On the Relay Placement Problem in a Multi-cell LTE-Advanced System with Co-channel Interference

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Abstract—**One of the main problems in LTE-A networks is the small rates achieved by cell-edge users. This is due to the adoption of a frequency reuse factor of 1, which aims at increasing the overall capacity. This occurs, however, at the expense of increasing the interference level for cell-edge users. Cooperative communication through the use of relays is an efficient technique to solve this problem. However, careful placement of the relays is a crucial factor in determining the expected capacity gain. In this paper, the relay placement problem in an LTE-A network is studied, taking into consideration the effect of co-channel interference. An optimization framework is proposed to maximize either the total cell capacity or the total cell-edge capacity. Simulation results show a capacity gain factor of 8.027 for cell-edge users due to relay deployment, under 100% cell load in center cell and adjacent cells.**

Keywords-component; LTE-A; Cooperative Communication; Relay Placement.

I. INTRODUCTION

LTE-Advanced (LTE-A), [1] and [2], has been selected as a candidate for true 4G wireless as defined by the ITU International Mobile Telecommunications (IMT)-Advanced [3]. LTE-A offers an order of magnitude increase in overall wireless rates over its LTE Rel. 8 predecessor. LTE-A also adopts a reuse-1 OFDMA-based access model that can potentially work with a reuse-1 system with a proper inter-cell interference coordination (ICIC) scheme. While reuse-1 typically results in higher overall cell rate, it usually results in unpredictable performance for cell edge users due to the large interference level. Exploiting relay stations (RSs) in LTE has been proven to be an efficient solution to solve this problem [2], where the weak link between the e-Node B (eNB) and the User Equipment (UE) is replaced by the stronger eNB-RS and RS-UE links, thus increasing the link capacity and reliability.

Cooperative Communications [4] is a fast growing research direction in wireless networks. Intermediate relay stations are placed in the network, where they exploit the broadcast nature of wireless network to overhear the transmitted messages by the eNB, and cooperate with it to forward the data to cell-edge users experiencing bad channel conditions with the eNB. Amplify-and-Forward (AF) and Decode-and-forward (DF) are the 2 main forwarding techniques in literature, where in the former, the data received by the RS is amplified and re-transmitted to UE; while in the later, the data are fully decoded and re-transmitted to the UE. The main drawback of AF technique is that RS amplifies its receiver noise, so it is used mainly in high SNR environments, On the other hand, DF technique prevents error propagation due to the full decoding at the RS; but it is characterized by its longer delay.

The placement of the relays inside the network is crucial in determining the required performance gain. This fact motivated the tackling of this problem in different contexts. In [5], the authors studied a general cooperative cellular network, in which the subscribers cooperate and relay information to each other to maximize the sum of network utility. An efficient algorithm was proposed to determine which node should act as a relay, which relay strategy should be used (AF or DF) and which frequency should be used for relaying. In [6], the authors studied the optimal placement problem of a given number of relays in a non-cooperative WLAN, where the Mobile Host (MH) may be connected to the Access point (AP) directly or connected to it through a relay. The authors proposed an efficient algorithm, which is based on Lagarangian relaxation with sub-gradient iteration, to minimize the network expected packet transaction time thus maximizing the network throughput. In [7], a general OFDMA relay enhanced cooperative network was studied where DF fixed RSs (FRSs) and Nomadic RSs (NRSs) were used. The RS placement and the bandwidth allocation were jointly optimized to maximize the network capacity. In [8], the authors studied a WiMAX network, where their main objective function was to minimize the required number of RSs, in order to meet the users traffic demand and cover the requested service area. In [9], a WiMAX network was studied, for which the Probability Mass Function (PMF) of the users' positions is given. They used both transparent and non-transparent RSs (TRSs & NTRSs) (which correspond to Type-I and Type-II relays, respectively, in the context of LTE-A [10]). The main goal was to determine the number of TRSs and NTRSs required as well as their placement to maximize the expected total transmission time (averaged on the PMF of the users' positions). In [11], the authors studied the problem of optimal RS placement for coverage extension in an LTE-A network.

Despite the rich literature in the RS placement problem, only limited work was conducted within the LTE-A context. Moreover, most of the literature considered a single-cell model and neglected the inter-cell interference. Only the work in [11] considered these issues where the authors assumed that the RSs are placed uniformly on a circle, and they proposed a solution based on optimizing the cell-radius, which is a sub-optimal solution, aiming at extending the coverage.

In this paper, we consider an LTE-Advanced relay enhanced cooperative cellular network, where the main objective is the optimal placement of a given number of RSs in a certain cell in order to maximize either the total cell capacity or the cell-edge capacity to ensure a fair capacity distribution over the cell. We take into account the effect of inter-cell interference as well as intra-cell interference resulting from the reuse of the same channel between the relay stations and the eNB. The rest of the paper is organized as follows. The system model is included in Section II. The problem formulation and the description of the simulation setups are presented in Section III. The simulation results are shown and discussed in Section IV. Finally, Section V concludes this paper.

