Application of Dynamic Clustering into CoMP Systems

E. M. G. Stancanelli, T. F. Maciel, Y. C. B. Silva, W. C. Freitas Jr. and F. R. P. Cavalcanti

***Abstract*— In the last few years, advanced multi-antenna systems attracted a lot of interest as a means to improve the spectral efficiency of conventional cellular networks. This is the case of Coordinated Multi-Point (CoMP) systems in the context of 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE). However, the large amount of signaling required to achieve a full coordinated transmission is somewhat worrying. Performing the coordination within clusters of Transmission Points (TPs) rather than within the whole set of TPs can be an alternative to lighten the signaling and processing required. In this work, we introduce the Clustering-based Assignment Algorithm (CbAA) to cluster dynamically the TPs for transmitting coherently to multiple selected User Equipments (UEs). In fact, this approach will result in some loss of spectral efficiency, however, depending on the application requirements, the signaling shrinkage is so significant as to justify its use.**

***Keywords*— CoMP. Assignment algorithm. Clustering.**

I. INTRODUCTION

In 3rd Generation Partnership Project (3GPP) Long Term Evolution (LTE), Coordinated Multi-Point (CoMP) has been seen as a promising technology for increasing data transmission rates. CoMP systems are basically composed of several geographically distributed Transmission Points (TPs) connected through a fast backhaul to a central controller. The Base Station (BS)'s sectors may be taken as the TPs as well as the Enhanced Node B (eNB) can play the role of the central controller. This way, new transmission strategies can be employed to enhance the link quality, investments made on the already deployed cellular system are protected, and networks can evolve in a cost-efficient manner [1].

By using Joint Processing (JP) in the downlink [2], multiple BSs work together as a distributed antenna array so that spatial multiplexing techniques can be used for transmitting to multiple User Equipments (UEs). Similar to well-known Multiple Input Multiple Output (MIMO) technology, CoMP can be seen as a means to boost the capacity of conventional cellular networks. However, we must be aware that a significant signaling cost exists associated with the coordination among BSs.

A way to deal with this cost is to restrict the number of BSs to be coordinated. Through clustering, the set of all available TPs belonging to a CoMP-cell can be partitioned into mutually exclusive subsets or clusters of TPs. Thus, each cluster forms a distributed antenna array which services the UEs associated with it. Traditionally the clustering approaches are classified into static [3] and dynamic [4], [5], depending on how frequently the transmitters coordination is updated. Here we focused just on the dynamic approach, since it is the only capable in adapting to the temporal variations of the radio channel.

In this work, based on a mathematical concept of cluster analysis [6], we introduce the Clustering-based Assignment Algorithm (CbAA), which takes the cluster choices suggested by every UE for determining a common set of TPs to transmit to them.

The remainder of this paper is divided as follows: section II presents the adopted system model; section III introduces the clustering concept applied to the assignment problem; section IV presents the computer simulation approach and the results obtained from it; finally, in section V, some final remarks and conclusions are drawn.

II. SYSTEM MODEL

Here we focus just on the downlink transmission, wherein the CoMP system services a number J of single-antenna UEs, indicated by $j = 1, 2, \ldots, J$, which are uniformly distributed over the coverage area. The CoMP system has a number C of CoMP-cells, indicated by $c = 1, 2, \ldots, C$, each of them controlling a number B of BSs, indicated by $b = 1, 2, \ldots, B$. In its turn, each BS-cell is three-sectorized, with each 120° sector serviced by its own TP; the antennas are on the corner shared by the three sectors. The TPs within a CoMP-cell are indicated by $j = 1, 2, \ldots, M$. In addition, each of K clusters will comprise a disjoint subset of all available TPs. There is no restriction that the TPs of a same BS will be associated to a same cluster.

The considered CoMP system employs Orthogonal Frequency Division Multiple Access (OFDMA), with equal power allocated among the S subcarriers. The subcarriers are grouped in blocks of $\check{S}$ adjacent subcarriers, which represent the Physical Resource Blocks (PRBs) [7]. The PRBs are indicated by $n = 1, 2, \ldots, N$, and each of them might be assigned to one or more $\langle$TP, UE$\rangle$ pairs within each CoMP-cell.

