Interference Evaluation for Distributed Collaborative Radio Resource Allocation in Downlink of LTE Systems

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***Abstract*—Collaboration among neighbouring eNBs in radio resource allocation, in the absence of a centralized control unit, is one of the challenges raised from the flat architecture suggested for the Long Term Evolution (LTE) networks. This paper investigates the system performance of a collaborative resource allocation scheme, in a scenario that consists of two tiers of collaborative Regions (CoR), and consider the gain achieved from the eNB collaboration and performance degradation due to the interference from neighbouring eNBs. Our results indicate that interference introduced from the cells outside the collaborating cluster can have significant impact on the system performance. However, Monte Carlo simulation based performance analysis demonstrates the effectiveness of collaborative resource allocation among adjacent eNBs for the LTE networks.**

I. Introduction

The introduction of a flat architecture for Radio Access Network (RAN) in beyond 3G standards such as Long Term Evolution (LTE) is a response to the requirement for reduced latency and higher data rates. In these networks, the Base Station Controller (BSC) in 2G or Radio Network Controller (RNC) in 3G architecture, which functions as a coordinating and controlling node among the base stations (BSs) (termed as eNB in the LTE standard) is removed from the architecture. Instead, X2 interface, which uses high speed backhaul links is introduced to connect eNBs so that they can exchange information and coordinate their different functionalities. Hence, the existing collaborative radio resource allocation schemes to improve spectral efficiency [1]-[3], can not be directly deployed in such networks. It would require the collaborative radio resource allocation to be implemented in a distributed manner. Besides, it must employ opportunistic resource allocation to improve spectral efficiency by harvesting multi-user diversity gain. Finally, to achieve higher data rates, dense frequency reuse is recommended for future cellular networks. However, its drawback is Inter-Cell Interference (ICI), which degrades the system performance in the cell edge area. In order to meet the above mentioned requirements in the new architecture, we propose a distributed resource allocation scheme in four dimensions of time, frequency, power and space in this paper.

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The radio resource allocation problem for multi-carrier systems, is usually formulated as an optimization problem, where the objective is to maximize the overall cell throughput, subject to some constraints such as fairness and transmission power [4]-[6]. Alternatively, the problem can be formulated as a utility maximization problem, where utility function quantifies the level of user satisfaction [7]-[8] rather than system-centric metrics like throughput and outage probability. The multi-cell resource allocation problem investigated in [9] deploys a collaborative scheme where a user is served by that BS which offers the best channel gain to that user.

In [10], a multi-cell semi-distributed scheme is proposed where Radio Resource Management (RRM) is done by coordination between RNC and BS. The scheme proves to be efficient but its semi-distributed approach involves controlling entities in the network. The presence of multiple BSs offers the benefit of spatial diversity gain (referred to as BS diversity), which has been exploited in [9] to improve the performance of Code Division Multiple Access (CDMA) networks. We intend to extend the concept and exploit eNB diversity in the framework of LTE networks.

In this paper, we consider the resource allocation problem for the DownLink (DL) of an Orthogonal Frequency Division Multiple Access (OFDMA)-based LTE system. We investigate a collaboration scheme that benefits not only from eNB diversity gain, but also uses the collaborative resource allocation among the neighbouring sector antennas. In this scheme, a Collaborative Region (CoR) is formed by the three most interfering sector antennas of the three adjacent cells, and resource allocation is done such that intra-CoR interference is mitigated. Radio resource allocation functionalities are performed locally in each eNB. In the proposed framework, the adjacent sectors communicate and perform scheduling in a distributed and collaborative manner. Expoiting the benefits of spatial diversity, each user is dynamically served by that eNB which has the best DL channel towards it, instead of being served by a fixed eNB. Simulation results demonstrate that the proposed scheme can improve the system performance in terms of spectral efficiency, while ensuring fairness amongst the users and reducing ICI.

