Indian Institute of Technology Bombay

Project Report

Optimal relay placement for coverage extension in LTE-A cellular systems

Authors:
Sahil Chawla - 140070060
Shruti Hiray - 14D070016
Himani - 14D070047

Guide:
Prof. Abhay Karandikar
Mentor:
Sadaf Ul Zahra

A report submitted in fulfillment of the requirements for EE764 Course Project

Department of Electrical Engineering
Indian Institute of Technology Bombay

April 2018

Abstract

Relay Nodes (RNs) can be used for capacity enhancement and coverage extension in LTE cellular systems. RNs provide a rapid low cost alternative to deploying new eNodeBs for coverage extension. Various factors need to be considered while deploying RNs in a cellular system. Consider a RN placed close to the cell edge. It has the advantage of providing high rates to the cell edge users but it may also lead to excessive interference in the neighboring cell. On the other hand, placing RNs away from the cell edge may defeat the purpose of using a RN if the edge users continue to remain in outage with a high probability. In this project, we study the optimal placement of RNs in LTE-A cellular systems. [1] gives some algorithms for optimal relay placement with and without interference considerations and simulate an LTE cellular system and use various algorithms for determining the placement of RNs in the system and compared performance of multiple algorithms.

Contents

Chapter 1

Introduction

1.1 Motivation

Provision of desired signal to interference and noise ratio (SINR) to users, especially at cell edge with rapid increase in number of cellular subscribers and scarce frequency spectrum available is a matter of concern. Easiest solution to support increasing users per cell is to decrease the cell radius which increases the base stations (known as evolved-NodeB (eNB) in 3GPP-LTE) required per area indirectly multiplying the infrastructure costs several times. Decreasing cell radius also increases the inter cell interference which has to be dealt separately then.

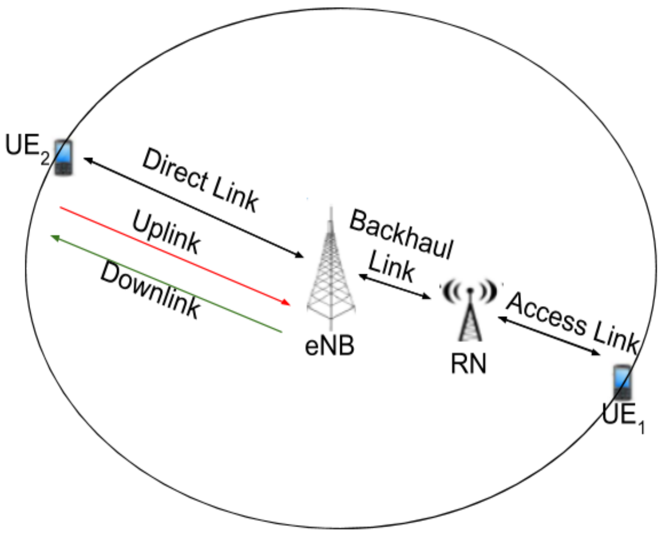

FIGURE 1.1: Relay Node Cellular Network.

Relaying is one of the features being proposed for the 4G LTE Advanced system with the aim to enhance both coverage and capacity. Increase in cell capacity is due to the link diversity achieved due to two links: direct link which is between User Equipment

(UE) and eNB or indirect link between UE to eNB via relay node (RN), shown in Fig1.1. This leads to lower blocking probability for incoming calls indicating that greater traffic of users can be supported with same cell area.

1.2 Relaying

Deployment of Relay Nodes (RNs) help increase the radio coverage (cell radius). RNs become closer to User Equipments (UEs) at cell edge as compared to eNBs and therefore the SINR desired at the UE is improved. This is because RNs being closer to the cell edge UEs than the eNB, improve received SINR to these UEs. The increase in cell radius depends upon the radial position of the RNs in the cell as it affects the eNB-RN (backhaul) and RN-UE (access) links. Placing RN close to eNB i.e. away from cell edge results in low SINR on access link(due to increase in path loss) which makes cell edge UEs more outage prone. Whereas, placing RN near cell edge results in low SINR on backhaul link and high interference to UEs(at cell edge) of neighbouring cells. Therefore, in order to achieve maximum extension in cell radius there is a need to determine optimal radial position of the RNs.

