Resource Allocation Strategies Based on the Signal-to-Leakage-plus-Noise Ratio in LTE-A CoMP Systems*

Rana A. Abdelaal, Mahmoud H. Ismail and Khaled Elsayed
Department of Electronics and Communications Engineering, Cairo University
Giza 12613, Egypt
rabdelaal@ieee.org, mhismail@ieee.org, khaled@ieee.org

***Abstract*— In this paper, we present two novel Resource Allocation (RA) strategies based on the Signal-to-Leakage-plus-Noise-Ratio (SLNR) for the downlink (DL) of Coordinated Multi Point (CoMP) transmission in LTE-Advanced (LTE-A) system. The proposed RA strategies select the UEs that can efficiently share the same Resource Block (RB) without degrading the overall throughput by using the SLNR metric. In addition, we compare the proposed strategies to the RA based on the more common Signal-to-Interference-plus-Noise-Ratio (SINR) strategy. The SLNR-based RA is shown to provide significant gains in the overall system throughout that reach up to 80% and is shown to have even less complexity than the typical SINR-based RA, which makes it a very attractive choice for the implementation of CoMP in practical cellular systems.**

Keywords; Coordination; coordinated multi point; cellular networks; LTE; interference mitigation; Resource Allocation.

I. INTRODUCTION

The capacity of wireless cellular networks is mainly restricted by interference. In cellular systems, a geographical region is typically divided into cells, which handle interference through the use of pre-defined frequency reuse patterns. This guarantees that near cell-edge users belonging to adjacent cells do not share similar frequencies and thus have limited inter-cell interference (ICI). Recently, as bandwidth progressively becomes a more scarce resource, future cellular networks shift gradually closer to the maximal frequency reuse of unity [1]. Consequently, efficient Resource Allocation (RA) will play an essential role in future networks.

One of the promising techniques in Long Term Evolution-Advanced (LTE-A) is Coordinated multi-point (CoMP) transmission, which is introduced in an attempt to meet the high data rate requirements of IMT-Advanced [2]. Specifically, it is considered as one of the candidate techniques to increase the average cell throughput and cell-edge user throughput. The basic idea of CoMP is to eliminate ICI through cooperation between a number of base stations (BSs) or enhanced-node Bs (eNBs) under the command of a central entity that turns interference into a useful signal. CoMP systems are able to exchange data, control information and Channel State Information (CSI) and, consequently, coordinate interference.

As an alternative architecture, a cell can consist of several Remote Radio Equipments (RREs), which can be connected to a central BS or eNB. Full coordinated transmission is achieved among the RREs through unified radio resource management at the central BS/eNB [2]. Since the interface connecting the central BS and the RREs can be implemented through the use of optical fibers or radio interface, high-speed transfer of signals is possible. RREs are effectively used in the existing cellular networks by installing small BSs in limited space.

The main objectives of CoMP are to mitigate the interference, provide high spectral efficiency over the entire cell area, and increase the overall throughput especially the cell-edge throughput [3]. Although CoMP naturally increases the system complexity, it provides significant capacity and coverage benefits, making it worth a more detailed consideration.

In the downlink (DL) of CoMP systems, two approaches are often considered. The first approach is Coordinated Scheduling (CS) where the data are transmitted from one RRE at a time with scheduling decisions being made with coordination between all RREs. The second approach is Joint processing (JP) where the data is made available at each RRE and is transmitted from several RREs simultaneously to each user equipment (UE) [4].

Typically in the literature, CS and JP are based on the use of the Signal-to-Interference-plus-Noise-Ratio (SINR) as the performance metric as in [5], for example. In our work at hand, we propose two novel CS and JP RA strategies based on the Signal-to-Leakage-plus-Noise-Ratio (SLNR) instead, which pick the UEs that can efficiently share the same RB without degrading the overall throughput. SLNR metric was first introduced in the framework of MIMO systems in [6]. It was shown that the use of SLNR as an objective metric outperforms the SINR metric as no closed form solutions are obtainable for the SINR metric due to the difficulty and the coupled nature of the resulting optimization problem. Conversely, the SLNR metric leads to a decoupled optimization problem and admits an analytical closed form solution [6]. In this paper, we provide a comprehensive comparison between four RA strategies; CS scheme based on SLNR, JP scheme based on SLNR, CS scheme based on SINR

* This work is part of the 4G++ project supported by the National Telecom Regulatory Authority of Egypt.

that has been addressed in [5], and finally JP scheme that is based on SINR. The proposed strategies are analyzed through simulations. It is shown through simulations that the RA strategies based on SLNR achieve an improved performance compared to RA strategies based on SINR. Moreover, we also show that the SLNR-based CS scheme has a significant complexity reduction as compared to the SINR-based version.