The channel gain, $G_{j,m,c}$ in dB, from TP m of CoMP-cell c to UE j is composed of average path loss, shadowing, antenna gain and short-term fading parcels. The average path loss $G^{(\text{pl})}_{j,m,c}(d)$, in dB, for a UE j distant d meters from TP m of CoMP-cell c is modeled according to [1],

$$G^{(\text{pl})}_{j,m,c}(d) = 35.3 + 37.6 \log_{10}(d).$$

The shadowing is modeled as a log-normal random variable with standard deviation σ_{sh} [8].

The authors are with GTEL - Wireless Telecommunications Research Group, Federal University of Ceará, Fortaleza-CE, Brazil. E-mails: {emiguel, maciel, yuri, walter, rodrigo}@gtel.ufc.br. This work was supported by the Innovation Center, Ericsson Telecomunicações S.A., Brazil, under EDB/UFC.32 Technical Cooperation Contract.

The antenna radiation pattern is defined over both the horizontal and vertical planes, in accordance with [9]. The horizontal antenna gain for half-power beamwidth of 65° and the vertical one for 6.2° are, in dB:

$$\begin{aligned} G^{(a)}_{horizontal}(\theta) &= -\min\left\{12\left(\frac{\theta}{65}\right)^2, 30\right\} + 18, \\ G^{(a)}_{vertical}(\phi) &= \max\left\{-12\left(\frac{\phi-\phi_{tilt}}{6.2}\right)^2, -18\right\}, \end{aligned} \tag{1}$$

where θ is the azimuth; ϕ is the negative elevation angle and ϕ_{tilt} the electrical downtilt angle, all in degrees.

Frequency selectivity is modeled using a tapped-delay channel model and the short-term fading on each tap is modeled using Jakes' model [10]. The channel coherence bandwidth is assumed to be larger than the bandwidth of a PRB.

The link adaptation searches for the modulation scheme – among Binary Phase-Shift Keying (BPSK), 4-, 16- and 64-Quadrature Amplitude Modulation (QAM) – that yields the maximum throughput under the current Signal to Interference-plus-Noise Ratio (SINR). None of the UEs transmits with a SINR value below 5.6 dB, since the allocated resource probably will be wasted. We assumed that SINR estimations are available to the CoMP-cells, since each eNB has perfect channel knowledge about all UEs associated with the TPs that the eNB controls.

On top of that, it is assumed that UEs make use of a non-real time service – which does not have strict packet delay requirements – and always have data to receive.

III. Cluster Analysis

Clustering is an unsupervised method for assigning a set of observations into mutually exclusive subsets or clusters (for further details, refer to [6]). Observations assigned to a same cluster have some kind of similarity among themselves; observations belonging to different clusters should be as dissimilar as possible. Measures of similarity are closely related to the application and the success of clustering depends on favorable characteristics of data as well as the parameters taken into account to determine the clusters.

Let $\mathcal{M} = \{1, 2, \cdots, M\}$ be the active set comprising all the TPs belonging to a CoMP-cell c. Let $\mathbf{v}_{j,c,n}$ be the strength vector with length M associated to CoMP-cell c, UE j and PRB n, whose elements are given by the channel gain $G_{j,m,c,n}$ in dB from TP $m \in \mathcal{M}$ to UE j at PRB n and CoMP-cell c. The strength vector of each UE is taken as a simple observation, and, therefore, we have J observations to be partitioned into K clusters per CoMP-cell. Because the observations are disposed in the $\mathbb{R}^M$ space, it will not be feasible to visualize them, neither the clusters, for $M > 3$. Without loss of generality we assume that the number of clusters for each CoMP-cell is the same and represented by K. Moreover, since our discussion is restricted to a single CoMP-cell c and PRB n, we omit the indexes c and n for simplicity of notation, i.e. $\mathbf{v}_{j,c,n} = \mathbf{v}_j$.

