A Framework for Decentralising Multi-Cell Cooperative Processing on the Downlink

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***Abstract*—Multi-cell cooperative processing (MCP) is well acknowledged for significantly improving spectral efficiency and fairness amongst users. Nevertheless MCP comes together with some shortcomings which have also been recognised. Cooperating Base Stations (BSs) need to be inter-connected via a Control Unit (CU) which gathers channel state information (CSI). CU is the entity responsible for performing MS scheduling and defining the transmission parameters. Under a practically feasible linear precoding framework, CU performs user scheduling and designs the beamforming matrix for the chosen users. Therefore MCP implementation adds a very significant infrastructure cost as it requires a CU and low latency links connecting cooperating BSs with it. Furthermore this entails an important protocol complexity in order for all this signaling to be coordinated. In this paper a new framework is proposed that allows MCP on the downlink without the need of costly modifications on the infrastructure comparing to the existing cellular networks. The needed operations are performed in a distributed fashion by the cooperating BSs and this is shown to be a good alternative facilitating MCP implementation.**

I. Introduction

The increasing demand for high quality and throughput wireless services (mobile Internet), together with the scarcity of radio spectrum have boosted research on aggressive reuse systems. In contemporary systems, where Base Stations (BSs) are densely deployed in order to provide the needed capacity, aggressive reuse systems have an interference limited performance due to the increased inter-cell interference (ICI). Multi-cell cooperative processing (MCP) has been recognised as an effective solution to this shortcoming. In MCP enabled systems, groups of BSs (cooperation clusters) are envisaged to be inter-connected via a Control Unit (CU) with the use of low latency wireline or wireless links and jointly process signals; this can significantly reduce ICI and thus boost performance [1]. This especially suits the downlink since interference mitigation burden is moved to the infrastructure side. However the benefits do not come without any setbacks. On the downlink of cellular systems the advantages advertised by BS cooperation come at the following costs:

- Estimation of a greater number of channels by the Mobile Stations (MSs), equal to the number of cooperating antennas (CSI estimation).
- CSI feedback from MSs to BSs.
- Exchange of local CSI with the CU.
- Increased backhaul overhead and routing complexity (each BS buffers data of an increased number of MSs).

Therefore research has shifted towards overhead reduction techniques. A natural way of reducing overhead is by limiting the number of cooperating BSs per cluster. In this direction, *limited static clustering* has been proposed, where BS clusters are of a limited size, a fact which necessarily reduces overhead [2]. Furthermore, the possibility of smart *dynamic creation of limited clusters* has been investigated in order for the limited cooperation clusters to be optimally formed [3]. In addition, ways of optimising system performance under a constraint backhaul have been considered [4]. Another direction for achieving overhead reduction is the use of smart signaling techniques for reducing the overhead of the already formed cooperation clusters [5]. However, it is demanding that the cost related to the changes in system architecture entailed by MCP is alleviated and this aspect is not addressed in the aforementioned contributions.

According to the existing framework for downlink MCP of FDD systems, a MS estimates the channels related to the BSs of its cooperation cluster (CSI estimation). Then it feeds back to the BS of its cell (usually the one that it receives the maximum SNR from, defined as Master BS) either full or partial CSI (i.e long-term CSI) [7]. In the case of TDD systems, downlink CSI is obtained by uplink training using the principle of channel reciprocity. Subsequently, the BS forwards this local information (CSI) to the CU of the cluster which gathers local CSI from all cooperating BSs. Local CSI for a BS is considered the one related to the MSs belonging to its cell. Non-local CSI is the one of the MSs belonging to different cells of the cooperation cluster. The CU selects the users to be served (scheduling phase) and calculates the transmission parameters which are then sent to the corresponding BSs for the transmission to take place (transmission phase). In this paper a practically feasible linear precoding framework is adopted for transmission [6].

In the existing centralised framework a CU and the CU to BSs low latency links are necessary [7]-[9], a fact which complicates system architecture and increases its cost. In this contribution a framework for decentralising MCP is proposed which aims at overcoming these setbacks. It is assumed that each BS collects local together with non-local CSI; each MS sends its CSI estimate to all cooperating BSs. In this case, each BS can perform scheduling and transmission design independently, without the need of any CSI exchange with a central entity as explained in section IV.

