User-Location Aware Downlink Performance Analysis of LTE Networks

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ABSTRACT

In order to evaluate the performance of Long Term Evolution (LTE) networks, system-level simulation with detailed focus on network related effects such as mobility, scheduling and interference management must be emphasized. Existing studies evaluate user throughput and dimension LTE networks usually assuming uniform distribution of users within the cell. These studies report average user throughputs over the cell and the 5th percentile throughputs as estimates of the performance of the users at the cell edge. In this thesis, we have extended an existing state-of-the-art simulation framework to take user locations into account and to validate the current performance measures. In particular, taking the locations of users into consideration may be important when estimating the throughput of users at the edge of an LTE cell. In addition, the distribution of user locations within a cell may not be expected to be uniform as it is generally assumed in existing studies. As a result, a clustered deployment of mobile users is also analyzed in order to compare performance results with the existing ones. With the extended user-location aware simulator, it is observed that 5th percentile throughput may be incompatible with cell edge throughputs and non-uniform user distributions may result in very different performance measures.

Keywords: Cell Edge Performance, Clustered Mobile Users, Long Term Evolution (LTE), System-Level Simulation.

ÖZ

Long Term Evolution (LTE) ağlarının performansını değerlendirmek için, devingenlik, çizelgeleme ve karışma yönetimi gibi ağ ile ilgili etkenlere önem veren sistem seviyesinde simülasyon yapılmalıdır. Şimdiye kadar yapılan çalışmalar, LTE kullanıcılarının hızını değerlendirirken çoğunlukla bu kullanıcıların hücre içerisinde birbiçimli şekilde dağılmış olduğunu varsaymaktadır. Bu çalışmalar, genellikle kullanıcıların ortalama hızını ve hücre kenarındaki hızını tahmin için 5. yüzde birlik dilim hızını vermektedir. Bu tezde, güncel bir simülasyon programı, kullanıcıların yerlerini de dikkate alacak bir şekilde genişletilmiş ve varolan performans ölçütlerinin geçerliliği incelenmiştir. Özellikle, kullanıcıların yerlerini dikkate almak, hücre kenarındaki kullanıcıların hızlarını doğru tahmin etmek için önem taşıyabilmektedir. Ek olarak, kullanıcıların hücre içerisindeki dağılımının genelde varsayıldığı gibi birbiçimli olmasi beklenmemektedir. Dolayısıyla, topaklanmış bir kullanıcı dağılımıyla analiz yapılıp performanslar varolanlarla karşılaştırılmıştır. Genişletilmiş kullanıcı yeri bilgisine sahip simülasyonlar 5. yüzde birlik dilim hızın hücre kenarındaki hızla uyumlu olamayabileceğini ve birbiçimli olmayan kullanıcı dağılımlarının çok farklı performans sonuçları verebileceğini göstermektedir.

Anahtar kelimeler: Hücre Kenarı Performansı, Topaklanmış Gezgin Kullanıcılar, Long Term Evolution (LTE), Sistem Seviyesinde Simülasyon.

With love to my parents who affectionately raised me in the fear of God and made me learn to excel, my loving sisters and my critics who were gracious enough to identify my incompetency; they have been invaluable to me.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2G	Second-Generation wireless telephone technology
3G	Third-Generation wireless telephone technology
3GPP	Third Generation Partnership Project
BS	Base Station
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
eNodeB	evolved NodeB
FDMA	Frequency Division Multiple Access
LTE	Long Term Evolution
MIMO	Multiple Input Multiple Output
OFDMA	Orthogonal Frequency-Division Multiple Access
PF	Proportional Fair
SINR	Signal to Interference and Noise Ratio
SL	System Level
SNR	Signal to Noise Ratio
TTI	Transmission Time Interval
UE	User equipment

Chapter 1

INTRODUCTION

As technology evolves, there is an increased traffic demand in wireless cellular network and there are expectations of more increments over the next few years. To adequately handle this anticipated explosion in traffic demand and intensity, a new system and generation of mobile cellular network, Long-Term Evolution (LTE) which is a successor to the available 2G and 3G technologies, was developed [1]. LTE technology makes use of Orthogonal Frequency Division Multiple Access (OFDMA) which is a multiple access technology for the air interface of broadband wireless system with orthogonal carrier signals, eliminating sub-channel crosstalk and the need for guard bands between carriers [2]. OFDMA enables high spectral efficiency as it allows flexibility of deployment over different frequency bands with little adjustments made to the air interface [2]. LTE provides support for MIMO [3] (Multiple Input, Multiple Output), a technique that improves the radio link capacity for high traffic demand by the use of at least two transmission and reception antennas in order to take advantage of multipath propagation [4]. With this technique, signals are transmitted simultaneously over the same frequency spectrum through different paths using different antennas.

1.1 General Overview

Considering the rapidly increasing demand for data traffic by users described previously, the existing 2G and 3G systems do not have such required capacity and a need to replace them becomes inevitable. Consequently, Long Term Evolution (LTE) networks which employ orthogonal frequency division multiple access (OFDMA) and multiple-input multiple-output (MIMO) techniques to achieve significant performance improvements over previous technologies are employed as successors to the 2G and 3G cellular technologies. Dimensioning of LTE networks is mostly done based on coverage metrics assuming static users with full user buffers although some recent work suggests insufficiency of the coverage point of view for dimensioning LTE users with dynamic traffic [5].

1.2 Problem Statement

Considering a cluster of cells with or without inter cell interference (ICI), wireless signal are transmitted from a central base station (BS) to user equipment (UE) within the coverage region with decreasing signal strength (attenuation) as distance increases due to pathloss and other factors. Reduced throughput of edge users is experienced as a direct result of power law decay of radio signals over the propagation distance [8] and inter cell interference as cell edge effects from neighboring BS transmitters is introduced, which is the signal quality deterioration experienced due to interference from adjacent cells.

Consequently, measuring the capacity (throughput) of a LTE network using the traditional dimensioning metrics which do not put the location of UEs into consideration may fail to produce reliable results as users at the edge of the network suffer a significant loss in signal quality and hence, scheduling unfairness as the base station or eNodeB tries to manage resources efficiently. Available studies have provided measurements taken from simulation scenarios with uniformly distributed users, reporting the average UE throughput and the 5th percentile throughput (as an indicator of the cell edge throughput) as performance measures of the system [6] [9]

[10]. Although this approach has gained wide application, its accuracy can be questioned as uniform distribution of users does not fully replicate a realistic deployment scenario due to the fact that network providers, in a bid to meet targets install equipment in highly populated areas (where users form a cluster). Also, 5th percentile throughput, which may or may not reflect the actual performance of users at the cell edge might require further investigation.

1.3 Objectives of the Thesis

This thesis work is structured to address the issues raised in the problem statement (Section 1.2) above. In order to do this, baseline results were produced with uniform UEs by running a state-of-the-art simulator using its already available features.

The simulator was then extended to handle the positioning of users, providing support needed to investigate clustering in UE deployment and evaluate UE regionalization in order to obtain a reliable measurement metric and realistic distribution environment.

Figure 1 shows the flow chart of the methodology adhered to for this thesis work, starting with an introductory study of the Long Term Evolution system. A review of previous work done in the field is also done in order to capture the vitals of the research. It was observed at this stage that there are only a few simulators as the one used for this study available for public use, with the Vienna System Level Simulator probably being the only simulator available having its codes publicly accessible for research and academic purposes [6].

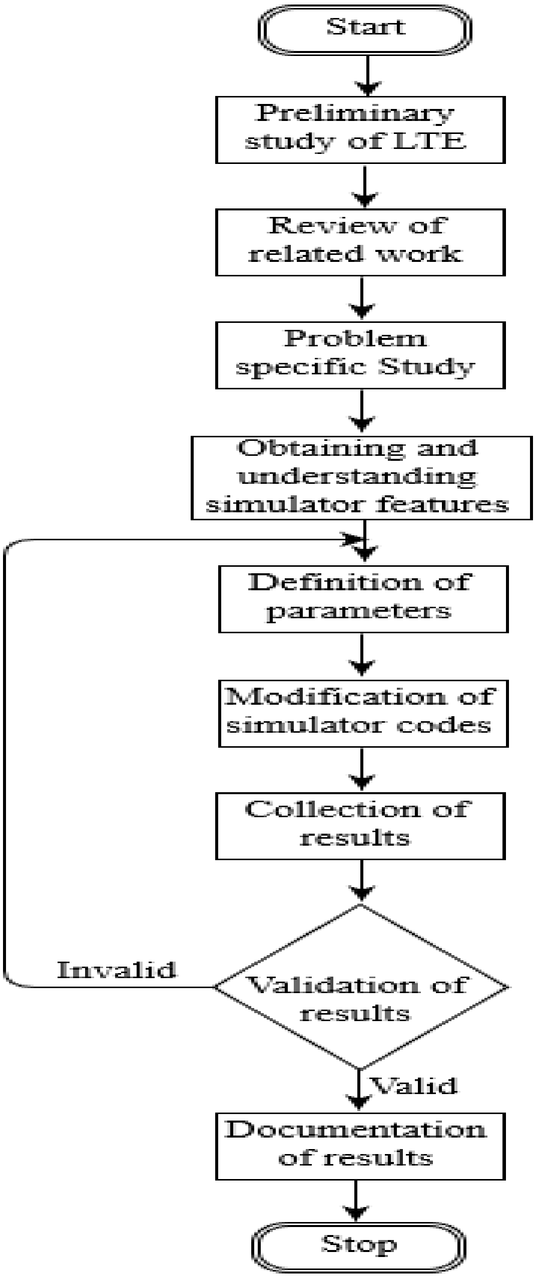


Figure 1: Flow chart of the study

To better understand the simulator and its functions, much assistance was obtained from the simulator forum page [7].

Modifications were made to the codes in order to ensure its suitability for the purpose of the study, after which the results were collected, validated and documented. The major codes used for the extension are in Appendix A.

1.4 Organization of the Thesis

The thesis is made up of five chapters. Chapter 1 covers the introduction, general overview, problem definition, goals and objectives of the research with the flowchart of operations. The contents of subsequent chapters are as follows:

Chapter 2 presents the literature review to the study

Chapter 3 discusses the project implementation using the Vienna LTE SL Simulator.

Chapter 4 contains the obtained results from the simulation.

Chapter 5 concludes the thesis and contains a summary of the study and projected future work.

Chapter 2

LITERATURE REVIEW

In this chapter, we present a review of wireless cellular systems from the earlier generations to the LTE system under investigation. Wireless systems have been available for some years now and have gained application in many areas ranging from wireless garage door openers to cordless phones. They have evolved over time as depicted in the development of cellular systems over a space of time from the first generation cellular system, the second generation and the third through to the recent LTE systems introduced by the 3GPP.

In the telecommunications world, the last decade and a half have perhaps proved to be the most productive and innovative years for cellular systems. The sporadic increase in the number of subscribers, three years after the dawn of the millennium from about 34 million to an outstanding 5.5 billion within a space of 8 years could be directly linked to an unrestrained access to the global telephone network through the use of a convenient portable device called the User Equipment (UE) [11].

2.1 The First-Generation Cellular Systems

The mobile cellular era began in the late 1970s, with the first generation mobile system which uses analog mode for the transmission of speech services. The first cellular network was operated by Nippon Telephone and Telegraph (NTT) in Japan. Within the space of 5 years, cellular systems were established in Europe with Total Access Communication Systems (TACS) and Nordic Mobile Telephones (NMT) with full handover and roaming capabilities but an obvious disadvantage of being unable to inter-operate between countries. In 1982, the Advanced Mobile Phone System (AMPS) was launched in the United States with a 40-MHz bandwidth within the 800MHz-900MHz range issued by the Federal Communication Commission (FCC) for AMPS. By 1998, an Expanded Spectrum (ES) of 10 MHz was assigned to AMPS with an initial deployment in Chicago within a coverage area of 2100 square miles, it had 832 channels and a data rate of 10 kbps. Forward channel transmissions from the BS to the UE occurred using frequencies in the range of 869-894 MHz while the reverse or uplink channel used to transmit information from the UE to the BS was in the range of 824-849 MHz. Later in the 1980s, the cellular systems applied frequency division multiplexing (FDM) technique where a number of independent information signals were combined into an aggregated signal, fit for transmission over a physical medium, leading to the second generation of cellular systems [12].