Downlink and Uplink scenarios in cellular system are asymmetrical in terms of coverage due to difference in the transmit power. Considering them individually will give different relay node placements. Therefore, a joint optimization problem for relay node placement is formulated considering both downlink and uplink transmissions in the system. Maximizing the coverage area of the cell (defined in terms of the probability of correct decoding at a point), the optimal RN placement is achieved for the single cell scenario as well as multi cell scenario (i.e. including interference form neighbouring cells). Variation in optimal location of RN placement for varying decoding thresholds is also observed. The documentation is organized as follows: Chapter 2 deals with the system model and problem formulation along with the algorithms for scenarios with and without interference, and Chapter 3 concludes the report presenting the simulation results and inferences.

Chapter 2

System Model

2.1 Introduction

The system model comprises of two hop LTE-A cellular system. Each cell consists of N_R Relay Nodes (RNs) placed symmetrically at radial distance R_B around every eNB as shown in Fig. 1. The reference cell is surrounded by first tier of co-channel cells.

The maximum transmit power of eNB, RN & UE is denoted by P_{eNB}, P_{RN} & P_{UE} respectively. The gains of eNB, RN & UE is denoted by G_{eNB}, G_{RN} & G_{UE} respectively. The pathloss exponent is denoted by η, thermal noise level by N.The maximum transmit power values are 46, 30 and 24 dBm and antenna gains are 16, 5 and -1 dB for eNB, RN and UE respectively as per the LTE-A specifications [2]

The log-normal shadowing ξ is on each link, where ξ is a Gaussian random variable with mean 0 and standard deviation σ_a and σ_b for the access and backhaul links respectively. The effect of fast fading on all wireless links is ignored for a long term coverage perspective and hence the model is applicable for both Frequency Division Duplex (FDD) & Time Division Duplex (TDD) LTE-A based systems.

2.2 Coverage Radius, Relay Placement & No. of Relays

Coverage Radius is a metric of the cell coverage. Considering direct transmission from eNB to UE in DL located at distance d, the received SNR at UE is given by $SINR_{eNB-UE} = P_{eNB} - 10 * \eta * \log d - N + \xi$. Let T be the threshold required of the minimum SNR for correct decoding of the received signal. Let pc^d be the probability of correct decoding of the received signal. Then,

$pc^d = Pr(SINR_{eNB-UE} > T)$
$= Pr(P_{eNB} + G_{UE} - 10 * \eta * \log d - I_{UE} - N + \xi > T)$
$= Pr(\xi > T - P_{eNB} - G_{UE} + 10 * \eta * \log d + -I_{UE} + N)$
$= Q(\frac{T+N+I_{UE}-P_{eNB}-G_{UE}+10*\eta*\log d}{\sigma})$

........(1)

We define a point to be covered if pc^d at the point is greater than or equal to 0.5. Coverage Radius R_{cov} is the distance at which pc^d equals 0.5. We thus get,

$$R_{cov} = 10^{\frac{P_{eNB}+G_{UE}-T-N-I_{UE}}{10*\eta}}$$

........(2)

Considering RN-assisted LTE-A system, for UE outside the coverage area of eNB, it is handed to one of the RNs of the cell. Thus pc^d is,

$pc^d = pc^d_b * pc^d_a$
$= Pr(SINR_{eNB-RN} > T) * Pr(SINR_{RN-UE} > T)$
$= Q(\frac{T+N+I^d_{RN}-P_{eNB}-G_{RN}+10*\eta*\log R^d_b}{\sigma_b}) * Q(\frac{T+N+I_{UE}-P_{RN}-G_{UE}+10*\eta*\log R^d_a}{\sigma_a})$

........(3)

where pc^d_b is the probability of correct decoding in eNB-RN link and pc^d_a is the probability of correct decoding in RN-UE link and $R^d_b and R^d_a$ are the distances from eNB-RN link and RN-UE link respectively.

Optimal location to deploy a RN must lie on the line joining eNB and UE. $R^{d*}_{cov} = R^{b*}_{cov} + R^{a*}_{cov}$ where R^{b*}_{cov} is the optimal RN placement radius in DL and R^{a*}_{cov} is the distance between RN and UE such that pc^d equals 0.5

Coverage radius R^{d*}_{cov} is the maximum distance from eNB at which pc^d is greater than or equal to 0.5 in DL scenario.

However the UL transmission scenario is different as maximum transmit power of UEs is lesser than eNB in DL. A relay at R^{d*}_b may result in pc^u to be less than 0.5. Hence a joint optimization problem of UL and DL is necessary.