The paper is structured in the following way: In section II the system model is presented and in section III the existing centralised framework is described. In section IV the proposed decentralised framework is presented and discussed and in section V some numerical results are shown related to feedback errors affecting performance of both frameworks. The paper is concluded in section VI.

Notation: Lower and upper case boldface symbols denote vectors and matrices respectively, $(.)^T$ and $(.)^H$ denote the transpose and the transpose conjugate respectively. $\|.\|_F$ represents the Frobenius norm, $|.|$ the cardinality of a set, $[.]_{nn}$ the n-th element of a matrix diagonal and $\mathbb{C}^k$ the complex space with k dimensions.

II. System Model

A *cooperation cluster* is considered which comprises B base stations with one antenna each and K single antenna mobile stations overall. Thus there is cooperation amongst B cells. If MCP is enabled, the antennas of the cluster jointly combine and serve at most B mobile stations simultaneously under a linear precoding framework. The complete channel matrix is

$$\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_K]^T \tag{1}$$

where $\mathbf{h}_i \in \mathbb{C}^{B\times 1}$ is the channel vector of the i-th MS. Let $\mathcal{S}$ be the set of MSs scheduled to be served ($|\mathcal{S}| \le B$) in a specific time slot. Therefore $\mathbf{H}(\mathcal{S})$ is the channel matrix related to these MSs, $\mathbf{y}$ is the received signal vector, $\mathbf{u}$ is the vector of transmit symbols and $\mathbf{n}$ is a vector of independent complex circularly symmetric additive Gaussian noise components, $n \sim \mathcal{NC}\left(0, \sigma^2\right)$. Therefore $\mathbb{E}\left\{\mathbf{n}\mathbf{n}^H\right\} = \sigma^2 \mathbf{I}_{|S|}$.

A. Single-cell Processing

In the case of single cell processing (absence of cooperation), the Signal to Interference plus Noise Ratio (SINR) of the i-th MS γ_i, when k is its associated BS, is

$$\gamma_i = \frac{\|h_{ik}\|^2 p_k}{\sum\limits_{j\neq k} \|h_{ij}\|^2 p_j + \sigma^2} \tag{2}$$

where $\|h_{ik}\|^2$ corresponds to the channel gain related to the useful signal and $\sum_{j\neq k} \|h_{ij}\|^2$ corresponds to the detrimental ICI, p_k and p_j represent the respective power allocation levels. In this paper equal power allocation is considered across MSs for simplicity.

B. MCP with Linear Precoding

Linear precoding is considered for MCP transmission since it provides a good trade-off between performance and complexity and also scales optimally with a large number of MSs and smart scheduling [6]. $\mathbf{W}(\mathcal{S})$ is the precoding matrix of size $B \times |\mathcal{S}|$ and $\mathbf{y}$ is the received signal vector. The signal model can be represented in the following way

$$\mathbf{y} = \mathbf{H}(\mathcal{S})\,\mathbf{x} + \mathbf{z} + \mathbf{n} \tag{3}$$

where $\mathbf{x} = [x_1, \ldots, x_B]^T$ is the vector containing the antenna outputs and $\mathbf{z}$ is the vector containing the received inter-cluster interference components, $\mathbf{z} = \left[z_1, \ldots, z_{|\mathcal{S}|}\right]^T$, since cooperation clusters are assumed to be of a limited size. The vector of transmit symbols $\mathbf{u} = \left[u_1, \ldots, u_{|\mathcal{S}|}\right]^T$ with power $\mathbf{p} = \left[p_1, \ldots, p_{|\mathcal{S}|}\right]^T$, where $p_i = \mathbb{E}\left\{|u_i|^2\right\}$, is mapped to the transmit antennas,

$$\mathbf{x} = \mathbf{W}(\mathcal{S})\mathbf{u}. \tag{4}$$

The precoding matrix of the scheduled users is

$$\mathbf{W}(\mathcal{S}) = \left[\mathbf{w}_1, \mathbf{w}_2, \ldots, \mathbf{w}_{|\mathcal{S}|}\right] \tag{5}$$

where $\mathbf{w}_i \in \mathbb{C}^{B\times 1}$ is the beamforming vector corresponding to MS i. Therefore the scheduled MSs receive

$$\mathbf{y} = \mathbf{H}(\mathcal{S})\,\mathbf{W}(\mathcal{S})\mathbf{u} + \mathbf{z} + \mathbf{n}. \tag{6}$$

