SINR BALANCING COMBINED WITH SDMA GROUPING IN COMP SYSTEMS

R. L. Batista, T. F. Maciel, Y. C. B. Silva and F. R. P. Cavalcanti
Federal University of Ceará, Wireless Telecommunications Research Group (GTEL)
CP 6005, Campus do Pici, 60455-760, Fortaleza-CE, Brazil
{rodrigobatista, maciel, yuri, rodrigo}@gtel.ufc.br

***Abstract*—Space Division Multiple Access (SDMA) grouping algorithms are usually employed in order to find a suitable set of User Equipments (UEs) for spatial multiplexing. The largest SDMA group is not always the best SDMA group in a given transmission such that higher gains might be achieved by dynamically adjusting the SDMA group size. Besides, algorithms that balance the Signal to Interference-plus-Noise Ratio (SINR) among different links might ensure a certain level of link quality and so provide a more reliable communication for the scheduled UEs. This paper provides system-level analyses for strategies of Radio Resource Allocation (RRA) in Coordinated Multi-Point (CoMP) systems, which consider dynamic SDMA grouping, joint precoding and power allocation for SINR balancing. Our results show that Sequential Removal Algorithms (SRAs) and SINR balancing provide gains of system spectral efficiency.**

I. INTRODUCTION

Coordinated Multi-Point (CoMP) systems can be seen as geographically distributed multiple transmission points over the system's coverage area performing cooperative transmission. By allowing coordination among adjacent Evolved NodeBs (eNBs), cooperative transmission strategies can be applied at the same time that the intra-cell interference is managed [1].

The Channel State Information (CSI) available in CoMP systems can be used to mitigate intra-cell interference and efficiently separate streams intended to different User Equipments (UEs) through spatial precoding and adaptive Space Division Multiple Access (SDMA) grouping. In [1], Radio Resource Allocation (RRA) algorithms that exploit the cooperative transmission in the downlink of CoMP systems are investigated in order to improve the system spectral efficiency. The SDMA grouping in [1] selects a set of spatially compatible UEs that can efficiently share the same resource in space.

The throughput of the UEs in an SDMA group can be improved when each one is subject to a Signal to Interference-plus-Noise Ratio (SINR) constraint. An iterative algorithm to maximize the minimum SINR of a set of co-channel links is proposed in [2] such that data streams are transmitted from multiple antennas to several single-antenna UEs under a sum power constraint. However, this solution is not optimal when per-antenna power constraints are considered.

In [3], the optimal power allocation problem for downlink multi-user multiple input multiple output systems under per-eNB power constraints was solved. Nevertheless, it is difficult to obtain an efficient solution for the optimization problem, which motivates the use of more efficient algorithms. It was shown in [3] that the sub-optimal power allocation based on the scaled water-filling algorithm provides near-optimal performance.

The main contribution of this paper is to provide system-level analyses for the performance gains achieved with the RRA strategies for rate maximization in CoMP systems under per-antenna power constraints, as described in the following:

- Improvements on the work done in [1], now with sequential removals of UEs of the SDMA group;
- SINR balancing with scaled power allocation is performed in SDMA group [2], [3], in which UEs are subject to strong inter-cell interference [1];
- Power minimization is performed in order to reduce the power used in excess and hence the inter-cell interference [2].

Some notational conventions are adopted: we use italic letters for scalars, lowercase boldface letters for vectors and uppercase boldface letters for matrices. Calligraphic letters are used to represent sets and $|\cdot|$ denotes the set cardinality. $\|\cdot\|_1$ and $\|\cdot\|_2$ denote 1- and 2-norms, respectively. $(\cdot)^T$ and $(\cdot)^H$ denote transpose and conjugate transpose, respectively. Finally, the j^{th} component of a vector $\mathbf{p}$ is denoted by p_j.

The remainder of this paper is organized as follows: Section II discusses the system model. Section III presents the formulations for the SDMA grouping and SINR balancing problems. In section IV we show some RRA strategies in CoMP systems. Section V presents and discusses simulation results. Finally, section VI draws the main conclusions.

