Impact of Relay Station Positioning on LTE Uplink Performance at Flow Level

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Abstract—**Long Term Evolution (LTE) is the latest cellular system that is being standardized by the 3rd Generation Partnership Project (3GPP) and is expected to substantially improve end-user throughput and reduce user plane latency, while at the same time significantly improve user experience with full mobility. To realize these expectations, 3GPP is investigating the relay station (RS) usage in LTE networks, which is an intermediate station placed between a Mobile Station (MS) and evolved Node-Bs (eNode-Bs). The RS positioning is an important factor that severely influences the LTE uplink performance. This paper analyses the impact of RS positioning on the LTE uplink performance at flow level by using numerical and simulation experiments.**

Keywords-LTE; uplink performance; relay station positioning

I. INTRODUCTION

The ever increasing customer demand for faster and more diverse services in combination with an increasing demand for user experience with full mobility, motivates standardization bodies, such as the 3rd Generation Partnership Project (3GPP) to standardize new cellular systems. The latest cellular system that is being standardized by 3GPP is Long Term Evolution (LTE), see [1], [13]. The main goals of LTE are to substantially improve end-user throughput, i.e., up to 100 Mbps in the downlink and up to 50 Mbps in the uplink, and reduce user plane latency, i.e., under the 5 ms, while at the same time significantly improve user experience with full mobility.

An LTE network consists of two main parts, the Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and the Evolved Packet Core (EPC) network. The typical E-UTRAN consists only of evolved Node-Bs (eNode-s), which represent the Base Stations (BSs) used to provide radio access to all Mobile Stations that are within its radio coverage. The EPC grants users: (1) permission to the LTE cellular system, (2) support for multimedia service connectivity, roaming and mobility. EPC consists of several network entities such as: (a) the Mobility Management Entity (MME) that supports the mobility management, (b) the Home Subscriber Server (HSS) that maintains the subscription profiles of each user, (c) the Packet Data Network Gateway (PGW) that represents the packet data network gateway to the Internet, (d) the Serving Gateway (SGW) that manages the user data tunnels between the eNode-Bs and the PGW, under the supervision of the MME.

The radio air interface used between the eNode-B and the MS consists of the downlink interface (eNodeB to MS) and the uplink interface (MS to eNodeB). The downlink interface uses the Orthogonal Frequency Division Multiple Access (O-FDMA) multiple access scheme and the uplink interface is using the Single Carrier Frequency Division Multiple Access (SC-FDMA) multiple access scheme. Both schemes are using the principle of frequency orthogonality, where the available frequency spectrum is subdivided into many sub-carriers. The sub-carriers are 15 kHz apart and are used to transmit part of the available data. It can easily be derived that 7.5 SC-FDMA symbols can be transmitted in 0.5 ms when sub-carriers are 15 kHz apart.

Most research activities in cellular systems have been focusing on downlink traffic scenarios, since traffic in the downlink direction dominates communication. However, in LTE/E-UTRAN this situation is changing, since popular file uploading and social network applications will be supported that require large uplink traffic. Due to these facts the focus of this paper will be on the LTE uplink performance.

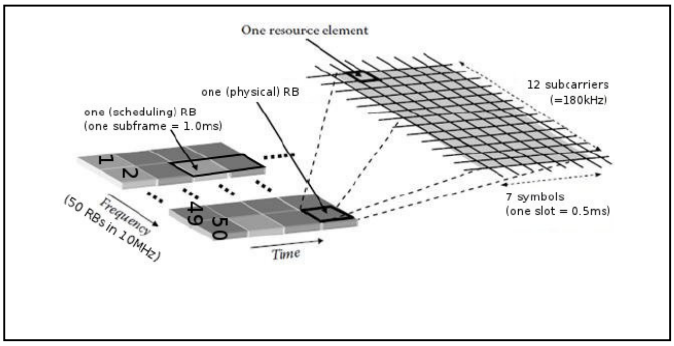

Figure 1. Uplink resource grid (based on [14]).