2.2 The Second-Generation Cellular Systems (2G, 2.5G, 2.75G)

The second-generation technology presented systems with advanced integrated circuits, enabling digital communication with support for advanced source coding. This in turn allowed an efficient usage of the spectrum, reducing the amount of bandwidth needed for audio and video. Error correction techniques like error correction coding (ECC) could now be used to reduce interference and fading and to allow a reduced transmit power. The second generation systems can be classified by their multiple access techniques as either FDMA, TDMA or CDMA [12].

In the FDMA system, the entire spectrum is subdivided into slots of different frequencies and users are assigned each a unique frequency to transmit in. In the

TDMA, users transmit using the same frequency but in distinct time slots which is defined by an algorithm. CDMA applies the rule of direct sequence spread-spectrum (DSSS). The signals are modulated using signature waveforms also called codes which distinguish the signals even though they are transmitted at the same time on the same frequency due to their very low cross correlation.

2.2.1 GPRS (General Packet Radio Service) 2.5G

2.5G is an acronym for second and half generation which defines a wireless cellular technology within the 2G systems which operate within a packet switched domain. Even though the technology is popularly known by the name 2.5G, it is more of an informal tag solely put in place for marketing and advertising purposes unlike other officially defined standards as the 2G and 3G. The 2.5G or GPRS system could offer data transmission rates within the range of 56kbit/s and 115kbit/s. It offered services such as SMS mobile games, directory lookup, Wireless Application Protocol (WAP) and Multimedia Messaging Service (MMS) [12].

2.2.2 EDGE (Enhanced Data rates for GSM Evolution) 2.75G

The EDGE technology offered enhancements to the existing 2G and 2.5G GSM networks. EDGE was an extended version of the GSM technology which offered swift transmission of data and information and possessed the capability of supporting packet switched and circuit switch data. An outstanding benefit of this technological improvement was that existing 2.5G users can benefit from 2.75G facilities without making any hardware or software modifications [12].

2.3 The Third-Generation Cellular Systems (3G, 3.5G, 3.75G)

The term 3G is used to define the third generation of mobile systems technology which achieved a larger network capacity and provided better services to users through an improved spectral efficiency, which is defined as the amount of data that can be transmitted on a specified bandwidth in a data communication system. Some of the added functionalities are video calls and High Speed Packet Access (HSPA) data capabilities which enabled data delivery at rates around 14.4Mbit/s downlink for forward channel and 5.8Mbit/s for the reverse channel, causing a paradigm shift in possible transmission capabilities. The High Speed Packet Access (HSPA) is a set of mobile telephony protocols that increase the efficiency and performance of existing UMTS protocols [12].

Third-generation network technologies make use of the Time Division Multiple Access and the Code Division Multiple Access medium sharing techniques and they offer exceptionally fast data rates.

2.3.1 HSDPA (High-Speed Downlink Packet Access) 3.5G

3.5G or HSDPA is a mobile telephony protocol which offers a smooth evolutionary path for UMTS-based 3G network offering high downlink data rate between the ranges of 8Mbit/s to 10Mbit/s and even better (20Mbit/s) when the antenna is MIMO. Adaptive Modulation and Coding, fast cell search and Multiple Input Multiple Output are applied in HSDPA implementations [12].

2.3.2 HSUPA (High-Speed Uplink Packet Access) 3.75G

While HSDPA provided high downlink data rates, HSUPA provides High Speed Packet Access in the reverse direction with priority being the uplink channel. HSUPA provides instant enhancements to advanced person to person data applications with increased and similar data rates. Initial releases offered high uplink rates in the region of 1.4Mbps while later versions support up to 5.8Mbps [12].

2.4 The Fourth-Generation Cellular Systems

The fourth-generation system is basically an extension of the 3G predecessor, offering more bandwidth and services. Two systems were developed for commercial purposes namely: 3GPP’s Long Term Evolution (LTE) and the Mobile WiMAX standards, defined as ‘True 4G’ by ITU [13]. LTE provides more broadband internet access, forming the access section of the Evolved Packet System (EPS). High spectral efficiency, short Round Trip Time (RTT), high peak data rates and frequency/bandwidth flexibility form the primary requirements for this new access network. Figure 2 summarizes the various 3GPP releases and dates.

The fourth-generation (4G) wireless cellular systems have been quite interesting since 3G systems attained maximum potentials in 1997. Consequent to the increase in demand for higher data transmission rate for mobile broadband and the QoS, LTE was developed simultaneously with the System Architecture Evolution (SAE) as the LTE/SAE which is also termed the Evolved Packet System (EPS) in a bid to offer an efficient, low delay, packet optimized and thoroughly secure service. Orthogonal Frequency Division Multiplexing (OFDMA) and Multiple Input Multiple Output MIMO are some of the most crucial features of this new technology. Also, an all IP flat architecture has been employed at the network layer.

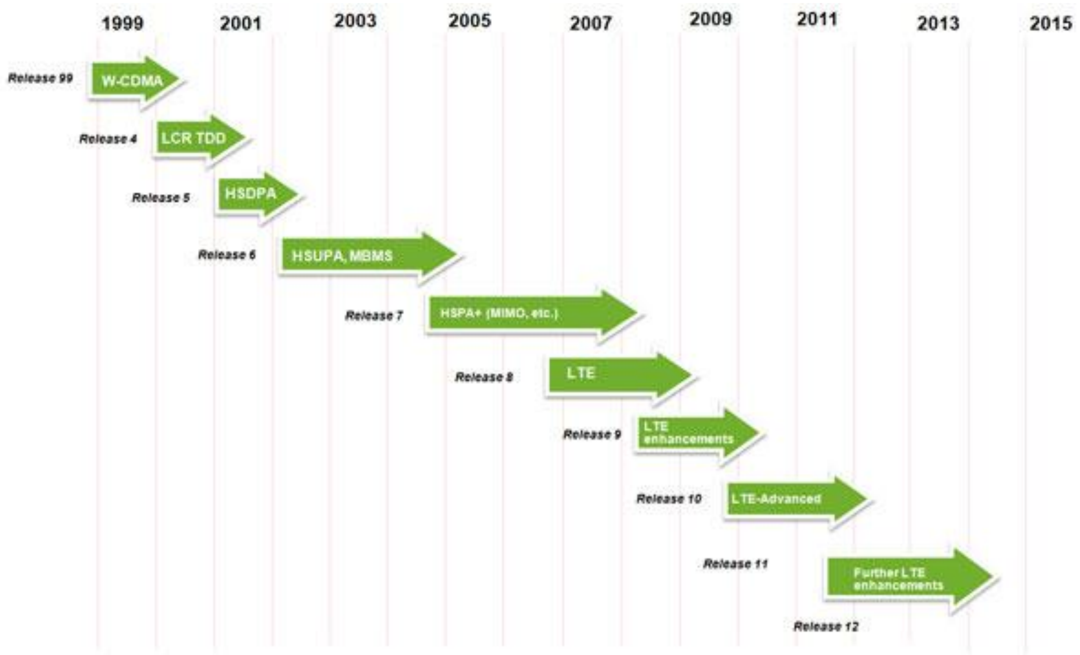


Figure 2: 3GPP Radio Systems over recent releases [14]

In order to fully define the network architecture, the requirements of the Evolved Packet Service expected to serve as a foundation for future network generation was specified by 3GPP in its Release 8 which led to the specification of the Evolved Packet Core (EPC), Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network, with each corresponding to the core network, air interface and radio access network respectively [15]. The Evolved Packet System offers IP connectivity between a User Equipment (UE) and an external packet data network using the Evolved Universal Terrestrial Radio Access Network.

2.5 Motivation for LTE

As the system is expected to function at peak level for many years, the requirements for sustainability and competitiveness seem to be quite enormous. The following are the set of objectives outlined in the development of the LTE system [12] [15] [16]:

1. Low latency (<5 ms).

2. Scalable bandwidth (1.25MHz to 20MHz).
3. Increased peak data rate (100Mbps for the downlink, 50Mbps for the uplink).
4. Increased cell edge performance.
5. Backward compatibility and interoperability with existing and non-3GPP systems.
6. Full support for mobility.
7. Ease of migration.
8. 2 to 4 times capacity improvement over the existing Release 6 scenario with HSUPA and HSDPA.

Amongst others, LTE also benefits from the use of multiple transmit and receive antennas (MIMO) which offers an elegant approach to high speed signal transmission between eNodeBs and UEs. Spatial multiplexing is a transmission method in MIMO which increases the system throughput by transmitting streams of signals from multiple transmit antennas simultaneously [17].

2.6 Multiple Access Techniques

In order to attain the requirements defined in Section 2.5 above, a suitable air interface technology was adopted. Orthogonal Frequency Division Multiplexing was implemented in the downlink and a single-carrier-based Frequency Division Multiple Access with dynamic bandwidth was implemented in the uplink to lower power consumption at the UE [18] [19].

For the downlink, OFDM / Cyclic Prefix is the transmission technique in use. A single transmission frame (Figure 3) is of 10ms duration and is subdivided into 10 sub-frames, each being 1ms with each sub-frame further divided into two time slots, having 0.5ms each. Finally, each time slot is made up of 6 or 7 OFDM symbols [20]. A resource block (RB) which is the smallest unit employed by the scheduling algorithm to allocate resource to the UE (RB/bandwidth allocation is described in Table 1) is defined to contain 12 frequency sub-carriers with 14 continuous symbols in time.

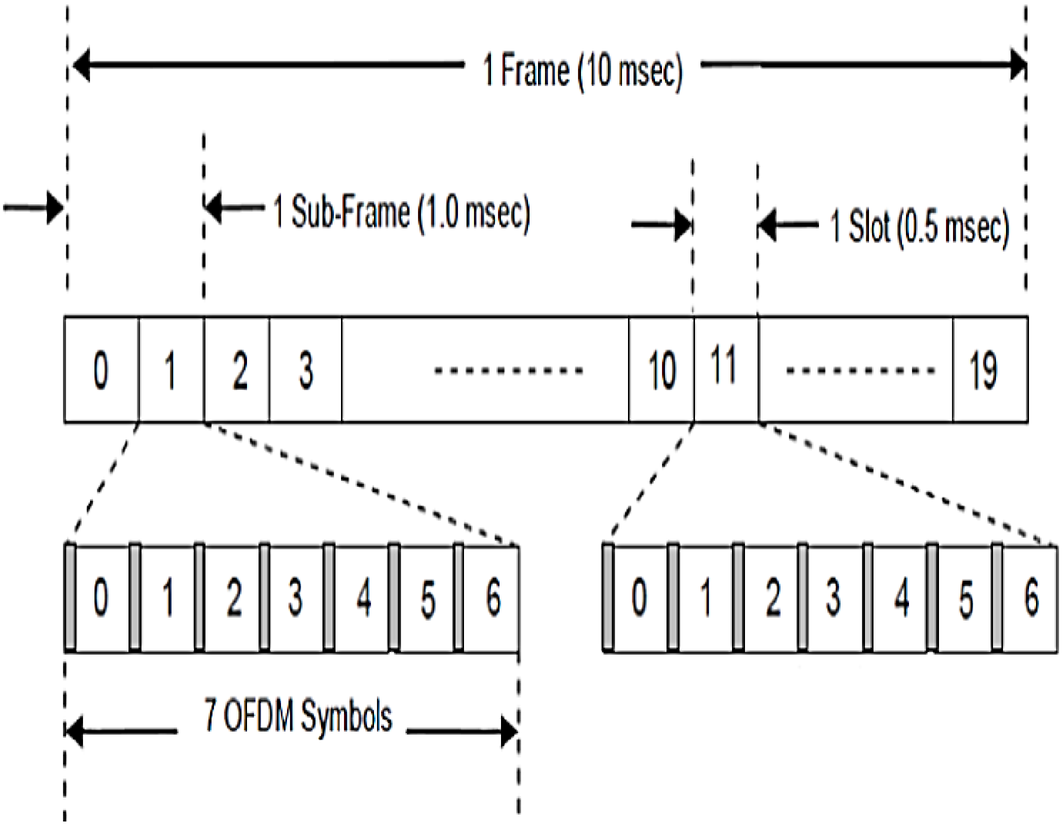


Figure 3: LTE Downlink Frame Details [20]

