A Dynamic Clustering Approach in Wireless Networks with Multi-Cell Cooperative Processing

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***Abstract*—Multi-cell cooperative processing (MCP) has recently attracted much attention because of its potential for co-channel interference (CCI) mitigation and spectral efficiency increase. MCP inevitably creates inter-base signalling overhead. Therefore in practice only a limited number of base stations (BSs) can cooperate in order for the signalling overhead to be affordable. The intrinsic problem of which BSs should cooperate in a realistic scenario has been only partially investigated. In this contribution Zero-Forcing (ZF) beamforming has been considered for the sum-rate maximisation of the uplink. A novel dynamic greedy algorithm for the formation of the clusters of cooperating BSs is presented in a realistic cellular network incorporating MCP. The objective of the clustering algorithm is sum-rate maximisation. This approach is chosen to be evaluated under a fair MS scheduling scenario (round robin). The proposed cooperation scheme is compared with some fixed cooperation cluster schemes. It is shown that a dynamic clustering approach with a cluster consisting of 2 cells outperforms static coordination schemes with much longer cluster sizes.**

I. Introduction

The constantly growing demand for higher data rates in wireless communications services, together with the scarcity of radio spectrum favour the deployment of systems with multiple antennas (MIMO) and aggressive reuse. However aggressive reuse systems suffer from co-channel interference (CCI) which limits their spectral efficiency [1].

In the conventional aggresive reuse cellular systems, CCI can be mitigated at no extra bandwidth cost with the use of advanced receiver processing, rejection in the spatial and other domains [2], [3]. On the downlink, receiver processing necessarily burdens the mobile station (MS) by adding complexity, a fact which is considered disadvantageous.

An alternative very promising way of facing CCI is Multi-cell cooperative processing (MCP) [4]-[6]. With MCP a number of base stations (BSs) cooperate and jointly serve the MSs by forming a distributed antenna array. This implies that the cooperating BSs are connected via high capacity backhaul links (optic fibers or wireless links) which undertake the needed inter-base signalling. CCI mitigation can be moved to BSs and therefore MS complexity can be kept low. The cooperation is achieved at the cost of channel state information (CSI) exchange between the cooperating BSs and joint processing. Transmission schemes for MCP have been investigated and capacity results for a simplistic Wyner model have been presented in [7]-[9]. However the aforementioned contributions do not address the problem of MCP in a realistic cellular system since they assume unlimited inter-base signalling between all BSs of the network.

In realistic systems only a limited number of BSs can cooperate in order for the inter-base signalling overhead to be affordable [10]-[15]. In [11]-[13] some BS selection algorithms are presented that refer to the uplink problem. Interestingly in [11] and [12] static clustering of BSs together with minimum mean square error (MMSE) beamforming has been proven to significantly improve the spectral efficiency of cellular systems with sectorised cells on the uplink. The limitations in the existing work however are the use of big cluster sizes which yield significant inter-base signalling and a lack of diversity with respect to changing channel conditions.

In this paper uplink transmission is considered with the target of sum-rate maximisation. It is assumed that BSs have full local and non-local receive channel state information (CSIR). Non-local CSIR is obtained by CSIR exchange between BSs via high capacity backhaul links. For the reception Zero-Forcing (ZF) beamforming is used as an example of low complexity MIMO precoding scheme. A new dynamic greedy approach for the formation of the clusters of the cooperating BSs is presented. As we are interested in schemes that provide user fairness, the MSs to be served are selected in a round robin fashion. The algorithm can be extended for the case of proportionally fair scheduling (PFS) [10], [12]. The BS grouping algorithm divides the available BSs into a number of disjoint cooperative clusters at each time slot. Each cluster is optimally assigned to serve a group of MSs. Thus, each cluster forms a distributed antenna array which serves the selected MSs associated with it. The dynamic algorithm for cluster formation is compared with static ways of forming clusters of BSs.

The paper is structured in the following way: In section II the signal and system model together with the problem definition are presented. In section III techniques that are targeting to maximise the system sum-rate by exploiting dynamic clustering are presented. A novel greedy approach exploiting the benefits of dynamic clustering in cellular networks with MCP is described. It is shown to outperform the static schemes. Furthermore issues related to the system architecture are discussed. In section IV numerical results are presented and in section V the paper is concluded.

Notation: Lower case 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 and $\rightarrow$ the mapping operator.