The frequency radio spectrum is distributed over a variety of users (MSs), who have data available to transmit, or who want to download data. This feature is realized by a scheduler that is located at the eNode-B. In order to realize this process, the Resource Block (RB) is defined, which consists of the intersection of 12 consecutive sub-carriers (180 kHz) with 0.5ms (7 SC-FDMA symbols) see Fig. 1. If for example, the carrier bandwidth is 10 MHz, then 50RBs are needed, when reasonable guard bands are used (50 * 0.180 = 9 MHz + 1 MHz guard bands). The time period of one RB is denoted as a slot, and two slots are denoted as a subframe. The scheduler operates in such a way that the throughput is maximized and the Quality of Service (QoS) requirements (e.g., for voice calls) are ensured. Scheduling decisions are taken maximally once per subframe. For the uplink radio air interface, these decisions are sent on the Physical Downlink Control CHannel (PDCCH) to the MSs. The MSs will then transmit their user data on the Physical Uplink Shared Channel (PUSCH), complying the scheduling decisions.

In contrary to downlink scheduling, in uplink scheduling the RBs assigned to a certain user (MS) must be contiguous[1]. Due to the fact that the assigned RBs needs to be contiguous, the scheduler can simply send a starting RB and the number of allocated RBs to the MS. This is more efficient than specifying for each RB whether it is assigned or not assigned to a certain user (MS). In LTE/E-UTRAN however, this procedure is even further improved by combining the starting RB and the number of allocated RBs in a single Resource Indication Value (RIV).

As already mentioned, the smallest scheduling unit is the RB. But since scheduling decisions are made at most once every subframe, that is 1ms, and a (physical) RB only takes 0.5 ms, at least two RBs are scheduled to an MS. For the sake of simplicity, these two RBs are typically denoted as a (scheduling) RB, see also e.g., [5].

The LTE/E-UTRAN specification does not recommend the use of a specific scheduling algorithm by eNode-B's. This is up to the eNode-B vendors to implement. Many different uplink scheduling algorithms exists, such as the Fair Fixed Assignment (FFA), Fair Work Conserving (FWC) and Maximum Added Value (MAV), see e.g., [5]. FFA and FWC are considered to be channel-unaware and resource-fair schedulers, while (MAV) is considered to be a channel-aware and greedy resource-unfair scheduler. Note that a scheduler is channel-aware when the taken scheduling decisions are depending on channel conditions. When these scheduling decisions are not depending on channel conditions then the scheduler is denoted as being channel-unaware. In [5] it is shown that compared to FFA and MAV, the FWC scheduler (see Fig. 2) performs the best on average.

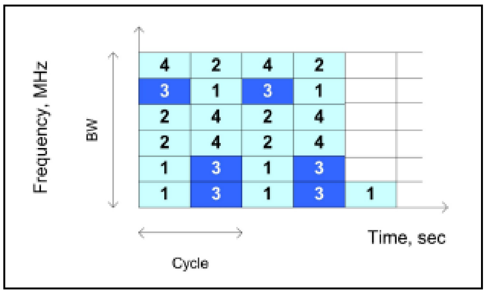

Figure 2. Fair Work Conserving Scheme (FWC) for LTE uplink, the numbers 1 to 4 stand for different MSs (copied from [4]).

Among the channel-unaware schedulers, the FWC scheduler outperforms other schedulers since no resources are wasted and all RBs are scheduled as fair as possible in every subframe. There are however, channel-aware schedulers, such as the Proportional Fair (PF) schedulers, see [11], which can outperform channel-unaware schedulers, such as the FWC scheduler. The main drawback of the PF scheduler is related to its implementation complexity. Therefore, the FWC scheduler will be modeled and used in the performance experiments accomplished in this study.

In the FWC scheduler, see Fig. 2, within each subframe (1) as many different MSs as possible are scheduled, and (2) the scheduler tries to share the RBs as equally as possible in each subframe. If the RBs are not equally dividable within a subframe, the scheduler assigns to certain MSs more RBs in one subframe, and other MSs more RBs in the following subframe(s). This is done in such a way that after a certain amount of subframes each MS has been granted an equal amount of RBs. This certain amount of subframes is called a cycle, and this cycle is repeated until an MS finishes its upload, or a new MS has a file to transmit.

The bottleneck for data rate of an LTE-network usually resides in the E-UTRAN part, since for the support of the high LTE downlink and uplink data rates a large frequency spectrum is required, while there is only a limited useful frequency spectrum available. The solution to gain higher data rates using the same frequency spectrum is to have a higher spectral efficiency. One way of implementing this solution is by using Relay Stations (RSs), which are intermediate stations placed between MSs and Node-Bs.

