoking non-coordinated cochannel interference (CCI). Thus, the received downlink signal $\mathbf{y}^m$

at the mobile terminal (MT) m in the cellular environment is given by

$$\mathbf{y}^m = \underbrace{\mathbf{H}_i^m \mathbf{b}_{i,m}}_{\bar{\mathbf{h}}_m} \sqrt{p_{i,m}}\, x_{i,m} + \underbrace{\sum_{\substack{j=1\\ j\neq m}}^{M} \mathbf{H}_i^m \mathbf{b}_{i,j} \sqrt{p_{i,j}}\, x_{i,j}}_{\zeta_m} + \underbrace{\sum_{\substack{\forall l\\ l\in\mathcal{L}\setminus\mathcal{K}}} \sum_{j=1}^{N_T} \mathbf{H}_l^m \mathbf{b}_{l,j} \sqrt{p_{l,j}}\, x_{l,j} + \mathbf{n}}_{\mathbf{z}_m} \tag{2}$$

The desired data stream $x_{i,m}$ transmitted to the mth user from the ith cluster is distorted by the intra-cluster and inter-cluster interference plus noise aggregated in ζ_m and $\mathbf{z}_m$, respectively. $\mathbf{H}_i^m$ spans the $N_R \times KN_T$ channel matrix for user m formed by the ith cluster and $p_{i,m}$ is its power allocation. Thus, ζ_m denotes the interference generated within the cluster. In this work, we consider the average sum-rate per cell as well as the cell-edge user throughput for performance evaluations. Both are based on Shannon information rates using signal to interference and noise ratios (SINRs) as given below

$$\mathrm{SINR}_m = \frac{||\mathbf{w}_m^H \mathbf{H}_i^m \mathbf{b}_{i,m}||^2 p_{i,m}}{\sum_{j=1, j\neq m}^{M} ||\mathbf{w}_m^H \mathbf{H}_i^m \mathbf{b}_{i,j}||^2 p_{i,j} + \mathbf{w}_m^H \left[\mathbf{z}_m \mathbf{z}_m^H\right] \mathbf{w}_m}, \tag{3}$$

with $\mathbf{w}_m$ being the combining weights at the receiver, e.g. optimum combining (OC) [8] or maximum ratio combining (MRC).

3. Scheduling-assisted partial joint processing (PJP)

3.1 Benefit of partial joint processing (PJP)

In this section, we consider the downlink of the ith cluster in the system. Within the cluster, a partial joint processing (PJP) scheme is proposed in order to reduce with respect to a fully centralized joint processing (CJP) approach (1) both the inter-base information exchange and feedback from the users. To evaluate this scheme, we assume single-antenna users ($N_R = 1$), whereas a zero-forcing (ZF) precoder is jointly designed by the BSs, $\mathbf{C}_i = \mathbf{H}_i^H(\mathbf{H}_i\mathbf{H}_i^H)^{-1}$. The maximum available transmit power at each BS is restricted to a P_{max} value, and hence, under an equal user power allocation assumption, matrix $\mathbf{P}_i$ can be written as $\mathbf{P}_i = \{\min_{k=1,\ldots,K}(P_{max}/||\mathbf{C}_i^{(k)}||_F^2)\} \cdot \mathbf{I}_{[M\times M]}$, where $\mathbf{C}_i^{(k)}$ are the rows of matrix $\mathbf{C}_i$ related to the kth BS, and $\mathbf{I}_{[M\times M]}$ is the $M \times M$ identity matrix [9].

In the PJP scheme, the user receives its data from a subset of the K BSs or active set [10]. Therefore, from the system point of view, three benefits are provided: feedback reduction, lower inter-base information exchange and transmit power saving. 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 $\mathbf{C}_i$. In order to define the subset of BSs transmitting to a given user, assume that this user is assigned to a master BS, which is the one with the highest channel gain. The user estimates the average channel gain from the remaining BSs in the cluster, $K - 1$, and compares it to the channel gain from the master BS. BSs are included in the active set only if their channel gains are above a relative threshold with respect to the master BS. 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. Therefore, the PJP scheme includes as a particular case the fully CJP case.

