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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 a lot of attention because of its potential for co-channel interference (CCI) mitigation and spectral efficiency increase. MCP inevitably requires increased signaling overhead and inter-base communication. Therefore in practice, only a limited number of Base Stations (BSs) can cooperate in order for the overhead to be affordable. The intrinsic problem of which BSs shall cooperate in a realistic scenario has been only partially investigated. In this contribution linear 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 for a cellular network incorporating MCP. This approach is chosen to be evaluated under a fair MS scheduling scenario (round-robin). The objective of the clustering algorithm is sum-rate maximisation of the already selected MSs. The proposed cooperation scheme is compared with some fixed cooperation clustering schemes. It is shown that a dynamic clustering approach with a cluster consisting of 2 cells outperforms static coordination schemes with much larger 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 aggressive 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 signaling and user data exchange. CCI mitigation can be moved to BSs and therefore MS complexity can be kept low. Inter-base signaling consists of the needed local channel state information (CSI) exchange. 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 signaling between all BSs of the network.

In realistic systems only a limited number of BSs can cooperate in order for the inter-base communication 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 linear beamforming has been proven to significantly improve the spectral efficiency of cellular systems with sectorised cells. The limitations in the existing work however are the use of big cluster sizes which yield significant inter-base communication overhead and a lack of diversity with respect to changing channel conditions, since cooperation clusters are static.

In this paper uplink transmission is considered with the target of sum-rate maximisation. The technique proposed can be also generalised for the downlink. 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 the backhaul links. For the reception Zero-Forcing (ZF) beamforming is employed as an example of low complexity MIMO beamforming 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 in the network 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 subset of the selected 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 targeting to maximise the system sum-rate by taking advantage of dynamic clustering are presented. A novel greedy approach exploiting the benefits of dynamic clustering in cellular networks with

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MCP is described and 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. $\mathbb{C}^k$ represents the complex space with k dimensions, $\mathcal{NC}$ a complex gaussian distribution and $\rightarrow$ the mapping operator.

II. SIGNAL AND SYSTEM MODEL

The network consists of N base stations with M antennas each and K active 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 *cooperation cluster*. Therefore $B \times M$ antennas participate in the cooperation. The antennas of each cluster, under a linear beamforming framework, jointly combine and process the signal from at most $B \times M$ mobile stations simultaneously. Flat fading and spatio-temporally independent channels are considered. The complete channel matrix of the system for the uplink within a cooperation cluster is

$$\mathbf{H} = [\mathbf{h}_1, \mathbf{h}_2, \ldots, \mathbf{h}_{B \times M}]^T \tag{1}$$

where $\mathbf{h}_i \in \mathbb{C}^{K \times 1}$ is the channel vector of the i-th cluster 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. It is assumed that 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 at a time. The proposed system operation scenario is as follows:

- A scheduling algorithm forms a set of cooperation antenna clusters $\mathcal{C} \subset \mathcal{B}$, where $|\mathcal{C}| = \frac{N}{B}$ ($|\mathcal{C}|$ needs to be an integer).
- These clusters are mapped to a group of MS clusters $\mathcal{K}$ ($\mathcal{C} \rightarrow \mathcal{K}$), 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 uplink channel matrix related to this BS cluster and group of MSs, $\mathbf{y}(\mathcal{V})$ is the received signal vector by the BS antennas, $\mathbf{u}(\mathcal{S})$ is the vector of transmit symbols and $\mathbf{n}(\mathcal{V})$ is a vector of independent complex circularly symmetric additive Gaussian noise components, $n \sim \mathcal{NC}\left(0, \sigma^2\right)$. Therefore $\mathbb{E}\left[\mathbf{nn}^H\right] = \sigma^2 \mathbf{I}_{B \times M}$. For the transmit symbols it is assumed that they are independent complex Gaussian with unit variance, $\mathbb{E}\left[\mathbf{uu}^H\right] = \mathbf{I}_{|S|}$. $\mathbf{A}$ is the diagonal MS power allocation matrix,

$$\mathbf{A}(\mathcal{S}) = \begin{bmatrix} \sqrt{P_1} & \ldots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \ldots & \sqrt{P_{|\mathcal{S}|}} \end{bmatrix} \tag{2}$$

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

$$\mathbf{A}(\mathcal{S}) = \sqrt{P} \times \mathbf{I}_{|\mathcal{S}|} \tag{3}$$

The received signal of the antennas of cluster $\mathcal{V}$ is

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

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

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 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,

$$R^{(G)} = \sum_{\mathcal{V} \in G} \sum_{k \in \mathcal{S}(\mathcal{V})} \log_2\left(1 + SINR_k\right) \tag{5}$$

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 a spatially orthogonal way.