This paper analyses the impact of Relay Station positioning on the LTE uplink performance. Special attention is dedicated to the impact of flow level dynamics, i.e., the random user behaviour regarding the initiation and completion of data flow transfers. The research questions that are answered by this paper are:

1) Which performance model can be used to analyse the effect of the uplink LTE performance, when the positions of the RS and LTE Mobile Station are known?

2) What is the impact of the RS positioning on the LTE uplink total uplink throughput and mean transfer time?

This paper is organized as follows. Section II is providing a brief overview of relaying in LTE networks, including the uplink air interface. In Section III the related work is described. Section IV describes the performance model used and answers the first research question. The experiments, the results and their analysis are described in Section V, which also answers the second research question. The conclusions and recommendations for future work are described in section VI.

II. Relaying in LTE Networks

An important reason of using RSs in an MS – eNode-B uplink communication channel is due to the fact that the signals transmitted by an MS experience path loss. In particular, signals degenerate very fast (more than linear) over distance.

When assuming an urban setting, the *Cost 231 Hata* path loss model, see Eq. 1, for urban setting can be used to give the relation between distance and the path loss, see [9], [5]. The L_{fix} is a parameter that depends on, among others, antenna height

1 In 3GPP Release 10, it is made possible to assign two different contiguous blocks.

and transmitting frequency, a is the path loss exponent, and d is the distance between the transmitter and the receiver (in km). Eq. 2 expresses the received signal strength (received power) P^{rx} as a function of the distance d and the transmitted signal strength P^{tx}.

In the experiments accomplished in this research the path loss constant α=3.53 is used. So the signal degenerates more than cubic with the distance.

$$L(d)=10^{\frac{L_{fix}}{10}} \cdot d^{a} \text{ (linear)} \quad (1)$$

$$P^{rx} = \frac{P^{tx}}{L(d_i)} \quad (2)$$

Let us assume that an MS needs to transmit data to a eNode-B. For this it needs to overcome a certain distance. Now if an RS is placed halfway, only half the distance has to be overcome, which means $0.5^{3.53}$=0.087 times the path loss. So using an RS, less than five times transmitting power can be used by the MS for the RS to receive the signal just as strong as the eNode-B would have done otherwise. Of course the RS needs to transmit the information to eNode-B afterwards, but the RS is usually connected to an electricity power grid, meaning that the transmitting power is not limited. However, the level of the transmitting power might affect the level of interference. If the same power is needed for the RS to e-NodeB link, the same connection is achieved with 2.5 times less MS battery power. So whether an RS is used to save MS battery power or to increase the data rate, the use of RS is useful and it is worth investigating the impact of Relay Station positioning on the LTE uplink performance.

There are several ways to incorporate relaying into a system. The simplest way is by using the Amplify & Forward (AF) RS. These relays, also called repeaters, were already a part of the first LTE release (3GPP Release 8) and simply amplify the signal and forward it. Such relays do not decode the signal, and therefore cannot support bit/frame error detection and correction. Another type of relay is the Decode & Forward (DF) RS. This type of RSs is being researched for LTE-Advanced as Type II RS. The last type on RS is the so-called self-backhauling RS, and is categorized into three different types: “Type I, Type Ia and Type Ib”, according to [2], [8].

In this study Type I relaying is used, as then the RS can transmit control information about for example signal strength or retransmission to the MS himself, which saves bandwidth and has less delay. Also, Type I relays are part of the LTE-Advanced specifications, while Type II relays are still being considered as a study item.

A. Uplink scheduling with relaying

Scheduling with relaying is considered to be more complex than scheduling without relaying. Fig. 3 shows an example of eNode-B scheduling when the FWC uplink scheduling scheme is used that incorporates the use of an RS. Due to the fact the eNode-B needs to eliminate the interferences between the signals transmitted by the MS and RS, it is considered that only one device (RS or MS) can transmit to the eNode-B at any given time.