II. SYSTEM MODEL

We consider a typical 7-cell model, where $\mathcal{J}=\{0,1,..,j,..,6\}$ is the set of indices of the 7 eNBs in the model. We focus our attention on the centre cell, which will be given the index 0. We also consider an arbitrary geographical distribution of N UEs, where $\mathcal{N}=\{1,2,..,n,..,N\}$ is the set of indices of UEs. Based on a threshold received SINR, UEs are classified to either cell-centre or cell-edge UEs, where $\mathcal{N}_{\text{cell-centre}}$ and $\mathcal{N}_{\text{cell-edge}}$ are the sets of indices of cell-centre and cell-edge UEs, respectively ($\mathcal{N}=\mathcal{N}_{\text{cell-centre}} \cup \mathcal{N}_{\text{cell-edge}}$). We assume cell-edge deployment of RSs where cell-edge UEs use the RSs to increase their capacity and their link reliability via cooperative diversity, while cell-centre UEs are connected directly to the eNB.

Furthermore, we consider a given number of RSs (L), and a given number and geographical distribution of candidate positions (CPs), which are identified to be suitable for placing RSs after site planning, where $\mathcal{M}=\{1,2,..,m,..,M\}$ is the set of indices of CPs in the central cell. L RSs are distributed uniformly in each of the adjacent cells, where $\mathcal{M}_A=\{1,2,..m,..,L\}$ is the set of indices of RSs. For simplicity, we assume the RSs in the adjacent cells are distributed on a circle with equal angles from each other. The system model is shown in Fig. 1. The RSs use in-band half-duplex relaying [10] where the eNB-UE, eNB-RS and RS-UE links are assigned to the same set of contiguous OFDM subcarriers, namely Resource block (RB) [2], and the relaying is done over 2 timeslots. The relaying strategy is fixed DF [1] [4] and the time resource allocation is shown in Fig. 2, where the eNB transmits the data to all UEs in the 1st timeslot and the RSs overhear the transmitted data to cell-edge users and decode the messages. In the 2nd timeslot, the RSs re-encode the messages and send them to their cell-edge UEs, and the eNB continues its data transmission to all users. To increase the total cell capacity, the

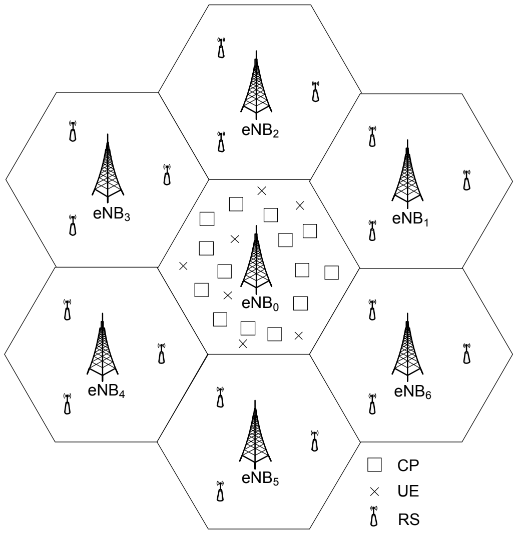

Figure 1: System Model.

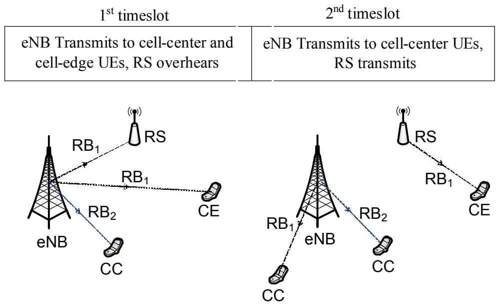

Figure 2: Time Resource Allocation.

eNB can reuse the RBs assigned to the RS-UE links to transmit data to cell-centre UEs which results in intra-cell interference.

One of the main concerns in OFDMA-based 4G and beyond wireless systems is co-channel interference, where the frequency reuse factor is set to 1 in order to increase the total capacity. Moreover, in some architectures, there could be a frequency reuse in the same cell, where the RBs assigned to the eNB-RS backhaul links or the eNB-UE access links can be reused by the RS-UE links. We take into consideration these issues by taking into account the inter-cell interference from the first tier of adjacent cells, and the intra-cell interference due to frequency reuse inside the same cell as will be shown in the sequel. Moreover, we assume that no power control scheme is implemented, where the transmitting power of eNBs per RB and of RSs per served cell-edge user are P_{eNB} and P_{RS}, respectively.

III. PROBLEM FORMULATION

We assume the following decision variables [7]: X_m, which is set to 1 if an RS is placed at CP_m, and is set to 0 otherwise. Y_{mn}, which is set to 1 if an RS placed at CP_m is used to relay to UE_n, and is set to 0 otherwise. According to [4], the

[1] In Laneman and Tse's paper [4], the relaying schemes were classified into fixed and selective. Fixed DF means that the relays decode, then re-encode, and retransmit the messages; whereas, Selective DF relays retransmits the decoded message only if the measured SNR is above a certain threshold to prevent error propagation (allowing the relay to select a suitable cooperative (or non-cooperative) action based upon the measured SNR)

maximum achievable data rate $r_{m,n}$, in the 2 timeslots, for a cell-edge user UE_n relayed via an RS placed at CP_m is:

$$r_{m,n} = \frac{1}{2}\min\left\{\begin{array}{c} C(\mathrm{SINR}_{\mathrm{eNB_0,RS}_m}), \\ C(\mathrm{SINR}_{\mathrm{eNB_0,UE}_n} + \mathrm{SINR}_{\mathrm{RS}_m,\mathrm{UE}_n}) \end{array}\right\}, \quad n \in \mathcal{N}_{\mathrm{cell-edge}} \tag{1}$$

where $C(x) = \log_2(1+x)$ is the Shannon capacity formula. The maximum data rate, in each timeslot, for a cell-centre UE_n connected directly to the eNB is:

$$r_n = C(\mathrm{SINR}_{\mathrm{eNB_0,UE}_n}), n \in \mathcal{N}_{\mathrm{cell\_centre}} \tag{2}$$

We assume full synchronization between the eNBs and the RSs of all cells, where eNBs transmit to cell centre and cell edge UEs in the 1st timeslot, and then the eNBs and RSs transmit to cell-centre and cell-edge UEs in the 2nd timeslot, respectively, as explained earlier.