The rest of the paper is organized as follows. System model is described in Section II. Section III explains the proposed distributed collaborative scheduling scheme. Simulation results

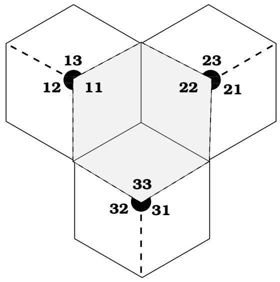

Fig. 1. Collaborative Region

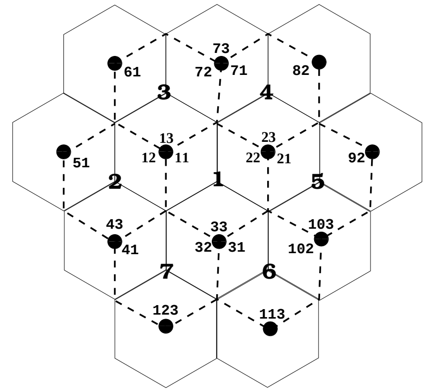

Fig. 2. Two-Tier model of collaborative regions

are discussed in Section IV and conclusions in Section V.

II. System Model

We consider the DL of an OFDMA-based system with M eNBs. The eNBs are assumed to be connected to each other via high speed, high capacity X2 interface links used in LTE system architecture. Each eNB uses three Sector Antennas (SAs) located at the centre of the cell. The collaborative region (CoR) of collaborating eNBs is the building block of our system model as shown by the central shaded area in Fig.1. A collaborative region is defined as the coverage area of the three most interfering sector antennas from the three adjacent eNBs. These sectors antennas are uniquely indexed with ms, where $m \in \mathcal{M} = \{1, 2, \ldots, M\}$ shows eNB index, and $s \in \mathcal{S} = \{1, 2, 3\}$ shows sector antenna index. Here, sectors 11, 22, and 33 are the SAs forming the central CoR. Surrounding the central CoR, there is a second tier of six CoRs, as shown in Fig. 2. We use a wrap-around system model and assume the interference from third tier of CoR to be negligible.

In an OFDMA-based system, each Resource Block (RB) comprises a set of adjacent subcarriers grouped together as per LTE recommendations [11]. Each CoR has total N resource blocks, indexed with $n \in \mathcal{N} = \{1, 2, ..., N\}$. There are total K users in the CoR, indexed with $k \in \mathcal{K} = \{1, 2, \ldots, K\}$. A saturated case is considered, where users always have backlogged traffic. The channel condition is assumed to be known at the three sector antennas forming a CoR.

In a conventional scenario and without collaboration, each user is served by the eNB it is attached to; known as the serving eNB. Each serving eNB receives the incoming traffic destined to its users through the core network, and independently performs resource allocation. However, we apply the scheme from [12], where X2 links are used for collaboration among the SAs in the CoR and S1 interface links are used by core network to redirect the traffic to the collaborating eNB that will temporarily serve a specific user.

III. Distributed Collaborative scheduling and interference

In this section, we first briefly review the original collaborative radio resource allocation as an optimization problem. Then we illustrate the collaborative scheduling scheme and finally discuss the impact of interference on it.

A. Problem Formulation

For the convenience of reader, Table I, tabulates symbols representing different parameters used in this paper. The system level objective is defined as maximizing system throughput in the collaborative region, while maintaining fairness, and mitigating intra-CoR interference in that region.

To compare the effectiveness of scheduling schemes, we consider a simplified physical layer modulation and coding scheme that can achieve Shannon's capacity. It is because our aim is to compare the performance of radio resource allocation schemes, and not the physical layer schemes. Hence, system throughput in the collaborative region is computed as:

$$R_{CoR} = \sum_{ms \in CoR} \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \phi_{k,n}^{(ms)} \, log_2(1 + p_{k,n}^{(ms)} \beta_{k,n}^{(ms)}). \quad (1)$$