For UL transmission probability of correct decoding pc^u is given by:
$pc^u = R_b^{max} * pc_b^u$
$= Pr(SINR_{UE-RN} > T) * Pr(SINR_{RN-eNB} > T)$
$= Q(\frac{T+N+I_{RN}^u - P_{UE} - G_{RN} + 10*\eta*\log R_b^u}{\sigma_b}) * Q(\frac{T+N+I_{eNB} - P_{RN} - G_{eNB} + 10*\eta*\log R_a^u}{\sigma_a})$

........(4)

We need to find R_b such that the probability of correct decoding in both uplink pc^u and downlink pc^d is greater than or equal to 0.5
$R_b^* = \underset{R_b \in (0, R_b^{max}]}{argmax} \ \min\left((R_a^u + R_b), (R_a^d + R_b)\right)$ s.t. $\min\left(pc_a^u, pc_b^u, pc_a^d, pc_b^d\right) = 0.5$

........(5)

where $R_b^{max} = \min\left(R_b^{umax}, R_b^{dmax}\right)$ and R_b^{umax}, R_b^{dmax} are the maximum possible placement relay distances for UL and DL respectively.

R_{cov}^* is the maximum coverage extension & R_b^* is the optimal relay placement. R_a^* is given as $R_{cov}^* - R_b^*$ and number of relays N_R is given by,

$$N_R = \left\lceil \frac{\pi}{sin^{-1}(\frac{R_a^*}{R_b^*})} \right\rceil$$

........(6)

2.3 Algorithm

2.3.1 Algorithm for Interference-free Scenario

In single cell scenario (i.e interference free), we have $I_{UE} = I_{RN}^d = I_{RN}^u = I_{RN}^d = I_{eNB}$ $= 0$. Follow the below steps to determine the optimal value of RN placement (R_b^*), cell coverage (R_{cov}^*) and number of relay nodes required (N_R). [3]

1. Determine the value of R_b^{umax} and R_b^{dmax} by equating $pc_b^u = 0.5$ and $pc_b^d = 0.5$. And, $R_b^{max} = \min\left(R_b^{umax}\ ,\ R_b^{dmax}\right)$.
2. For $R_b = 1$, compute R_a^u such that $pc_b^u.pc_a^u = 0.5$. Then, assign $R_{cov}^u = R_b + R_a^u$.
3. For $R_b = 1$, compute R_a^u such that $pc_b^d.pc_a^d = 0.5$. Then, assign $R_{cov}^d = R_b + R_a^d$.

4. $R_{cov}^{(0)} = \min\ (R_{cov}^{u}, R_{cov}^{d})$.

5. Repeat the Steps 2 and 3 $\forall\ R_b \in (1, R_b^{max}]$ and form the array R_{cov}.

6. Finally compute $R_{cov}^{*} = \max\ (R_{cov})$ and optimal relay placement distance R_b^{*} is the value of R_b corresponding to R_{cov}^{*}. Also, $N_R = \left\lceil \frac{\pi}{sin^{-1}(\frac{R_{cov}^{*} - R_b^{*}}{R_b^{*}})} \right\rceil$.

2.3.2 Algorithm for Interference-inclusive scenario

The algorithm for interference-inclusive scenario uses the results of $R_{cov}^{*}\&N_R$ obtained from interference-free scenario is fed into the values $(R_{cov}^{noint})\&N^{noint}$. In Downlink scenario, I_{RN}^{d} at the reference RN is the sum of interference powers from neighboring eNBs depicted in Fig. 2.1: [1]

$$I_{RN}^{d} = \sum_{i=1}^{6} I_{rd}^{i} = \sum_{i=1}^{6} p_{act}(Q_{eNB} + G_{RN})d_i^{-\eta}$$

where I_{rd}^{i} and d_i are the interference power and distance from the i^{th} eNB to the reference RN.

Similarly I_{UE} in downlink at reference UE is calculated as:

$$I_{UE} = \sum_{i=1}^{6} I_u^{i} = \sum_{i=1}^{6} \frac{p_{act}}{N_R} \sum_{r=1}^{N_R} (Q_{RN} + G_{UE})d_{i,r}^{-\eta}$$

where I_u^{i} is the interference power received at reference UE from RNs of i^{th} neighboring cell and distance and $d_{i,r}$ is distance between reference UE and the r^{th} RN of i^{th} cell.