B. Static BS Clustering ($B < N$)

A practically feasible solution for MCP would be the formation of some pre-specified BS clusters. In this case BSs that form each specific cluster do not change in time. Therefore clusters are static and BSs that need to communicate with each other remain the same. Furthermore, cooperation schemes that belong to this category do not need to route CSI and user signals to a central Control Unit (C-CU) which would perform the coherent combining of the signals, as in the case of full coordination described below. The coherent combining of the signals can take place in distributed CUs (D-CUs) instead (there is a need of one D-CU per cluster), a fact which reduces inter-base communication overhead and significantly simplifies the routing of user signals. The problem arising in this case is which BSs shall form the static clusters in order for the system 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 but it

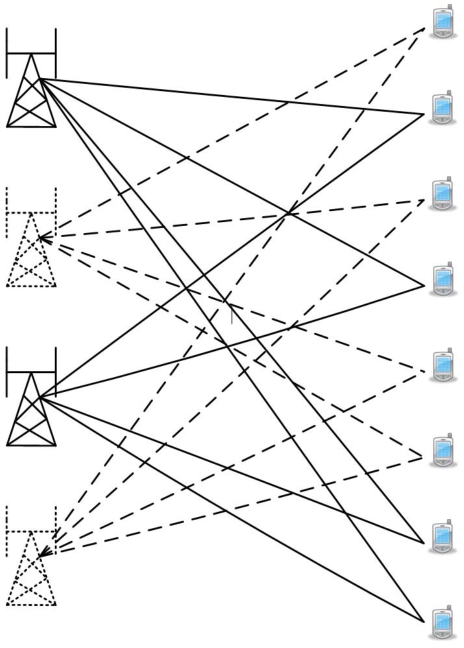

Fig. 1. A graph representation of the case of 4 BSs with 2 antennas each. The cluster size is 2, which implies that each cluster consists of 2 BSs. At most 4 MSs can be served simultaneously by each cluster.

dramatically reduces the inter-base communication burden of the optimal case. The cost is that inter-cluster interference is not completely eliminated and therefore system performance remains CCI limited. Furthermore the MSs at the edge of the cluster suffer more from inter-cluster CCI and therefore system fairness is compromised.

C. Linear Beamforming Model

In this paper linear beamforming has been considered for its low complexity. $\widetilde{\mathbf{y}}\left(\mathcal{S}\right)$ is the extracted signal vector corresponding to the selected users and $\mathbf{W}\left(\mathcal{S},\mathcal{V}\right)$ is the beamforming matrix. The extracted signal from (4) is

$$\widetilde{\mathbf{y}}\left(\mathcal{S}\right)=\mathbf{W}\left(\mathcal{S},\mathcal{V}\right)\mathbf{y}\left(\mathcal{V}\right) \tag{6}$$

Hence, by plugging (4) to (6),

$$\begin{aligned}\widetilde{\mathbf{y}}\left(\mathcal{S}\right)=\mathbf{W}(\mathcal{S},\mathcal{V})\mathbf{H}\left(\mathcal{V},\mathcal{S}\right)\mathbf{A}\left(\mathcal{S}\right)\mathbf{u}(\mathcal{S})+\\ \mathbf{W}\left(\mathcal{S},\mathcal{V}\right)\sum_{\mathcal{Q}\neq\mathcal{S}}\mathbf{H}\left(\mathcal{V},\mathcal{Q}\right)\mathbf{A}\left(\mathcal{Q}\right)\mathbf{u}(\mathcal{Q})+\mathbf{W}(\mathcal{S},\mathcal{V})\mathbf{n}\left(\mathcal{V}\right)\end{aligned} \tag{7}$$