II. Signal and System Model

The network consists of N base stations with M antennas each and K mobile stations overall with a single antenna each. An uplink scenario is considered where a number of B base stations cooperate, where $B \leq N$, and form a *cooperating cluster*. Therefore $B \times M$ antennas participate in the cooperation. The antennas of each cluster jointly combine and process the signal from at most $B \times M$ mobile stations simultaneously. Flat fading channels are considered. The complete channel matrix of the system within a cooperation cluster is

$$\mathbf{H} = \left[\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{B\times M}\right]^T \quad (1)$$

where $\mathbf{h}_i \in \mathbb{C}^{K\times 1}$ is the channel vector of the i-th antenna.

Let $\mathcal{B}$ be the set of all disjoint cooperation clusters of $B \times M$ antennas that are subsets of the overall $N \times M$ antennas of the system. Antennas belonging to the same BS cannot participate in different cooperation clusters. Let $\mathcal{U}$ be the set of all disjoint groups of at most $B \times M$ users that could be possibly scheduled and served by a cooperation cluster. The proposed system operation scenario is as follows:

- A scheduling algorithm forms a set of cooperation clusters $\mathcal{C} \subset \mathcal{B}$, where $|\mathcal{C}| = \frac{N}{B}$.
- These clusters are mapped to a group of MS clusters $\mathcal{C} \rightarrow \mathcal{K}$, where $\mathcal{K} \subset \mathcal{U}$ and $|\mathcal{K}| = |\mathcal{C}|$.

Let $\mathcal{V} \in \mathcal{C}$ be one of the selected antenna clusters and $\mathcal{S} \in \mathcal{K}$ the MS cluster mapped to it $(\mathcal{V} \rightarrow \mathcal{S})$ by the scheduler. Thus $\mathcal{S}(\mathcal{V})$ is the MS cluster which will be served by the $\mathcal{V}$ group of cooperating antennas. Therefore $\mathbf{H}(\mathcal{V}, \mathcal{S})$ is the channel matrix related to this BS cluster and group of MSs, $\mathbf{y}(\mathcal{V})$ is the received signal vector, $\mathbf{u}(\mathcal{S})$ is the vector of transmit symbols and $\mathbf{n}$ is the vector with the additive white Gaussian noise components. It is assumed that $\mathbb{E}\left[\mathbf{u}\mathbf{u}^H\right] = \mathbf{I}_S$ and $\mathbb{E}\left[\mathbf{n}\mathbf{n}^H\right] = \sigma^2 \mathbf{I}_{B\times M}$. The received signal of the antennas of this cluster is

$$\mathbf{y}(\mathcal{V}) = \mathbf{H}(\mathcal{V}, \mathcal{S})\,\mathbf{u}(\mathcal{S}) + \sum_{\mathcal{Q}\neq\mathcal{S}} \mathbf{H}(\mathcal{V}, \mathcal{Q})\,\mathbf{u}(\mathcal{Q}) + \mathbf{n}(\mathcal{V}) \quad (2)$$

where $\sum_{\mathcal{Q}\neq\mathcal{S}} \mathbf{H}(\mathcal{V}, \mathcal{Q})\,\mathbf{u}(\mathcal{Q})$ represents the CCI term.

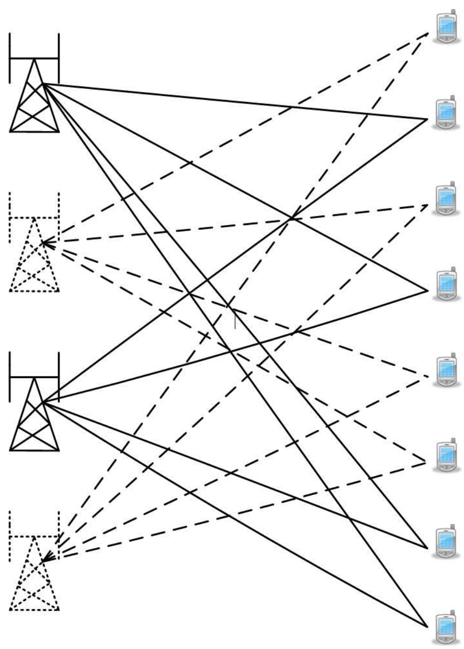

Fig. 1. A graph representation of the case of 4 BSs with 2 antennas each. The cluster size is 2, which implies that each cluster consists of 2 bases. At most 4 users can be served simultaneously by each cluster

A. Graph Interpretation

The problem of the formation of the clusters of BSs that will serve the MSs can be expressed by the aid of graphs. Sum-rate is targeted to be maximised. The constraint is that the graphs that are formed by connecting BSs (which form clusters) and MSs need to be disjoint, since each BS and MS can belong to a single BS and MS cluster respectively.