The rest of this paper is organized as follows. Section II discusses the system model. Section III describes the proposed resource allocation strategies. Section IV presents and discusses the simulation results. Finally, Section V draws the main conclusions of the paper.

II. SYSTEM MODEL

In this section, the model adopted to evaluate the proposed strategies performance is presented. We consider a cellular system where each cell consists of one eNB, M RREs under its control, and serves K single-antenna UEs. An example of such a cell is shown in Fig. 1. There exists N Resource Blocks (RBs) in the system and each of them may be assigned to one or more UEs. Each RB has 12 subcarriers that are spaced 15 kHz apart from each other.

Channel coherence bandwidth is assumed to be larger than the bandwidth of the RB leading to flat fading over each RB. Uniform power allocation among RBs is considered and the overall transmit power available for each RRE (P) is uniformly divided among the N RBs. So, the power allocated to each RB is simply: $P_n = P/N$ (assuming all RBs are utilized by the RRE). Each RRE is assumed to have a single antenna. UEs are uniformly distributed over the cell's coverage area.

CoMP model has been studied previously in many papers; as in [5], the major metric considered was the SINR measured at each UE. In contrast, in this paper; SLNR is considered as the performance metric, which greatly reduces the computational complexity as will be shown later in the sequel. It is thus considered more suitable for RA in practical cellular networks. The SLNR (β) at the kth UE over the nth RB can be expressed as:

$$\beta_k = \frac{P_n\ |\underline{\mathbf{h}}_k\,\underline{\mathbf{w}}_k|^2}{\sum_{k' \neq k}^{K} P_n\ |\underline{\mathbf{h}}_{k'}\ \underline{\mathbf{w}}_k|^2 + |\eta_k|^2}\,, \tag{1}$$

where $k \in \{1, 2, \dots, K\}$, $\underline{\mathbf{h}}_k$ is the complex channel vector of the links between the kth UE and all M RREs of the CoMP cell, η_k is the Additive White Gaussian Noise (AWGN), and $\underline{\mathbf{w}}_k$ is the (precoding) weighting vector for the kth UE in which it defines all links between all RREs and this UE. The weighting vector depends on the used scheme (CS or JP) as will be discussed in more details in section III.A. In (1), a single RB is considered and its index (n) is dropped for simplicity of notation.

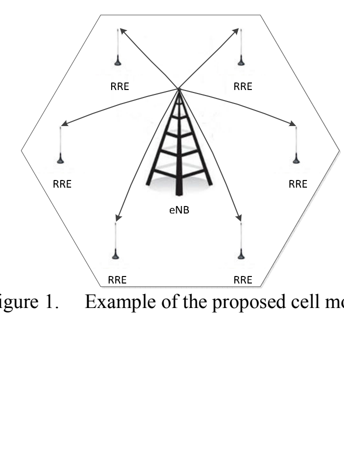

Figure 1. Example of the proposed cell model

III. THE PROPOSED RESOURCE ALLOCATION STRATEGIES

In this section, the RA strategy considered in this paper is discussed. The general aim of allocating resources in a CoMP system is to maximize the throughput, so our proposed strategy aims at maximizing the throughput per each RB which directly leads to maximizing the overall throughput achieved by the entire bandwidth.

For each RB, a set $S \subset \{1, 2, \dots, K\}$ of UEs will be selected to be given data over the same RB. Scheduling decisions can be taken to determine dynamically which UEs can simultaneously use the same RB.