Similarly we compute the interference power for Uplink scenario. I_{eNB} at reference eNB is the sum of interfering powers from RNs of neighboring cells. This is depicted in Fig. 2.2 [1]

$$I_{eNB} = \sum_{i=1}^{6} I_e^{i} = \sum_{i=1}^{6} \frac{p_{act}}{N_R} \sum_{r=1}^{N_R} (Q_{RN} + G_{eNB})de_{i,r}^{-\eta}$$

where I_e^{i} is the interference power at reference eNB from RNs of i^{th} neighboring cell and $d_{e,r}$ is distance between reference eNB and the r^{th} RN of i^{th} cell.

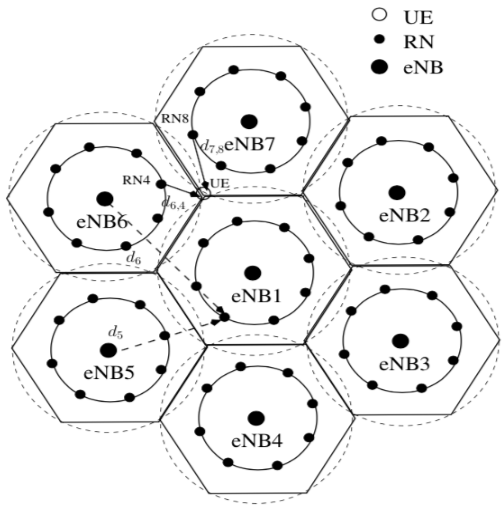

FIGURE 2.1: Interference Scenario in DL

For I_{RN}^u, the assumption is that UEs are uniformly distributed in cell.

$$I_{RN}^u = \sum_{i=1}^{6} I_{ru}^i = \sum_{i=1}^{6} \frac{p_{act}}{N_{UE}} \sum_{u=1}^{N_{UE}} (P_{UE} + G_{RN}) dr_{i,u}^{-\eta}$$

where I_{ru}^i is the interference power at reference RN from UEs of i^{th} neighboring cell and $dr_{i,u}$ is distance between reference RN and the u^{th} UE of i^{th} cell.

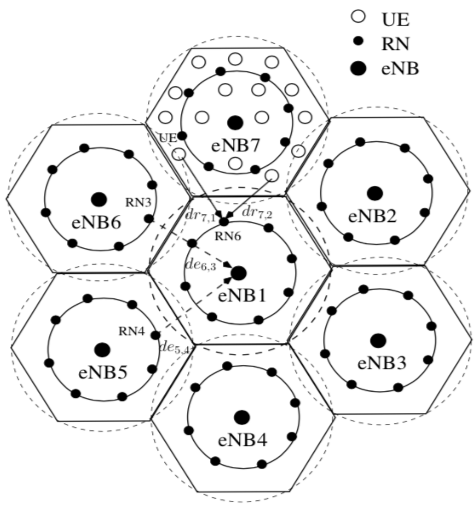

FIGURE 2.2: Interference Scenario in UL

The algorithm is as follows: $R_{cov}^{(1)} \leftarrow R_{cov}^{(noint)}$: value of R_{cov}^* obtained from interference free scenario

$R_{cov}^{(0)} \leftarrow 0$

$N_R^{(1)} = N_R^{(noint)}$:value of N_R obtained from interference free scenario

$i \leftarrow 1$
while $|R_{cov}^{(i)} - R_{cov}^{(i-1)}| > \epsilon$ do

For **Downlink** Scenario:
for each $R_b \in (0, R_{cov}^{(i)}]$
$R_{cov}^{d} \leftarrow \phi$
Compute I_{RN}^{d} and I_{UE}
$pc_b^d = Q(\frac{T+N+I_{RN}^d-Q_{eNB}-G_{RN}+10*\eta*\log R_b^d}{\sigma_b})$
flag $= 0$
if $pc_b^d < 0.5$ then
set flag $= 1$ and break the loop
end if
$pc_a^d = Q(\frac{T+N+I_{UE}-Q_{RN}-G_{UE}+10*\eta*\log R_a^d}{\sigma_a})$
Solve $pc_a^d . pc_b^d = 0.5$ for R_a^d
Append $R_a^d + R_b$ to R_{cov}^d
end for