	1BS	DJP	2BS	PJP-10dB	PJP-20dB	PJP-40dB	CJP
Median TP	1.0	1.6	2.0	2.1	3.4	4.7	4.7

Table 1: Gains with respect to 1BS case and at $Distance/R = 1$.

Both the CJP and PJP approaches imply the need of a central unit to design the precoding scheme. For comparison purposes, we also consider a decentralized joint processing (DJP) scheme, where only local CSI is available at each BS and the power allocation and the precoding are locally implemented at each BS. However, the user may receive its data from several BSs (joint processing), depending on its given channel conditions. 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, and a multibase scheduling algorithm is required in order to assign users to BSs. In this paper, the multibase scheduling problem is solved allowing each BS in the cluster to serve its set of $\mathcal{M}_k$ users. As shown in [11], with this solution, each of the M users can be served by a number of BSs that ranges from zero to K. Hence, the DJP scheme implies that a certain number of users in the cluster may remain without service.

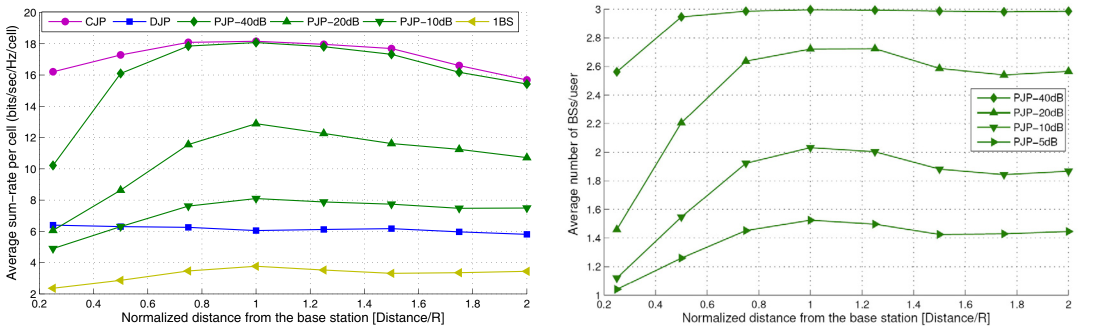
3.1.1 Numerical Results

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. For this reason, we characterize and compare the performance of the CJP, PJP and DJP schemes over the cluster area. We consider a cluster of $K = 3$ BSs, each one equipped with an array of $N_t = 3$ antennas, and $M = 6$ single-antenna users. The cluster radius is $R = 500$ meters. 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, $\gamma_s \sim \mathcal{N}(0, 8\,\text{dB})$, 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 Fig. 1(a), the average sum-rate per cell obtained by the different transmission schemes is plotted when moving away from one of the BSs of the cluster. In this case, $M = 6$ users are placed in each position. The PJP plots stand for active set threshold values of 10, 20 or 40 dB, respectively. Results for the conventional single-BS transmission scheme, '1BS', are also included as a base-line.

For low mobility users, the backhaul overhead related to exchanging the user data between the BSs is higher than the required for exchanging the channel coefficients. Then, the combined value of backhaul exchange and feedback from the users can be roughly estimated by means of the average number of BSs that are transmitting to a user, $\bar{N}_{BS}$. In the CJP and DJP schemes, this parameter remains fixed regardless of the location of the users in the cluster area. However, for the PJP scheme, $\bar{N}_{BS}$ depends both on the active set threshold value and the user position over the cluster area (see Fig. 1(b)).

3.2 *Dynamic base station clustering*

In this section, the BS clusters are created in a dynamic way, in other words at each time slot t the sets of coordinated BSs are generated in order to maximize a given



(a) Average sum-rate per cell versus normalized distance.

(b) PJP scheme: average number of BSs transmitting to each user, $\bar{N}_{BS}$, for different threshold values versus normalized distance.