A. Selecting Weighting Vectors

1) For CS scheme: This approach determines which RRE should serve each UE. Assuming that all RREs have perfect knowledge about all channel parameters. Even though the relationship between the SLNR metric and the throughput is not straightforward, it is very intuitive to conclude that by increasing the SLNR metric, the throughput will be improved. Thus, The weighting vector ($\underline{\boldsymbol{w}}_k$) will be set in order to maximize (1) subject to $\|\underline{\boldsymbol{w}}_k\|^2 = 1$ and each element in $\underline{\boldsymbol{w}}_k$ is either one or zero. Since in CS, each UE is served by only one RRE. Thus, the weighting vector will be a vector with all elements equal to zero except only one element will be unity. This element is corresponding to the serving RRE.

2) For JP scheme: The main difference from the CS approach is that the same data packet is sent to a specific UE from all RREs. The weighting vector ($\underline{\boldsymbol{w}}_k$) will be selected in order to maximize (1) subject to $\|\underline{\boldsymbol{w}}_k\|^2 = 1$. Since in JP, each UE is served by all RREs jointly. In this case, the weighting vector is not as simple as in the CS scheme. This optimization problem has been solved in [6] and the solution is given by:

$$\underline{\mathbf{w}}_k = \max \text{eig. vec.}\left(\left(|\eta_k|^2\mathbf{I}_M + \widehat{\mathbf{H}}_k^*\widehat{\mathbf{H}}_k\right)^{-1}\underline{\mathbf{h}}_k^*\underline{\mathbf{h}}_k\right), \tag{2}$$

where, $\widehat{\mathbf{H}}_k$ is a $(K-1)\times M$ matrix given by $\widehat{\mathbf{H}}_k = \left[\underline{\mathbf{h}}_1\underline{\mathbf{h}}_2 \cdots \underline{\mathbf{h}}_{k-1}\underline{\mathbf{h}}_{k+1} \cdots \underline{\mathbf{h}}_K\right]^T$, $\mathbf{I_M}$ is the $M \times M$ identity matrix, and $\underline{\mathbf{w}}_{\boldsymbol{k}}$ is the eigenvector corresponding to the maximum eigenvalue of the matrix computed in (2).

B. The Grouping Algorithm

The task of the grouping algorithm is to select the UEs that can efficiently share the same RB without degrading the overall throughput. In other words, the UEs that leak the least on each other should be assigned the same RB. In that way, the overall throughput will be enhanced and the available bandwidth will be utilized. In both of the proposed schemes, the grouping algorithm is the same. The following steps will be repeated for every RB available. The set of UEs S is initialized to the empty set and in both schemes will be populated in the following manner:

1) Initialization: Choose the UE with maximum SLNR and set to be the first item in the set (S): The UE with maximum SLNR is the one that has a relatively strong direct channel and also has relatively low interference on other UEs. Hence, it is the UE that will leak the least towards other UEs when sharing the RB with them. The initial element in set (*S*) will thus be chosen as follows:

$$k' = \text{argmax}_k(\beta_k), S = \{k'\}. \quad (3)$$

2) Compute the leakage value vector from set (S) in the direction of the rest of UEs: This vector represents the amount of leakage from the set (*S*) to the rest of UEs. Leakage refers to the interference caused by the signals intended for the UEs belonging to the set (*S*) on the remaining UEs, i.e., leakage is a measure of how much signal power leaks into the other UEs. The leakage value vector for a UE $s' \notin S$ can be calculated as follows:

$$L_{s,s'} = \left|\underline{\mathbf{h}}_{s'}\, \underline{\mathbf{w}}_s\right|^2, \forall s' \in S', S' \not\subset S \quad (4)$$

where S' is the set that includes all UEs that do not belong to the set *S*.

3) Add the UE with the least amount of leakage to the set S: In that step, the UE that will be affected the least will share the RB with the UEs belonging to the set. This UE will be selected according to the following equation:

$$S = S \cup \text{argmin}_{s'}(L_{s,s'}). \quad (5)$$

4) Repeat steps 2-3 till the overall leakage value reaches a certain threshold or till a certain condition is satisfied: The stopping criterions are described in details in the next subsection.