if flag $= 1$ then
Append $0s$ to R_{cov}^d to fill the remaining array
end if

For **Uplink** Scenario:
for each $R_b \in (0, R_{cov}^{(i)}]$
$R_{cov}^{u} \leftarrow \phi$
Compute I_{RN}^{u} and I_{eNB}
$pc_b^u = Q(\frac{T+N+I_{eNB}-Q_{RN}-G_{eNB}+10*\eta*\log R_b^u}{\sigma_b})$
flag $= 0$
if $pc_b^u < 0.5$ then
set flag $= 1$ and break the loop
end if
$pc_a^u = Q(\frac{T+N+I_{RN}^u-Q_{UE}-G_{RN}+10*\eta*\log R_a^u}{\sigma_a})$
Solve $pc_a^u . pc_b^u = 0.5$ for R_a^u
Append $R_a^u + R_b$ to R_{cov}^u
end for

if flag $= 1$ then
Append $0s$ to R_{cov}^u to fill the remaining array

end if

R_{cov} = min (R^d_{cov},R^u_{cov})
$i \leftarrow i + 1$
$R^{(i)}_{cov}$ = max R_{cov}
$R^{(i)}_b$ = argmax R_{cov}
$N^{(i)}_R = \left\lceil \frac{\pi}{sin^{-1}(\frac{R^{(i)}_{cov} - R^{(i)}_b}{R^{(i)}_b})} \right\rceil$

end while

The coverage radius is obtained as,
$$R_{cov} = \underset{R_b \in (0, R^{max}_b]}{argmax} \ \min\left((R^u_a + R_b), (R^d_a + R_b)\right)$$

........(7)

In case of interference scenario, SINR at the receiver is not only dependent on transmit power and antenna gains but also on the number of RNs in each cell and the distance between transmitter and receiver. Therefore, the value of R_{cov} is required to determine R_a for a given value of R_b.

Chapter 3

Simulation Results

The following sections will show in detail the numerical results of using the algorithms specified in subsections 2.3.1 & 2.3.2. The value of maximum transmit power and antenna gains for eNB, RN and UE are based on LTE-A specifications [2].
The value of Noise level (N) is considered to be -100 dBm, decoding threshold (T) is 3.8 dB, number of UEs (N_{UE}) is 120, and number of subcarriers (N_{sc}) is 512. Standard deviation of shadowing on access (σ_a) and backhaul (σ_b) links are assumed to be 6 and 3 dB respectively. Path loss exponent η is taken to be 3.5.

3.1 Simulation 1

Simulation 1 is for interference-free scenario using the algorithm given in the subsection 2.3.1. In Fig 3.1 we see the effect of coverage radius (R_{cov}) against relay placement radius (R_b) for interference-free scenario in joint optimization of downlink and uplink. The optimal coverage radius (R^*_{cov}) obtained is 3.530 km & the optimal relay placement radius (R^*_b) is 2.59 km. The number of relay nodes N_R (from(6)) is 9.

3.2 Simulation 2

In the simulation of interference-inclusive scenario, the results obtained from simulation 1 (interference-free) is fed into the algorithm in the subsection 2.3.2. (i.e. (R^{noint}_{cov}) = $3.53km$ and $N^{noint} = 9$. Using decoding threshold T = 3.8 dB and probability of sub-activation $p_{act} = 1$ and, the value of coverage radius R^*_{cov} converges to 2.45 km (Fig. 3.2). The corresponding value of optimal RN placement location R^*_b is 1.644 km and the number of RNs N_R required is 7. In the same figure, (Fig. 3.2), we also observe

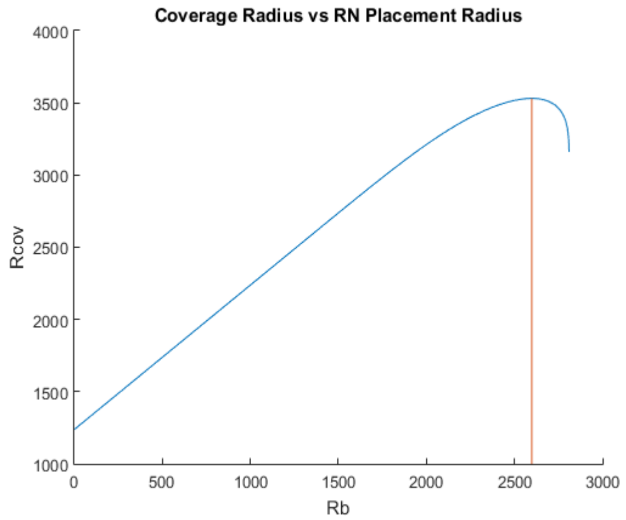

FIGURE 3.1: Coverage Radius vs Optimal RN Placement Radius (in m) for interference-free scenario

the impact of p_{act} on R_{cov}. Upon increasing p_{act} the value of coverage radius decreases. This is because, reduction in p_{act} implies lesser subcarriers being used and hence lower interference on the reference cell, resulting in increased cell coverage. $p_{act} = 1$ represents a worst case scenario where all the subcarriers in a cell are being used as a result it gives least coverage radius.