Table 1: Bandwidth to Resource Block (RB) mapping

Bandwidth (MHz)	Resource Blocks
1.4	6
3	13
5	25
10	50
15	75
20	100

2.7 Channel Quality Indicator Feedback

The Channel Quality Indicator (CQI) in an LTE system is employed for optimal resource allocation in the downlink transmission channel. In order to efficiently allocate resource blocks (RB), eNodeBs require that UEs report their corresponding current channel conditions, as they, apart from scheduler, UE speed and fading play a major role in determining how and in what state resource blocks arrive the destination, consequently allocating resources accordingly [21]. Practically, if the eNodeB fails to consider the channel quality value before assigning resources to a channel with low quality, there exists a probability that a portion of the transmitted signal gets truncated or lost prior to delivery, effecting a retransmit. The CQI is a numerical value between the range of 0 (which is the worst) and 15 (the best) [16].

The CQI plays a major role in this research as it reports essential signal related information from the UE to the eNodeB in order to appropriately allocate resources by the resource scheduler. Among others is the best CQI scheduler which allocates resource blocks to a user with the best channel condition per transmission time. Because scheduling is a function of the link measurement model, it is further explained in Chapter 3.

Next chapter will describe the simulation framework for LTE downlink.

Chapter 3

THE SIMULATION FRAMEWORK

3.1 The Vienna LTE System Level (SL) Simulator

The Vienna LTE SL simulator v1.8r1375 [6] [22] is an open-source simulator that supports system level simulations of the Universal Mobile Telecommunications System (UMTS) Long-Term Evolution (LTE). The main role of the Vienna LTE SL simulator is to execute algorithms and procedure as done by the network related section of the LTE system. The simulator is freely provided for non-commercial academic use license, which aids academic research and allows a closer teamwork between different universities and research facilities [6].

The system level evaluation and simulations give detailed insight into issues that bother heavily on the allocation of resources using schedulers, management of UE mobility, admission control, handling of network interference etc. [22] [23].

While the System Level simulator provides the possibility to perform network related analysis like scheduling and interference management, a physical layer or link level simulator offers the possibility to investigate the complementary section of the system by providing a platform to study antenna configurations and gains, Adaptive Modulation and Coding (AMC) feedback and related functions [6].

It should be noted that because of the vast amount of data processing that is needed for simulating the radio links between all the terminals and base station, it is impossible to integrate a detailed physical layer simulation into the SL evaluation. In a bid to supply the required link level parameters into the System Level simulation, the physical layer has been abstracted using simplified models which with high efficiency and low complication have been able to capture its essential features [6]. Figure 4 describes the schematic block diagram of the LTE system level simulator which is divided into two parts.

A Region of Interest (ROI) is defined in which eNodeBs are deployed with their attached users (UEs). The duration of the simulation is specified in Transmission Time Intervals (TTIs) defined as 50TTIs in this study. It is noteworthy that the deployment of UEs is only done within this ROI.

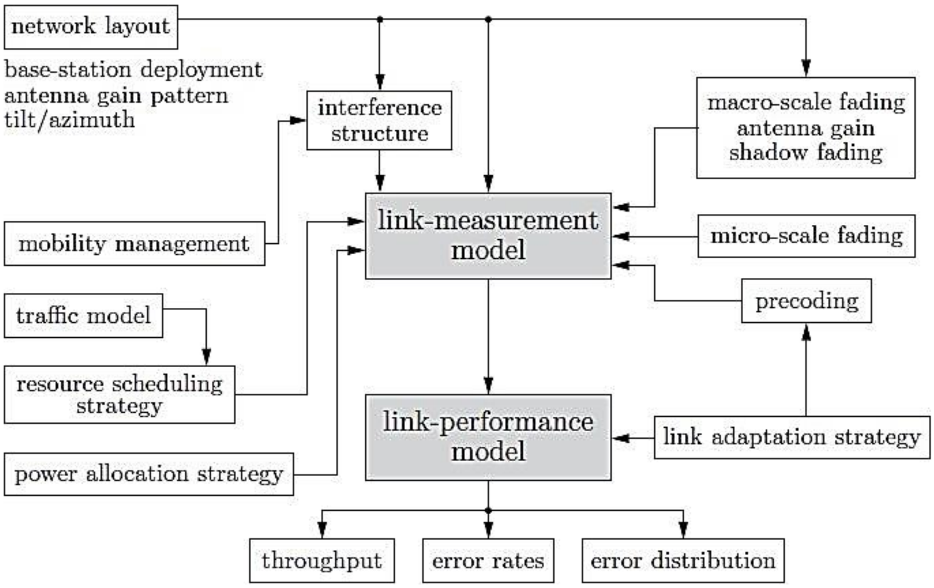


Figure 4: Schematic block diagram of the LTE SL Simulator [6] [22]

3.1.1 Link Measurement model

In the link measurement model, the link quality is evaluated using SINR (Signal to Interference plus Noise Ratio) as metric and a direct abstraction of the measurements of the link adaptation and the measurement of the resource allocation is done in order to eliminate computational complexity during run time or reduce it by generating most of the needed parameters ahead of the run in a process called pre-generation. The process of pre-generation enables a faster code execution, shifting a large portion of the computational load to an offline process, storing the results which can be re-applied during a simulation run as trace files. Note that link adaptation refers to a set of techniques where crucial parameters are changed to better match the condition on the radio link. LTE uses Adaptive Modulation and Coding (AMC) as the link adaptation technique to adapt transmission parameters, modulation scheme and code rate dynamically to the channel. For example, to adapt the modulation scheme if the SINR is high, a higher order modulation scheme with a higher spectral efficiency is used (64-QAM). However if the SINR is low, a lower order modulation scheme should be used like QPSK (better performance in transmission errors, but has a lower spectral efficiency). In addition, to adapt the code rate we use a higher code rate when the channel quality is better, leading to a higher data rate. Finally, in order to evaluate the time and spatial correlation of the channels of a wireless cellular system, the link quality model was sub divided into three units which will be further described, they are;

i. Macroscopic pathloss

ii. Shadow fading

iii. Small-scale fading

i) Macroscopic pathloss

The macroscopic pathloss between the sector of an evolved Node B and an attached UE could be employed to model the propagation pathloss as a factor of the antenna gain and the distance between the eNodeB and the UE. It is denoted by: L_{M,b_i,u_j} where b_i is the i-th eNodeB, 0 represents the desired eNodeB and 1,…N_{int} for the interferers u_j is the j-th UE.

The macroscopic pathloss is designed as a pathloss map that can be re-used if the network geometry is not altered after an initial computation, as it specifies the corresponding pathloss for each and any point (x,y) and each transmitter in the region of interest.

Figure 5 is a generated macroscopic pathloss map using an omnidirectional antenna and a distance dependent pathloss:$L = 40(1 - 4 \times 10^{-3} \times \Delta hb) \times \log_{10}(R[Km]) - 18\log_{10}(\Delta hb) + 21\log_{10}(f) + 80dB$, where Δhb is the base station height in meters, f is the carrier frequency in MHz and R is the separation between the base station and the UE in Km [24]. The minimum coupling loss (MCL) is defined as the minimum distance loss between the UE and an attached eNodeB, it explains why over the region of interest in Figure 5, signal measurement starts at 70dB.

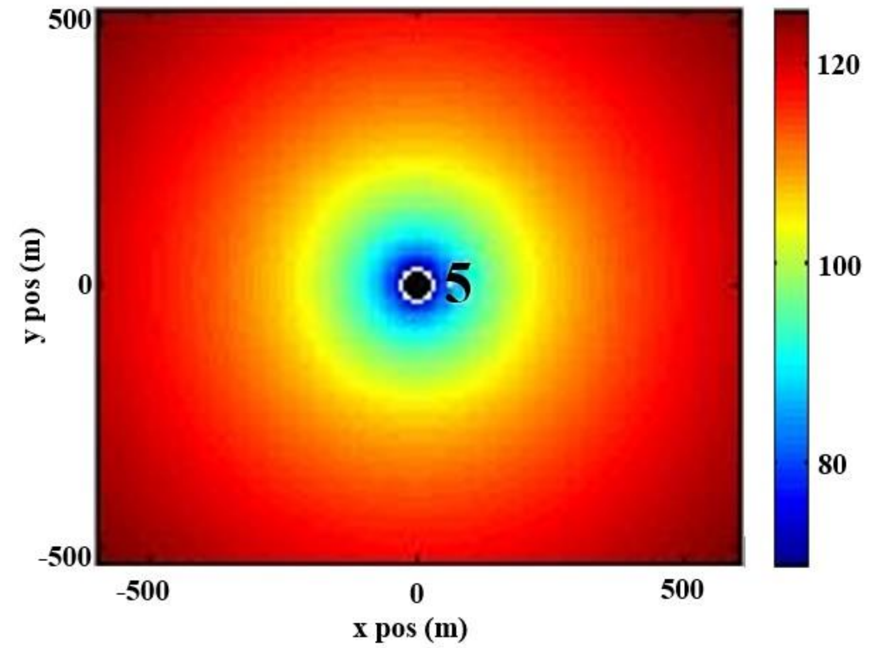


Figure 5: Macroscopic pathloss L_{M,b_i,u_j} 70dB Minimum Coupling Loss, omnidirectional antenna

ii) Shadow fading

Shadow fading L_{S,b_i,u_j} occurs when obstacles obstruct the propagation path between an eNodeB and an attached UE. It can be described as geographical inconsistencies in the attribute of the environment introduced in accordance with the average pathloss obtained from the macroscopic pathloss model.

Figure 6 illustrates the space-correlated shadow fading map obtained for a specified eNodeB in a simulation run. It should be noted that for a UE moving around the map, a slowly changing pathloss L_{S,b_0,u_0}due to shadow fading, L_{S,b_0,u_0} in correlation with L_{S,b_0,u_0}, i = 1, 2, 3. . N_{int} is experienced.