II. SYSTEM MODEL

In this section, the models adopted to evaluate the system performance are presented. In our notation, we assume the CoMP-cell comprises a fixed set of eNBs, which is the main component of the Long Term Evolution (LTE)-Advanced Resource Allocation (RAN) architecture, and CoMP transmission strategies are only allowed between eNBs belonging to the same CoMP-cell. We consider a CoMP system composed of C fixed CoMP-cells, where each one consists of several 3-sector cells under its control. In this model, each sector is represented by a regular hexagon and the transmission points, termed here Antenna Ports (APs), are placed at the corner shared by the sectors, like in [1].

For downlink CoMP, the 3rd Generation Partnership Project (3GPP) specifies the use of Orthogonal Frequency Division Multiple Access (OFDMA) technology. Usually, due to signaling constraints, subcarriers are not allocated individually, but in blocks of adjacent subcarriers, which represent the Physical Resource Blocks (PRBs) [4]. Channel coherence bandwidth is

This work was supported by the Innovation Center, Ericsson Telecomunicações S.A., Brazil, under EDB/UFC.32 Technical Cooperation Contract.

978-1-4244-8327-3/11/$26.00 ©2011 IEEE

assumed larger than the bandwidth of a PRB, leading to flat fading over each PRB. There exist N PRBs in the system and each of them might be assigned to one or more UEs in each CoMP-cell. In this paper, Equal Power Allocation (EPA) among PRBs is considered and the total transmit power P_{total} available on each sector is equally divided among the N PRBs, i.e., the maximum power allocated to each PRB is $P_{max} = P_{total}/N$.

Each CoMP-cell c controls a number M of APs and serves a number J of single-antenna UEs, which are uniformly distributed over its coverage area. In the following, our discussion is restricted to one PRB n, such that we will omit the index n for simplicity of notation. The modeling of the link between a UE j and an AP includes propagation effects on the wireless channel, namely, path loss, shadowing, short-term fading and also includes the antenna gains. Considering these effects, the signal $y_{j,c}$ received by UE j on a given PRB from all M APs in CoMP-cell c may be written as

$$y_{j,c} = \mathbf{h}_{j,c}\mathbf{x}_{j,c} + \underbrace{\sum_{j' \neq j}^{\mathrm{J}} \mathbf{h}_{\mathrm{j,c}}\mathbf{x}_{\mathrm{j',c}}}_{z_{j,c}^{intra}} + \underbrace{\sum_{c' \neq c}^{\mathrm{C}} \sum_{j'}^{\mathrm{J}} \mathbf{h}_{\mathrm{j,c'}}\mathbf{x}_{\mathrm{j',c'}}}_{z_{j,c}^{inter}} + \eta_{j,c}, \quad (1)$$

where $j = 1, 2, \ldots, J$, $c = 1, 2, \ldots, C$, $\mathbf{h}_{j,c} \in \mathbb{C}^{1 \times M}$ is the complex channel vector whose elements combine all the previously mentioned propagation effects and which models the link between the j^{th} UE and all M APs in CoMP-cell c, $\mathbf{x}_{j,c} \in \mathbb{C}^{M \times 1}$ is the symbol vector transmitted by the M APs of CoMP-cell c to the j^{th} UE, $\eta_{j,c} \in \mathbb{R}$ is the Additive White Gaussian Noise (AWGN) with zero mean and variance σ_η^2, perceived by the j^{th} UE in CoMP-cell c. The intra-CoMP-cell interference $z_{j,c}^{intra}$ is known within the CoMP-cell, since we assume the CoMP-cell has perfect channel knowledge regarding all links of its APs. Even though the inter-CoMP-cell interference $z_{j,c}^{inter}$ is unknown to the CoMP-cell, it can be estimated by the UE j and reported via feedback channel.