Let $\mathcal{V}$ be the set with the strength vectors v_j for every $j \in \mathcal{J}$. Every clustering will result in subsets of these observations, $\mathcal{V}_k$, for $k = 1, 2, \cdots, K$, disjoint of each other, so that $\mathcal{V} = \bigcup_{k=1}^{K} \mathcal{V}_k$ and $\mathcal{V}_{k_1} \cap \mathcal{V}_{k_2} = \varnothing,\ \forall \mathcal{V}_{k_1}, \mathcal{V}_{k_2} \in \mathcal{V} \mid k_1 \neq k_2$ and a cluster formation instance is denoted as $\mathcal{S} = \{\mathcal{V}_1, \mathcal{V}_2, \ldots, \mathcal{V}_K\}$. The cardinalities $|\mathcal{V}_k|$ are not necessarily the same.

Our investigations are based on the *k-means clustering problem*. In that problem, clusters must be formed to minimize the within-cluster sum of squares of the distances to the respective centroids:

$$\min_{\mathcal{S}} \sum_{k} \sum_{\mathbf{v}_j \in \mathcal{V}_k} \|\mathbf{v}_j - \bar{\mathbf{v}}_k\|_2^2, \tag{2}$$

where $\|\cdot\|_2$ denotes Euclidean norm, and $\bar{\mathbf{v}}_k$ is the kth-prototype vector obtained from the calculation of the centroid over all the strength vectors associated to cluster k, i.e. $\bar{\mathbf{v}}_k = \frac{1}{|\mathcal{V}_k|} \sum_{\mathbf{v}_j \in \mathcal{V}_k} \mathbf{v}_j$.

Each prototype vector is an approximate strength vector valid to all the related UEs. The closer the strength vectors of all UEs of a cluster are, the more representative for them will the prototype vector be. The algorithm employed to form a given cluster k has to look for UEs that can be serviced with an adequate level of quality by this same subset of TPs.

Basically, two steps are iteratively performed to solve that problem: firstly, each observation is *assigned* to the cluster whose centroid is the closest one; secondly, the *centroids are recalculated* leading to a new partitioning of the observations. A stop criterion is met when, for example, there is no significant change in the clusters or a maximum number of iterations is achieved.

Once the clusters are properly formed in $\mathbb{R}^M$ space, we compare the K prototype vectors and assign each TP to the cluster in which it is strongest, i.e.

$$k_m = \arg\max_{k} \{\bar{\mathbf{v}}_k(m)\}, \tag{3}$$

thereby the subset $\mathcal{M}_k$ will be given by $\mathcal{M}_k = \{m : k_m = k\}$ for every $k \in \mathcal{K}$. The number M_k of TPs assigned to each cluster k is independent and time variant, but we expect that it will be around M/K.

The M_k TPs of cluster k will be employed to perform Zero-Forcing (ZF) precoding and service M_k UEs, which is the maximum supported number. Because of that, we run into the subproblem of choosing which M_k UEs will be preferentially provided. That subproblem was already addressed in [11], when the Best Fit (BF) algorithm proved to be very adequate. Based on the Channel State Information (CSI) available at the eNB of the CoMP-cell, we select first the UE with the highest channel gain for each PRB. Next, BF algorithm finds, in a greedy way, the most spatially compatible UE with respect to the previously admitted ones, by projecting the channel vectors of all current candidates onto the null-space of the channel vectors of those UEs already admitted [12], [13]. This is performed successively until the group of M_k UEs is completed. It is worth to highlight that the BF algorithm is an efficient grouping algorithm, albeit not optimal.

The CbAA is summarized in Algorithm 1, whose description is given below.

The kmeans function takes all available strength vectors $\mathbf{v}_j$ and the number K of clusters in order to perform the k-means

Algorithm 1 Clustering-based Assignment Algorithm (CbAA).