We define the objective function as:

$$\max_{\phi_{k,n}^{(ms)} \, p_{k,n}^{(ms)}} R_{CoR} \quad (2)$$

subject to:

$$\sum_{ms \in CoR} \sum_{k \in \mathcal{K}} \sum_{n \in \mathcal{N}} \phi_{k,n}^{(ms)} \, p_{k,n}^{(ms)} \leq P_{BS} \quad (3)$$

$$\sum_{ms \in CoR} \sum_{k \in \mathcal{K}} \phi_{k,n}^{(ms)} = 1 \qquad \forall n \quad (4)$$

$$p_{k,n}^{(ms)} \geq 0 \qquad \forall n, k \quad (5)$$

$$Fairness\ constraints \quad (6)$$

Without considering a mechanism to guarantee fairness constraint in (6), the above objective function implies a pure opportunistic approach which maximizes system throughput. Opportunistic scheduling is a throughput optimal resource allocation scheme [13]. However, its disadvantage is that it is an unfair resource allocation scheme whenever there are significant discrepancies among the average quality of channels for different users. Specifically, users located in the cell edge area, experience high interference from neighbouring cells, and higher levels of pathloss due to their location farther away from eNB. To overcome the problem of unfairness,

TABLE I
LIST OF NOTATIONS

Symbol	Description
M	Number of eNBs in the network
K	Number of users in the CoR
N	Number of OFDMA resource blocks in CoR
k	User index belonging to $\mathcal{K} = \{1, 2, \ldots, K\}$
n	RB index belonging to $\mathcal{N} = \{1, 2, \ldots, N\}$
ms	eNB and SA index belonging to $\mathcal{M} = \{1, 2, \ldots, M\}$ and $\mathcal{S} = \{1, 2, 3\}$
$r_{k,n}^{(ms)}$	Achievable rate for user k on RB n when served by SA ms
$g_{k,n}^{(ms)}$	Channel gain of user k on RB n in SA ms
$p_{k,n}^{(ms)}$	Power allocated to user k on RB n in SA ms
$\phi_{k,n}^{(ms)}$	Allocation variable for user k on RB n in SA ms belonging to $\varphi = \{0, 1\}$
$\beta_{k,n}^{(ms)}$	$= \frac{g_{k,n}^{(ms)}}{N_0 B}$ Received SNR of user k on resource block n in SA ms with unity power
I_{ms}	Interference received in SA ms
N_0	Noise spectral density
B	Bandwidth

opportunistic fair scheduling schemes have been proposed [5] and used in [12]. We deploy proportional fairness to meet the fairness constraint in (6). Using moving average calculator, the instantaneous average rate for user k in all three sectors, $\tilde{R}_k(t)$, is updated in each scheduling epoch t as follows:

$$\tilde{R}_k(t) = (1 - \frac{1}{T_c})\tilde{R}_k(t-1) + \frac{1}{T_c} R_k(t). \qquad (7)$$

where T_c is a time constant for moving average calculator, and $R_k(t)$ is the kth user's achievable rate on all RBs in time t.

B. Distributed Collaborative scheme

The optimization problem in (2) is an NP-Complex optimization problem, as its complexity increases exponentially with an increase in the number of users, RBs and levels of allocated power. This problem can not be solved using conventional techniques; hence, some reasonable simplifications can be made to reduce its complexity. To meet the first constraint of the problem, (3) can be simplified by using equal power allocation to all the RBs, i.e.,

$$p_{k,n}^{(ms)} = \frac{P_{BS}}{N} = p \qquad \forall n, k. \qquad (8)$$

As there is no central control unit to perform radio resource allocation globally for the CoR, we aim at using a scheduling scheme that provides collaboration among the SAs, while maintaining their autonomy and limited information exchange.

Assuming that the channel conditions are available in each SA, and by keeping track of each user's past rates, each sector independently calculates a *"Scheduling Coefficient"*, which is defined for proportional fair scheduling as:

$$Sc_{k,n}^{(ms)} = r_{k,n}^{(ms)} / \tilde{r}_{k,n}^{(ms)} \qquad (9)$$

Here, $\tilde{r}_{k,n}^{(ms)}$ is calculated using (7) where $R_k(t)$ is replaced with $r_{k,n}^{(ms)}$.