The CSI available at the CoMP-cell can be used to mitigate the intra-cell interference $z_{j,c}^{intra}$ and efficiently separate streams intended to different UEs. This task is accomplished, e.g., by employing precoding techniques [5] which adaptively weigh the symbols transmitted from each antenna in the CoMP-cell. We write the transmitted signal $\mathbf{x}_{j,c}$ as

$$\mathbf{x}_{j,c} = \mathbf{w}_{j,c}\sqrt{p_{j,c}}s_{j,c}, \quad (2)$$

where $\mathbf{w}_{j,c} \in \mathbb{C}^{M \times 1}$ is the unitary-norm precoding vector for the link between UE j and the APs of the CoMP-cell c, $p_{j,c} \in \mathbb{R}$ is the transmit power allocated for the UE j and $s_{j,c} \in \mathbb{C}$ is the unit-variance data symbol to be sent to UE j.

In the following, we restrict ourselves to a single CoMP-cell and omit its index c for simplicity of notation. For each CoMP-cell and PRB, the scheduler will select a set $\mathcal{G} \subset \{1, 2, \ldots, J\}$ of UEs to receive data, where the number of UEs it contains will be denoted by $G = |\mathcal{G}|$. Then, considering an SDMA group $\mathcal{G}$, we can also define a channel matrix $\mathbf{H} = \left[\mathbf{h}_1^{\mathrm{T}}\ \mathbf{h}_2^{\mathrm{T}}\ \ldots\ \mathbf{h}_G^{\mathrm{T}}\right]^{\mathrm{T}}$, a precoding matrix $\mathbf{W} = \left[\mathbf{w}_1\ \mathbf{w}_2\ \ldots\ \mathbf{w}_G\right]$ and a power allocation vector $\mathbf{p} = [p_1\ p_2\ \cdots\ p_G]^T$.

At each Transmission Time Interval (TTI) we consider instantaneous spatial covariance values instead of values calculated with the expectation, during which the time-fluctuating fading channel is assumed constant over all symbols. Defining the approximate spatial covariance matrices as

$$\mathbf{R}_j = \tilde{\mathbf{h}}_j^H \tilde{\mathbf{h}}_j, \qquad \forall j \in \mathcal{G}, \quad (3)$$

the SINR $\gamma_j(\mathbf{W}, \mathbf{p})$ perceived by UE j is given by

$$\gamma_j(\mathbf{W}, \mathbf{p}) = \frac{p_j \mathbf{w}_j^H \mathbf{R}_j \mathbf{w}_j}{\underbrace{\sum_{j' \neq j}^{G} p_{j'} \mathbf{w}_{j'}^H \mathbf{R}_j \mathbf{w}_{j'}}_{z_j^{intra}} + z_j^{inter} + \sigma_\eta^2}, \forall j \in \mathcal{G}. \quad (4)$$

III. Problem Statement

RRA strategies can be used for joint data transmission to multiple UEs by using the distributed antenna array of CoMP systems. While the spatial multiplexing of signals intended to different UEs is done using precoding, spectral efficiency gains are often obtained by transmitting to spatially compatible UEs, i.e., a given group of UEs whose channels are favorable for spatial separation [6]. The problem to be solved here is to choose a set $\mathcal{G}$ of UEs that can efficiently share the same PRB in space. We present the formulation for this SDMA grouping problem in section III-A.

In order to provide a more reliable communication for the UEs of the SDMA group $\mathcal{G}$, it is desirable to support a certain level of link quality, which mainly depends on the SINR. Hence, the quality of UEs' links might be assured if individual target SINR values are met [2]. We present the SINR balancing problem in a CoMP scenario where each UE is subject to an SINR constraint in section III-B.

A. SDMA Grouping Problem

To solve this problem, SDMA grouping algorithms which avoid placing UEs with highly correlated channels in the same SDMA group $\mathcal{G}$ are usually employed [6]. Normally, SDMA grouping algorithms are heuristics composed by two elements: a **grouping metric** and a **grouping algorithm** [6]. While the metric measures the spatial compatibility among the UEs in an SDMA group based on the CSI available at the CoMP-cell, the grouping algorithm, based on the grouping metric, builds and compares different SDMA groups. Once the SDMA group $\mathcal{G}$ is determined, **precoding**, **power allocation** and link adaptation can be realized. Additionally, performance gains can be achieved with dynamic adaptation of the SDMA group size.