The SINR γ_i of the i-th MS, where $i \in \mathcal{S}$, is

$$\gamma_i = \frac{\|\mathbf{h}_i\mathbf{w}_i\|^2 p_i}{\sum\limits_{j\in\mathcal{S}, j\neq i} \|\mathbf{h}_i\mathbf{w}_j\|^2 p_j + \chi_i + \sigma^2} \tag{7}$$

where $\mathbf{w}_m$ is the beamforming vector for the m-th MS and $\mathbf{h}_m$ is the channel vector between the m-th MS and all the antennas of the cooperation cluster. The term $\sum_{j\in\mathcal{S},j\neq i} \|\mathbf{h}_i\mathbf{w}_j\|^2 p_j$ corresponds to the intra-cluster interference power and χ_i corresponds to the inter-cluster interference power, where $\chi_i = \mathbb{E}\left\{|z_i|^2\right\}$. The evaluation metric is the average achieved sum-rate per cell,

$$\mathcal{C} = \frac{1}{B}\mathbb{E}_H\left\{\sum_{i\in\mathcal{S}} \log_2(1+\gamma_i)\right\}. \tag{8}$$

Realistic per-antenna power constraints are considered justified by the fact that cooperating antennas are spatially distributed and therefore they cannot share their power. It is assumed that each antenna has an average power constraint and thus $\mathbb{E}\left\{|x_n|^2\right\} \le P_n$ for $n = 1, \ldots, B$. In the case of equal power allocation $\mathbf{p} = p\mathbf{1}$, the formulation for the power constraints becomes $\left[\mathbf{W}\mathbf{W}^H\right]_{nn} p \le P_n$ for all $n = 1, \ldots, B$ [1]. The power allocation vector is

$$\mathbf{p} = \min_{n=1,\ldots,B}\left\{\frac{P_n}{\left[\mathbf{W}\mathbf{W}^H\right]_{nn}}\right\}\mathbf{1} \tag{9}$$

where $\mathbf{1}$ is a column vector of 1s with dimension $|\mathcal{S}|$. The SINR of the i-th MS is

$$\gamma_i = \frac{\|\mathbf{h}_i \mathbf{w}_i\|^2}{\sum\limits_{j\in\mathcal{S}, j\neq i} \|\mathbf{h}_i \mathbf{w}_j\|^2 + (\sigma^2 + \chi_i) / \min\limits_{n=1,\ldots,B} \left\{ \frac{P_n}{\left[\mathbf{W}\mathbf{W}^H\right]_{nn}} \right\}}. \tag{10}$$

With equal power allocation and an equal power constraint P per BS, the expression for the power allocation matrix (9) reduces to $\mathbf{p} = \frac{P}{\max_{n=1,\ldots,B}\left\{\left[\mathbf{W}\mathbf{W}^H\right]_{nn}\right\}}\mathbf{1}$.

The precoding matrix is chosen to meet the Zero-Forcing criteria, $\mathbf{H}(\mathcal{S})\mathbf{W}(\mathcal{S}) = \mathbf{I}_{|\mathcal{S}|}$, where $\mathbf{I}_{|\mathcal{S}|}$ is an identity matrix with dimension equal to the number of scheduled users. Hence, the selected precoding matrix is the Moore-Penrose pseudoinverse of the channel matrix

$$\mathbf{W}(\mathcal{S}) = \mathbf{H}^H(\mathcal{S}) \left[\mathbf{H}(\mathcal{S})\mathbf{H}^H(\mathcal{S})\right]^{-1}. \tag{11}$$

Note that other choices of precoding (MMSE etc.) can be considered. With equal power allocation and equal per-antenna power constraints P the SINR expression becomes

$$\gamma_i = \frac{P}{\max\limits_{n=1,\ldots,B}\left\{\left[\mathbf{W}\mathbf{W}^H\right]_{nn}\right\}(\sigma^2 + \chi_i)}. \tag{12}$$

With zero-forcing precoding, intra-cluster interference is completely eliminated.

III. Centralised Framework

MCP implies that a group of BSs behave as a large distributed antenna array and therefore the notion of a BS or a cell goes beyond the one of the conventional cellular systems. Nevertheless these terms are kept in the literature for simplicity. The implementation of MCP, as it has been envisaged, entails the interconnection of BSs via low latency links. These links carry the needed control signals that permit a number of BSs to behave as a single entity. Furthermore a CU is needed in order to gather CSI and centrally perform MS scheduling operations and to design signal transmission. Therefore the CU plays the role of the "head" of what is called a *cooperation cluster*.