Using the probability of subactivation $p_{act} = 1$, Fig 3.3 plots the convergence of coverage radius R_{cov} for various values of decoding threshold. We see that the cell coverage radius increases with the decrease in decoding threshold with least value of coverage radius at T = 4.2 dB and highest value of coverage radius at T = 3.8 dB. This is because a lower limit of threshold, relaxes the required SINR values, hence increased interference is tolerated with increase in coverage radius.

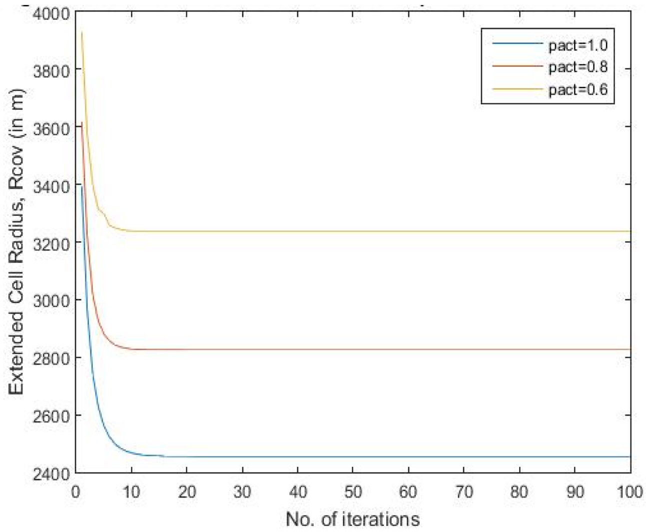

FIGURE 3.2: Convergence of Coverage Radius with probability of subcarrier activation value p_{act} at threshold $T = 3.8$ dB

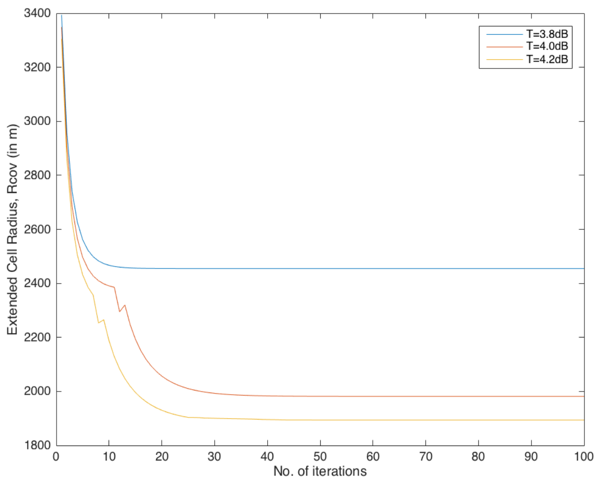

FIGURE 3.3: Convergence of Coverage Radius for varying threshold values T keeping probability of subcarrier activation value $p_{act} = 1$

Chapter 4

Conclusion & Future Work

In the project we explored the algorithm of optimal relay placement location for interference and interference-free scenarios. As a result along with optimal relay placement location we could also provide the estimates of coverage radius and number of relays required in a cell. We have also seen that the optimization problem has to consider both UL and DL scenarios because of their asymmetrical nature because calculations considering only DL can degrade UL performance.

We have also explored the effect of probability of subactivation carriers and decoding threshold on the coverage radius. These algorithms can also be simulated on non-LTE-A based systems by changing the required parameters.

We plan to explore more algorithms and compare the performance of various algorithms on the optimal relay placement location problem.

Bibliography

[1] S. Khakurel, M. Mehta, and A. Karandikar. Optimal relay placement for coverage extension in lte-a cellular systems. In *2012 National Conference on Communications (NCC)*, pages 1–5, Feb 2012. doi: 10.1109/NCC.2012.6176739.

[2] 3GPP TSG-RAN WG1 R1-08426. Text proposal for evaluation methods. 2008.

[3] G. Joshi and A. Karandikar. Optimal relay placement for cellular coverage extension. In *2011 National Conference on Communications (NCC)*, pages 1–5, Jan 2011. doi: 10.1109/NCC.2011.5734705.