A. Interference and Resource Block Congestion Model

In the center cell, we use the M/M/C/C queuing model to model congestion in the network, i.e., the case when a user requests access to a certain RB but it is not available due to the finite number of RBs in the system, and the request is then blocked. Complete Sharing (CS) session admission control policy is used and the handovers are not considered for simplicity. The cell load σ is equal to the total user activity given by:

$$\sigma = \frac{\rho}{c} = \frac{\lambda}{c\mu} = \frac{N\lambda_u}{c\mu} \tag{3}$$

where ρ is the traffic intensity, λ is the total arrival rate of users, λ_u is the arrival rate of each user, μ is the service rate of each user, which is normalized to 1 without loss of generality, and c is the number of available RBs in the network. We can then calculate the user blocking probability in the centre cell by using the Erlang-B formula as:

$$P_{\mathrm{blocking}} = \frac{\frac{\rho^c}{c!}}{\sum_{i=0}^{c}\frac{\rho^i}{i!}} = \frac{\frac{(\sigma c)^c}{c!}}{\sum_{i=0}^{c}\frac{(\sigma c)^i}{i!}} \tag{4}$$

The achievable rates in (1) and (2) are thus multiplied by the factor $(1 - P_{\mathrm{blocking}})$ to get the average achievable rates.

In order to model variations in the cell load, we use equation (3) to calculate the number of users for each value of the cell load:

$$N = \left\lceil \frac{\sigma c \mu}{\lambda_u} \right\rceil \tag{5}$$

where $\lceil x \rceil$ represents the ceiling of the number x.

The total transmit power of an eNB ($P_{\mathrm{eNB,total}}$) is divided equally on the number of RBs available (c), and the transmit power of a RS in the central cell ($P_{\mathrm{RS,total}}$) is divided equally on the average number of served cell-edge users (v), i.e.,

$$P_{\mathrm{eNB}} = \frac{P_{\mathrm{eNB,total}}}{C}, P_{\mathrm{RS}} = \frac{P_{\mathrm{RS,total}}}{v} \tag{6}$$

For simplicity, the adjacent cells are assumed to have the same cell load (σ_A), which can differ from the cell load of the center cell (σ). σ and σ_A are defined as the proportion of RBs that are assigned for eNB transmission in the center and adjacent cells, respectively [11]; i.e., the proportion of RBs assigned for an eNB transmission to a UE or an RS. So, σ and σ_A can be used as estimates for the probabilities that an RB is assigned for eNB transmission in the center and adjacent cells, respectively. These probabilities are used to calculate the average desired signals and average interference power from the adjacent eNBs on each RB as follows:

$$I_{j,x}^{\mathrm{eNB}} = \begin{cases} \sigma \dfrac{P_{\mathrm{eNB}}}{PL_{j,x}}, j = 0 \\ \sigma_A \dfrac{P_{\mathrm{eNB}}}{PL_{j,x}}, j \neq 0 \end{cases}, \quad x \in \mathcal{N} \cup \mathcal{M}, j \in \mathcal{J} \tag{7}$$

where $I_{j,x}^{\mathrm{eNB}}$ is the average desired signal or interference power on the x^{th} node (UE_n or RS_m) due to the j^{th} eNB and $PL_{j,x}$ is the path loss of the link between the j^{th} eNB and the x^{th} node. Similarly, we can use this approximation to calculate the average interference power due to the RSs on each RB. We assume that the RSs can reuse any RB in the whole bandwidth and assume that all RSs in each cell have equal probabilities to be assigned to each RB [11]. So, the probability that an active RB is assigned to an RS-UE link in the central cells and adjacent cells are, respectively:

$$\alpha = \frac{\sigma}{L} \text{ and } \alpha_A = \frac{\sigma_A}{L} \tag{8}$$

These probabilities are used to calculate the average interference power from the RSs on each RB as follows:

$$I_{j,m,n}^{\mathrm{RS}} = \begin{cases} \alpha \dfrac{P_{\mathrm{RS}}}{PL_{m,n}^{j}}, j = 0, m \in \mathcal{M} \\ \alpha_A \dfrac{P_{\mathrm{RS}}}{PL_{m,n}^{j}}, j \neq 0, m \in \mathcal{M}_A \end{cases} \quad n \in \mathcal{N}, j \in \mathcal{J} \tag{9}$$

where $I_{j,m,n}^{\mathrm{RS}}$ is the average interference power on UE_n due to RS_m placed in the j^{th} adjacent cell, $PL_{m,n}^{j}$ is the path loss of the link between RS_m in the j^{th} cell and UE_n. The RS placement for the central cell is now studied in 3 different setups detailed in the following subsections.