In the existing framework for MCP, each MS is associated to a Master BS and it conceptually belongs to its corresponding cell. There are three main phases in downlink communications of FDD systems that consider incorporating MCP [7]-[9],

1) *Phase 1*
   - BSs send training sequences. MSs estimate the CSI related to all cooperating BSs, i.e MS i estimates the following channel vector $\hat{\mathbf{h}}_i = \left[\hat{h}_{i1}, \hat{h}_{i2}, \ldots, \hat{h}_{iB}\right]$.
2) *Phase 2*
   - *MSs feedback their CSI ($\hat{\mathbf{h}}_i$) to their Master BS* with the proper power and modulation and coding scheme in order for the BS to be able to decode the information. All cooperating BSs gather local CSI, the CSI of the MSs belonging to their cells.
   - BSs forward the local CSI to the CU of the cluster. The CU collects global CSI (figure 1).

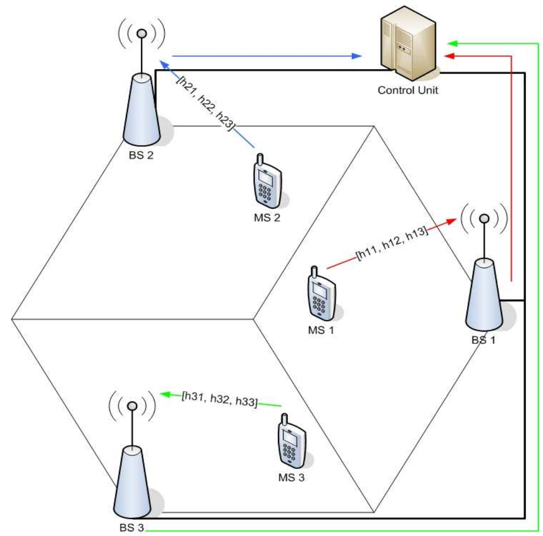

Fig. 1. Phase 2 of the existing centralised framework: MSs feedback their CSI to their Master BS and local CSI is exchanged with a Control Unit.

3) *Phase 3*
   - The CU schedules MSs based on their CSI.
   - The CU designs the beamforming weights for each cluster antenna and sends these weights to the corresponding BSs.

This framework requires a significantly increased infrastructure cost, as there is a demand for low latency inter-base links and a CU per cooperation cluster. Furthermore there is a need for an increased protocol complexity in order for these entities to interoperate properly. These facts inevitably require changes in the current architecture of cellular systems in order for MCP to be enabled, which entail high cost. Hence it is crucial that changes to the current structure of cellular systems are kept to a minimum in order for the costs and complexities to remain low.

IV. Decentralised Framework

In order to face all the aforementioned setbacks we propose a framework that does not require centralised scheduling and transmission design, but still can achieve the same performance. The main reason justifying the need of centralised processing is that the involved BSs at each cooperation cluster are assumed to lack global user CSI. Therefore taking this into account, the phases of the proposed framework for the downlink are,

1) *Phase 1*
   - BSs send training sequences. MSs estimate the CSI related to all cooperating BSs, i.e MS i estimates the following channel vector $\hat{\mathbf{h}}_i = \left[\hat{h}_{i1}, \hat{h}_{i2}, \ldots, \hat{h}_{iB}\right]$ (this phase remains the same).
2) *Phase 2*
   - *MSs feedback their CSI ($\hat{\mathbf{h}}_i$) to all cooperating BSs* with the proper power and modulation and coding scheme in order for all cluster BSs to be able to

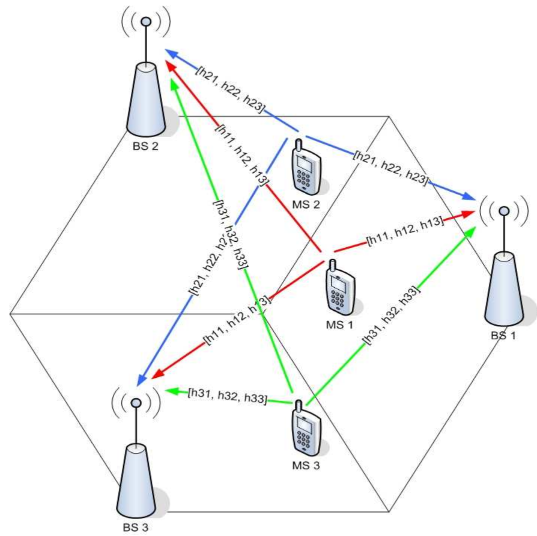

Fig. 2. Phase 2 of the proposed decentralised framework: MSs feed back their CSI to all cooperating BSs.

decode the information. All cooperating BSs gather global CSI, the CSI of the MSs of all cooperating cells (figure 2).