The incorporation of the RS influences scheduling as follows. If an MS can get a higher effective data rate when connected to an RS, it will then connect to the RS. In Fig. 3, MSs 1 and 4 are connected to the RS, and MSs 2 and 3 are directly connected to the eNode-B. Then, instead of transmitting data to the eNode-B in each cycle, during the first cycle the data will be transmitted to the RS, '1M' and '4M' in Fig. 3. During the second cycle the MS will not transmit, and the RS transmits the data to the eNode-B, '1R' and '4R'. It can easily be seen that the MS can only transmit on half of the RBs compared to the situation that the MS is connected directly to the eNode-B; compare the amount of '1M's to '3's in Fig. 3.

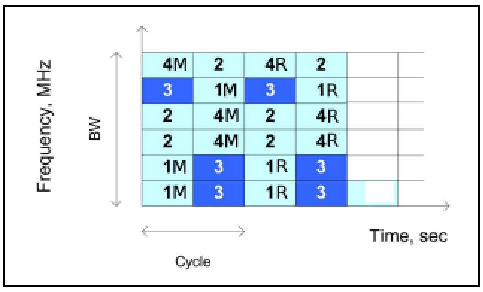

Figure 3. FWC uplink scheduling with RS (only MS1 and MS4 are connected to RS, M= MS transmits, R= RS transmits).

The disadvantage of this scheduling scheme is that some resources are wasted. Assume that the RS – eNode-B link is optimal: the RS is connected to an electricity power grid, and the antenna can be placed in direct sight of the enode-B. Therefore, the link between the MS and RS can at best achieve the same data rate as the link RS – eNode-B. If the link between MS and RS is not performing as good as the link RS – eNode-B, resources are wasted, as not the full capacity of the RB at the RS – eNode-B link is used.

III. Related Work

There are several research studies conducted on the topic of LTE relaying. Unfortunately, the authors of this paper have not found any research studies that focus on the analysis of the impact of Relay Station positioning on the LTE uplink performance, which is the main goal of this paper. Most research studies only consider downlink relaying performance, which operates in principle the same way as uplink relaying, with the essential difference that the power transmitted by the MS is not taken into account. Since no studies were found that consider uplink performance as a function of RS position, at least one downlink research study that, among others, considered optimal relay placement [3] has been analyzed. In this research study, the optimal place for a relay, in terms of increased average capacity of the BS, is calculated as lying between 70% and 80% of the cell radius, depending on the transmitted power by the relay. However, [3] is different than the research study performed in this paper, since (1) it focuses on downlink performance, (2) flow dynamics are not taken into account, (3) it uses a different relaying approach where using a direct eNode-B link has no advantage over using an indirect RS link.

There are however few research studies found that do consider uplink performance in relay enhanced LTE-networks, like [12], [7], [6] and [10], but they all investigate a different parameter than relay positioning.

Furthermore, no studies have been found that take flow dynamics into account. Fortunately, most studies do conclude that the use of a RS improves the throughput significantly, see [12], [10], [7]. For example, [10] concludes that 'the system performance is greatly improved when relays are introduced'.

It can be concluded that the research study documented in this paper is novel, since no other research study has been found that investigates the impact of Relay Station positioning on the LTE uplink performance, when flow level dynamics are being considered.

IV. MODEL DESCRIPTION

This section presents the considered network scenario, the specific performance measures and the performance model used in the accomplished experiments.

A. *Network scenario and performance measures*

1) *Network scenario*

A single LTE/E-UTRAN cell is considered. The cell has one RS, whose position is variable; since the optimal position for the RS in the cell needs to be calculated. The cell supports users in a radius of 1000 meters. The cell is set in an urban area, for which the *Cost 231 Hata* path loss model is used, see Section II. The parameters for the path loss model are chosen as L_{fix} = 141.6 dB and α = 3.53, as in [5].

The scheduling scheme being used is the FWC scheme with an RS addition, see Fig. 3. MSs can use 200 mW uplink power. The total bandwidth for uplink is 10 MHz, which translates to 50 RBs. The file an MS uploads is chosen to be 1Mbit in size. New file transfers, at random locations in the cell, are initiated according to a Poisson process with rate λ. The power of the RS (which is connected to the electricity grid) is large enough to achieve the highest data rate for each of the RBs used in the transmission.

2) *Performance measures*

First it is important to find in which part of the cell the MSs should use the RS, given the position of the RS in the cell. This part of the cell is called the RS's service area.