Figure 1: Results are shown for $M = 6$ users and an edge-of-cell SNR of 15 dB.

objective function.
We define $C_l(t), l = 1, \ldots, L$ as the set of BS indexes belonging to the lth cluster at the time slot t and $U_l(t), l = 1, \ldots, L$ as the set of user indexes scheduled for transmission in a given cluster at the time slot t. We define $\mathcal{C}(t) = \{C_1(t), \ldots, C_L(t)\}$ and $\mathcal{U}(t) = \{U_1(t), \ldots, U_L(t)\}$ respectively as a BS clustering and a user allocation at the tth time slot. Let's for sake of clarity drop the dependance on the time slot t. We define $R_l(\mathcal{C}, \mathcal{U}, \mathcal{W}, \mathcal{P})$ as the throughput achievable in the lth clusters, given the user allocation $\mathcal{U}$, the clustering $\mathcal{C}$, the antenna weights $\mathcal{W}$ and the power allocation $\mathcal{P}$. We emphasize that in this work we are not assuming a particular physical layer technique $(\mathcal{W}, \mathcal{P})$, as the proposed technique is transparent to the physical layer scheme.

We assume a star network topology that represents the case of multiple BSs connected with a central unity or the case of multiple BSs connected to the network, where one of them acts as central unit. We assume that scheduling, BS clustering, calculation of the beamforming coefficients and power allocation are realized in the central unit.

The proposed technique can be summarized as follows:

- **Phase I**. Each BS sends the channel estimates to the central unit.
- **Phase II**. Based on the CSI and on the scheduling requirements, the central unit jointly creates the clusters of collaborating BSs, schedules the users in these clusters and calculates the beamforming coefficients and the power allocation.
- **Phase III**. The central unit sends to the BSs beamforming coefficients, power allocation, indexes of the coordinated cells and indexes of the selected users. At this point, the BSs belonging to the same cluster need to share the data of the selected users between them.

With respect to full network coordination (CJP), the proposed technique allows the reduction of signaling due to data sharing, while requiring the same amount of signaling due to channel estimates exchanges.The problem of jointly clustering and user selection can be formalized as follows

$$\begin{cases} \max\limits_{\mathcal{C},\mathcal{U}} \sum_{l=1}^{L} R(\mathcal{C}, \mathcal{U}, \mathcal{W}, \mathcal{P}) \\ U_k \cap U_j = \phi, \forall U_k, U_j \in \mathcal{U}, k \neq j \\ C_k \cap C_j = \phi, \forall C_k, C_j \in \mathcal{C}, k \neq j \end{cases} \tag{4}$$

	non-CoMP	static CoMP	proposed algorithm	full CoMP
Median (cell-edge) TP	1.0 (1.0)	0.9 (1.1)	1.3 (2.0)	1.6 (2.8)

Table 2: Summary of the performance of the proposed algorithm in terms of gains with respect to the non-CoMP case. The cell-edge performance is measured at the 5%-tile of the user throughput CDF

The objective function $\sum_{l=1}^{L} R\left(\mathcal{C}, \mathcal{U}, \mathcal{W}, \mathcal{P}\right)$ is a function of both the BS clusters and of the users scheduled in each cluster. For example, under a ZF precoding assumption the optimum must at the same time minimize the inter-cluster interference and select a quasi-orthogonal set of users to be scheduled in each cluster. The two constraints are related respectively to the assumption of non-overlapping clusters and to the assumption that each user cannot be served at the same time by BSs belonging to the same cluster.

The optimal solution of (4) requires a brute force search over the sets of users and possible BS clusters. In the following we propose a sub-optimal approach based on the idea of restricting the search space. This approach consists in two different stages an off-line stage, and an on-line stage.

> **Off-line phase.** The candidate clusterings are chosen off-line taking into account path loss and shadowing (or more in general average user distribution and average channel estimates).
>
> **On-line phase.** At each time frame t the central node estimates the weighted sum-rate achievable for each cluster. This sum-rate estimation involves the choice of a candidate set of users to be scheduled with a brute force user selection or with a greedy user selection technique and the calculation of the power allocation that solves. Finally, the clustering that maximizes the weighted sum-rate and the associated set of users, beamforming coefficients and power allocation are used for transmission in the tth time slot.