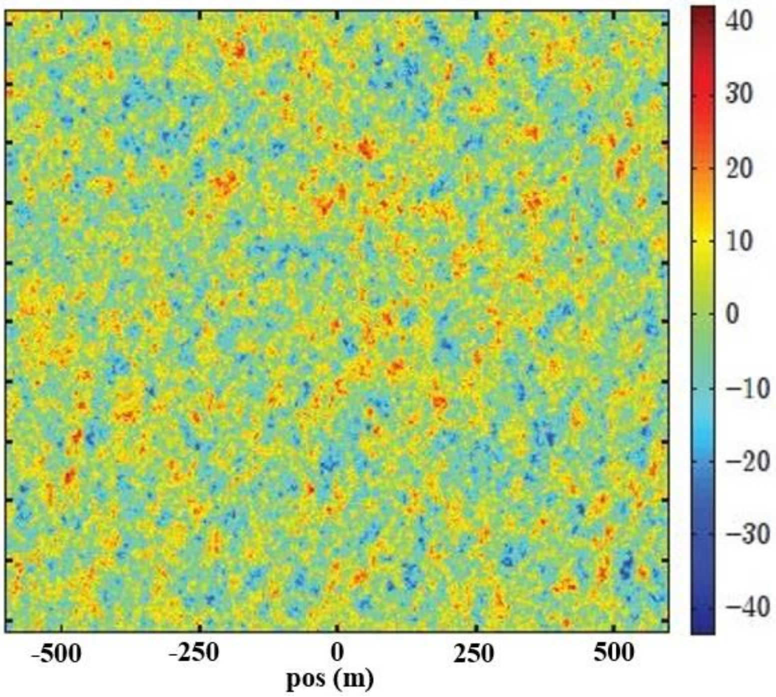


Figure 6: Space-correlated shadow fading map L_S, b_1, u_j

iii) Small scale fading

It is evident that macroscopic pathloss and shadow fading produce losses that depend on the UE position but are independent of time. In contrast to these, losses from small scale fading are time dependent variations caused by changes in the transmission medium [6].

3.1.2 Link Performance model

Second part of the simulator is the link performance model which predicts the Block Error Ratio (BLER), defined as the ratio of the number of error blocks received to the total number of blocks sent through the link at the receiver given a certain resource allocation, modulation and coding scheme (based on the link measurement model).

3.1.3 General System Requirements

The LTE System Level simulator and our extensions are implemented using MATLAB R2013a. The system configuration and requirements of our extensions are as follow [7];

- Windows PC
    - 64bit Windows 10 Operating System
    - Intel core i7 CPU running at 2.50GHz
    - 8.0 GB RAM
- MATLAB R2013a; a numerical computing platform from MathWorks Inc. which supports multiple programming paradigm [25]. The simulator only runs on MATLAB versions R2008a and higher as it employs the code modularity capacity of OOP which is available only new versions [7].
- Statistics toolbox. This is a MATLAB internal toolbox that provides functions and applications to illustrate, analyze and model data using statistics and machine learning.

3.2 Simulator Extensions

The features of the Vienna System Level LTE simulator v1.8r1375 was extended for the purpose of this study as the simulator does not possess features to replicate some of the study scenarios and demands. To make such modifications as required for our study, thorough understanding of the functionality of the simulator codes, dependencies and calls is required. The following features and capabilities were added to the simulator;

i) Clustered UE distributions

ii) Uniform UE Distributions

iii) Loading of generated position file

iv) Location regionalization using concentric hexagons

v) Display of UE specific statistics

vi) Adjustment and re-design of the GUI

3.2.1 Clustering

In order to achieve clustering, a new MATLAB script was written in which the radius of the coverage region (R), number of UEs to be deployed (N) and σ (which defines the degree of clustering) are taken as input parameters. Radius R is used to plot the hexagonal Region of Interest (ROI) which is equal to the coverage radius of the transmitting base station.

The clustered deployment then is obtained by generating UE positions with x and y coordinates from a Gaussian distribution with mean 0 and standard deviation σ whose deployment into the ROI (the hexagon constructed using radius R) is tested using the MATLAB built-in ‘inpolygon’ function call. Only points which pass the ROI test are accepted while others are rejected until N UEs are obtained.

3.2.2 Uniform Distribution

Although the simulator already supports uniform distribution of users, an extra script had to be written in order to save generated points for later application to consequent scenario for a valid basis of comparison which is enabled by the simulator’s feature for using predefined UE coordinates (see Section 3.2.3). R and N are accepted as input values and the generated points are also tested to check if they fall within a predefined ROI and are rejected if not until N UEs are achieved.

3.2.3 Loading of Generated Position File

In order to obtain consistency which is an important basis for comparison, generated UE positions are saved in a .mat file as an array of ‘x’ and ‘y’ coordinates and reloaded into a related simulation run. To load an array of positions into a simulation run, we changed ‘UE_distribution’ parameter in the simulator to pre-defined (which accepts points defined manually by user). The generated coordinates are loaded into the simulation workspace and applied as input to the line ‘UE_positions’.

3.2.4 Location Regionalization Using Concentric Hexagons

Coverage range of wireless signals has been estimated to be in the shape of a hexagon [1]. In order to categorize UEs according to their regions based on their distance from the eNodeB, the hexagonal coverage region was subdivided into concentric hexagonal sub-regions, five (5) for the purpose of the study. Five concentric hexagons were deployed to regionalize UEs in this work as it ensured that approximately five (5) UEs were deployed in the innermost region (smallest hexagon) when performing statistical analysis and also, to arrive at a balance in the thickness of each region, thus appropriately defining the edge.

The polygons were plotted by adding necessary lines of code to an existing script in the simulator. The radius of the coverage region was employed in plotting the largest hexagon while smaller ones were plotted after dividing the radius accordingly.

UEs were tested to determine in which region they belonged by checking which hexagon they belonged to using the ‘conditional inpolygon’ function.

3.2.5 Display of UE Specific Statistics

Various UE specific statistics are required for this study which are not displayed by default in the simulator. They are the UE location, the UE index and the UE throughput. Several lines were also added to the previously modified existing MATLAB script to provide support for these features.

3.2.6 Adjustment and Re-Design of the GUI

To display needed information and to provide support for the improved features, the Graphical User Interface (GUI) of the simulation was modified. The modifications include the adjustment of the GUI size and the creation of frames to handle the newly added features.

3.3 Simulation Scenarios

3.3.1 Uniform UE Distribution Scenario

In the uniform distribution scenario using eNodeB 5 as the investigated eNodeB in a cluster of seven eNodeBs, all 6 surrounding eNodeBs had power, attached UEs and radiated signals (acting as interferers). This was done as a means to investigate the impact of inter-cell interference of neighboring cells on then UEs attached to the reference cell in general, on cell edge users as it just would be in a real life situation and on the entire cell performance. The simulation was run with 10 and 20 user equipment, for Round Robin, best Channel Quality Indicator and Proportional Fair schedulers over 50 TTIs [10]. A typical deployment is illustrated in Figure 7.

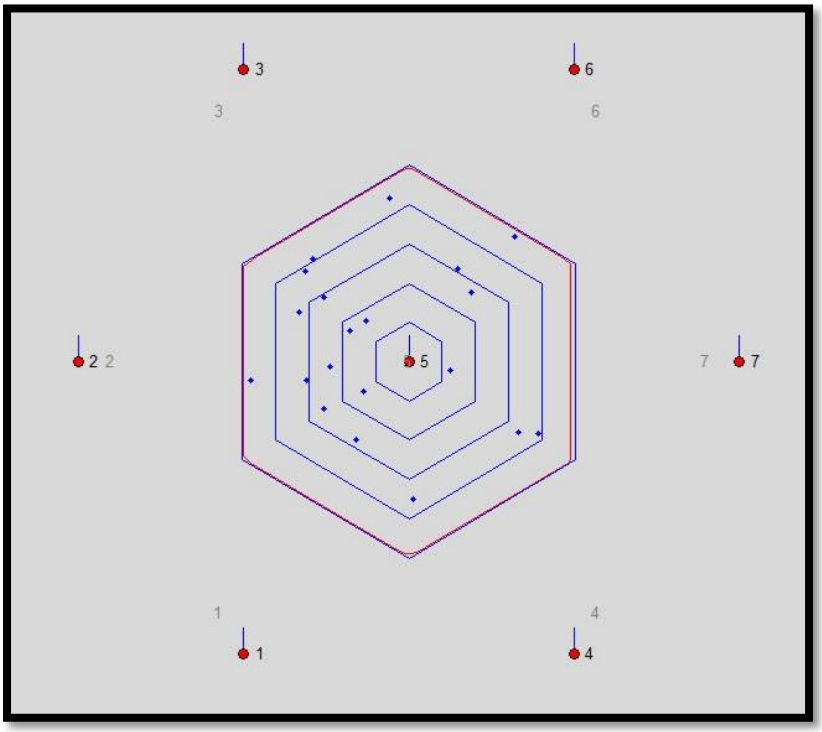


Figure 7: Uniform distribution of UEs

3.3.2 Clustered UE Distribution Scenario

Hotspots are wireless configurations that provide connectivity to users in close proximity. It is observed that the users attached to a hotspot have a distribution just around the transmitter in the form of a cluster. Hence in this scenario, effort has been made to model a hotspot by modifying the distribution of UEs, placing them in very close proximity to the each other and the transmitter forming a cluster [26]. The simulation scenario is illustrated in Figure 8.

Hotspot like clusters can be found in;

- Cafes
- Event locations (football matches, graduation ceremony)

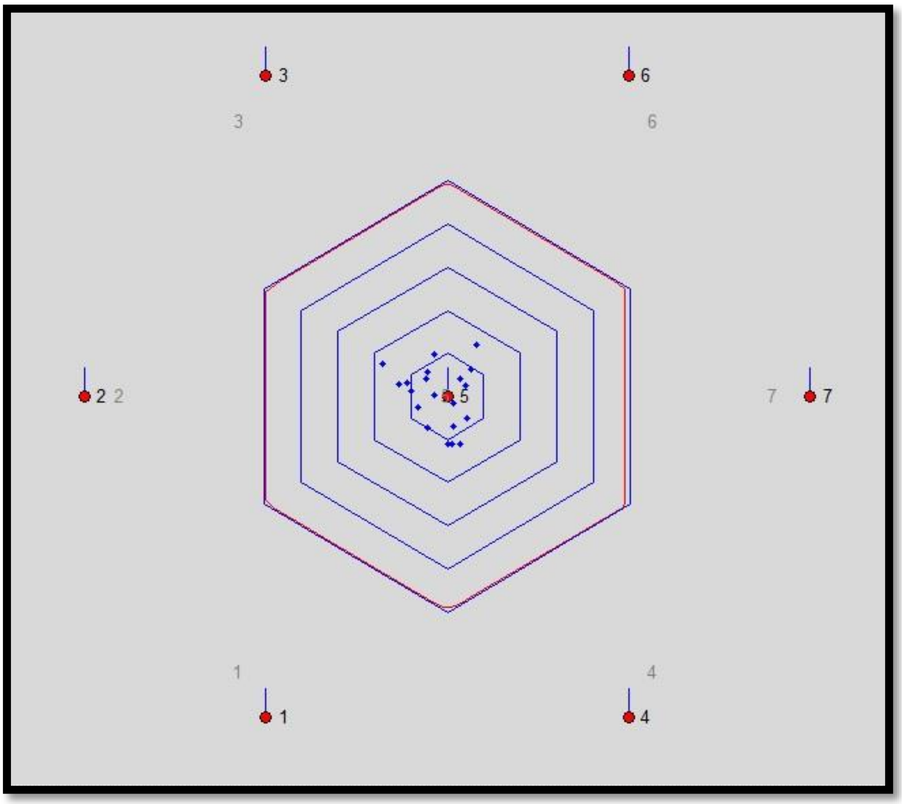


Figure 8: Fully clustered distribution of UEs

3.3.3 Hybrid Distribution Scenario

It is essential to investigate a deployment scenario where a proportion of the UEs form a cluster (closer to the eNodeB) while other UEs are uniformly distributed outside the region of the clustered UE but within the overall ROI. To obtain such a scenario, two distributions are applied during UE deployment. Gaussian distribution is employed for the clustered region, generating points for UE placement which are tested for compliance with the ROI requirements. For the larger region, a uniform distribution was implemented and UEs were deployed according to the points generated. Figure 9 shows a typical hybrid deployment scenario.