Once the RS's service area is defined, the total uplink throughput of the cell in Mbit/s, for different positions of the RS in the cell and for different arrival rates is investigated. The total uplink throughput is defined as the number of bits per second successfully received by the BS, whether from RS or directly from an MS.

Closely related hereto, the capacity of the system expressed in arrivals per second will be studied, which is defined as the maximum arrival rate supported by the system before the system becomes unstable.

Finally, the mean file transfer time in seconds will be investigated. This is done for different positions of the MS in the cell and for different arrival rates, when also flow dynamics are considered. This measure is defined as the average time in seconds it takes for an MS to upload a file of 1 Mbit to the BS.

B. *Performance Model*

To facilitate the necessary calculations, the cell surface is discretized, i.e. split into a large number of small parts where the MSs are assumed to have the same distance (and hence the same data rate) to the BS and/or RS. This is done by dividing the cell into zones and sectors, as can be seen in Fig. 4. The intersection of a zone and a sector is called a segment.

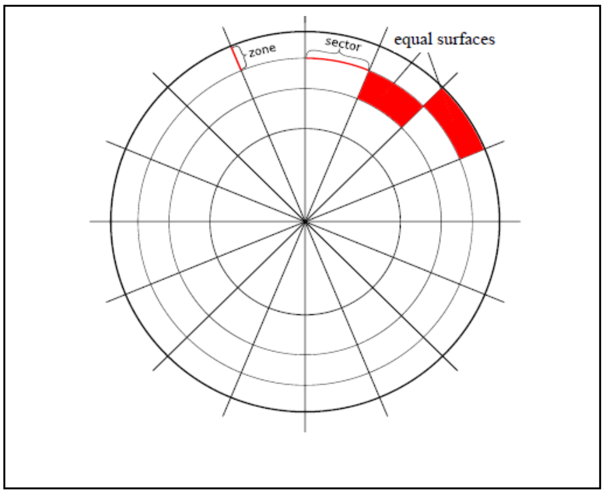

Figure 4. Model of the cell.

To calculate the surface per zone, C, see Eq. 3, it is needed to divide the total surface by the amount of zones (z_{total}), i.e. when the radius of the cell is denoted by r_{cell}.

$$C = \frac{\pi r_{cell}^2}{z_{total}}. \tag{3}$$

Determining the segments is very straightforward as every zone is divided by the same number of sectors, i.e. the surfaces of the created segments will be equal.

1) *Determining data rate*

By incorporating the proportionality constant, the path loss, and multiple RBs into Shannon's formula for channel capacity, the model for the data rate of a MS in a segment at distance *d* from the receiver (BS or RS) is obtained, see Eq. 4.

$$\text{rate} = 0.4 \cdot RBs \cdot 180\text{kHz} \cdot \log_2\left(1 + \frac{0.2}{L(d) \cdot N \cdot RBs}\right). \tag{4}$$

2) *Deciding when to use the relay*

To decide whether an MS should use the RS or the BS it is needed to know which station offers the highest effective data rate. Because data rate is a function of the distance, the distance from MS to BS and to RS needs to be calculated. Also, the fact that traffic to the RS has to be transmitted in two parts, first from MS to RS, and afterwards from RS to BS has to be considered. Using the FWC scheduling scheme discussed in Section I and II, transmitting via the RS effectively halves the data rate, since the MS only gets half the RBs assigned to upload compared to if it uses the BS directly. Given this, and using Eq. 4, for each position of a MS in the cell it can easily be determined, whether or not it is beneficial to transmit via the RS. This defines the service area of the RS.

3) Flow dynamics

New file transfers are initiated by the MSs with a rate λ (i.e. λ file transfer initiations per second). File transmissions are homogeneously spread over the cell, i.e. a MS that starts to transmit is assumed to be located in a randomly chosen segment where it will stay until the complete file is transmitted. Many experiments are done for multiple values of λ to consider the system under various loads.

The FWC scheduler model applied in this paper is not taking into account the individual data rates, but is using the *average* data rate instead. This is done as described in [5] by calculating the data rates belonging to the specific amounts of RBs, weighing them by the corresponding fractions of time that they occur, and finally summing the results.