$([\bar{\mathbf{v}}_1\ \bar{\mathbf{v}}_2 \cdots \bar{\mathbf{v}}_K], [c_1\ c_2 \cdots c_J]) \leftarrow \text{kmeans}([\mathbf{v}_1\ \mathbf{v}_2 \cdots \mathbf{v}_J], K)$
$[q_1\ q_2 \cdots q_M] \leftarrow \arg\max_{k} {}_r \{[\bar{\mathbf{v}}_1\ \bar{\mathbf{v}}_2 \cdots \bar{\mathbf{v}}_K]\}$
for $k = 1$ to K **do**
  $\mathcal{M}_k \leftarrow \text{find}([q_1\ q_2 \cdots q_M] = k)$
  $\mathcal{J}_k \leftarrow \text{find}([c_1\ c_2 \cdots c_J] = k)$
  $\mathcal{J}_k^\star \leftarrow \text{bestfit}(h_{j,m,c,n}, J_k), \quad \forall m \in \mathcal{M}_k, \forall j \in \mathcal{J}_k$
end for

algorithm; it returns the prototype vectors $\bar{\mathbf{v}}_k, k = 1, 2, \cdots, K$, as well as c_j for $j = 1, 2, \cdots, J$, which represents the index of the cluster associated to UE j. The cluster q_m supposed to use the mth TP is that one whose mth prototype entry has the largest value, which is achieved by finding the position of the largest value row-by-row in the matrix $[\bar{\mathbf{v}}_1\ \bar{\mathbf{v}}_2 \cdots \bar{\mathbf{v}}_K]$, through the $\arg\max_r$ function. Now the set $\mathcal{M}_k$ of TPs and the set $\mathcal{J}_k$ of UEs assigned to each cluster k are known. The bestfit function takes the complex channel coefficients related to all possible connections between TPs in $\mathcal{M}_k$ and UEs in $\mathcal{J}_k$ comprised in the kth cluster as well as the number J_k of UEs to be scheduled. The bestfit function just returns the J_k most spatially compatible UEs found, $\mathcal{J}_k^\star$. Since we aim at scheduling the maximum supported number of UEs, we assume $J_k = |\mathcal{M}_k|$.

IV. Results and Analyses

System-level simulations have been executed based on the models previously described. A set of 7 BS-cells composes a CoMP-cell, and a set of 7 CoMP-cells composes the system. Besides that, a wrap-around approach is used to avoid border effects. The maximal diameter D of the hexagon representing each sector is equal to 334 m. The electrical downtilt angle is $\phi_{tilt} = 8°$. The link budget is designed so that cell border experiences at least 5.6 dB SNRs, i.e. interference is neglected at this point.

For the shadowing, a standard deviation of $\sigma_{\text{sh}} = 8$ dB is considered. Short-term fading assumes an average UE speed of 3 km/h. The CoMP system considers a carrier frequency f_c of 2 GHz and $N = 25$ PRBs, each composed of $\check{S} = 12$ subcarriers spaced of $\Delta f = 15$ kHz. In each subcarrier, 14 symbols are transmitted per Transmission Time Interval (TTI), which has a duration of 1 ms. Moreover, we assume perfect knowledge at the eNB about the channels of all links within the CoMP-cell.

Simulations are organized in snapshots, each taking just 1 s of the system behavior. In each snapshot, path loss and shadowing are assumed to remain constant, but the time variations of short-term fading are considered. The results over several snapshots are taken into account so that the confidence interval at 90% level can be estimated.

In spite of the changes in signal and interference strengths not being clearly predictable, the system spectral efficiency should be an appropriate metric to be evaluated, since it captures the balance between the effects of these two parcels. Fig. 1 shows the system spectral efficiency versus offered load for several clustering configurations: no-clustering case, 2 or 3 clusters and their variants named $1/2$, $1/3$ and $2/3$ clusters. The notation x/K clusters is a simplification to express the partial selection of clusters. This means that the 21 available TPs in a CoMP-cell are partitioned into K clusters, but just $x \leq K$ clusters will be enabled simultaneously. Also note that 2 and 3 clusters might be alternatively expressed as $2/2$ and $3/3$ clusters, respectively. By envisaging the maximization of capacity, the choice of x among the K clusters prioritizes the selection of those clusters with the largest number M_k of TPs available for coordinated transmission.