3) *Phase 3*
- The BSs schedule MSs independently based on their CSI. Cluster BSs are synchronised and employ the same scheduling algorithm. Since they receive the same input parameters, the schedulers end up selecting exactly the same MSs.
- Each BS designs the complete beamforming matrix and keeps the antenna weights corresponding to it.

Under this framework, infrastructure cost and signaling protocol complexity are minimised since neither a CU is required nor the low latency links connecting it with the cooperating BSs. Hence, the structure of MCP enabled cellular networks can remain almost the same with the structure of the conventional cellular systems. Note that under this framework, radio feedback overhead remains the same comparing to the conventional centralised framework, provided that the same resources are allocated to the terminal for feeding back its CSI by each cooperating BS.

In case errors are introduced in the fed back information, under the decentralised framework error patterns can be different on each feedback link since MSs feed back their CSI to all cooperating BSs. Under the centralised framework, each MS utilises only one link in order to feed back its channel state information (CSI transmitted to the Master BS only) and therefore there is only one error pattern affecting feedback information per MS in this case. The impact of feedback errors is addressed in section V.

V. Numerical Results

In this section we evaluate the sum-rate performance of the proposed framework as a function of feedback errors. Three mutually interfering sectors of sectorised cells have been assumed to cooperate without taking into account interference originating from other cells. The channel coefficient between the i-th MS and the j-th sector is,

$$h_{ij} = \Gamma_{ij} \sqrt{G\left(\phi\right) \beta d_{ij}^{-\alpha} \gamma_{ij}} \tag{13}$$

where d_{ij} is the distance in km of the i-th MS and the j-th sector, α is the path-loss exponent and β the path-loss constant. For the pathloss, the 3GPP Long Term Evolution (LTE) pathloss model has been used. γ_{ij} is the corresponding log-normal coefficient which models the large-scale fading (shadowing), $\gamma_{dB} \sim \mathcal{N}\left(0\,dB, 8\,dB\right)$, and Γ is the complex Gaussian coefficient which models the small-scale fading, $\Gamma \sim \mathcal{NC}\left(0,1\right)$. $G\left(\phi\right)$ is the sector antenna power gain as a function of the angle ϕ in degrees following the LTE evaluation parameters.

We assume that each MS obtains a perfect estimate of the channel vector associated to all cooperating BSs ($\hat{\mathbf{h}}_i = \mathbf{h}_i$) and it feeds it back. In the centralised framework each MS feeds back its CSI to its Master BS only. In the decentralised framework each MS transmits its CSI to all cluster BSs in order for the decentralised cooperation to take place.

A. Analogue noisy feedback

It is assumed that CSI is fed back unquantized and that a noisy version of it arrives at the target BS or BSs for both centralised and decentralised approaches. The noise process is independent on each link, and therefore in the decentralised case each BS receives a different noisy version of the CSI. Under the assumption of noisy analogue feedback, each channel coefficient is received as follows,

$$\bar{h}_{ij} = \left(\Gamma_{ij} + w_{ij}\right) \sqrt{G\left(\phi\right) \beta d_{ij}^{-\alpha} \gamma_{ij}} \tag{14}$$

where $w \sim \mathcal{NC}\left(0, \sigma_w^2\right)$ represents the additive and spectrally white Gaussian noise affecting the received CSI. This inevitably leads to a performance degradation for both frameworks, since some useful information is lost by the addition of noise. This degradation is caused since the performance of the scheduling phase is degraded due to the corrupted CSI information and also beamforming matrix design is affected due to the same corrupted CSI. The decentralised framework can be more sensitive to scheduling degradation since inaccurate CSI might result to selection of different users by some of the cooperating BSs, depending on the scheduling algorithm employed, which will inevitably increase intra-cluster interference. However, round-robin scheduling is robust to CSI feedback errors since its scheduling decisions are not made based on CSI. This scheduling algorithm is selected for the present evaluation which focuses on the impact of feedback errors on the design of beamforming matrices.