B. Setup 1: No Relays

In this setup, we consider a network with no relays, where all UEs are connected directly to the eNB. The maximum achievable rate for the n^{th} UE on a single RB is calculated by:

$$r(n) = (1 - P_{\mathrm{blocking}})\, C(\mathrm{SINR}_{\mathrm{eNB,UE}_n}) \tag{10}$$

where

$$\mathrm{SINR}_{\mathrm{eNB,UE}_n} = \frac{I_{0,n}^{\mathrm{eNB}}}{N_0 W + \sum_{j=1}^{6} I_{j,n}^{\mathrm{eNB}}} \tag{11}$$

The term N_0 represents the power spectral density of noise and W represents the bandwidth of a single RB. We assume that each user is assigned to 1 RB only.

C. Setup 2: Uniform Relay Positions

In this setup, we consider a network where the L RSs in the center and adjacent cells are placed at equal angles on a circle.

The relaying is done only for cell-edge UEs on 2 timeslots as described before. For the cell-center UEs, the maximum achievable rate for the n$^{\text{th}}$ cell-center UE in the 1st timeslot is calculated by:

$$r_{1n} = \frac{1}{2}(1 - P_{\text{blocking}})C(\text{SINR}_{\text{eNB,UE}_n}) \tag{12}$$

where

$$\text{SINR}_{\text{eNB,UE}_n} = \frac{I_{0,n}^{\text{eNB}}}{N_0 W + \sum_{j=1}^{6} I_{j,n}^{\text{eNB}}} \tag{13}$$

whereas the maximum achievable rate for the n$^{\text{th}}$ cell-center UE in the 2nd timeslot is calculated by:

$$r_{2n} = \frac{1}{2}(1 - P_{\text{blocking}})C(\text{SINR}_{\text{eNB,UE}_n}) \tag{14}$$

where

$$\text{SINR}_{\text{eNB,UE}_n} = \frac{I_{0,n}^{\text{eNB}}}{\left(\begin{array}{c} N_0 W + \sum_{j=1}^{6} I_{j,n}^{eNB} + \\ \frac{1}{L}\sum_{j=1}^{6}\sum_{m=1}^{L} I_{j,m,n}^{RS} + \frac{1}{L}\sum_{m=1}^{L} I_{0,m,n}^{RS} \end{array}\right)} \tag{15}$$

The 2nd and 3rd terms in the denominator represent the average inter-cell interference due to the eNBs and RSs in the adjacent cells, respectively. The 4th term represents the average intra-cell interference due to the RS-UE links in the 2nd timeslot; the $\frac{1}{L}$ factor is used because only one RS from the L RSs may be assigned to the same RB of the eNB-UE link (RSs cannot be assigned to the same RBs in the 2nd timeslot, because this means that their backhaul links were assigned to the same RBs in the 1st timeslot, which is impossible). The total achievable rate over the 2 timeslots is thus calculated by [12]:

$$r_n = r_{1n} + r_{2n} \tag{16}$$

On the other hand, for the cell-edge UEs, the maximum achievable rate for the n$^{\text{th}}$ cell-edge UE served by RS_m over the 2 timeslots together is calculated by:

$$r_{m,n} = \frac{1}{2}(1 - P_{\text{blocking}}) \min\left\{\begin{array}{c} \text{C}(\text{SINR}_{\text{eNB,RS}_m}), \\ \text{C}(\text{SINR}_{\text{eNB,UE}_n} + \text{SINR}_{\text{RS}_m,\text{UE}_n}) \end{array}\right\} \tag{17}$$

where

$$\text{SINR}_{\text{eNB,UE}_n} = \frac{I_{0,n}^{\text{eNB}}}{N_0 W + \sum_{j=1}^{6} I_{j,n}^{\text{eNB}}} \tag{18}$$

$$\text{SINR}_{\text{eNB,RS}_m} = \frac{I_{0,m}^{\text{eNB}}}{N_0 W + \sum_{j=1}^{6} I_{j,m}^{\text{eNB}}} \tag{19}$$

$$\text{SINR}_{\text{RS}_m,\text{UE}_n} = \frac{I_{0,m,n}^{\text{RS}}}{N_0 W + \sum_{j=0}^{6} I_{j,n}^{\text{eNB}} + \frac{1}{L}\sum_{j=1}^{6}\sum_{m=1}^{L} I_{j,m,n}^{\text{RS}}} \tag{20}$$

where the summation in the 2nd term of the denominator of (20) starts from $j = 0$ to account for the intra-cell interference power due to eNB_0, and the 3rd term represents the inter-cell interference due to relays of adjacent cells.

D. Setup 3: Optimized Relay Positions

In this setup, the L RSs in the center cell are placed at the optimal L CPs, whereas the L RSs in adjacent cells are placed uniformly on a circle as in setup 2. The rate equations in this setup will be the same as setup 2, except for (15), which is changed to be:

$$\text{SINR}_{\text{eNB,UE}_n} = \frac{I_{0,n}^{\text{eNB}}}{\left(\begin{array}{c} N_0 W + \sum_{j=1}^{6} I_{j,n}^{\text{eNB}} + \\ \frac{1}{L}\sum_{j=1}^{6}\sum_{m=1}^{L} I_{j,m,n}^{\text{RS}} + \frac{1}{L}\sum_{m=1}^{M} X_m I_{0,m,n}^{\text{RS}} \end{array}\right)} \tag{21}$$