B. SINR Balancing Problem

In order to provide a more reliable communication to the UEs grouped whitin the SDMA group $\mathcal{G}$, target SINR values γ_j^t, $\forall j \in \mathcal{G}$, are defined by the link adaptation, which should be met as the result of the SINR balancing algorithm. For this purpose, consider a total power constraint on all antennas of each CoMP-cell expressed as $P_{sum} = GP_{max}$. Thus, the SINR balancing problem can be written as

$$C(P_{sum}) = \max_{\mathbf{W},\mathbf{p}} \min \frac{\gamma_j(\mathbf{W},\mathbf{p})}{\gamma_j^t}, \qquad \forall j \in \mathcal{G}, \quad (5a)$$

$$\text{subject to } \|\mathbf{w}_j\|_2 = 1, \quad (5b)$$

$$\|\mathbf{p}\|_1 \leq P_{sum}. \quad (5c)$$

IV. RRA Strategies

In section IV-A, an SDMA grouping algorithm is employed in order to find a suitable set of UEs for spatial multiplexing. After precoding, power allocation and link adaptation are conducted, futher performance gains can be achieved with dynamic SDMA group size adaptation, which is studied in section IV-B. Next, in section IV-C, the SINR balancing problem (5) is solved efficiently in the CoMP scenario by an iterative beamforming and power update algorithm [2]. Finally, power minimization can be performed after SINR balancing in order to reduce the power used in excess and consequently the inter-cell interference. This last study topic is treated in section IV-D.

A. SDMA Grouping

In the following, grouping metric, grouping algorithm, precoding and the power scaling are described.

Grouping metric: Here, we consider the sum of channel gains with null space successive projections as grouping metric [6]. For this metric, the channels of a set of UEs are successively projected onto the null space of the channels of previously selected UEs for the SDMA group. In [1], this metric is described in more details.

Grouping algorithm: In this work, we consider the Best Fit (BF) algorithm [1], which is a greedy scheduler. Starting from an SDMA group containing an initial UE j', the BF algorithm extends the group by sequentially admitting the most spatially compatible UE with respect to the UEs already admitted to the SDMA group. Adding UEs is done until the group size G reaches the target SDMA group size $G^{\star}$.

Spatial precoding: In this approach, Zero-Forcing (ZF) precoding is considered, which steers a beam towards UE j and nulls in the direction of the UEs $j' \neq j$, thus eliminating intra-CoMP-cell interference [5]. For the SDMA group $\mathcal{G}$ with channel matrix $\mathbf{H}$, the precoding vectors $\mathbf{w}_j$ building the precoding matrix $\mathbf{W}$ are given by

$$\mathbf{w}_j = \mathbf{h}_j^{\dagger}/\|\mathbf{h}_j^{\dagger}\|_2, \qquad \forall j \in \mathcal{G}, \quad (6)$$

where $\mathbf{h}_j^{\dagger}$ represents the j^{th} column of the pseudo-inverse $\mathbf{H}^{\dagger} = \mathbf{H}^{\mathrm{H}}\left(\mathbf{H}\mathbf{H}^{\mathrm{H}}\right)^{-1}$ of the group channel matrix $\mathbf{H}$ of $\mathcal{G}$.

Power scaling: Because no AP can use more power than P_{max}, power scaling is necessary. Since the vector $\mathbf{p}$ considers EPA among the UEs, the power scaling is simply performed by scaling the whole precoding matrix $\mathbf{W}$ so that the squared norm of the row with highest norm becomes equal to one [1].