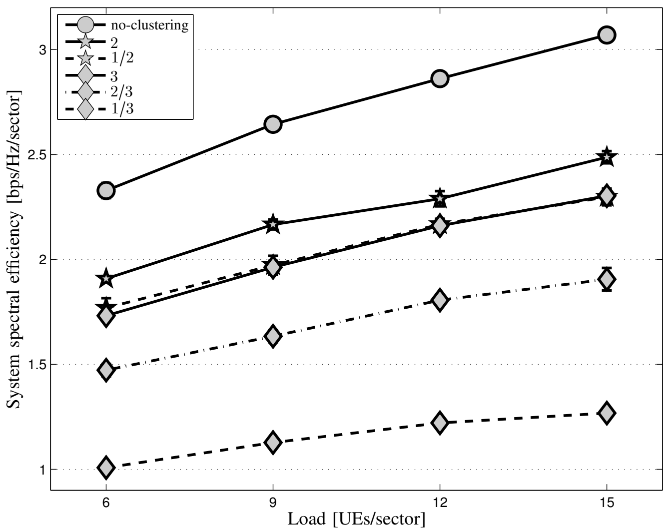

Fig. 1. System spectral efficiency for no-clustering case, 2 or 3 clusters and their variants of partial selection.

Through Fig. 1 we can perceive that the system spectral efficiency is reduced as we increase the number of clusters. We note a decrease of about 18.8% in system spectral efficiency when comparing the no-clustering case to the 2 clusters case for all evaluated loads, and about 25.2% when comparing the no-clustering case with the 3 clusters case. From 2 clusters to 3, we observe a decrease of about 7.9% in system spectral efficiency. This degradation is due to generation of more interference for each additional cluster.

Table I gathers the average values of the total interference suffered by the system at a load of six UEs per sector. Basically, the larger the number of clusters formed in full configuration, the higher the interference. We also observe that the interference can be alleviated through the partial selection of clusters. As the clusters are dropped, interference power can reach even lower levels than in full configurations with less clusters (including the no-clustering case). However, the benefit from diminishing the interference is not enough to overtake the loss in instantaneous coverage and capacity for each cluster dropped. Thus, the partial selection of clusters leads to a further reduction in the system spectral efficiency, as noted also in Fig. 1: from 2 clusters to $1/2$ configuration, the system spectral efficiency decreases about 7.3%; from 3 clusters to $1/3$, about 43.2%; and from 3 clusters to $2/3$, about 16.3%.

Another interesting aspect to be verified is the variability of

TABLE I
AVERAGE INTERFERENCE SUFFERED BY THE SYSTEM FOR SIX UES PER SECTOR AND SEVERAL CLUSTERING CONFIGURATIONS.

Clustering configuration	power (dBmW)
no-clustering	−86.2
2	−84.4
3	−82.9
2/3	−84.4
1/3	−89.4

the clusters composition. We simulated the configuration of 3 clusters enabled all the time and tracked whenever the cluster configuration changes: in 34% of occasions some change happened regarding the previous TTI. In the average, each of these changes involved about 3.7 TP per TTI per PRB.

Based on the same simulation, the stack bar chart in Fig. 2 shows the amount of times each TP participated in the composition of each cluster. That chart was plotted from storing the composition of all three clusters every TTI and PRB for that configuration of 3 clusters enabled all the time.