The optimal placement of RSs is calculated using the capacity maximization non-linear Integer problem (CMNIP), which is formulated as follows:

$$\max_{X,Y} \sum_{\substack{n\in\mathcal{N}_{\text{cell-edge}} \\ m\in\mathcal{M}}} Y_{mn} r_{m,n} + \sum_{n\in\mathcal{N}_{cell-centre}} r_n \tag{22a}$$

$$\max_{X,Y} \sum_{\substack{n\in\mathcal{N}_{\text{cell-edge}} \\ m\in\mathcal{M}}} Y_{mn} r_{m,n} \tag{22b}$$

subject to:

$$\sum_{m=1}^{M} Y_{mn} = 1, n \in \mathcal{N}_{\text{cell-edge}}, m \in \mathcal{M} \tag{23}$$

$$Y_{mn} \le X_m, n \in \mathcal{N}_{\text{cell-edge}}, m \in \mathcal{M} \tag{24}$$

$$\sum_{m=1}^{M} X_m = L, m \in \mathcal{M} \tag{25}$$

$$X_m, Y_{mn} \in \{0,1\} \tag{26}$$

where the objective function in (22a) is the maximization of the total cell capacity, while that in (22b) is the maximization of the total cell-edge capacity. Constraint (23) ensures that each UE_n is assigned to a single RS, while constraint (24) ensures that an RS cannot be assigned to a UE unless it is physically placed at CP_m. Constraint (25) means that the total number of placed RSs is L and finally, constraint (26) means that the decision variables are binary.

We propose solving this problem by obtaining an approximate preliminary solution using exhaustive search. The L RSs are placed at the CPs, which maximize the total cell capacity (or cell-edge capacity) via an exhaustive search over the M possible CPs. Each UE is assumed to be assigned to the RS that results in the maximum received signal strength at the UE. We do not seek to optimize the UE assignment to decrease the total number of combinations for the feasibility of exhaustive search. In other words, only the variable X in the system model is calculated. It is obvious that the exhaustive search is computationally expensive for large values of M. Moreover, the optimization for both X and Y variables will make the situation worse. To solve this problem, more intelligent mathematical programming techniques should be applied.

IV. Performance Evaluation Results

In this section, we show the results of different setups and different objective functions for the CMNIP. We built a MATLAB-based system level simulator to simulate the system and to find the optimal RS placement. In our system level simulator, we assume that the central cell contains uniformly distributed UEs with a distance r to the eNB and their angles to the horizontal are denoted by θ where

$$r \sim U(35m, R) \text{ and } \theta \sim U(0, 2\pi) \quad (27)$$

where $U(a, b)$ denotes a uniform distribution over the interval $[a, b]$, and the minimum distance between the eNB and UEs is 35m according to [13]. The threshold between cell-centre and cell-edge UEs is chosen to be the SINR threshold corresponding to a spectral efficiency of 0.033 bps/Hz [13]. All users are assumed to be indoors, so the eNB-UE and RS-UE links are affected by a penetration loss of 20 dB; whereas the RSs are outdoors, so there is no penetration loss on the eNB-RS links.

Each adjacent cell contains 3 RSs, where we assume the RSs in the six adjacent cells are placed at equal angles from each other on a circle of radius $0.7R$, which is a typical placement as in [11]. 30 CPs for the RSs are uniformly distributed with radius r and angle θ, where

$$r \sim U(0.6R, 0.8R) \text{ and } \theta \sim U(0, 2\pi) \quad (28)$$

We consider only the large-scale fading (path loss), and neglect the small-scale fading because the problem that we are tackling is a network planning problem. Winner II channel model [14] is used to obtain the path losses of all the available links. The eNB-UE, eNB-RS and RS-UE links are modeled as urban macro-cell links (C2), NLOS stationary feeder links (B5f) and urban micro-cell links, respectively. The C2 and B1 links propagation conditions (LOS or NLOS) are generated randomly by the Winner model using the distance-dependent empirical LOS probabilities [14], and the path loss is averaged over 10 iterations. The different simulation parameters are provided in Table 1.

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Cell Radius (R)	500m
Cell load in adjacent cells (σ_A)	1
eNB transmit power ($P_{\text{eNB,total}}$)	46 dBm
RS transmit power ($P_{\text{RN,total}}$)	30 dBm
Thermal noise (N_0)	-174 dBm/Hz
Bandwidth of 1 PRB (W)	180 KHz
Penetration loss	20 dB
NF of UEs	9 dB
NF of RSs	5 dB
Average number of users served by RS (v)	4

A. Optimizing for Cell Edge Throughput

Results are shown for the case when the objective function used is the total cell-edge rate. The rates of 50 users and their CDFs are shown in Figs. 3, 4 and 5. We note that the rates of cell-centre users have generally decreased after the use of relays. This is due to the frequency reuse among the eNB and RS in the 2nd timeslot, which adds intra-cell interference. On the other hand, the rates of cell-edge users have increased after the use of relays, and this increase is maximized in setup 3 by the optimal placement of RSs. This is shown in the optimal positions of RSs for the given user distribution (Fig. 6), where the circles and the plus signs represent the positions of the RSs in setups 2 and 3, respectively. The stars and the pentagons represent the cell-centre and cell-edge users, respectively. The optimal RS placement did not increase the rates of the 5$^{\text{th}}$ cell-edge user as shown in Fig. 4, because the objective function is the total cell-edge user rates, so it is not guaranteed to maximize the rates of every individual cell-edge user.