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

$$\mathbf{W}\left(\mathcal{S},\mathcal{V}\right)=\left[\mathbf{H}^{H}\left(\mathcal{V},\mathcal{S}\right)\mathbf{H}\left(\mathcal{V},\mathcal{S}\right)\right]^{-1}\mathbf{H}^{H}\left(\mathcal{V},\mathcal{S}\right) \tag{8}$$

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

$$SINR_i=\frac{\left|\mathbf{w}_i\mathbf{h}_{ii}\right|^2}{\sum\limits_{j\neq i,j\in\mathcal{S}}\left|\mathbf{w}_i\mathbf{h}_{ij}\right|^2+\sum\limits_{k\neq i,k\notin\mathcal{S}}\left|\mathbf{w}_i\mathbf{h}_{ik}\right|^2+\left(\left|\mathbf{w}_i\right|^2\sigma^2\right)/P} \tag{9}$$

where $\mathbf{w}_m$ is the receive beamforming row vector for the m-th MS and $\mathbf{h}_{mn}$ is the channel column vector between the m-th cluster of antennas and the n-th MS of the system. It is assumed that the m-th MS is assigned to the m-th antenna cluster. The terms $\sum_{j\neq i,j\in\mathcal{S}}\left|\mathbf{w}_i\mathbf{h}_{ij}\right|^2$ and $\sum_{k\neq i,k\notin\mathcal{S}}\left|\mathbf{w}_i\mathbf{h}_{ik}\right|^2$ correspond to the intra-cluster interference and to the inter-cluster interference respectively. The term $\left|\mathbf{w}_i\right|^2\sigma^2$ corresponds to the noise enhancement. With zero-forcing beamforming intra-cluster interference is eliminated and the SINR becomes,

$$SINR_i=\frac{1}{\sum\limits_{k\neq i,k\notin\mathcal{S}}\left|\mathbf{w}_i\mathbf{h}_{ik}\right|^2+\left(\left|\mathbf{w}_i\right|^2\sigma^2\right)/P} \tag{10}$$

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. The problem of sum-capacity maximisation can be expressed mathematically,

$$C_{max}=\max_{G\in\mathcal{G}}\left[R^{(G)}\right] \tag{11}$$

The expected value of the achievable sum-rate of the system is,

$$C=\mathbb{E}\left(C_{max}\right) \tag{12}$$

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

A. Full Coordination (B = N)

It is assumed that MSs are scheduled in a round-robin fashion in order to provide fairness. 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 be 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 signal extraction can take place in a C-CU which gathers all the local CSIR of the network and designs the beamforming matrix. With the optimal MCP scheme inter-cluster interference is completely eliminated and the sum-rate gains can be enormous [5]. However such a scheme would be practically infeasible due to the extremely high inter-base communication requirements; all CSI of the network and user signals need to be routed to the C-CU.

B. Greedy Dynamic Multi-Cell Processing ($B < N$)

Static MCP is not the most efficient way of forming cooperation clusters of a limited size. 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 addition, MSs located at the edge of a static cluster are much more prone to CCI originating from neighbouring clusters than the ones at the centre of the cluster. This compromises system fairness since MSs at the cluster border will always have a degraded performance.

To circumvent the aforementioned problems 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. It is assumed that MSs are associated with the BSs that they receive the strongest SNR from. 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, assigned to this BS, 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 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 selected MSs, the sum-rate increases significantly together with fairness across users. This is since clusters change dynamically, and therefore there are no cluster regions constantly at the edge and always very prone to CCI.

The greedy clustering algorithm benefits more clusters formed earlier than the ones formed at a later stage, since there are fewer choices of BSs available for selection to clusters formed later. In order for this fairness issue to be overcome each clustering formation phase starts from a random cell and not from a specific one (step 2). Therefore, on average, there are no BSs favoured more than others.