V. Experiments and Discussions

This section describes and analyses the simulations and numerical experiments performed in this study. The main question to be investigated is: Where should the RS be positioned in order to optimize LTE network's efficiency?

A. *Experiment 1: Service area of the Relay Station*

Due to lack of space, the description of the experiments regarding the service area of the RS at different positions in the cell is omitted. The details associated with these experiments can be found in [14].

B. *Experiment 2: Total throughput and cell capacity*

Another interesting characteristic to investigate is the impact of RS on the maximum arrival rate. When incorporating an RS, the total throughput to the BS should be higher, and so a higher arrival rate of users should be possible before the system becomes unstable. It is important to note that when users arrive at a faster rate than the system can serve them, the system becomes to be unstable.

1) Experiment setup

The same scenario is used as specified in Section V.A, but with fewer zones and sectors, respectively 500 and 499, in order to speed up the simulations. The performance measures that are investigated in this experiment are the total uplink throughput and the capacity of the system described in Section IV.A.2. The experiment was done for λ values varying between 4 to 7 (file transfer initiations per second), with steps of 0.5 and for the scenario 'without RS', and 'with RS' placed at 25%, 50%, 75% and 100%.

2) Results

The results are presented in Fig. 5. In order to verify the statistical accuracy of the results and after running the experiment multiple times, the 95% confidence intervals are calculated and plotted in Fig. 5.

From Fig. 5 it can be observed that 'Without RS' and 'RS at 25%' have reached maximum capacity around 5.3 Mbps, 'RS at 50%' and 'RS at 100%' reach maximum capacity around 5.7 Mbps and with 'RS at 75%' the capacity rises to 5.8 Mbps.

So, the maximum capacity is achieved when the RS is located at 75% from the BS towards the cell edge. Apparently, there is a trade-off to be made regarding the total capacity as function of the RS's position. Starting from the cell center, the more the RS is 'moved' towards the cell edge the more users with relatively poor performance will profit. However, from a certain position of the RS the throughput of the most 'problematic' users (i.e. the ones at the cell edge) will not increase any more as there is a limit on the achievable rate per RB.

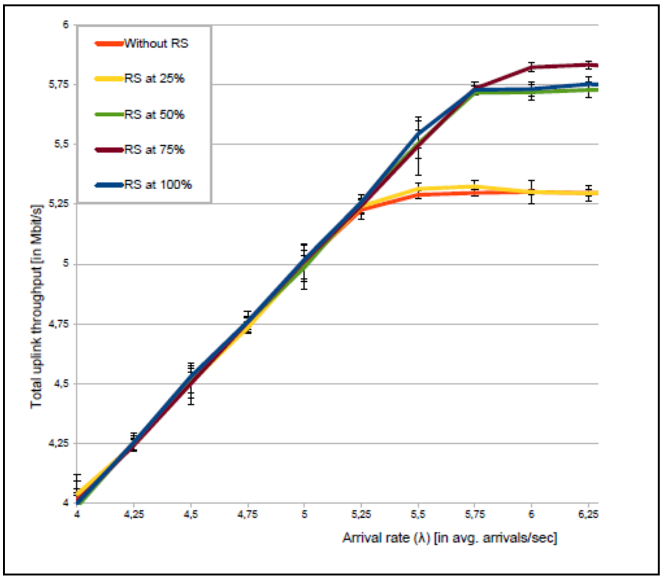

Figure 5. Total uplink throughput for various positions of the RS in the cell.

C. *Experiment 3: Impact of RS position on mean file transfer time per segment*

In this last experiment the file transfer time as function of the location (segment) in the cell is investigated. Obviously, in the situation without RS, the MSs far away from the BS (i.e. the MS at the cell edge) will have the highest file transfer times. What will then be the influence of the introduction of a RS?

1) Experiment setup

The experiment was done for λ = 1, 3, 5 (file transfer initiations per second), and for the scenario's 'without RS' as well as 'with the RS' placed at 25%, 50% and 75% towards the radio cell edge, seen from the BS. The performance measure that is investigated in this experiment is the mean file transfer time described in Section IV.A2.

2) Results

The results for λ = 3 (file transfer initiations per second) are presented in Fig. 6 to Fig. 10, for 'without RS', 'with the RS' at 25%, 50%, 75% and 100% near the cell edge, respectively. It is recommended to print and observe these figures in color.