C. Stopping Criterion

Selecting the stopping criteria is a very important issue as it directly affects the overall achieved throughput. We propose and investigate a number of stopping criteria as follows:

1) Selecting Leakage Threshold: The Leakage threshold is the value that is responsible for terminating the RA algorithm. The relationship between the leakage threshold and the number of UEs per cell is assumed to be linear. The general linear equation has been used, which is:

$$\lambda = aK + b, \quad (6)$$

where *K* is the number of UEs per cell, λ is the leakage threshold, and *a* & *b* are constants. In order to obtain *a* and *b*, simulations has been perforemd, and the grouping algorithm discussed in section III.B has been applied with calculating the total throughput per set *S* after adding each UE to the set. So, all the possible achieved throughput values per RB has been explored. Then, the leakage value leading to the maximum achieved throughput (λ) has been used along with the number of UEs per cell in order to obtain both constants *a* and *b* by means of curve fitting. It has been found that, *a* = 0.05257 and *b* = –0.5205 present good results considering different channel conditions.

The RA strategy based on leakage threshold assures stopping when achieving nearly the highest throughput per RB. On the other hand, the RA strategy addressed in [5] terminates when the throughput decreases which does not assure achieving the highest value. For instance, considering the scenario where k UEs are in the set and when another UE is added to the set, the total throughput will decrease, the algorithm as addressed in [5] will come to an end here. However, adding this UE may be useful if by adding another UE (so that; $|S| = k + 2$), the total throughput will increase more than it was when the group had only k UEs. Such scenario is expected to occur. As for adding a new UE to the group sharing the same RB, there is a throughput loss as well as a throughput gain and both values depend on the channel environment which is variable. Stopping using the leakage threshold leads to high throughput gains, but it is highly dependent on the channel parameters, and propagation scenarios. So in order to select a suboptimal leakge threshold, the channel should be explored first, and extra effort will be needed in order to obtain a proper value for a and b. We will use this stopping condition, as a benchmark for comparison with other proposed stopping criteria.

2) Marginal Utility: In this method a utility function (*U*) is defined as the log function of the acheived throughput [7] and a specific condition is checked so as to allow sharing the RB (to allow grouping). This condition is:

$$U_{s_{new}} + U_{UE_{new}} \geq U_{s_{old}}, \quad (7)$$

where, $U_{UE_{new}}$ is the utility function of the UE that is recently added to the set, $U_{s_{new}}$is the utility function of the UEs that have been previously in the group (excluding the newest UE) computed after adding the new UE and taking its interference effect on the attainable throughputs, and $U_{s_{old}}$ is the utility function of the set computed before adding the new UE. If (7) is satisfied then this UE (newest UE) will be added; otherwise the grouping will be terminated. This approach is efficient and provides high overall throughput gains but it does not take into consideration the case when the throughput drops by adding a particular UE while it has not reached the maximum throughput (global maximum to be reached) and so the algorithm might terminate early before reaching the highest achievable throughput.

3) Marginal Utility with look-ahead: In this method, the same marginal utility condition in (7) is used. However, if the condition is not fulfilled, there is an extra possibility to add the UE to the set via constructing a temporary set that includes the original set plus UE_i (where UE_i is the UE that may or may not be added to the set). Then another user (UE_{i+1}) will be selected and the marginal utility condition in (7) will be again checked for the temporary set with UE_{i+1}. If it is still not satisfied, the algorithm will terminate with the original set (not the temporary). However, if the condition is fulfilled then the algorithm will terminate with a new set which is the temporary set and UE_{i+1}.This algorithm is described in more details in Fig. 2. In general, this algorithm can include more than two stages of look-ahead, however, the algorithm with two stages has presneted high gains in terms of throughput as will be shown in section IV.

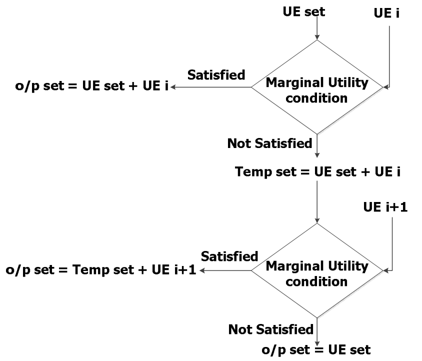

Figure 2. Marginal utility with look-ahead flow chart

This stopping condition is efficient as it does not terminate once the throughput decreases as in [5], and it also does not terminate once the utility function based condition is unfulfilled as the marginal utility stopping condition does. Furthermore, it has no pre-processing overhead as in case of using the leakage threshold condition. Although this stopping condition is suboptimal, it is practical and leads to high throughput gains as will be shown in section IV.