B. Dynamic SDMA Group Size

The previous steps may be insufficient to ensure a realible transmission of all UEs in an SDMA group $\mathcal{G}$. Sequential Removal Algorithms (SRAs) remove UEs from an SDMA group $\mathcal{G}$ while throughput gains are achieved. Thus, the power released after each removal can be redistributed among the remaining UEs in order to improve their performance. The UE j^* with the lowest effective channel gain is removed as defined below [7]

$$j^* = \arg\min_j |\mathbf{h}_j\mathbf{w}_j|^2, \qquad \forall j \in \mathcal{G}. \quad (7)$$

C. SINR Balancing

The downlink SINR values (4) of all UEs are coupled by the intra-cell interference z_j^{intra}, which depends on both beamforming vectors $\mathbf{w}_{j'}$ and transmission powers $p_{j'}$. Thus, the power allocation and the beamforming cannot be optimized separately. The downlink problem (5) is rather hard to solve, but its uplink dual can be more easily solved by an iterative uplink beamforming and power update algorithm [2].

However, in [2], a single-cell case is considered and inter-cell interference z_j^{inter} is not included in the model. In this section, we investigate this solution with small modifications in a CoMP scenario, in which there is a power limitation by AP and UEs are subject to strong inter-CoMP-cell interference. In order to achieve similar conditions, we incorporate the effect of z_j^{inter} into the effect of noise such that, now, we shall scale matrices $\tilde{\mathbf{R}}_j = \mathbf{R}_j/(\sigma_\eta^2 + z_j^{inter})$, $\forall j \in \mathcal{G}$. In the following, we present power assignment, beamforming and power scaling due to the power limitation P_{max} per AP.

Power assignment: For fixed beamformers $\tilde{\mathbf{W}}$, the downlink problem (5) reduces to a pure power assignment. The authors in [2] show that the optimum of the downlink power assignment is achieved for $\|\mathbf{p}\|_1 = P_{sum}$. An eigensystem can be formulated for problem (5) such that the optimal downlink power vector $\mathbf{p}$ is obtained as the dominant eigenvector associated to the maximal eigenvalue [2].

Beamforming: For a given power allocation $\tilde{\mathbf{p}}$, the beamformers $\mathbf{w}_j$, $\forall j \in \mathcal{G}$, are obtained by G decoupled problems, where the optimal beamformer of each UE is the solution of a generalized eigenvector problem [2].

Power scaling: Differently from power scaling under ZF precoding, the power assignment of SINR balancing achieves different power allocations for each UE. Thus, the power scaling must be performed by scaling the whole matrix $\mathbf{U} = \mathbf{W}\sqrt{\operatorname{diag}\{\mathbf{p}\}}$ and in this case the squared norm of the row with highest norm becomes equal to P_{max}.

D. Power Minimization

It is known that the total transmission power achieved with the SINR balancing can be minimized while the SINR feasibility is kept, i.e, $C(P_{sum}) > 1$ [2]. This strategy minimizes the interference and improves the power efficiency of the CoMP system. Clearly, the minimum transmit power is achieved when $C(P_{sum}) = 1$, i.e., $\gamma_{j(dB)} = \gamma_{j(dB)}^t$, $\forall j \in \mathcal{G}$.

In order to improve the SINRs it is possible to establish a safety margin under the target SINR $\gamma_j^t(dB)$, denoted here by SINR gap $\Delta_{\gamma_j^t(dB)}$. Even though this strategy adds power to the system in comparison to the previous strategy, it possibly reduces the Packet Error Rate (PER) and may lead to an additional performance improvement of system throughput. We scale the power vector $\mathbf{p}$ such that $\gamma_{j(dB)} = \gamma^t_{j(dB)} + \Delta_{\gamma_j^t(dB)}$ when $\gamma_{j(dB)} > \gamma^t_{j(dB)} + \Delta_{\gamma_j^t(dB)}$, $\forall j \in \mathcal{G}$.

V. Analysis

The RRA problems described in section III are analysed here through system-level simulations. These are organized in snapshots, during which the path loss and shadowing are assumed to remain constant for all the UEs while the time variations of fast fading are considered. In order to capture the impact of long term propagation effects on the system performance, several snapshots are simulated. The main parameters considered in the simulation are summarized in Table I.

Table I
Simulation parameters.