What these figures show really well is the impact of the RS on the mean file transfer times for MSs located at different segments. The mean file transfer time has decreased very much around the RS. But, as shown by these figures, also at other places in the cell, the MSs take advantage of the effect of the RS even if they do not use the RS by themselves. This is due to the fact that the smaller flow transfer times of MSs using the RS imply that the resources they require are occupied for a smaller time; these resources become additionally available for other active MS in the cell.

The RS's service area covers about a quarter of the cell, so it seems that adding roughly three more RSs would be sufficient to achieve the maximum improvement.

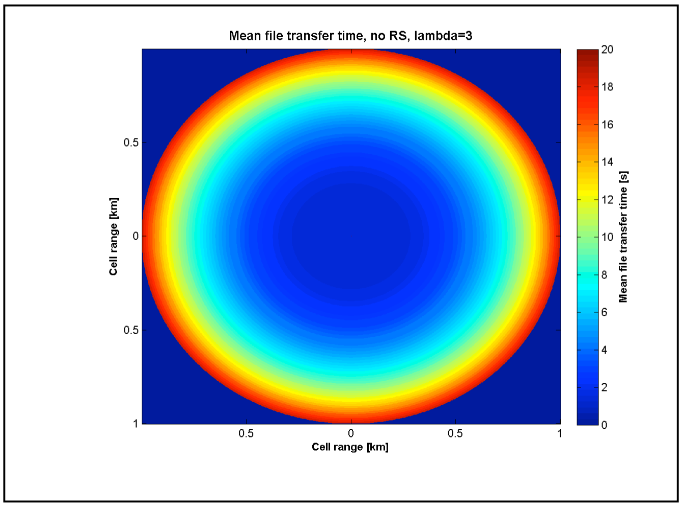

Figure 6. Mean file transfer time if no RS is used, with λ = 3.

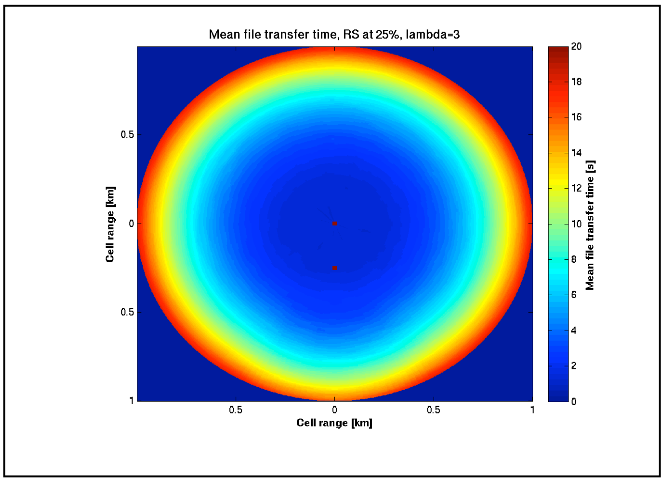

Figure 7. Mean file transfer time, with RS at 25%, with λ = 3.

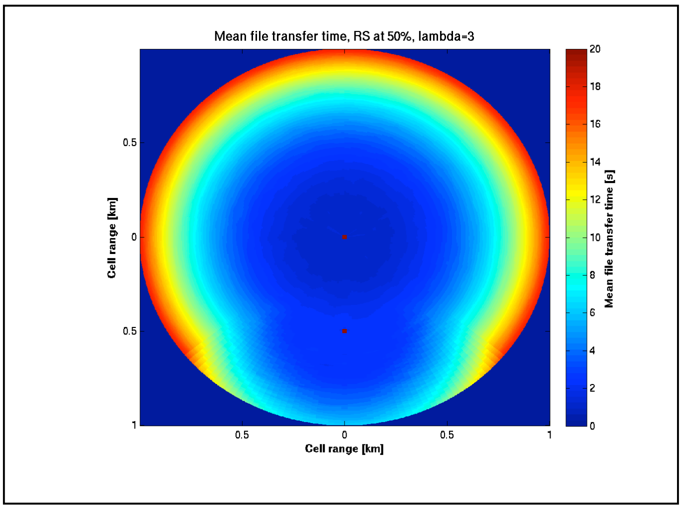

Figure 8. Mean file transfer time, with RS at 50%, with λ =3.