D. Complexity Comparison

In the proposed strategies, the weighting vector $\underline{\mathbf{w}}_k$ will be selected in order to maximize (1) as described in subsection III.A. Maximizing the SLNR metric (β_k) for the *k*th UE requires less number of computations compared to maximizing the SINR for the same UE. This is because maximizing the SLNR for each UE is an independent process. In other words, maximizing the SLNR for a certain UE requires checking all possible links only for this UE, and no need to check other UEs links. This is because SLNR measures the amount of signal power indented for this UE versus the amount of leakage on other UEs due to that link.

In contrast, maximizing the SINR metric is a very exhaustive process; as the SINR for each UE cannot be optimized independently. This is because the interference at each UE is dependent on the other UEs links. Thus, to optimize the SINR for a certain UE, an algorithm should try linking this UE with all possible links. Also, for each possibility it should try linking other UEs with all possible links.

Consequently, the proposed strategies' computational complexity is greatly reduced by considering the SLNR as the main metric. For example, the complexity order of maximizing the SINR metric for each UE assuming K UEs and M RREs and CS strategy is as follows:

$$\text{Number of computations in SINR-based RA} = \frac{M!}{(M-K)!}, \quad M > K \qquad (8)$$
$$= M * \frac{(K-1)!}{(K-M)!}, \quad \text{otherwise.}$$

This is because in order to maximize the SINR for a specific UE two stages are needed. The first is to try linking this specific UE to all RREs in the cell. The second is that while this specific UE is linked with any RRE, all possible links between the rest of UEs and the rest of RREs should be checked. The number of computations for the first stage is M in both cases mentioned in (8). However, the number of computations for the second stage depends on both M and K. When $M > K$, the second stage actually will need the same number of computations for selecting $K-1$ RREs from the available $M-1$ RREs to serve the $K-1$ UEs existing in the cell. Moreover, the order of selection should be taken into account. Consequently, the number of computations for the second stage will equal $(K-1)$-permutations of $(M-1)$ in case $M > K$. And, when $K \geq M$, the second stage will need the same number of computations for selecting $M-1$ UEs from the available $K-1$ UEs to be served by the available $M-1$ RREs existing in the cell. Moreover, the order of selection should be taken into account. Consequently, the number of computations for the second stage will equal $(M-1)$-permutations of $(K-1)$ in case $K \geq M$. By multiplying the number of computations of both stages and using the basic definition for permutations, (8) can be obtained.

On the contrary, the complexity of maximizing the SLNR metric for each UE considering the same model as above is simply of order M.

In order to overcome the high computational complexity of maximizing the SINR at each UE, some papers select the weighting vectors that are corresponding to the maximum channel gain, such as in [5]. However, selecting the weighting vectors in that way does not take into consideration the interference channels. In contrast, our proposed model maximizes the SLNR metric for each UE, which checks the interference channels as well as the direct channel.

IV. Results And Analysis

The RA strategies described in Section III are evaluated in this section through simulations. In order to capture the impact of long term propagation effects on the system performance, several snapshots are simulated and the results are averaged. The simulation parameters are listed in TABLE I.

In order to compare the performance of the proposed strategies, we consider the scenario of a CoMP system that chooses the weighting vectors that correspond to the highest channel gains. And allocates the available RB to the UE with the highest SINR and keep on allocating the same RB to the UE with the highest SINR and so on, until the overall throughput decreases. Afterwards, it moves to the next available RB and so on. Such algorithm is addressed for CS CoMP in [5].

The proposed CS and JP strategies provide gains compared to the strategies that are based on the SINR. Fig. 3 presents the average throughput per RB, in Kbps, of the simulated CS strategies as a function of the number of UEs per cell assuming typical urban macro-cell propagation scenario [8].

As shown in the figure, the best performance is for the CS strategy based on SLNR with leakage threshold stopping criterion. It outperforms the CS strategy based on SINR by an average of 80%. Also, The CS strategy based on SLNR with marginal utility and look-ahead criterion presents throughput gains by an average of 61% higher than that of the CS based on SINR strategy. Finally, the CS strategy based on SLNR with marginal utility criterion presents throughput gains of an average of 52% higher than that of the CS based on SINR strategy.