3.2.1 Numerical Results

A system simulator has been developed with 19 single antenna BSs and wraparound, 30 users per BS, edge-of-cell SNR of 15dB. Each single-antenna user is dropped with uniform probability inside each cell. Fairness is guaranteed by a proportional fairness scheduler. The reference SNR is defined as the SNR ad the cell vertex. The channel has been modeled considering Rayleigh and path loss effect (with path loss exponent equal to 4.5).

In Table 2 the performance of the proposed algorithm is summarized respectively in terms of average rate per cell and cell-edge rate (5% tile) for a cluster size of 10 BSs, which corresponds to a 50% reduction in the number of BSs sharing the data of the users scheduled for transmission in a given frame. Four different techniques are compared: non-cooperating BSs, static coordination, i.e. clusters of cooperating BSs are kept fixed during all the simulation and in each cluster the users are selected for transmission using a proportional fair scheduler, dynamic coordination and full coordination, i.e. all the N BSs cooperate together and up to N users are scheduled for transmission in each frame with a proportional fair approach.

3.3 Scalable CSI feedback and multi-antenna receivers

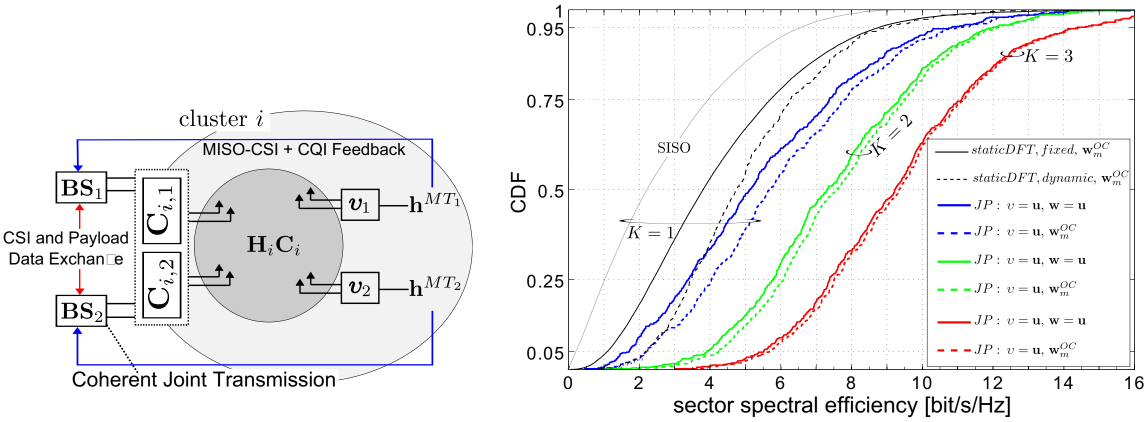
In this section, we use a distributed joint processing (JP) scheme, where K BSs perform the CoMP downlink transmission to a set $\mathcal{M}$ of active users each equipped with $N_R = 2$

receive antennas. In order to use the same ZF beamformer, we have to select appropriate receive spaces from $M \times N_R$ antennas. In maximum, the cluster can provide KN_T coherently transmitted data streams. Furthermore, the pre-coding algorithm has to be independent from the different capabilities of each user, i.e. selection of receive spaces. A total number of KN_T multiple-input single-output (MISO) channels, selected from a sufficiently large set of users $\mathcal{M}_{all}$, are composed to form a compound MIMO channel matrix of size $KN_T \times KN_T$, refer to Fig. 2(a). The basic idea is to enable each user to generate and provide CSI feedback by selecting a preferred receive strategy $\boldsymbol{\upsilon}_m$, which can differ from the equalizer $\mathbf{w}_m$ used in (3). Therefore, each user can choose its desired receive strategy according to its own computational capabilities and knowledge on channel state information at the receiver (CSIR) including interference, independently from other users. Each user is assumed to use linear receive filters $\boldsymbol{\upsilon}_m$ to transform the MIMO channel into an effective MISO channel [6], according to Fig. 2(a) $\mathbf{h}^{MT_m} = \boldsymbol{\upsilon}_m^H \mathbf{H}_i^m$. In this work, we limit the evaluation to a MET-based [7] approach: each user decomposes its channel $\mathbf{H}_i^m$ by a singular value decomposition (SVD) into orthogonal eigenspaces, i.e. $\mathbf{H}_i^m = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^H$. Further, we assume each MT is applying for a single data stream only. Thus, it is favorable to select the dominant eigenmode, i.e. the eigenvector corresponding to the highest eigenvalue. The effective channel after decomposition using the dominant left eigenvector, i.e. $\boldsymbol{\upsilon}_m = \mathbf{u}_{i,1}$ is given by $\mathbf{h}^{MT_m} = \mathbf{u}_{i,1}^H \mathbf{U}_i \boldsymbol{\Sigma}_i \mathbf{V}_i^H = \Sigma_{i,1} \mathbf{v}_{i,1}^H$. The scheme maximizes the signal power transfered from ith cluster to the user. Users should preferably be grouped such that their eigenmodes show highest orthogonality. This keeps the costs in received power reduction as small as possible.