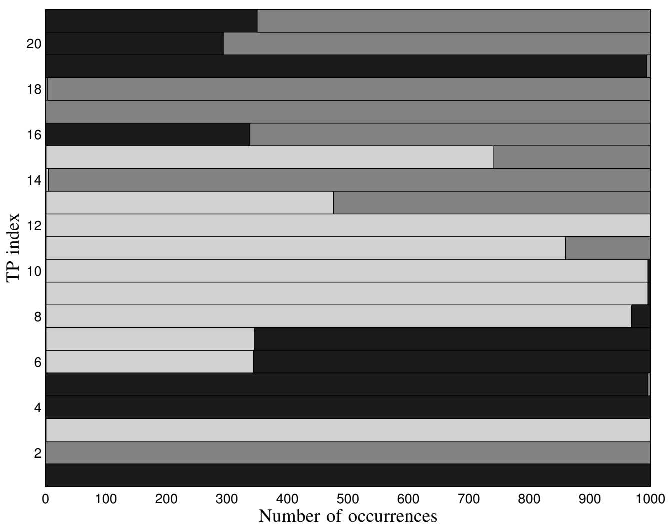

Fig. 2. Occurrence of each TP composing each cluster for 3-clusters configuration.

Firstly, we note that every TP is always employed, however every TP is present more often in one cluster than in the other two, as well as each cluster is predominantly composed by a given subset of TPs. At least in 51% of the observations, cluster 1 was composed at least of the TPs whose indexes are 3, 8, 9, 10, 11, 12 and 15; cluster 2 the TPs 2, 13, 14, 16, 17, 18, 20 and 21; and cluster 3 the TPs 1, 4, 5, 6, 7 and 19. This majority composition is helped by the TPs placement (as illustrated in Fig. 3) and depends on a combination of instantaneous link conditions. However there is no restriction on the assignment at all, as we can note in Fig. 2, for example, for TP 11 casually composing cluster 2.

In spite of the loss of performance, assignment algorithm based on cluster analysis allows to drastically reduce signaling costs and joint processing demands. In fact, estimates for all the links within the CoMP-cell are required to form the clusters. Nevertheless, just the absolute gains of the links need

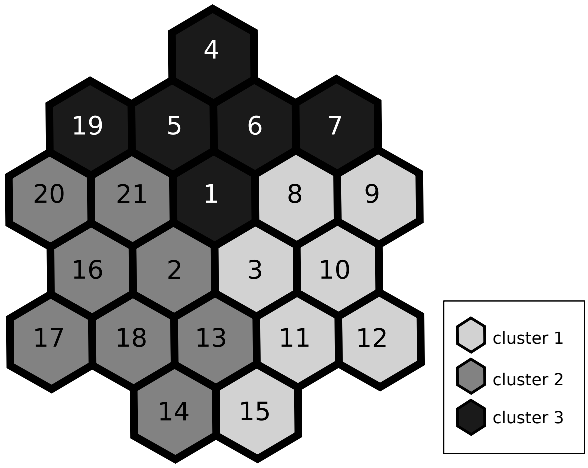

Fig. 3. Relationship of majority composition of three clusters with the TPs' indexes for 51% of the observations.

to be estimated. Once clustering is done, a decrease in the signaling and processing demanded to apply some precoding technique within every cluster is perceived, if compared to the case in which all the M TPs of the CoMP-cell are taken into account. Any information of any link *crossing* the clusters – i.e. any link between a given TP and a UE assigned to another TP – can be simply neglected. For example, suppose that currently J = 21 single-antenna UEs are being jointly serviced by M = 21 TPs. Then, assume that these TPs are uniformly partitioned into K = 3 clusters in a CoMP-cell, each one with 7 exclusive TPs that service 7 exclusive UEs. In the latter case, one has to estimate three 7×7 matrices, whereas in the former case the estimation is of one 21×21 matrix. In other words, by doing this clustering we can dispose of about 67% of estimates.

V. CONCLUSIONS AND FINAL REMARKS

In this work, we investigated the Coordinated Multi-Point (CoMP)-system performance with restricted number of Transmission Points (TPs) that could be coordinated. The set of all available TPs was partitioned into mutually exclusive clusters and, subsequently, Zero-Forcing (ZF) precoding was applied in each of them.

To form these clusters, just the absolute gains of all the links within the CoMP-cell have to be estimated. After clusters are formed, each ZF linear filter will require channel knowledge only with regard to the respective cluster. Any information about other clusters or even the links *crossing* the clusters can be discarded.