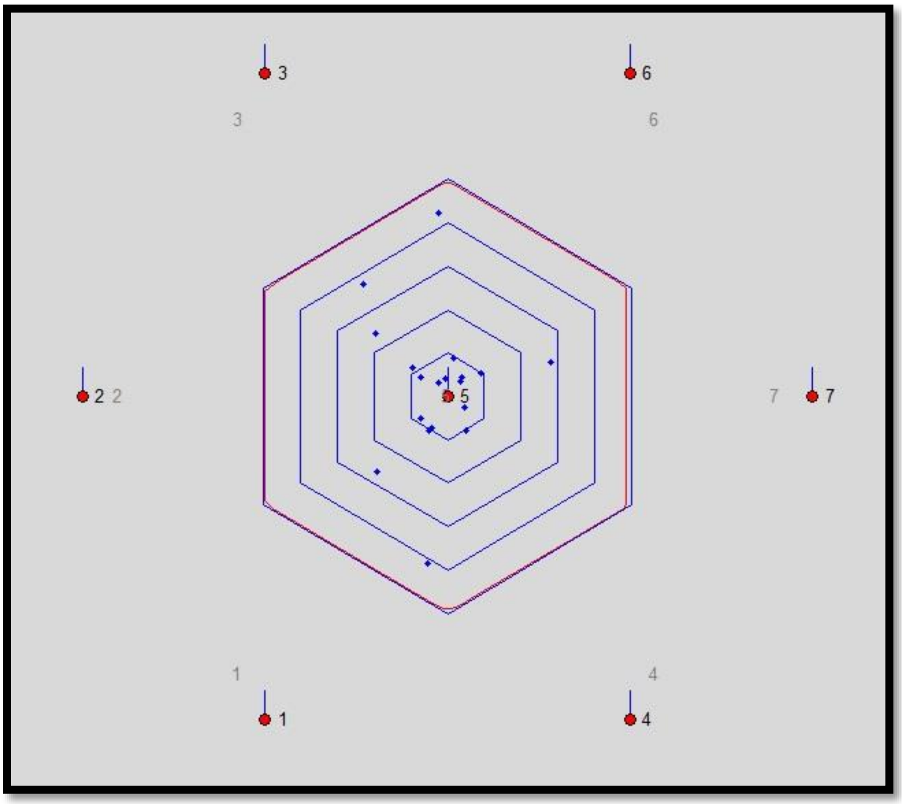


Figure 9: Hybrid distribution of UEs

3.4 Scheduler Selection

Schedulers, which are used to organize the allocation of resources to UEs, are algorithms that assign resources to UEs based on priority, prior utilization information or other factors. The scheduler to a large extent influences the UE throughput and hence, the overall cell throughput [21].

The scheduler allocates resources by considering the following;

- Application demands
- Cell related load balancing
- Interference effects control on cell (Edge UEs)
- Fairness
- Spectral efficiency

Three schedulers were employed in this simulation, the best CQI scheduler in which resource blocks are allocated to corresponding UEs based on the quality of the channel associated with the UE, the Proportional Fair scheduler in which more physical resource blocks are assigned to UEs with the best relative channel quality [21] [27] and the round robin scheduler allocates UEs with resources in a cyclical manner without taking channel quality into consideration [21].

3.4.1 Best Channel Quality Indicator Scheduler

In this scheduler, resource blocks are assigned to the UEs according to the radio link condition. User equipment upon request forward their channel quality information to the base station (eNodeB) and resource blocks are allocated as appropriate [23]. As channel quality reduces as the distance to the eNodeB increases, it is proper to expect that UEs located at the edge of the cell have less channel quality compared to UEs closer to the BS and indicates such in the feedback signal. Hence, RBs are assigned to UEs with highest CQI in order to avoid resource wastage which could be caused by signal degradation due to the poor channel. Consequently, this algorithm starves edge users maximally while increasing the average cell throughput, improving the capacity of the cell at the cost of fairness [23]. Best CQI scheduler operates according to the flowchart in Figure 10:

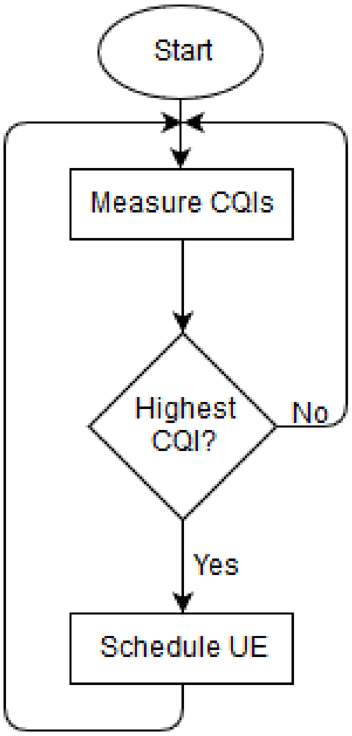


Figure 10: Best CQI scheduler operational flowchart for 1 time slot [20]

3.4.2 Proportional Fair Scheduler

This algorithm seeks to obtain a balance between maximizing fairness among UEs and cell throughput by attaining a minimum preset QoS target for all UEs. It allocates resources to users whenever they have good channel conditions and average channel quality, providing better results in terms of fairness to UEs as well as average user throughput while attaining the preset minimum QoS during the scheduling process [21]. The allocation fairness in proportional fair scheduling is a parameter that defines to the size of resources allotted per time slot.

A possible implementation approach is depicted in Figure 11.

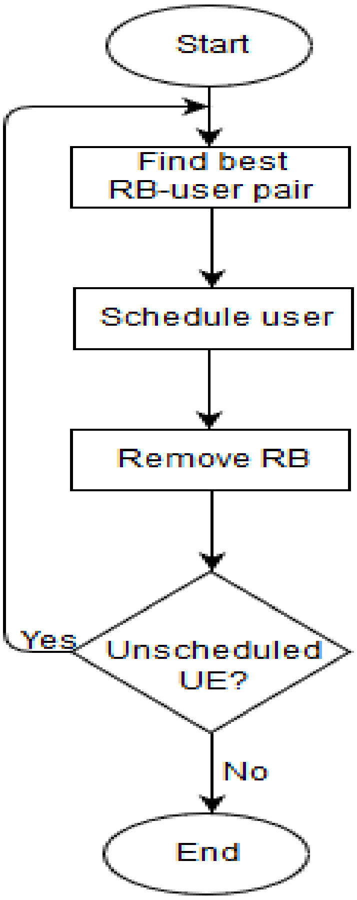


Figure 11: Proportional Fair Scheduler operational flowchart for 1 time slot [20]

3.4.3 Round Robin Scheduler

A round robin scheduler is defined by [10] as a non-channel dependent scheduler. The scheduler allocates resources equally to UEs in a cyclical manner without taking channel quality into consideration [21] [23]. Although it boasts to offer the greatest implementation ease and fairness in resource allocation, it suffers a major setback due to its poor overall cell throughput if there are users prone to resource wasting due poor channel condition [21]. UEs are placed on a waiting queue and served on a no-preference turn by turn basis. A possible implementation flowchart is drawn in Figure 12.

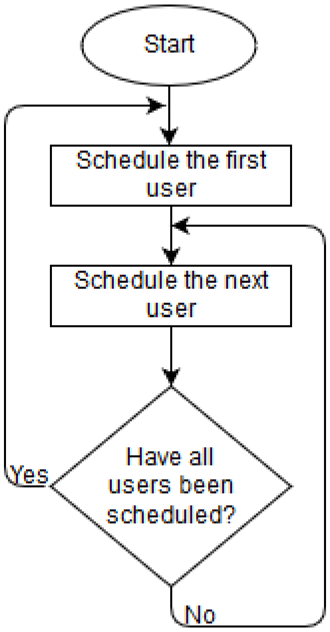


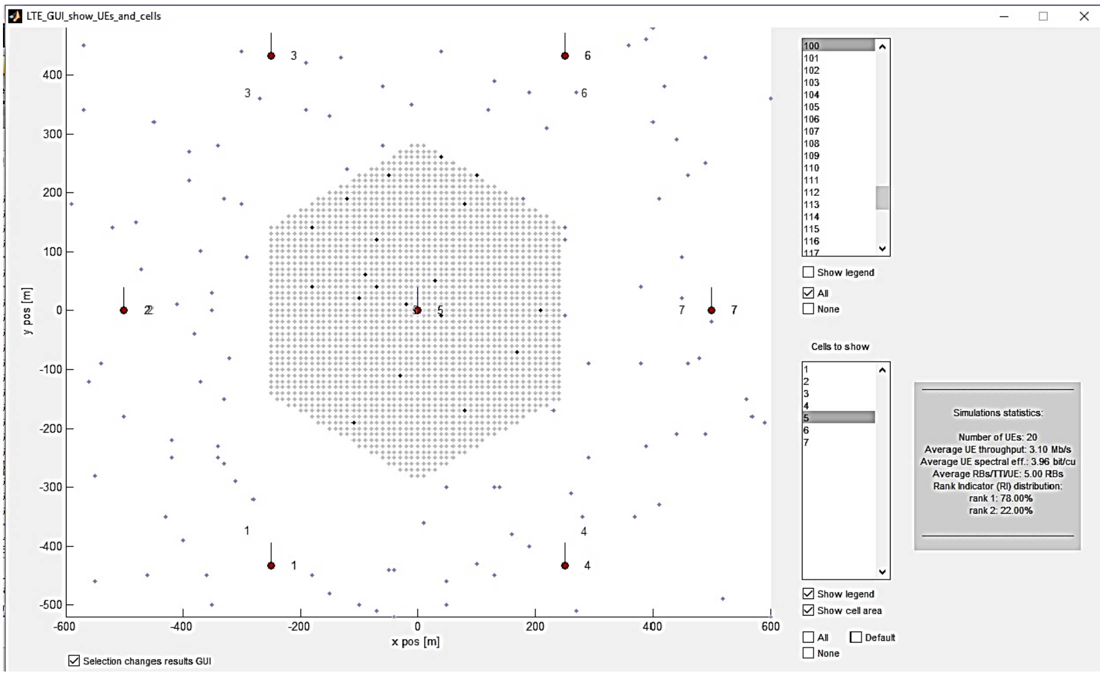
Figure 12: Round Robin Scheduler operational flowchart for 1 time slot [20]

With a good understanding of the mode of operation of the various schedulers employed in this work, next is to consider the results obtained in the study from varying scenarios using the schedulers. The following chapter contains the results obtained from the study.

Chapter 4

SIMULATION RESULTS AND ANALYSIS

In order to carry out this simulation, we added some currently unavailable features to the simulator in order to extend the LTE simulation environment. The simulator in its initial state had no functionality to identify the location of UEs according to distance from the eNodeB, generate and load UE position (uniform and clustered) for other scenarios nor display the throughput of each UE. Further extension was made to accommodate the new features on the Graphical User Interface (GUI). Figures 13 and 14 show the GUI for the un-modified and modified simulator respectively, notice the hexagonal regions in the modified interface.