The difference between the results in Fig.3 and Fig. 4 is the propagation scenario used. In Fig. 4, the propagation scenario used is the bad urban macro-cell scenario, which is same as the typical urban macro-cell scenario plus long delays [8]. As shown, the highest performance is still for the CS strategy based on SLNR with leakage threshold stopping criterion, and then the CS strategy based on SLNR with marginal utility and look-ahead criterion.

Results related to the JP strategies are shown in Fig. 5 and Fig. 6. Again, the difference between both figures is only in the propagation scenario used. In Fig. 5, typical urban macro-cell scenario is used, however, in Fig. 6; bad urban macro-cell scenario is used. It is shown in both figures that the JP strategy based on SLNR with leakage threshold presents the highest throughput gains. It outperforms the JP strategy based on SINR with an average of 31%. And the JP strategy based on SLNR with marginal utility and look-ahead criterion presents throughput gains of an average of 24% higher than that of the JP strategy based on SINR. Finally, the JP strategy based on SLNR with marginal utility presents throughput gains of an average of 7% higher than the JP based on SINR strategy.

As shown, the proposed RA strategies based on SLNR presents higher gains than that of the RA strategy based on SINR. That is basically due to the accurate choice of the stopping criteria and also for the reason that the weighting vectors are determined more accurately so as to maximize the SLNR metric for all UEs.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Number of RREs per cell	6
Number of UEs (k)	20, 30, 40
Carrier Center Frequency (GHz)	2
Subcarrier spacing (KHz)	15
Number of RBs (N)	100
Number of subcarriers per RB	12
System bandwidth (MHz)	20
Propagation Scenarios	Typical urban macro-cell and Bad urban macro-cell [8]
Number of antennas per UE	One
Number of antennas per RRE	One
Power distribution among RBs	Uniform
UEs distribution among cell area	Uniform
Scheduling algorithms	CS, JP
Used modulation schemes	QPSK, 16-QAM, 64-QAM
Number of UEs per set $\|S\|$	Less than or equal to 6 in case of CS and unlimited in case of JP