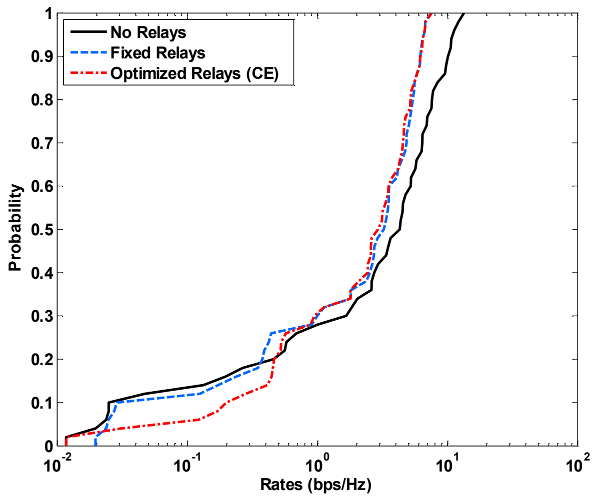

Figure 3: CDFs of users rates for different relaying scenarios.

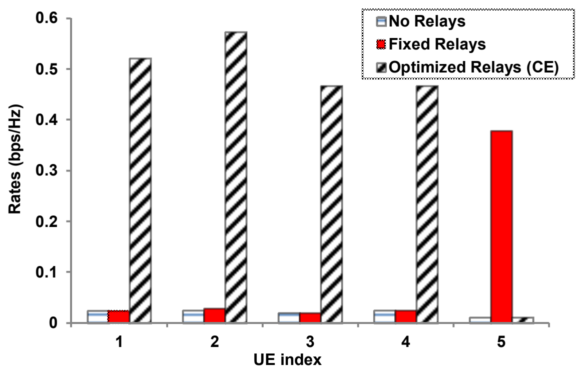

Figure 4: Rates of cell-edge users at $\sigma = \sigma_A = 1$.

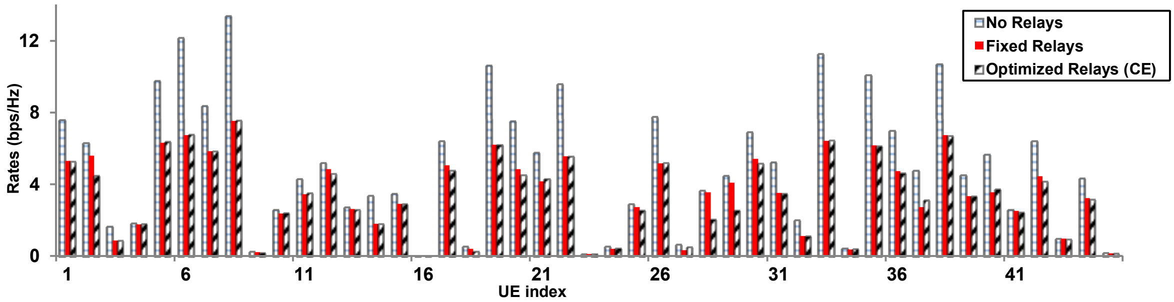

Figure 5: Rates of cell-center users at $\boldsymbol{\sigma} = \boldsymbol{\sigma}_{\mathbf{A}} = \mathbf{1}$.

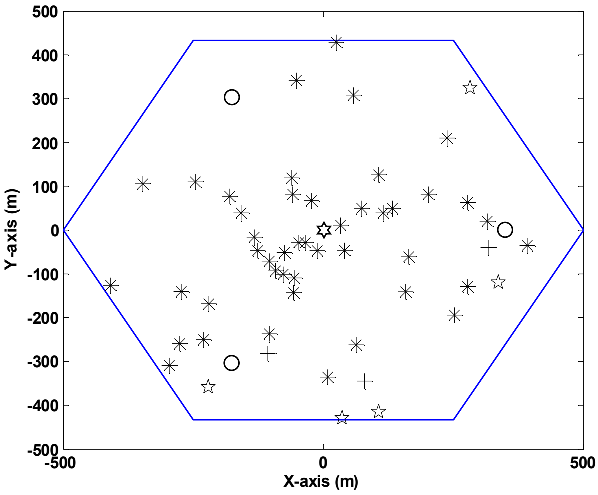

Figure 6: Optimal RS placement for the total cell-edge capacity objective function.

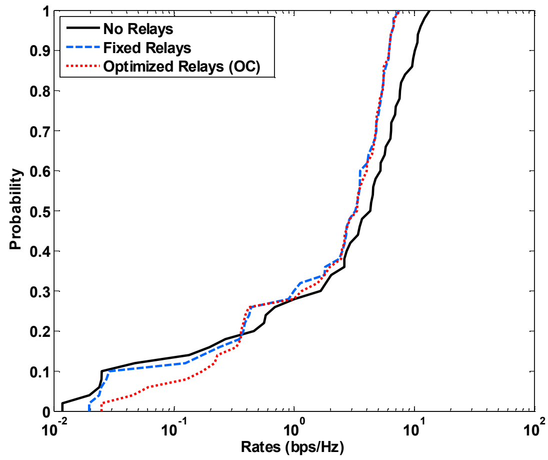

Figure 7: CDFs of users rates for different relaying scenarios.

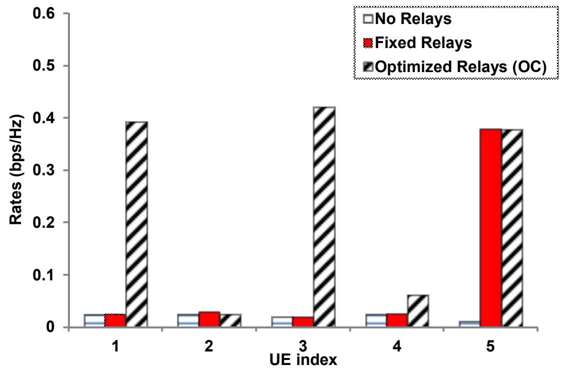

Figure 8: Rates of cell-edge users at $\sigma = \sigma_A = 1$.