☐ Show legend
☑ All
☐ None

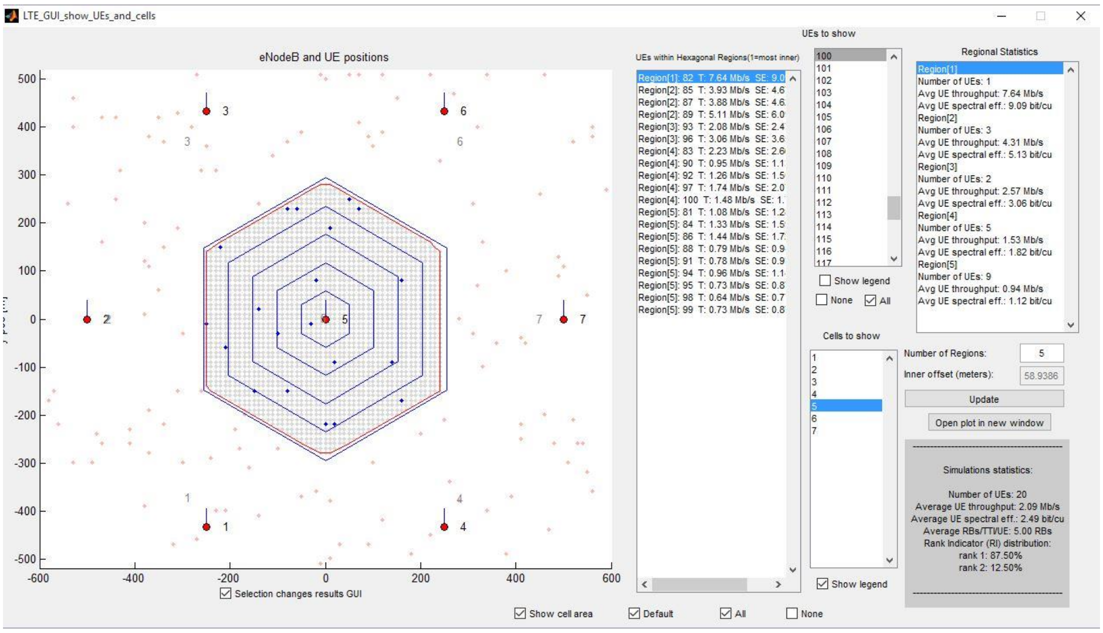
☑ Show legend
☑ Show cell area
☐ All ☐ Default
☐ None

☑ Selection changes results GUI

Simulations statistics:

Number of UEs: 20
Average UE throughput: 3.10 Mb/s
Average UE spectral eff.: 3.96 bit/cu
Average RBs/TTI/UE: 5.00 RBs
Rank Indicator (RI) distribution:
rank 1: 78.00%
rank 2: 22.00%

Figure 13: Vienna LTE SL Simulator v1.8r1375 default GUI



UEs within Hexagonal Regions(1=most inner)

```
Region[1]: 82  T: 7.64 Mb/s  SE: 9.0
Region[2]: 85  T: 3.93 Mb/s  SE: 4.6
Region[2]: 87  T: 3.88 Mb/s  SE: 4.6
Region[2]: 89  T: 5.11 Mb/s  SE: 6.0
Region[3]: 93  T: 2.08 Mb/s  SE: 2.4
Region[3]: 96  T: 3.06 Mb/s  SE: 3.6
Region[4]: 83  T: 2.23 Mb/s  SE: 2.6
Region[4]: 90  T: 0.95 Mb/s  SE: 1.1
Region[4]: 92  T: 1.26 Mb/s  SE: 1.5
Region[4]: 97  T: 1.74 Mb/s  SE: 2.0
Region[4]: 100  T: 1.48 Mb/s  SE: 1.
Region[5]: 81  T: 1.08 Mb/s  SE: 1.2
Region[5]: 84  T: 1.33 Mb/s  SE: 1.5
Region[5]: 86  T: 1.44 Mb/s  SE: 1.7
Region[5]: 88  T: 0.79 Mb/s  SE: 0.9
Region[5]: 91  T: 0.78 Mb/s  SE: 0.9
Region[5]: 94  T: 0.96 Mb/s  SE: 1.1
Region[5]: 95  T: 0.73 Mb/s  SE: 0.8
Region[5]: 98  T: 0.64 Mb/s  SE: 0.7
Region[5]: 99  T: 0.73 Mb/s  SE: 0.8
```

Regional Statistics

```
Region[1]
Number of UEs: 1
Avg UE throughput: 7.64 Mb/s
Avg UE spectral eff.: 9.09 bit/cu
Region[2]
Number of UEs: 3
Avg UE throughput: 4.31 Mb/s
Avg UE spectral eff.: 5.13 bit/cu
Region[3]
Number of UEs: 2
Avg UE throughput: 2.57 Mb/s
Avg UE spectral eff.: 3.06 bit/cu
Region[4]
Number of UEs: 5
Avg UE throughput: 1.53 Mb/s
Avg UE spectral eff.: 1.82 bit/cu
Region[5]
Number of UEs: 9
Avg UE throughput: 0.94 Mb/s
Avg UE spectral eff.: 1.12 bit/cu
```

Number of Regions: 5

Inner offset (meters): 58.9386

```
--------------------------------------------

Simulations statistics:

Number of UEs: 20
Average UE throughput: 2.09 Mb/s
Average UE spectral eff.: 2.49 bit/cu
Average RBs/TTI/UE: 5.00 RBs
Rank Indicator (RI) distribution:
rank 1: 87.50%
rank 2: 12.50%

--------------------------------------------
```

Figure 14: The new GUI of the extended Vienna LTE SL Simulator

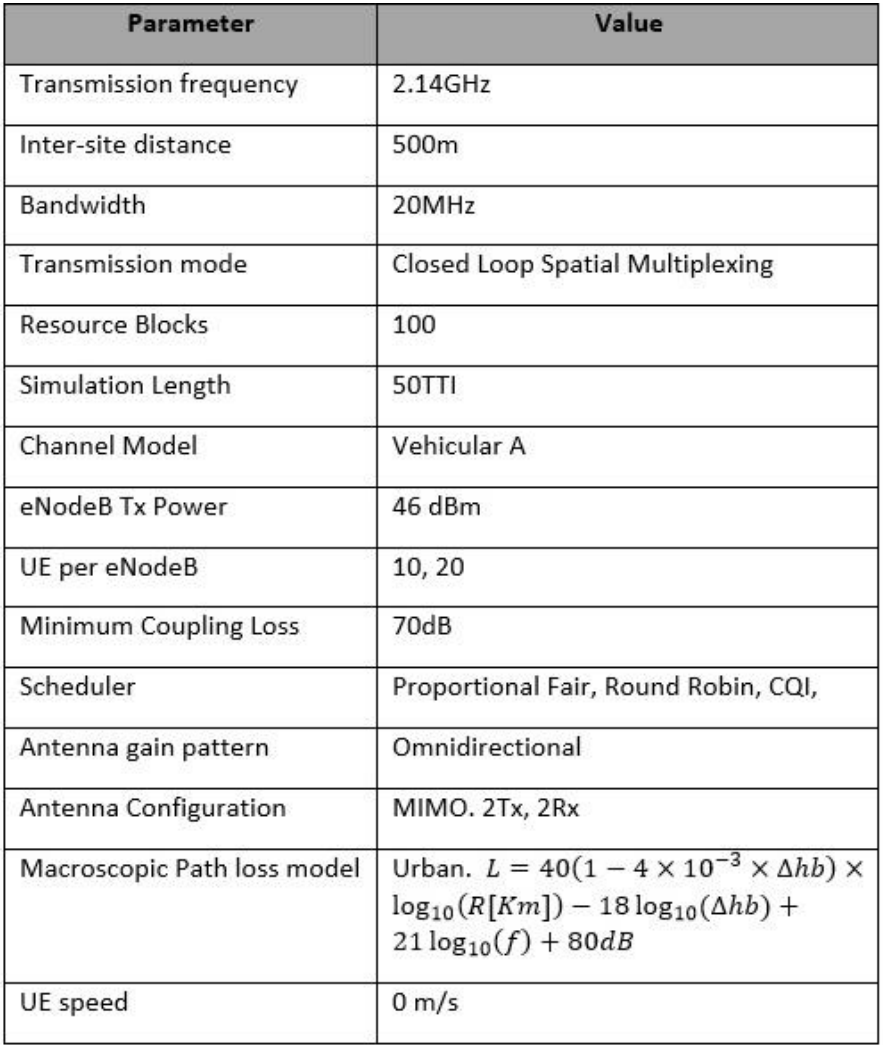
4.1 Simulation Parameters and Assumptions

The extended LTE system level simulator was run using parameters given in Table 2 [24]. The simulation runs could be broadly categorized into three scenarios, a scenario to depict a network situation with uniform distribution of users, a second scenario to describe a cluster of users and the third to describe a hybrid (partly uniform and partly clustered) scenario. In a 7 hexagonal cells deployment, throughput is computed for only the cell in the middle (receiving the highest interference impact) as normal network traffic proceeds in the other 6 cells in a careful attempt to evaluate the impact of the inter-cell interference on the entire UEs within the cell under investigation. The second scenario is structured to portray a wireless hotspot instance with UE distribution in the form of a cluster. Using the defined parameters, as system configuration described in Section 3.1.3, it takes about 4 minutes (real time) to complete a simulation run. For the purpose of our study, the UEs were kept static because mobility of UEs would nullify regional accountability of UE statistics as the UEs traverse the ROI.

The following assumptions were considered during the simulation:

- The base station (eNodeB) had infinite power.
- Every UE maintained connection with the eNodeB and hence, had sustained transmission throughout the simulation, including the inactive ones.
- All UEs also had infinite power.
- All UEs were randomly distributed but positions were maintained for each run over the different schedulers.

Table 2: Simulation Parameters [24]



Parameter	Value
Transmission frequency	2.14GHz
Inter-site distance	500m
Bandwidth	20MHz
Transmission mode	Closed Loop Spatial Multiplexing
Resource Blocks	100
Simulation Length	50TTI
Channel Model	Vehicular A
eNodeB Tx Power	46 dBm
UE per eNodeB	10, 20
Minimum Coupling Loss	70dB
Scheduler	Proportional Fair, Round Robin, CQI,
Antenna gain pattern	Omnidirectional
Antenna Configuration	MIMO. 2Tx, 2Rx
Macroscopic Path loss model	Urban. $L = 40(1 - 4 \times 10^{-3} \times \Delta hb) \times \log_{10}(R[Km]) - 18\log_{10}(\Delta hb) + 21\log_{10}(f) + 80dB$
UE speed	0 m/s

4.2 Dimensioning Metrics

The metrics below are essential for the purpose of our study, though it is noteworthy that adequate emphasis is placed on the achieved throughput at the cell level, regional level, UE and edge, as they form the basis for capacity evaluation. Also the 5th percentile throughput is evaluated and analyzed appropriately.

4.2.1 Cell Throughput

The cell throughput is the summation of individual UE throughput within a cell without considering the location or channel conditions. The cell throughput could be written as $C_{TP} = \sum_{i=1}^{N} U_{TP_i}$ where N is the number of UEs in the cell and U_{TP_i} is the throughput for user i. The average cell throughput is obtained by computing the mean of the overall cell throughput, considering the number of applicable UEs, it could be described as $C_{AT} = \frac{1}{N} C_{TP}$ or $C_{AT} = \frac{1}{N} \sum_{i=1}^{N} U_{TP_i}$.

4.2.2 5th Percentile or ‘Cell Edge’ Throughput

This is defined as the 5th percentile outcome in a sorted UE throughput results. It is the 5th percentile point of the CDF of the UE throughput [28]. It is considered as ‘edge’ estimates in existing studies [29] [30] [9] [31]. Although it attempts to estimate the throughput of users at the edge of the network, it fails to put into consideration the location of the UEs. This lack of location consideration might result in values which deviate from realistic findings and hence produce unreliable estimates especially when the users are non-uniformly distributed.

4.2.3 Location-Aware Edge Throughput

In this study, as it is of interest to evaluate UE throughput based on UE location within the cell, we will consider the UEs in the fifth (and farthest from the eNodeB) concentric hexagon as the edge users. This is because they experience the highest deterioration in signals due to pathloss and inter-cell interference and incessant hand-offs leading to ping-pong effects. In consideration of these, it is proper to assume that they contribute the largest reduction in the overall cell throughput while using the Round Robin and are most unlikely to be scheduled with the best Channel Quality Indicator scheduler. The summation of the throughputs of UEs in this region establishes the realistic throughput of the ‘real’ edge users.