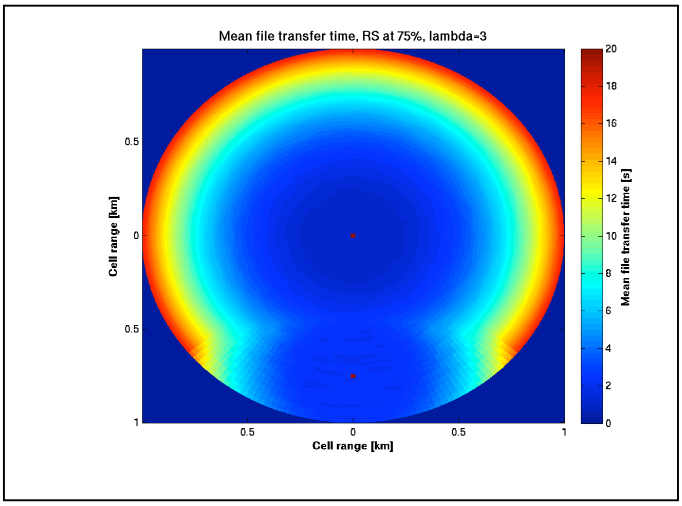

Figure 9. Mean file transfer time, with RS at 75%, with λ = 3.

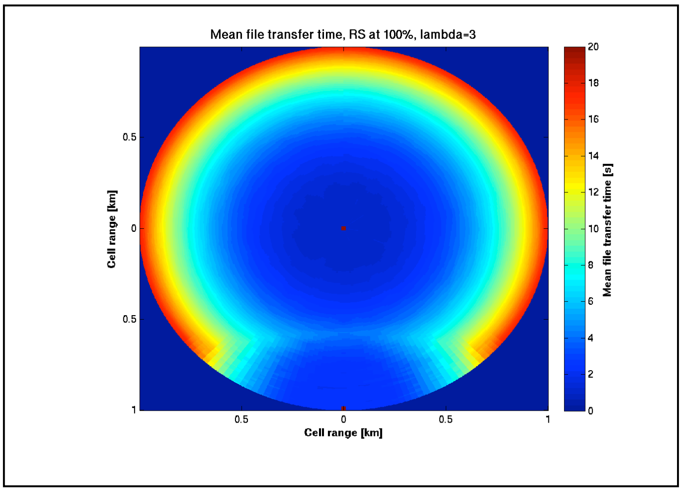

Figure 10. Mean file transfer time, with RS at 100%, with λ = 3.

VI. Conclusions and Future Work

This paper has investigated the uplink performance improvements that can be achieved by introducing relaying in LTE radio networks. The particular focus of this research was on answering the question of *where* a relay station (RS) should be positioned in a cell in order to (1) optimize network efficiency and (2) maximize throughputs of mobile stations (MSs) that generate traffic flows at random time instants and at random places in the network.

For this performance study, a model has been developed for a single LTE cell, which splits the cell into equally sized segments determined by a zone and sector coordinates. By using this cell model, the dynamic behavior of users within the cell can be easily simulated. In order to calculate the data rate of the MSs, standard models for path loss and achievable data rate were used. Furthermore, choices were made regarding the uplink scheduling scheme used for medium access control for both the RS and the MSs. In particular, the Fair Work Conserving (FWC) uplink scheduler is used, which is a channel-unaware and resource-fair scheduler.

First, the total uplink throughput and system capacity is investigated. It was shown that the RS placed at 75% of the cell radius (counted from the center towards the cell edge) provides the highest total uplink throughput, and therefore also provides the highest system capacity. This was further shown in the last experiment, where the mean file transfer time for each segment and for different arrival rates and RS positions was investigated.

So, under the conditions and assumptions used in this study, it can be concluded that the best place to locate an RS is at 75% near the cell edge.

Future study should be done to investigate the effect of (1) incorporating multiple RSs into the cell, (2) take interference from other cells into account, and (3) using other types of schedulers. Another issue that can be investigated is the impact of the back-haul link between RS and BS on the MS uplink performance. In the present paper, this link is modeled in such a way that the RS transmits at the same data rate for its communication to the BS as the MS does for the communication with the RS, which is not optimal.

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