Let $\mathcal{G} = \{G = [V, E]\}$ be the constrained graph set where BSs are arranged into disjoint clusters and each cluster is connected to an MS set such that all MS sets are disjoint. V stands for the vertices and E stands for the edges of the graph. In this case the vertices are the BSs and the MSs. The edges are the connections between them.

The evaluation metric is the system sum-rate which is given by the following expression,

$$R^{(G)} = \sum_{\mathcal{V}\in G} \sum_{k\in\mathcal{S}(\mathcal{V})} \log_2\left(1 + SINR_k\right) \quad (3)$$

As an example, the case of 4 BSs with 2 antennas each is shown in Figure 1. The cluster size is 2, which implies that each cluster consists of 2 BSs. Since each cluster has 4 antennas, it can serve up to 4 MSs simultaneously in an orthogonal way.

B. Static BS Clustering

A practically feasible solution for MCP would be to create a number of pre-specified BS clusters. In this case the BSs that form each specific cluster do not change in time. Therefore the clusters are static and the BSs that need to exchange CSI remain the same. Furthermore the cooperation schemes that belong to this category do not need to route CSI to a central Control Unit (CU) which would perform the coherent combining of the signals, as in the case of complete coordination described below. The coherent combining of the signals can take place in distributed CUs (there is a need of one CU per cluster), a fact which significantly simplifies data routing. The problem arising in this case is which BSs should form the static cluster in order for the sum-rate performance to be maximised. In this paper neighbouring BSs are chosen to form the static cluster, as they are the ones that on average interfere the most with each other in a conventional cellular system. Static clustering eliminates only a fraction of the inter-cluster interference proportional to the number of cooperating BSs. This kind of MCP dramatically reduces the inter-base signalling burden of the optimal case where all BSs exchange CSI. The cost is that inter-cluster interference is not completely eliminated.

C. Linear Beamforming Model

In this paper linear beamforming has been considered for its low complexity. $\widetilde{\mathbf{y}}(\mathcal{S})$ is the received signal vector corresponding to the selected users and $\mathbf{W}(\mathcal{S},\mathcal{V})$ is the beamforming matrix The signal model can be represented in the following way,

$$\begin{aligned}\widetilde{\mathbf{y}}(\mathcal{S}) = \mathbf{W}(\mathcal{S},\mathcal{V})\mathbf{H}(\mathcal{V},\mathcal{S})\,\mathbf{A}(\mathcal{S})\,\mathbf{u}(\mathcal{S}) + \\ \sum_{\mathcal{Q}\neq\mathcal{S}} \mathbf{W}(\mathcal{S},\mathcal{V})\,\mathbf{H}(\mathcal{V},\mathcal{Q})\,\mathbf{A}(\mathcal{Q})\,\mathbf{u}(\mathcal{Q}) + \mathbf{W}(\mathcal{S},\mathcal{V})\mathbf{n}(\mathcal{V})\end{aligned} \tag{4}$$

$\mathbf{A}$ is the diagonal MS power allocation matrix,

$$\mathbf{A}(\mathcal{S}) = \begin{bmatrix} P_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & P_{|\mathcal{S}|} \end{bmatrix} \tag{5}$$

In the rest of the paper equal power allocation across MSs is assumed. Therefore,

$$\mathbf{A}(\mathcal{S}) = P \times \mathbf{I}_{|\mathcal{S}|} \tag{6}$$

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

$$\mathbf{W}(\mathcal{S},\mathcal{V}) = \left[\mathbf{H}^H(\mathcal{V},\mathcal{S})\,\mathbf{H}(\mathcal{V},\mathcal{S})\right]^{-1}\mathbf{H}^H(\mathcal{V},\mathcal{S}) \tag{7}$$

Note that other choices of receiver processing (MMSE etc) could be considered. The Signal to Interference plus Noise Ratio (SINR) of the i-th MS, where $i \in \mathcal{S}$, when linear beamforming is employed is,

$$SINR_i = \frac{|\mathbf{w}_i\mathbf{h}_{ii}|^2 P}{\sum\limits_{j\neq i, j\in\mathcal{S}} |\mathbf{w}_i\mathbf{h}_{ij}|^2 P + \sum\limits_{k\neq i, k\notin\mathcal{S}} |\mathbf{w}_i\mathbf{h}_{ik}|^2 P + |\mathbf{w}_i|^2\sigma^2} \tag{8}$$

where $\mathbf{w}_m$ is the receive beamforming vector for the m-th MS and $\mathbf{h}_{mn}$ is the channel vector between the m-th MS and all the antennas of the receiving cooperating cluster. The terms $\sum_{j\neq i, j\in\mathcal{S}} |\mathbf{w}_i\mathbf{h}_{ij}|^2 P$ and $\sum_{k\neq i, k\notin\mathcal{S}} |\mathbf{w}_i\mathbf{h}_{ik}|^2 P$ correspond to the intra-cluster interference and to the inter-cluster interference respectively. The term $|\mathbf{w}_i|^2\sigma^2$ corresponds to the noise enhancement.