B. *Optimizing for Overall Cell Throughput*

In these set of results, the other objective function targeting the total cell rate is used. The rates and their CDFs of the same user distribution are shown in Figs. 7, 8, and 9. We note here that this objective function is in favor of cell-center users, because when the objective function is maximizing the total cell capacity, the cell-center users will have more weight as their rates are much larger than cell-edge rates. So, the optimal placement tends to decrease the effect of intra-cell interference of relays on cell-center users. This is shown in Fig. 10, where the RSs are placed as far as possible from the cell-center users. On the other hand, the placement does not care much about increasing the cell-edge rates, as their values are small and increasing them will not have much effect on the total cell capacity. This clear bias happened because of the large difference between the nominal values of cell-center and cell-edge rate.

C. *Variation with Cell Load*

The per-user rates and the cell-edge per-user rates are calculated for setup 1, 2, and the 2 versions of setup 3. The results are drawn for different values of number of users, which are indicated by the cell load (σ). The cell load of adjacent cells

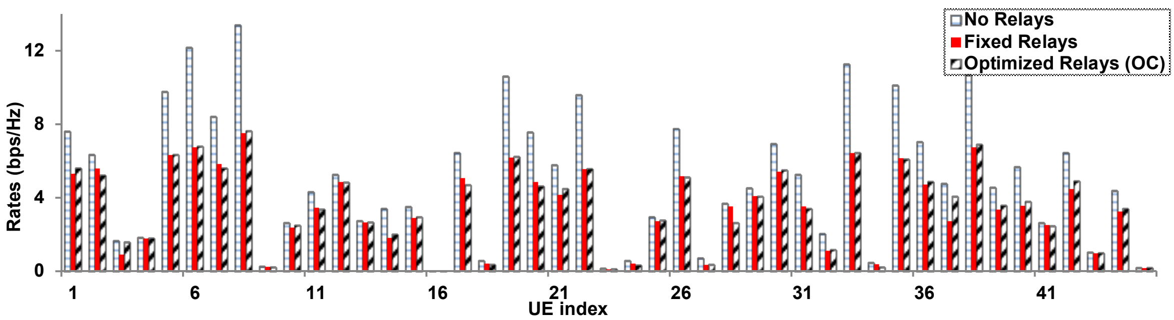

Figure 9: Rates of cell-center users at $\boldsymbol{\sigma} = \boldsymbol{\sigma}_{\mathbf{A}} = \mathbf{1}$.

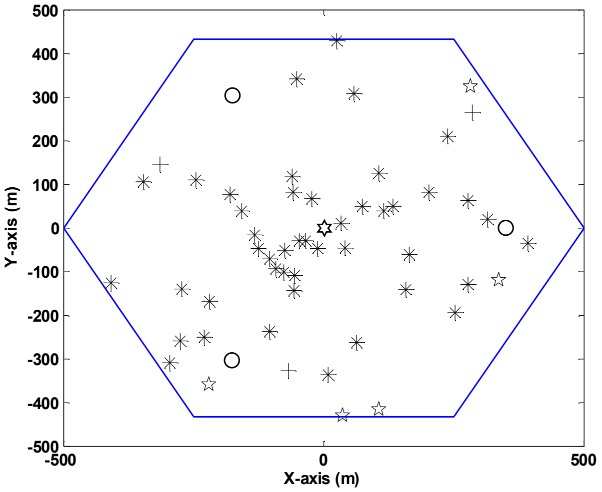

Figure 10: Optimal RS placement for the total cell capacity objective function.

is fixed at $\sigma_A = 1$ as a worst case. The effect of varying the cell load on the cell-edge per-user capacity is shown in Fig. 11.

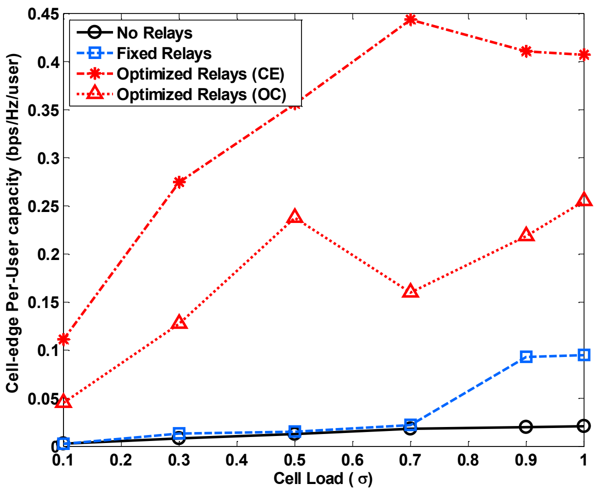

Figure 11: The Cell-edge Per-User Capacity vs. Cell Load.