This allows us to benefit from two major advantages: first, the multiple receive antennas are efficiently used for suppression of external interference at the user side. Second, by reducing the number of data streams per user, we enable the system to serve a larger set $\mathcal{M}$ of active users instantaneously and thus benefiting from multi-user diversity.

3.3.1 Numerical Results

A system simulator has been developed with $L = 57$ multi-antenna BS sectors and a wraparound using 3GPP's extended spatial channel model (SCME). A set $\mathcal{M} = \mathcal{M}_{all}$ of active multi-antenna terminals is uniformly distributed in the ith cluster of the cellular environment. All user sets $\mathcal{M}_k \subset \mathcal{M}$ are disjoint for different $k \in K$ and have a size of $|\mathcal{M}_k| = N_T$, i.e. all users are connected to a master BS. Further, we emulate a cluster selection which is user-centric and dynamic over frequency: the K strongest channel gains of the users in $\mathcal{M}_k$ are the ones of the K BSs within the cluster. Results are provided for different cluster sizes of $K \in \{1, 2, 3\}$. In Figure 2(b), the performance of the concept is demonstrated with respect to the spectral efficiency per sector within the cluster. For reference purpose, we provide results for SISO and MIMO 2x2 (static DFT) without any CoMP transmission. For the static DFT-precoded system, we perform simultaneous multi-user service to $M = 2$ users with a fixed or dynamic stream assignment. In contrast, the system using the distributed JP scheme performs simultaneous multi-user service to $M = 2K$ users. For $K = 3$ BSs in the cluster, this transmission strategy increases the median sector and cell-edge user throughput by a factor of 4.2 and 13, respectively, compared to the non-coordinated SISO setup.



(a) Distributed JP for cellular CoMP.

(b) Throughput CDFs for different system settings.

Figure 2: System throughput, w/ and w/o joint processing. Receivers are allowed to be changed according to the OC taking the residual interference into account.

	SISO	non-CoMP		CoMP with PJP		
	$K=1$	$K=1$	$K=1$	$K=1$	$K=2$	$K=3$
Median (cell-edge) TP	1.0 (1.0)	1.7 (2.5)	2.1 (5.0)	2.6 (5.0)	3.4 (9.7)	4.2 (13)

Table 3: Gains with respect to SISO case. Cell-edge is measured at the 5%-tile of the user throughput CDF

4. Conclusions

Joint processing as a possible enabler of coordination in future cellular networks is considered as a very promising technique to increase both the cell-edge user as well as the average system throughput. However, joint processing CoMP implies high complexity for required data exchange among base stations and the related impacts on system architectures. WINNER+ focused on joint processing, while investigating the most feasible implementation issues: clustering and scheduling-assisted techniques. In this paper, three different approaches for joint processing-based CoMP are proposed. The first one uses a user-centric partial joint processing scheme to reduce the inter-base information exchange and the feedback from the users. The second one proposes a dynamic and network-centric clustering approach, where a central unit jointly creates the clusters of collaborating base stations, schedules the users in these clusters, calculates the beamforming weights and the power allocation. The third one combines a user-centric and dynamic clustering technique with multi-antenna receivers and a scalable feedback scheme.

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