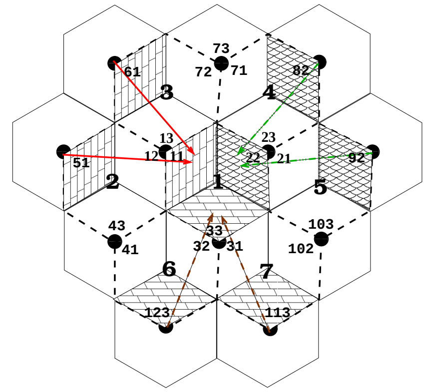

Fig. 3. Potential Interferers: Non-Collaborative

Using $Sc_{k,n}^{(ms)}$, each SA ms forms the Scheduling Coefficient Matrix $[Sc_{k,n}^{(ms)}]_{K \times N}$. In the next step, it chooses the highest scheduling coefficient on each RB, and records the coefficient and ID of the corresponding user. The SA hence makes a new matrix, called "Best Matrix":

$$SC_{best}^{(ms)} = \{Sc_{k^*,n}^{(ms)} \mid k^* = \arg\max_k Sc_{k,n}^{(ms)} \qquad \forall n\}. \qquad (10)$$

After sharing this information among the collaborating SAs, each of the three collaborating SAs will know the best scheduling coefficients on each RB for all the three SAs in CoR. Then each SA will individually compare its own scheduling coefficient with that of the other two SAs on each RB, and schedules the user on that RB if its own coefficient is the highest, otherwise it will not transmit on that RB at all. At the same time, each SA updates the average rate for each user using the best matrix.

C. Interference Analysis

1) Intra-Collaborative Region interference: As illustrated in the above scheme (III-B); inside a single CoR, when a RB is used by a SA, it will not be used by any other SA in the same collaborative region, hence intra-CoR interference is mitigated using the proposed scheme.

2) Inter-Collaborative Region interference: When we consider a second tier of CoRs in the system model, the interference received from the neighbouring CoRs (i.e.inter-CoR interference) would not be zero. This is due to the fact that the same frequency band is used in all the neighbouring CoRs. This interference will degrade the overall system performance. Thus, we investigate system performance in the presence of inter-CoR interference. The system model considered for inter-CoR interference calculation is as shown in Fig. 2. As mentioned earlier, each SA is recognized using ms, where m is the cell index, and s is the SA index. The number shown at the centre of each CoR is the CoR region number. The second tier of CoRs contains twelve hexagonal cells. Here, focus is on the performance of collaborative schemes, with reference region taken as CoR 1, in the presence of interference received from all the second tier CoRs, i.e. CoR 2 to 7.

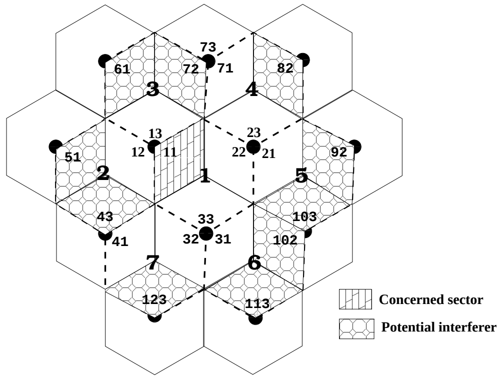

Fig. 4. Potential Interferers to SA_{11}: Collaborative

Non-Collaborative Scenario: When RBs are statically assigned to each SA, the interference observed at each SA in the central CoR is determined by the neighbouring SAs from the second tier CoRs, with the same sector index s facing towards it. Fig. 3 shows this scenario and as it can be seen, each SA can receive interference from a maximum of two SAs.