A C-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 antennas perform coherent combining of the signals in order to serve the MSs. The signal extraction can take place at D-CUs (one per cluster), a fact which implies that the received signals need to be routed to the cluster D-CU. Therefore routing burden and inter-base communication requirements of the optimal case are 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:

$$h_{ij} = \Gamma_{ij}\sqrt{G\beta d_{ij}^{-\alpha}\gamma_{ij}} \tag{13}$$

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 coefficient which models the small-scale fading, $\Gamma \sim \mathcal{NC}(0,1)$. G is the BS antenna power gain which is assumed to be 9 dB (gain on the elevation). For the pathloss, the 3GPP Long Term Evolution (LTE) pathloss model has been used,

$$PL_{ij}^{dB} = 148.1 + 37.6\log_{10}\left(d_{ij}^{km}\right) \tag{14}$$

In figure 2 the average sum-rate performance of the different clustering techniques can be seen (12). The average sum-rate per cell is plotted against the system SNR. The system SNR is the average SNR a BS receives from a MS located 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 MCP techniques outperform single cell processing since the amount of CCI is significantly reduced. 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 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.

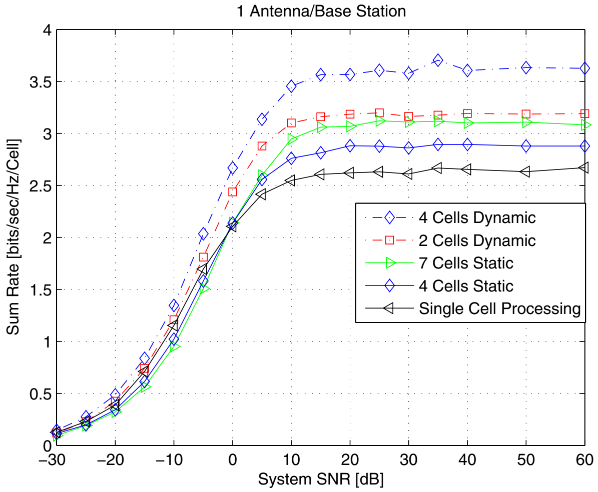

Fig. 2. A plot of the average achievable sum-rate per cell versus the system SNR for the uplink. Different cluster sizes have been considered. It can be seen that dynamic clustering outperforms static clustering with much larger cluster sizes. For a specific cluster size, when all clusters have been formed, the remaining BSs (less than the cluster size) form a smaller cluster. This is since there are 19 BSs overall which is a prime number.

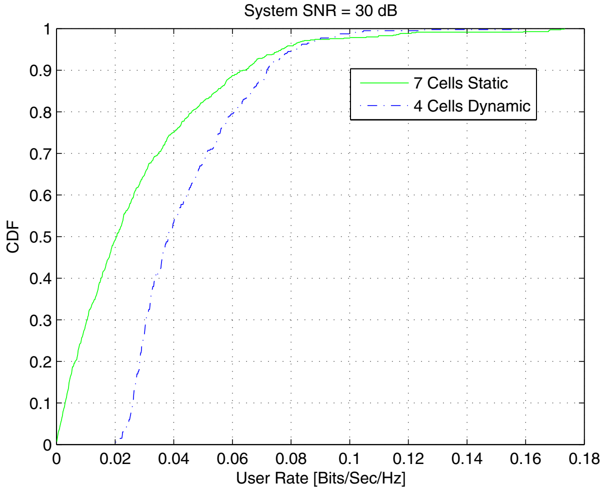

Fig. 3. A plot of the cumulative distribution function of the user rates (100 users/cell are assumed). Dynamic cluster formation enhances system fairness since its cdf curve is steeper.

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 necessity of increased signaling and inter-base communication. In practice, only a limited number of BSs can cooperate and jointly process the received or transmit signals, in order for the inter-base communication overhead to be affordable. The obvious solution of creating static clusters of cooperating BSs, even though it provides sum-rate gains, is not optimal as it does not fully exploit the macro-diversity which is inherent to the distributed nature of MCP. Furthermore it compromises system fairness since users at the cluster edge experience degraded performance, as they are more prone to CCI. In this paper a novel greedy algorithm has been proposed for dynamic BS clustering which leverages the knowledge of the instantaneous channel state. It groups BSs in a dynamic way that maximises the sum-rate performance of the MSs to be served at each time slot. This strategy leads to significant sum-rate gains and enhances the fairness of the system comparing to static clustering schemes.

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