The main side effect of clustering-based Radio Resource Management (RRM) algorithm is the increase of interference into the system and the consequent decrease of the spectral efficiency. For interference limited scenarios, partial selection of clusters may be more suitable, which provides K clusters and afterwards drops some of them. Although the spectral efficiency may still be below the non-clustering case since many TPs are left unused, now the interference is drastically reduced. The final decision whether it is advantageous depends on the application requirements.

Another interesting aspect is that the variability of the clusters composition does not happen all the time. In the simulated scenarios the changes in the clusters composition occurred about every three Transmission Time Intervals (TTIs). Therefore, we can potentially save even more efforts in estimating, signaling and processing.

In summary, clustering is an interesting approach to make use of TPs coordination under practical constraints, as long as the loss in performance is an affordable cost.

REFERENCES

[1] S. Parkvall, E. Dahlman, A. Furuskär, Y. Jading, M. Olsson, S. Wänstedt, and K. Zangi, "LTE-Advanced - Evolving LTE towards IMT-Advanced," in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, Sept. 2008, pp. 1–5.

[2] Q. Wang, D. Jiang, G. Liu, and Z. Yan, "Coordinated Multiple Points Transmission for LTE-Advanced Systems," in *Proceedings of the International Conference on Wireless Communications, Networking and Mobile Computing (WiCom)*, Sept. 2009, pp. 1 –4.

[3] F. Boccardi and H. Huang, "Limited downlink network coordination in cellular networks," in *Proceedings of the IEEE Personal, Indoor and Mobile Radio Communications (PIMRC)*, Sept. 2007, pp. 1 –5.

[4] A. Papadogiannis, D. Gesbert, and E. Hardouin, "A dynamic clustering approach in wireless networks with multi-cell cooperative processing," in *Proceedings of the IEEE International Conference on Communications (ICC)*, May. 2008, pp. 4033 –4037.

[5] M. Kamoun and L. Mazet, "Base-station selection in cooperative single frequency cellular network," in *Proceedings of the IEEE Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, Jun. 2007, pp. 1 –5.

[6] P. Hansen and B. Jaumard, "Cluster analysis and mathematical programming," *Mathematical Programming*, vol. 79, no. 1-3, pp. 191–215, Oct. 1997.

[7] 3GPP, "Physical Layer Aspects for Evolved Universal Terrestrial Radio Access (UTRA)," 3^{rd} Generation Partnership Project, Tech. Rep. TR 25.814 V7.1.0 - Release 7, Sept. 2006. [Online]. Available: http://www.3gpp.org

[8] UMTS, "Selection procedures for the choice of radio transmission technologies of the UMTS," UMTS 101.112 v.3.2.0, Tech. Rep., Apr. 1998.

[9] F. Gunnarsson, M. Johansson, A. Furuskar, M. Lundevall, A. Simonsson, C. Tidestav, and M. Blomgren, "Downtilted base station antennas - a simulation model proposal and impact on HSPA and LTE performance," in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, Sept., 2008.

[10] W. C. Jakes, *Microwave mobile communications*, 1st ed. New York: John Wiley & Sons, 1974.

[11] R. L. Batista, R. B. dos Santos, T. F. Maciel, W. C. Freitas Jr., and F. R. P. Cavalcanti, "Performance Evaluation for Resource Allocation Algorithms in Conventional and CoMP Systems," in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, Otawa, Sept. 2010.

[12] P. Tejera, W. Utschick, G. Bauch, and J. A. Nossek, "Subchannel allocation in multiuser Multiple-Input-Multiple-Output systems," *IEEE Transactions on Information Theory*, vol. 52, no. 10, pp. 4721–4733, Oct. 2006.

[13] T. Yoo and A. Goldsmith, "Optimality of zero-forcing beamforming with multiuser diversity," in *Proceedings of the IEEE International Conference on Communications (ICC)*, vol. 1, May. 2005, pp. 542–546.