4.3 Results and Analysis

Outlined here are the results obtained by running the afore-described simulation using the parameters stated after which a comparison is done with the baseline values which are values obtained as the average and the 5th percentile throughput representing the edge UEs. Multiple scenarios exist with either 10 or 20 UEs and different schedulers. All results are reported with 95% confidence with each scenario repeated 10 times. Assuming that the mean is normally distributed, the confidence values were computed in Microsoft Excel using the formula below

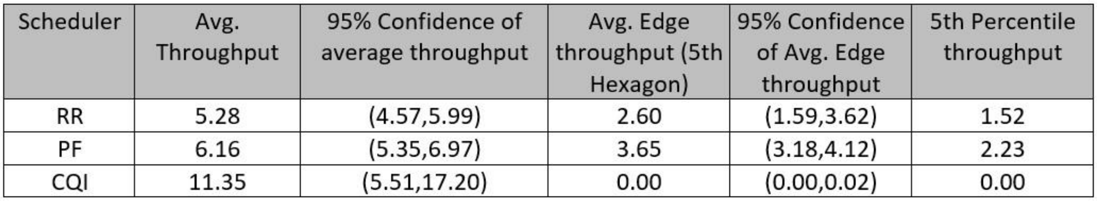
95% confidence, $Z_{95} = \bar{X} \pm Z_{\frac{\alpha}{2}} \sqrt{\frac{Var(\bar{X})}{n}}$

where $\bar{X}$ is the mean throughput, $Z_{\frac{\alpha}{2}}$ =1.96, n is the number of throughput measurements and $Var(\bar{X})$ is the variance of the throughput values.

4.3.1 Uniform UE Distribution Scenario

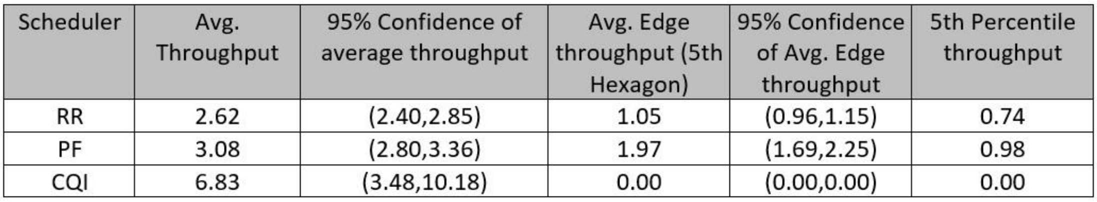
Results obtained in the uniform distribution scenario are presented here. It should be noted that only a summary of essential findings were included. Table 3 contains the values obtained from the simulation.

Table 3: Throughput statistics for the uniform distribution of 10UEs (Mbps).



Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	5.28	(4.57,5.99)	2.60	(1.59,3.62)	1.52
PF	6.16	(5.35,6.97)	3.65	(3.18,4.12)	2.23
CQI	11.35	(5.51,17.20)	0.00	(0.00,0.02)	0.00

Table 4: Throughput statistics for the uniform distribution of 20UEs (Mbps).



Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	2.62	(2.40,2.85)	1.05	(0.96,1.15)	0.74
PF	3.08	(2.80,3.36)	1.97	(1.69,2.25)	0.98
CQI	6.83	(3.48,10.18)	0.00	(0.00,0.00)	0.00

For the uniform scenario, UEs were deployed uniformly all over the hexagonal ROI as described in 3.2.2 with an intent to obtain the throughput of UEs located at the edge of the network and make a careful comparison with the results estimated using the 5th percentile approach. The simulation was run for 10 and 20 UEs and the results are tabulated in Tables 3 and 4. It was observed that the throughput obtained from the 5th percentile values of the simulation runs were less than the evaluated average of the throughput of UEs in the ‘edge region’. The throughput of UEs in the edge region were considerably and consistently higher than those obtained from the 5th percentile. The following number of samples were considered for the statistical calculations. For 10 UEs, n=100 for average throughput calculations and n=29 for edge throughput. For 20 UEs, n=200 for average throughput calculations and n=50 for edge throughput.

From Tables 3 and 4, column 4 contains the average throughput for edge UEs (UEs in the outermost hexagon) as obtained from the simulation run while column 6 contains throughput values estimated using the 5th percentile method for the same simulation run. Using a 95% confidence interval, Figure 15 shows the plot of the results already available in Table 3 and 4 for visual assessment.

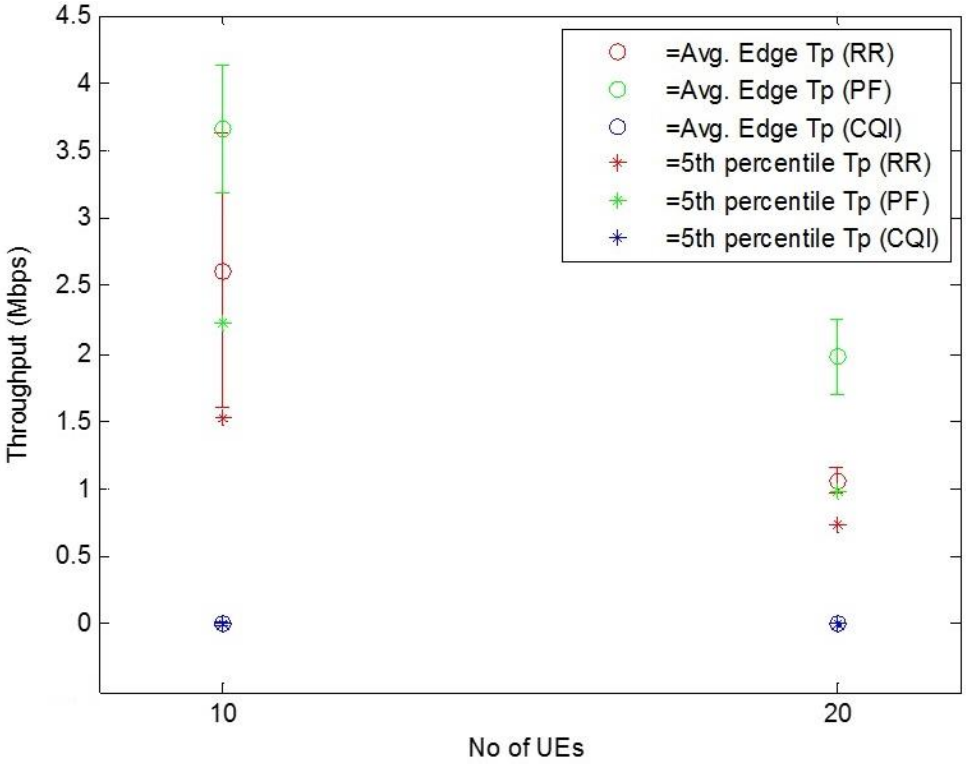


Figure 15: Plot of UE throughput (Tp) showing the deviation of the 5th percentile values from the average edge throughput (5th Hexagon) using 95% confidence interval in the uniform scenario.

From Figure 15, it can be observed that the 5th percentile value for every scheduler is below the value for the simulation result except for the best CQI scheduler. Also, it can be observed that the Proportional Fair scheduler offers the highest throughput in the uniform scenario. From the results of the study, it can be inferred that the 5th percentile throughput generally reported in studies underestimates the edge throughput.

In order to evaluate the performance of the network, attention must be paid to the impact of edge users on the overall throughput of the cell as their channel conditions and other factors to a great deal determine the performance of the system. From the results, the impact of scheduler implementation is seen requiring that a trade-off should be well set between efficiency and fairness in resource allocation.

4.3.2 Clustered UE Distribution Scenario

Network operators seek to have coverage, not mere ground coverage but coverage of active UEs in order to maximize available channels owing to the obvious fact that base stations are more efficiently utilized when positioned in densely populated areas (office, industrial or residential) where the convergence of users has a high probability. With this knowledge, it becomes unrealistic to assume that users are always uniformly distributed within a region of interest as generally assumed in existing studies. Using the Gaussian distribution as described earlier in 3.2.1, σ (which defines the degree of clustering) was set to 40. To fix σ, we obtained a balance between over-clustering and under-clustering by varying the value of σ till the UE distribution is appropriate for the study.

With respect to this, users were deployed in a clustered manner and the following results were obtained. Values for edge throughput is reported as N/A (Not Applicable) because there were no UEs present in the 5th hexagon for the clustered scenario. For 10 UEs, n=100 is the number of measurement for average throughput and 200 for 20 UEs. No UEs were located at the edge.

Table 5: Throughput statistics for the clustered distribution of 10UEs (Mbps)

Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	14.14	(13.56,14.71)	N/A	(N/A)	8.40
PF	13.56	(12.01,15.11)	N/A	(N/A)	7.21
CQI	16.65	(13.92,19.37)	N/A	(N/A)	0.00

Table 6: Throughput statistics for the clustered distribution of 20UEs (Mbps)

Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	6.88	(6.66,7.09)	N/A	(N/A)	3.86
PF	6.55	(5.83,7.26)	N/A	(N/A)	3.67
CQI	8.14	(7.32,8.92)	N/A	(N/A)	0.00

Results obtained in Tables 5 and 6 show the effects of user dispersion on overall cell throughput. Due to clustering as described in 3.3.1, it was observed that the throughput of users increased significantly as fewer low quality channels were employed during the RB allocation process. Results are also presented in Figure 16. In this study, the properties of the applied schedulers were more exploited. It is interesting to note that the Round Robin scheduler in this scenario allocated resources to users more efficiently and had an improved overall throughput when compared with the uniform counterpart. The RR scheduler and PF explicably had comparable results with 95% confidence. It was observed that 5th percentile estimates largely proved undependable when CQI scheduler throughput is considered, although the CQI scheduler had the overall best performance (16.65Mbps for 10UEs) regardless of unfairness, 5th percentile estimates claim that the value is expected to be negligible (0 Mbps). When the 5th percentile throughputs in Tables 3 and 4 with uniform UE distribution are considered (as in existing studies) and compared with those in Tables 5 and 6, the uniform distribution technique incorrectly represents the realistic scenario and hence provides inaccurate results as realistic UE deployment is clustered. Also, the average throughput obtained with uniform UE distribution assumption is an underestimate.

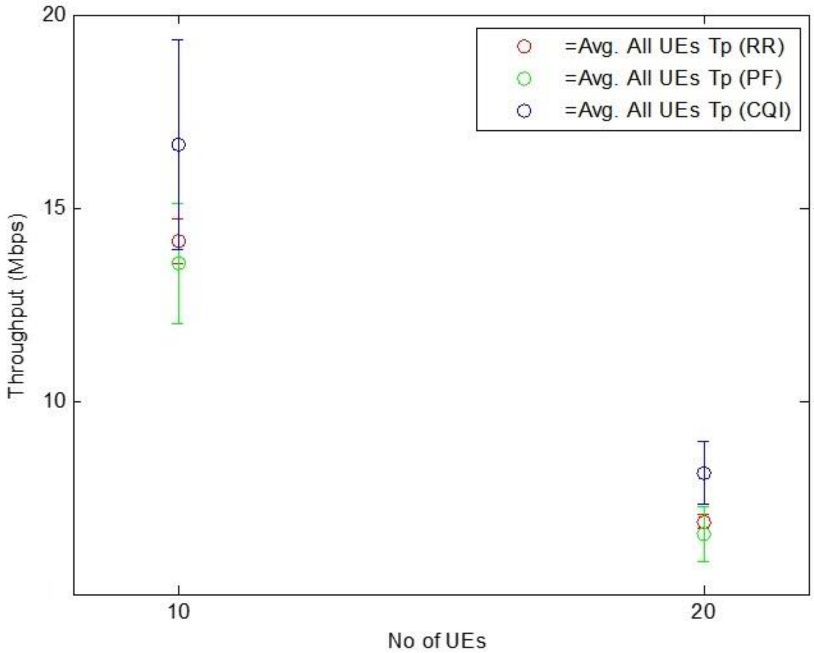


Figure 16: Plot of UE throughput (Tp) in the clustered scenario showing the impact of scheduler selection on cell throughput. Notice the results overlap between RR and PF.