With zero-forcing beamforming intra-cluster interference is eliminated and the SINR becomes,

$$SINR_i = \frac{P}{\sum\limits_{k\neq i, k\notin\mathcal{S}} |\mathbf{w}_k\mathbf{h}_{ik}|^2 P_k + |\mathbf{w}_i|^2\sigma^2} \tag{9}$$

III. Dynamic Clustering Based Coordination

In this section there is a description of some cooperative schemes that aim to maximise the sum-rate of the system. Issues related to the system architecture of MCP schemes are also discussed.

The target is to form the disjoint graphs in a way that maximises the sum-capacity of the system. The problem of sum-capacity maximisation can be expressed mathematically,

$$C_{max} = \max_{G\in\mathcal{G}} \left[R(G)\right] \tag{10}$$

The ergodic sum-capacity of the system is,

$$C = \mathbb{E}\left(C_{max}\right) \tag{11}$$

where $\mathbb{E}$ is the expectation operator over all random fading realisations and MS locations.

A. Full Coordination (B = M)

It is assumed that MSs are scheduled in a round robin fashion in order to provide fairness in the system. At each time slot a number of MSs equal to the total number of antennas in the system is selected. The optimal MCP strategy in a cellular network would require that all BSs are inter-connected and form a single cooperation cluster. The BSs perform joint beamforming and serve the selected users simultaneously by forming a large distributed antenna array. The coherent combining of the signals can take place in a central CU which would gather all the CSI of the network. An alternative would be that coherent combining is done in a decentralised fashion, i.e each BS being responsible for the processing of the signals originating from its closest MSs. This would imply that every BS needs the local CSI of all the other BSs of the network. With the optimal MCP scheme the inter-cluster interference is completely eliminated and the sum-rate gains can be enormous [5]. However such a scheme would be practically impossible to implement due to the extremelly high inter-base signalling required; all CSI of the network needs to be routed to the central CU.

B. Greedy Dynamic Multi-Cell Processing

Static MCP is not the most efficient way of forming the cooperation clusters. This is because by forcing specific BSs to cooperate, the macro-diversity provided by the distributed nature of MCP is not fully exploited. An MS might experience much better channel conditions to a more distant BS than to a closer one due to the randomness of small and large-scale fading. Therefore for a specific MS it is more effective to force the BSs with the most favourable channel conditions exchange CSI and cooperate irrespective of their geographical location.

In this fashion cooperation clusters can be formed dynamically. It is assumed that each cooperation cluster serves a number of MSs equal to the number of antennas it has. Due to round robin scheduling specific MSs need to be served at each cell at a time. The following algorithm is proposed for sum-capacity maximisation with adaptive MCP,

1) **Step 1:**
    a) Specify the cluster size (number of cooperating BSs).
2) **Step 2:**
    a) Start from a random cell that has not been chosen so far. This corresponds to one BS and some specific MSs that need to be served at this time slot.
3) **Step 3:**
    a) Find the BS (with the MSs associated with it) that maximise the joint capacity with the initial BS and MSs. Joint capacity is calculated with the use of joint linear beamforming.
    b) Continue in the same fashion until the BS cluster is formed (the specified cluster size is reached). B bases and $B \times M$ users are connected.
4) **Step 4:**
    a) Go to step 2 until all the BS clusters are formed.

By introducing intelligence in the way that the BSs form clusters in order to serve the wanted MSs, the sum-rate increases significantly together with fairness across users. A central Control Unit (CU) is needed in order to gather the CSI and run the adaptive algorithm for cluster formation. The fact that BS clusters are formed dynamically means that at each time slot different BSs perform coherent combining of the signals in order to serve the MSs. The signal combining can take place at distributed CUs (one per cluster), a fact which implies that the received signals need to be routed to the cluster CU. Therefore the routing burden of the optimal case is dramatically reduced.