Collaborative Scenario: In this case, as any RB can be used in any SA, the possible set of interferers increases, and it includes any sector from the second tier of CoRs, facing the SA in central CoR. Fig. 4 illustrates all potential interferers to SA_{11}. In this scenario, if we denote the interference towards any SA_{ms} with I_{ms}, and use index $m's'$ for interfering SAs, then total interference observed at SA_{ms} will be:

$$I_{(ms)} = \sum_{m'=1}^{12} \sum_{s'=1}^{3} \phi_{k,n}^{(m's')} \phi_{k,n}^{(ms)} p_{k,n}^{(m's')} g_{k,n}^{(m's')}, \tag{11}$$

where $\phi_{k,n}^{(m's')} \in \{0, 1\}$ is the allocation variable, which equals to 1 if an RB n is used for user k in SA $m's'$, and equals to 0 otherwise. $p_{k,n}^{(m's')}$ and $g_{k,n}^{(m's')}$ indicates the power and channel gain associated with user k on RB n in SA $m's'$. Note that in this case, $\beta_{k,n}^{'(ms)} = \frac{g_{k,n}^{(ms)}}{N_0 B + I_{(ms)}}$ is used to compute R_{CoR}.

IV. Simulation Results

In the MATLAB simulations, a CoR is used as a building block of the model that consists of three neighboring SAs as shown in Fig. 1. This CoR is the total coverage area of three most interfering SAs from the neighbouring eNBs. Using the scheme discussed in III-B, each RB will only be used by one SA at any time instant. Thus, interference is mitigated by using the proposed scheduling schemes at CoR level. A second tier of collaborative regions is introduced in order to investigate the effect of inter-CoR interference. This model is shown in Fig. 2. The cell radius and hence the CoR radius is assumed to be 500 m. Each SA has a maximum transmit power of 46 dBm with transmit antenna gain of 16 dBi and receiver antenna gain of -1 dBi. Time slot duration is 1 ms; the total bandwidth is 10 MHz, and each RB comprises 12 subcarriers with a bandwidth of 15KHz each. The channels from the eNBs to users are modelled considering path loss (with a path loss coefficient of 3.5) and shadowing (with a standard deviation of 8 dB). The users are distributed symmetrically around the centre of CoR, where interference from all the sectors is at its maximum levels. For comparison, two simulation schemes- Non-Collaborative (NCP), and Collaborative (CP) are considered. In NCP, each user is served by that SA, to which it is attached based on its geographical location. In CP scheme, each user is dynamically served by that SA which offers the best scheduling coefficient to it. A proportional fair resource allocation scheme is considered. In simulating NCP scheme, three independent schedulers are implemented, where each scheduler uses one third of the available RBs, for each of the three SAs in the common coverage area. For simulating CP scheme, the distributed collaborative scheduler scheme explained in III-B is implemented.

In addition, fairness aspects of both CP and NCP schemes are investigated in this work. The scheme defines a radio resource allocation method, which facilitates a fair distribution of system resources amongst the users. Fairness index is a metric to determine the fairness of a scheduler. As a measure of the fairness provided by different schemes and schedulers, Gini fairness index (GFI) is used to ensure accuracy of results as follows:

$$GFI = \frac{1}{2K^2\bar{u}} \sum_{x=1}^{K} \sum_{y=1}^{K} |u_x - u_y|. \tag{12}$$

where $u = \{u_i | u_i = \tilde{R}_i\}$ and $\bar{u} = (\sum_{i=1}^{K} u_i)/K$. Fairness of a scheduler increases with the decrease in Gini Index GFI.

The simulation results for the performance of NCP acheme, as well as the proposed CP scheme with and without collaboration, for a total number of users varying from 6 to 36 is illustrated in Fig. 5. As it is observed, the performance improves as collaboration is introduced in the system. But when the effect of interference from the second tier CoRs is considered, there is reduction in the overall system performance. However, it is shown that, even in the presence of interference, the collaborative scheme, outperforms the non-collaborative. The overall system performance versus different number of users, for all the schemes, is illustrated in Fig. 6. As we can see, the collaborative schemes significantly outperform the non-collaborative ones. But, when interference is considered, the overall system performance degrades. However, the amount of performance degradation differs in CP and NCP schemes. This is due to the different number of potential interfering SAs in the two schemes. As it can be seen in Fig. 3. and Fig. 4. there are only two potential interfering SAs when using NCP, where as for CP there are a total of 10 potential interfering SAs, which cause more degradation in system performance. However, the results with interference are still much better for CP scheme when compared to NCP due to the fact that coordination based resource allocation maximizes throughput and eliminates intra-CoR interference. The Gini fairness index for different schemes is illustrated in Fig. 7. As it can be observed, the collaborative scheme has the best performance in terms of fairness and there is only slight degradation in fairness with interference into consideration.