Parameter	Value
Number of CoMP-cells (C)	7 (with wrap-around) [1]
Number of APs per CoMP-cell	21 (7 three-sectorized cells)
Sector radius	334 m
Minimum AP-UE distance	50 m
Snapshot duration	1 s
Effective TTI duration	1 ms
Number of symbols/TTI	14
Carrier frequency	2 GHz
Subcarrier bandwidth	15 kHz
Number of subcarriers per PRB	12
Number of PRBs (N)	6
System bandwidth	1.92 MHz
Path loss model	$35.3 + 37.6\log_{10}(d)$ dB [8]
Antenna pattern	$A(\theta^\circ) = -\min\left\{12\left[\frac{\theta^\circ}{70^\circ}\right]^2, 20\right\}$ dB [9]
Channel profile	Typical Urban (TU) [9]
Shadowing standard deviation	8 dB
Required SNR at the cell border	10.7 dB
Traffic model	Full buffer
User distribution	Uniform in entire network
Number of UEs per sector	3, 6, 9 and 12
Average UEs' speed	3 km/h
Power control	EPA among PRBs
Modulation scheme	4-QAM, 16-QAM, 64-QAM
BER for uncoded QAM	BER $\approx$ $\frac{4}{q}\left(1-\frac{1}{\sqrt{2^q}}\right)Q\left(\sqrt{\frac{3}{2^q-1}\gamma_j}\right)$ [10]
PER	$\text{PER} = 1-(1-\text{BER})^{Lq}$ [10]
Modulation scheme	$M^\star = \underset{M=2^q, q\in\{2,4,6\}}{\arg\max}\ \{(1-\text{PER})Lq\}$

Regarding the knowledge assumed about the inter-CoMP-cell interference for a given UE and PRB, we use the last measured interference value as the inter-CoMP-cell interference estimate of the current TTI.

In order to capture communication errors and their impact on the system throughput, we employed a model to determine packet loss based on the PER. The Quadrature Amplitude Modulation (QAM) scheme for each transmission is chosen such that the average throughput is maximized, where q is the number of bits/symbol and L the number of symbols being transmitted on a single PRB during one TTI.

Next, we will investigate the performance obtained by the SDMA grouping algorithm described in section IV-A. Figure 1 presents the system spectral efficiency achieved by SDMA grouping for various fixed group sizes.

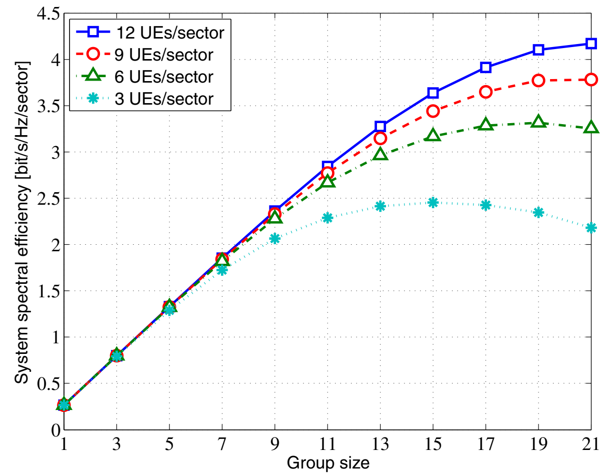

Figure 1. Fixed SDMA group size G.

As we can see in Figure 1, for low loads, expressed in number of UEs/sector, the maximum spectral efficiency is achieved by SDMA group sizes G smaller than the maximum SDMA group size $G = 21$, while for the highest load the maximum spectral efficiency value is reached for $G = 21$.

When the SRA is considered the group size is dynamically adjusted. Thus, the distribution of the group size provides a general view of the behavior of removals, which allows us to analyse the efficiency of SRA. Figure 2 presents the distribution of the group size for various loads of UEs.