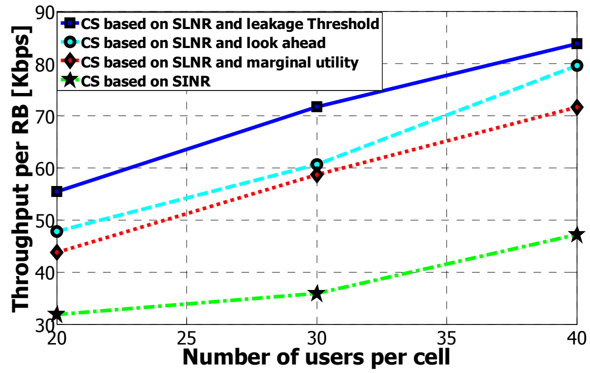

Figure 3. Throughput of the CS strategies in urban macro-cell scenario

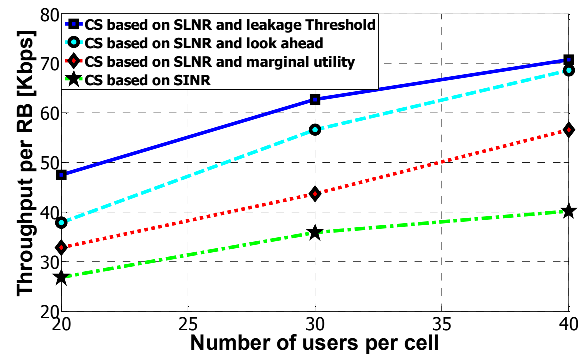

Figure 4. Throughput of the CS schemes in bad urban macro-cell scenario

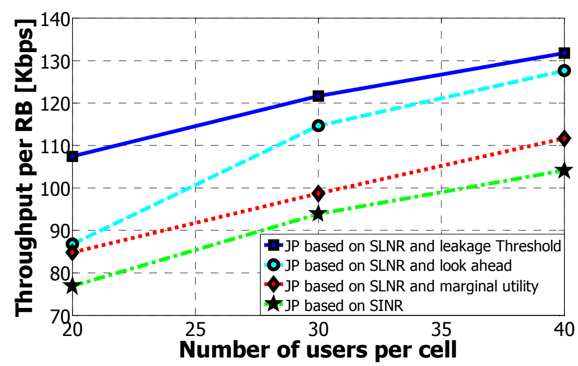

Figure 5. Throughput of the JP strategies in urban macro-cell scenario

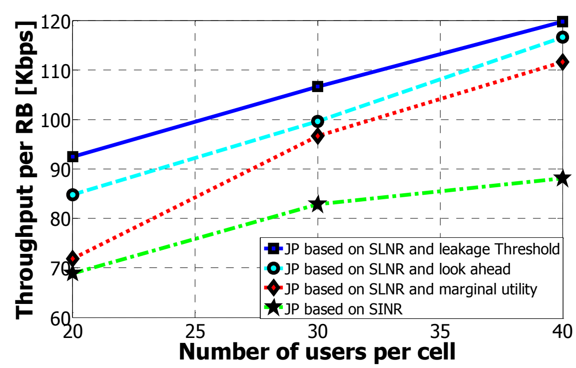

Figure 6. Throughput of the JP schemes in bad urban macro-cell scenario

It is worth noting here that in CS, the number of UEs sharing the same RB is restricted by the number of RREs in the cell, as each RRE can serve only one UE over the same RB. However, in case of JP, the number of UEs sharing the same RB is not related to the number of RREs, as all RREs are serving each UE. Consequently, the JP leads to higher throughput gains compared to the CS as evident from the presented results.

V. Conclusion

In this paper, RA strategies based on SLNR have been proposed for CoMP systems. We have shown that the use of the SLNR criterion provides significant gains as compared to the more classical SINR one. Also, different stopping criteria have been investigated. It has been shown that using a leakage threshold for terminating achieves high throughput gains, but obtaining this threshold requires further pre-processing and depends on channel parameters which may not be known in advance. In contrast, using the marginal utility condition with look-ahead criterion achieves relatively high gains and is more efficient as it does not require further pre-processing required for estimating the proper value of the leakage threshold criterion.

References

[1] W. Yu, T. Kwon, and C. Shin, "Joint scheduling and dynamic power spectrum optimization for wireless multicell networks," in Proc. CISS, 2010, pp.1-6.

[2] S. Parkvall et al., "LTE-Advanced - Evolving LTE towards IMT-Advanced," in Proc. VTC 2008-Fall Vehicular Technology Conf. IEEE 68th., 2008, pp. 1-5.

[3] Qixing Wang, Dajie Jiang, Guangyi Liu, and Zhigang Yan, "Coordinated Multiple Points Transmission for LTE-Advanced Systems," in Proc. 5th Int. Conf. Wireless Communications, Networking and Mobile Computing WiCom '09., 2009, pp. 1-4.

[4] Y. Kishiyama, A. Morimoto, D. Nishikawa, and M. Tanno, "Coordinated multipoint transmission/reception techniques for LTE-Advanced," IEEE Wireless Communications, vol. 17, no. 3, 2010.

[5] R. L. Batista, R. B. dos Santos, T. F. Maciel, W. C. Freitas, and F. R. Cavalcanti, "Performance evaluation for resource allocation algorithms in CoMP systems," in Proc. IEEE 72nd Vehicular Technology Conf. Fall (VTC 2010-Fall)., 2010, pp. 1-5.

[6] M. Sadek, A. Tarighat, and A.H. Sayed, "A Leakage-Based Precoding Scheme for Downlink Multi-User MIMO Channels," presented at IEEE Transactions on Wireless Communications, 2007, pp.1711-1721.

[7] M. Al-Rawi, R. Jantti, J. Torsner, and M. Saqfors, "Channel-Aware Inter-Cell Interference Coordination for the Uplink of 3G LTE Networks," in Wireless Telecommunications Symposium, 2010, pp. 1-5.

[8] IST-WINNER II, D1.1.2 "WINNER II Channel Models," ver 1.0, Sep 2007, www.ist-winner.org/WINNER2-Deliverables/.