IV. Numerical Results

A network consisting of two tiers of cells has been considered ($N = 19$ cells overall). BSs are located in the centre of each cell. Each BS has one omnidirectional antenna ($M = 1$). The channel coefficient between the i-th antenna and the j-th MS is:

$$h_{ij} = \Gamma_{ij} \sqrt{\beta d_{ij}^{-\alpha} \gamma_{ij}} \tag{12}$$

where d_{ij} is the distance in km of the i-th antenna and the j-th MS. α is the path-loss exponent and β the path-loss constant. γ_{ij} is the corresponding log-normal coefficient which models the large-scale fading (shadowing), $\gamma_{dB} \sim \mathcal{N}(0\,dB, 8\,dB)$, and Γ is the complex Gaussian fading coefficient which models the small-scale fading, $\Gamma \sim \mathcal{NC}(0, 1)$. For the pathloss, the Long Term Evolution (LTE) pathloss model has been used,

$$PL_{ij}^{dB} = 148.1 + 37.6 \log_{10} d_{ij}^{km} \tag{13}$$

In Figure 2 the ergodic sum-rate performance of the different clustering techniques can be seen. The sum-rate per cell is plotted against the system SNR. The system SNR is the average SNR received at the edge of the cell without taking into account the CCI. Therefore this is a system parameter which defines the transmit power of the MSs. It can be seen that static clustering techniques outperform SCP since the amount of CCI is reduced by a factor proportional to the number of BSs that form each cluster. The dynamic clustering scheme proposed provides significant sum-rate gains since it exploits the knowledge of instantaneous CSI in the formation of clusters. A dynamic clustering scheme with cluster size of 2 (2 BSs participate in the cooperation) outperforms static clustering schemes with large cluster sizes.

In Figure 3 the cumulative distribution function (CDF) of the user rates for two different clustering schemes can be seen. Except from sum-rate increase, dynamic clustering improves significantly the fairness amongst the MSs of the network. This can be seen by the fact that the CDF of the dynamic grouping scheme is steeper than the one corresponding to the static grouping scheme.

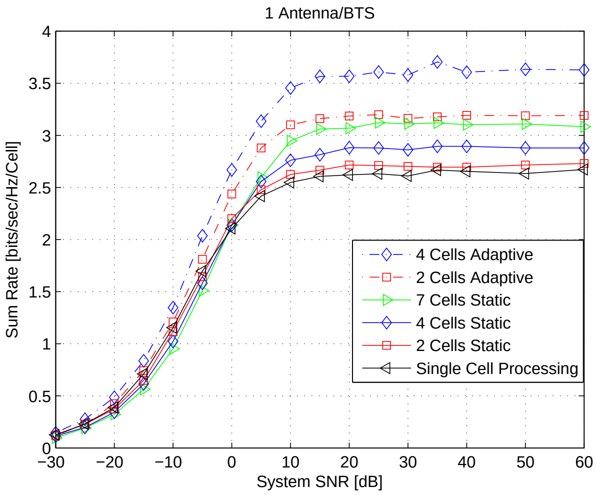

Fig. 2. A plot of the ergodic sum-rate versus the system SNR for the uplink.

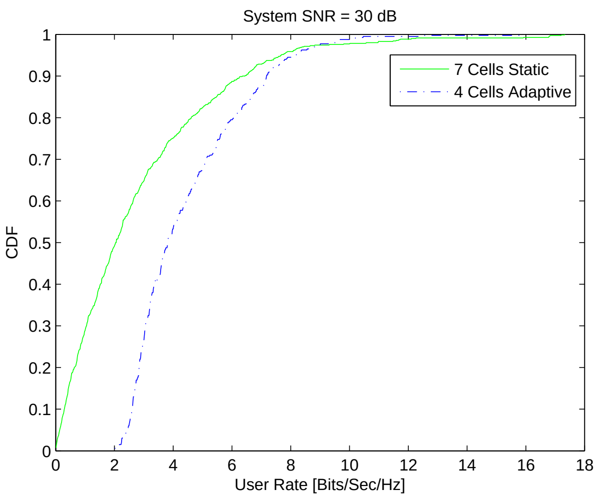

Fig. 3. A plot of the cumulative distribution function of the user rates.

V. Conclusion

Multi-cell cooperative processing has been proposed as an effective way of facing co-channel interference and increasing spectral efficiency in cellular systems. Its main drawback is the need of significant inter-base signalling. In practice only a limited number of base stations can cooperate and jointly process the received or transmit signals, in order for the inter-base signalling overhead to be affordable. In this paper some base station clustering schemes that enable the utilisation of MCP in realistic cellular systems have been investigated. The obvious solution of creating static clusters of cooperating BSs is not optimal since it does not fully exploit the macro-diversity which is inherently provided by the distributed nature of MCP. However it does provide sum-rate gains since it reduces CCI. The proposed algorithm for dynamic clustering leverages the knowledge of the instantaneous channel state and groups the BSs that provide the most favourable channel conditions to the MSs to be served at each time slot. This strategy leads to significant sum-rate gains and enhances the fairness of the system.

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