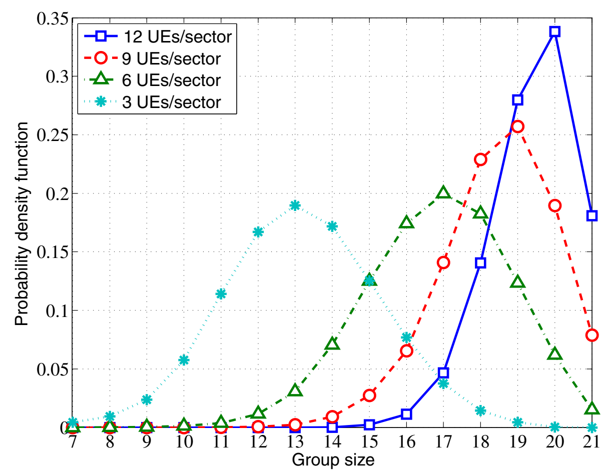

Figure 2. Adaptive SDMA group size G.

From Figure 2, the best SDMA group size $G^\star$ is dynamically adapted according to channel conditions and load of UEs. This result shows that the performance of SDMA grouping for a fixed group size $G = 21$ is being degraded.

In the following we evaluate the performance gains achieved with removal of UEs and SINR balancing. Figure 3 presents the spectral efficiency of SDMA grouping, with and without removal of UEs, of the SINR balancing with and without inter-CoMP-cell interference knowledge and of the SINR balancing with power minimization for an SINR gap $\Delta_{\gamma_j^t} = 2.5$ dB.

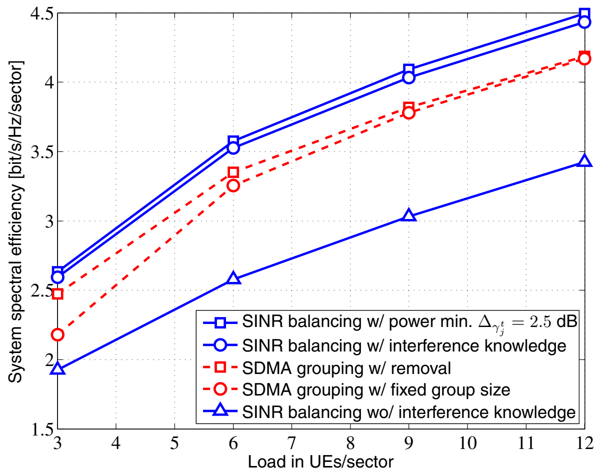

Figure 3. System spectral efficiency.

From Figure 3, we can see that for low loads of UEs significant gains in spectral efficiency can be achieved with the SRA. We also see that incorporating the effect of inter-CoMP-cell interference into the effect of noise provides satisfactory gains to SINR balancing. In general, the SINR balancing provides significant gains in relation to SDMA grouping, since it performs a better power distribution, but the SINR balancing with power minimization does not add significant gains.

Figure 4 presents the spectral efficiency of the SINR balancing with power minimization for various SINR gaps $\Delta_{\gamma_j^t}$.

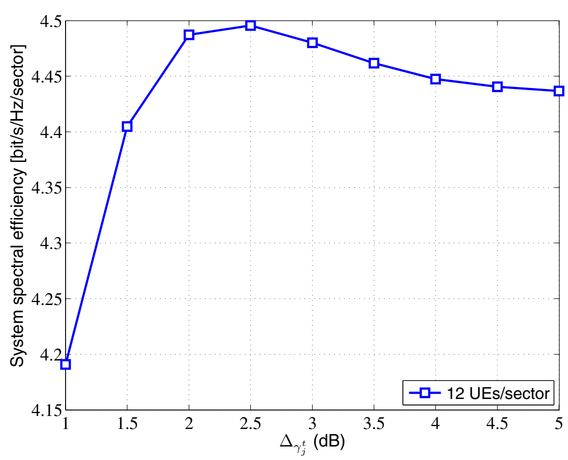

Figure 4. Power minimization.

From Figure 4, the maximum gain achieved with the power minimization occurs for an SINR gap $\Delta_{\gamma_j^t} = 2.5$ dB, around 1.5%, which is negligible. It doesn't provide more changes in the spectral efficiency but minimizes the power consumption.