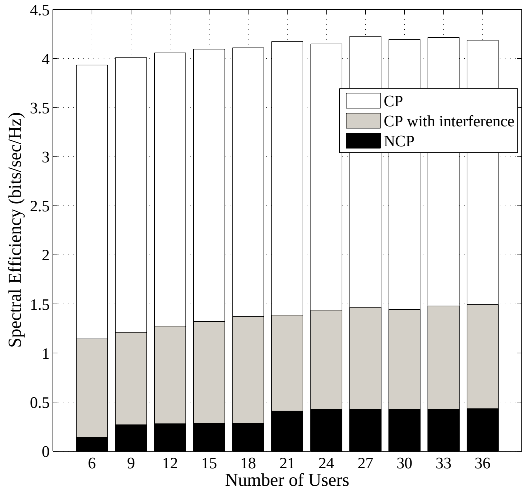

Fig. 5. User performance using different scheduling schemes, with and without interference

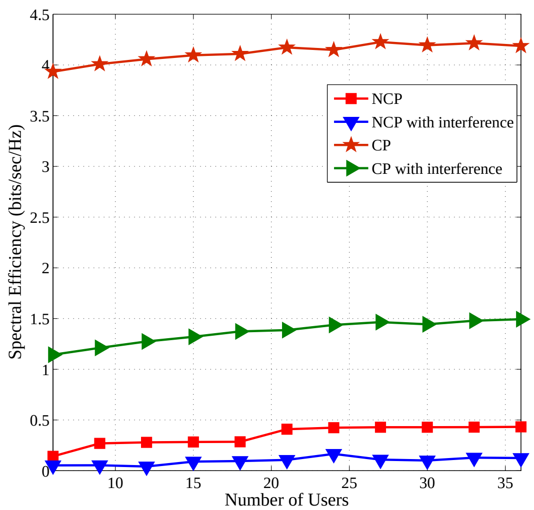

Fig. 6. System performance using different scheduling schemes, with and without interference

V. Conclusion

In this paper, we have considered a distributed and collaborative radio resource allocation scheme for the DL of an LTE cellular system. We have introduced a CoR which is formed by three sector antennas from three neighbouring eNBs. We investigated the effect of interference from a second tier of CoRs. The collaborative scheme enables each sector to process the information individually, and make independent scheduling decisions after exchanging limited information with the other SAs forming the CoR. The proposed scheme provides a framework for dynamic resource allocation and interference mitigation in any given CoR and is scalable to any size of network. However, inter-CoR interference is not avoidable and it reduces the overall system performance. Simulation results verify that although there is a degradation in the overall

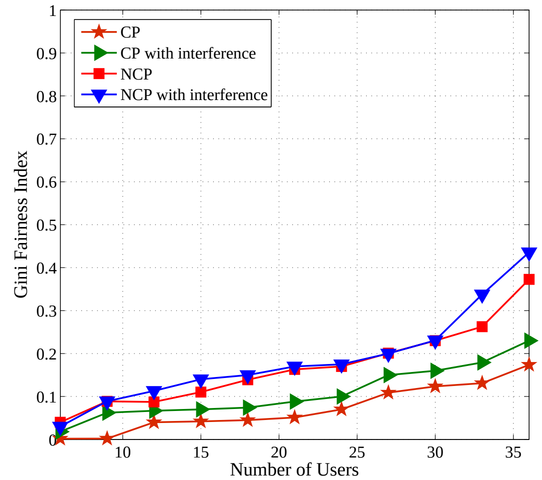

Fig. 7. Gini fairness index using different scheduling schemes, with and without interference

performance when interference is taken into account, there is improvement in system throughput by using collaborative radio resource allocation scheme.

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