In figure 3 the average sum-rate performance is plotted against the noise variance of the fed back CSI for system SNR equal to 20 dB. System SNR is the average SNR that a MS experiences at the edge of the cell taking into account only the thermal noise and not the ICI. It can be noted that

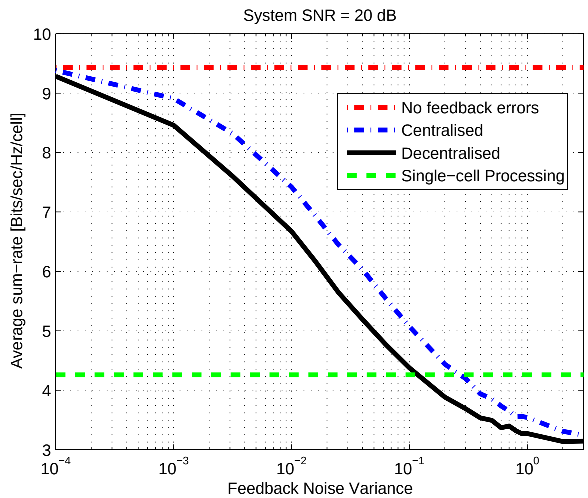

Fig. 3. Analogue feedback: a plot of the average sum-rate as a function of the feedback error noise variance for the decentralised and the centralised framework respectively.

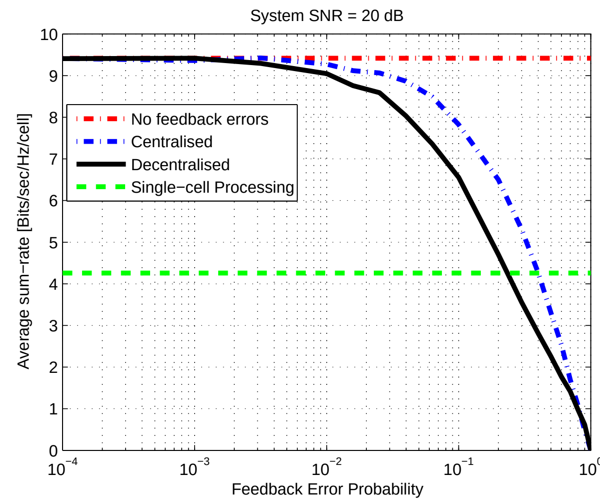

Fig. 4. Digital feedback: a plot of the average sum-rate as a function of the feedback error probability for the decentralised and the centralised framework respectively.

the centralised framework is slightly more robust to feedback noise.

B. Digital feedback with error detection

It is assumed that CSI is quantized with the use of an infinite number of bits (perfect CSI) and fed back. Errors can occur and corrupt the feedback and these errors can be always detected but not corrected. Each link is associated with a feedback error probability, hence the probability of feedback error is independent across different radio links. In the decentralised framework, if errors are detected in a fed back vector, each BS replaces the received CSI vector with a zero vector. In the centralised framework, if errors are detected, the CU replaces the received CSI vector with a zero vector. In figure 4 the average sum-rate performance is plotted against the probability of feedback errors when MSs are scheduled in a round-robin fashion for system SNR equal to 20 dB. It can be seen that the centralised framework is a little more robust to feedback errors than the decentralised one, although for feedback error probability less than 10^{-2} the difference is negligible.

VI. Conclusion

Multicell cooperative processing promises significantly improved spectral efficiency and fairness for future cellular systems. However, this comes at the cost of increased signaling, infrastructure complexity and centralised processing. In the existing conception of MCP, cooperating BSs need to be connected to a control unit which plays the role of the "cluster head". It gathers local CSI from the BSs, it performs user scheduling and designs the transmission parameters. In this paper a new framework has been proposed that allows MCP on the downlink to take place in a decentralised fashion; neither a CU is needed nor the complicated signaling protocols that coordinate CSI exchange. Each BS receives CSI feedback from all the users of the cluster (global CSI) and designs transmission independently. Therefore by just increasing the processing burden of each BS, MCP can be achieved in a decentralised fashion. A first assesement of the performance of the proposed framework under feedback noise and errors has been performed, and it has been shown that the proposed scheme shows little degradation comparing to the centralised alternative, while allowing MCP to be implemented with very few changes compared to the current network architecture.

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