Figure 5 presents the power reduction achieved by the SINR balancing with and without power minimization in relation to SDMA grouping for an SINR gap $\Delta_{\gamma_j^t} = 2.5$ dB.

As we can see in Figure 5, the SINR balancing saves up to 45% percent while the SINR balancing with power minimization saves up to 50% percent in the power consumption of SDMA grouping, which are substantial amounts of power. The power minimization was not able to provide major gains in system spectral efficiency, but the power consumption gain is already considerable. This strategy is also motivated by the low complexity of the power scaling.

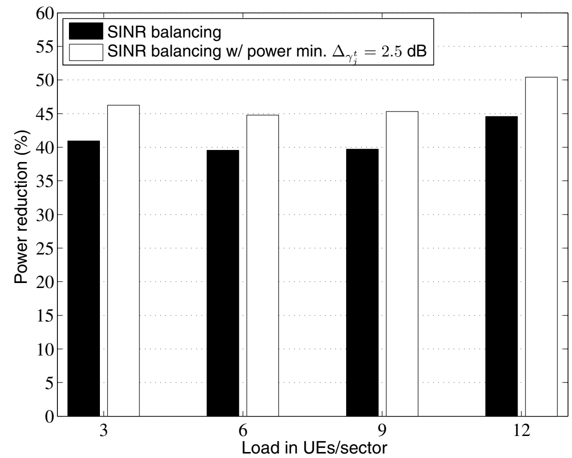

Figure 5. Power reduction in comparison to SDMA grouping.

VI. Conclusions

From the considered RRA strategies, it was shown that SRA achieved performance gains mainly for low load situations. For higher loads the SDMA grouping is better capable of choosing spatially uncorrelated UEs, due to the multi-user diversity, thus reducing the need for UE removal. As for the SINR balancing, even though it does not aim at rate maximization, slight throughput gains were achieved, given that by reaching the SINR targets the PER is reduced and the considered power reduction can further decrease the interference levels.

References

[1] R. Batista, R. dos Santos, T. Maciel, W. Freitas, and F. Cavalcanti, "Performance evaluation for resource allocation algorithms in CoMP systems," in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, 2010, pp. 1 –5.

[2] M. Schubert and H. Boche, "Solution of the multiuser downlink beamforming problem with individual SINR constraints," *IEEE Transactions on Vehicular Technology*, vol. 53, no. 1, pp. 18 – 28, 2004.

[3] J. Zhang, R. Chen, J. Andrews, A. Ghosh, and R. Heath, "Networked MIMO with clustered linear precoding," *IEEE Transactions on Wireless Communications*, vol. 8, no. 4, pp. 1910 –1921, 2009.

[4] 3GPP, "Physical layer aspects for evolved UTRA," Third Generation Partnership Project, Tech. Rep. TR 25.814 V7.1.0, sept. 2006.

[5] V. Stankovic, "Multi-user MIMO wireless communications," Ph.D. dissertation, Technische Universität Ilmenau, Germany, Nov. 2006.

[6] T. Maciel and A. Klein, "On the performance, complexity, and fairness of suboptimal resource allocation for multi-user MIMO-OFDMA systems," *IEEE Transactions on Vehicular Technology*, vol. 59, no. 1, pp. 406–419, jan. 2010.

[7] T. Maciel, "Suboptimal resource allocation for multi-user MIMO-OFDMA systems," Ph.D. dissertation, TU Darmstadt, 2008.

[8] S. Parkvall et al., "LTE-Advanced - Evolving LTE towards IMT-Advanced," in *Proceedings of the IEEE Vehicular Technology Conference (VTC)*, sept. 2008, pp. 1–5.

[9] 3GPP, "Spatial channel model for MIMO simulations," 3GPP, Tech. Rep. TR 25.996 V8.0.0, dec. 2008.

[10] J. G. Proakis, *Digital Communications*, 4th ed., ser. Electrical Engineering Series. McGraw-Hill, 2001.