The figure shows the high gain of cell-edge rates after using the RSs, where this gain is maximized in setup 3, with the total cell-edge capacity as an objective function. However, this gain comes at the expense of decreasing the cell-center rates due to the intra-cell interference added by the RSs. For the case of total cell capacity objective function, the exhaustive search aims to decrease the effect of intra-cell interference due to RSs, but it cannot outperform the original setup (setup 1). This is shown in Fig.12, where the effect of varying the cell load on the per-user capacity is shown. At $\sigma = 1$, the values of the 10%tile capacity for the setups 1, 2 and the two versions of setup 3 (Cell-edge capacity and Overall capacity objective functions) are 0.02484, 0.0288, 0.1994, and 0.1724, respectively. This is corresponding to capacity gain factors of 1.159, 8.027 and 6.940, in setup 2 and the 2 versions of setup 3, respectively. This shows that maximum cell-edge rate is achieved by setup 3, with cell-edge capacity objective function. On the other hand, the relative decreases in cell-centre per-user

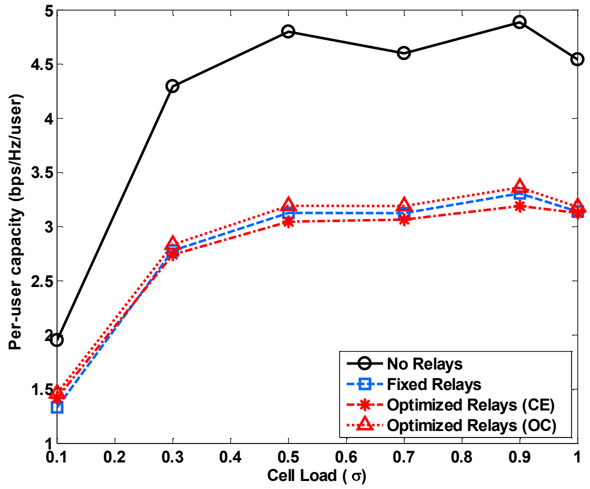

Figure 12: Per-user Capacity vs. Cell Load.

capacity values are 30.06%, 32.06% and 30.50%, in setup 2 and the 2 versions of setup 3, respectively.

When we repeat the above calculations for 25 CPs only, the capacity gain factors for the 2 cases of setup 3 become 2.884 and 2.119 only. This shows that assuming more CPs increases the probability of finding the RSs at better location, thus it increases the capacity gain for the cell-edge users; but this increases the total number of combinations.

D. Variation of Adjacent Cell Loads

The per-user rates and the cell-edge per-user rates are calculated for setup 1, 2, and the 2 versions of setup 3. The results are drawn for different values of adjacent cell loads (σ_A), whereas σ is fixed at the value 1. The results are shown in Figs. 13 and 14, where we note that the range of the users rates is relatively higher than that in Figs.11 and 12. This is because the cell load σ is assigned its maximum value of 1, and the adjacent cell loads σ_A are decreased resulting in higher rates in the center cell.

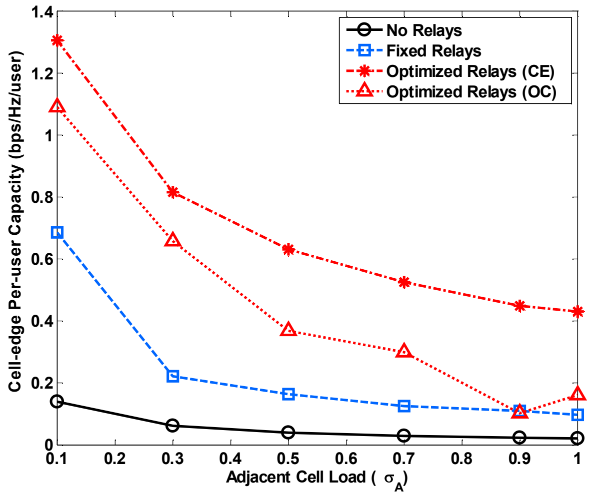

Figure 13: Cell-edge Per-user capacity vs. Adjacent Cell Load.

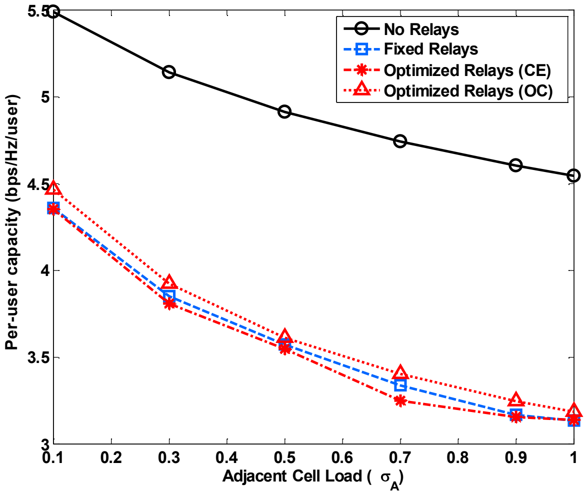

Figure 14: Per-user Capacity vs. Adjacent Cell Load.

V. COCNLUSION

In this paper, we studied the relay placement problem within LTE-A context taking into account both inter-cell and intra-cell interference. We proposed an optimization framework to maximize the total cell capacity or total cell-edge capacity. The simulation results show that adding RSs to the cell increases the capacity for the cell-edge users, where the capacity gain factor reaches the value of 8.027. This high gain was achieved without a severe effect on the cell-centre users, where the maximum relative decrease in the per-user capacity is 31.62%. To solve large-scale problems, we need to solve this problem by more sophisticated mathematical methods because the exhaustive search will be computationally prohibitive in that case. To make the model more realistic, we can account for the randomness of the user positions by adding a stochastic user distribution model to our system model.

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