4.3.3 Hybrid UE Distribution Scenario

To conclude a thorough investigation, a mix scenario was also simulated where 70% of users clustered around the eNodeb with the remaining 30% uniformly distributed over the ROI, forming a hybrid distribution. From this scenario, it was gathered (Table 7 and 8) that the PF scheduler efficiently allocated resources to UEs at the edge of the network than the RR, doubling the average throughput of the RR scheduler at the same location. The following number of samples were considered for the study. For 10 UEs, n=100 for average throughput and n=14 for edge. For 20 UEs, n=200 for average throughput and n=21 for edge.

Interestingly, 5th percentile throughput for estimating the edge throughput was satisfactory in the hybrid scenario as seen in Figure 17. More studies might be required to evaluate the sensitivity of the estimates to the deployment scenarios.

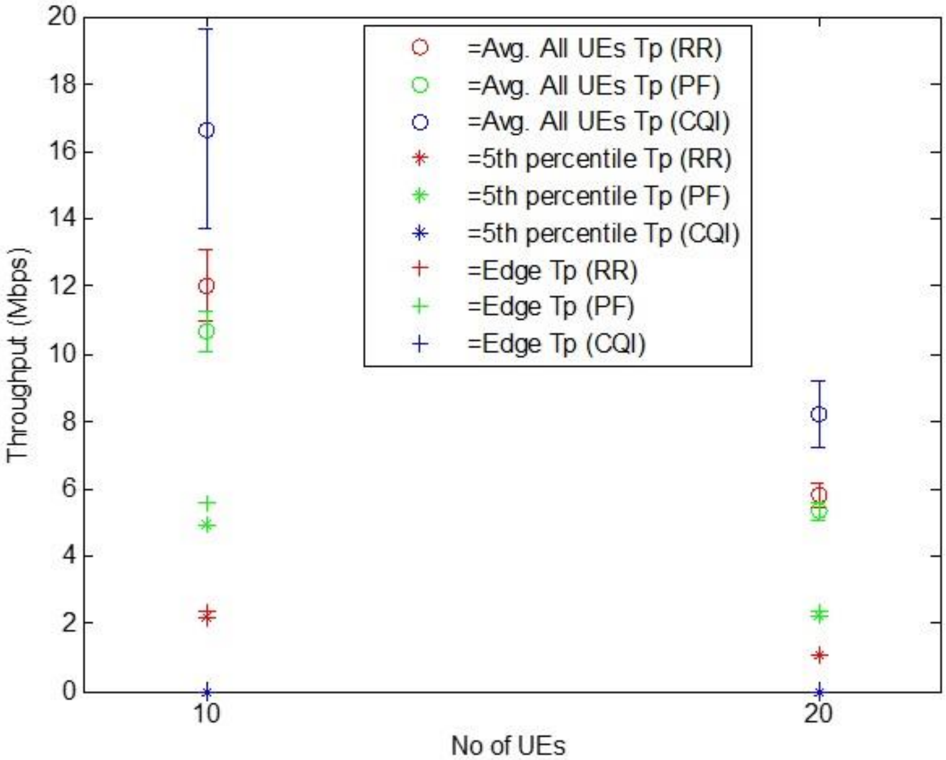


Figure 17: Plot of UE throughput (Tp) showing the deviation of the 5th percentile values from the Avg. Edge throughput with 95% confidence.

Table 7: Throughput statistics in the hybrid scenario, deploying 10UEs (Mbps)

Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	12.02	(10.96,13.09)	2.38	(2.16,2.60)	2.22
PF	10.69	(10.10,11.28)	5.60	(4.72,6.48)	4.93
CQI	16.64	(13.70,19.59)	0.00	(0.00,0.00)	0.00

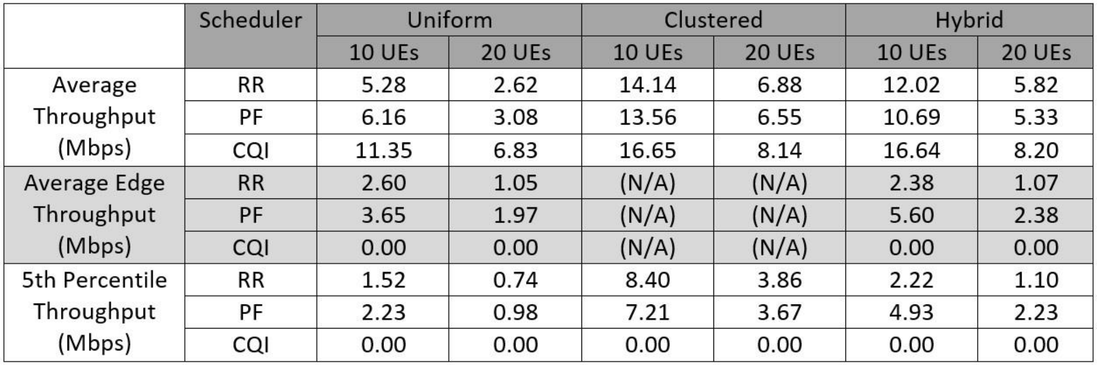
Table 8: Throughput statistics in the hybrid scenario, deploying 20UEs (Mbps)

Scheduler	Avg. Throughput	95% Confidence of average throughput	Avg. Edge throughput (5th Hexagon)	95% Confidence of Avg. Edge throughput	5th Percentile throughput
RR	5.82	(5.46,6.19)	1.07	(0.96,1.19)	1.10
PF	5.33	(5.05,5.60)	2.38	(2.15,2.61)	2.23
CQI	8.20	(7.21,9.18)	0.00	(0.00,0.00)	0.00

Also from Tables 4 through 8, it can be observed that for the average throughput, the round robin scheduler was statistically indistinguishable from the proportional fair scheduler in UE scheduling and resource allocation at the clustered center of the cell from the proportional fair scheduler, a contrast to the performance at the edge of the cell where proportional fair is mostly a winner (Tables 5, 7 and 8).

In summary, it can be inferred that the throughput of the user equipment in an LTE system largely depends on the distribution of the users within the coverage region and the situational suitability of the scheduler employed for resource allocation. The results are collated in Table 9.

Table 9: Comparison of UE performance over the three scenarios



	Scheduler	Uniform		Clustered		Hybrid	
		10 UEs	20 UEs	10 UEs	20 UEs	10 UEs	20 UEs
Average Throughput (Mbps)	RR	5.28	2.62	14.14	6.88	12.02	5.82
	PF	6.16	3.08	13.56	6.55	10.69	5.33
	CQI	11.35	6.83	16.65	8.14	16.64	8.20
Average Edge Throughput (Mbps)	RR	2.60	1.05	(N/A)	(N/A)	2.38	1.07
	PF	3.65	1.97	(N/A)	(N/A)	5.60	2.38
	CQI	0.00	0.00	(N/A)	(N/A)	0.00	0.00
5th Percentile Throughput (Mbps)	RR	1.52	0.74	8.40	3.86	2.22	1.10
	PF	2.23	0.98	7.21	3.67	4.93	2.23
	CQI	0.00	0.00	0.00	0.00	0.00	0.00

The conformity of the average edge throughput of the UEs (5th hexagon) with the 5th percentile throughput in the hybrid scenario introduces a clear indication of the importance of evaluating the UE distribution while setting standards for LTE dimensioning, as there appears to be an absence of correlation between the 5th percentile throughput values and the throughput obtained as the average edge throughput in the 5th hexagon.

Chapter 5

CONCLUSION AND FUTURE WORK

5.1 Conclusion

The degree of clustering (σ) plays a critical role in the distribution of UEs as it determines the allowed 'distance apart' of the deployed UEs. Hence, the UEs were deployed ensuring that a balance was obtained between over-clustering (a situation where UEs are excessively deployed in a small region) which leaves excessive eNodeB region empty and uniformly (where UEs are sparsely distributed in the region) which does not represent clustering.

Throughput values obtained from the various scenarios evaluated in the study reflects the various impacts impressed by the distribution mechanism employed. Average throughput in the clustering scenario is higher than that obtained in the uniform distribution scenario because fewer UEs were at the edge of the network to suffer from poor channel conditions (a realistic scenario), making the throughput values obtained using a uniform distribution an underestimate. Also, 5th percentile throughput values appear to be underestimates.

For the hybrid scenario, the 5th percentile throughput provided an acceptable estimate of the cell edge throughput. Detailed investigation might be required in future work on the hybrid scenario.

The selection of five (5) concentric hexagons with the width of each region being an essential constituent in the makeup of the regionalization as an excessively thin region tends to have fewer UEs than required for statistical analysis while an excessively thick region is bound to have more UEs than required and hence fails to describe the edge.

5.2 Future Work

In the nearest future, we intend to study femtocells as they have clustered structure of peculiar interests, they are like multiple hotspots in a wireless area. Clustered UE arrangements with patterns like the femtocell are currently unavoidable in practice as natural situations may impose the localization of devices and users in a confined geographical region. Due to the limitation of channel availability, optimization and dimensioning of the network takes more complexity as users traverse the hotspot and traffic and channel demand grows rapidly. In the nearest future through possible means, we intend to investigate the impact of inter-cell interference in femtocells and how with coordinated scheduling between eNodeBs, allocation of resources is done in a highly robust way reducing interference impact. Multiple user clusters with varying degrees of clustering offer an interesting scope of study.

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APPENDIX

Appendix A: Simulator Codes

Here are some of the codes used for the simulator extension

Configuration codes

```
close all force;
clc;
cd ..

simulation_type = 'omnidirectional_eNodeBs';
simSet = [4 2 2];

%% Base configuration
LTE_config = LTE_load_params(simulation_type);
LTE_config.bandwidth                      = 20e6;
fName='uniform20_6.mat';  %uniform distribution
%fName='clustered20_5.mat'; %clustered distribution
LTE_config.scheduler      = 'best cqi';
LTE_config.UE_distribution              = 'predefined';
load(fName);
LTE_config.UE_positions                = V;
LTE_config.network_geometry              = 'regular_hexagonal_grid';
LTE_config.shadow_fading_type             = 'none';
LTE_config.UE_per_eNodeB = 10;
LTE_config.simulation_time_tti = 10;
% % Misc options
LTE_config.keep_UEs_still               = true;
LTE_config.compact_results_file         = true;
LTE_config.always_on                      =true;

LTE_config.nTX     = simSet(2);
LTE_config.nRX     = simSet(3);
LTE_config.tx_mode = simSet(1);
ticIdx = tic;
output_results_file = LTE_sim_main(LTE_config);
time = toc(ticIdx);

simulation_data                   = load(output_results_file);
GUI_handles.aggregate_results_GUI =
LTE_GUI_show_aggregate_results(simulation_data);
GUI_handles.positions_GUI         =
LTE_GUI_show_UEs_and_cells(simulation_data,GUI_handles.aggregate_res
ults_GUI);
```

For the GUI

```
hold on;
NumberOfUEs = zeros(1,str2num(get(handles.edit1,'String')));
UEsInRegion =
zeros(str2num(get(handles.edit1,'String')),length(simulation_data.UE
s));
NumberOfRegions = str2num(get(handles.edit1,'String'));
k = convhull(PathLossNodes(:,1),PathLossNodes(:,2));
plot(PathLossNodes(k,1),PathLossNodes(k,2),'r-');
dist = max(pdist(PathLossNodes(k,:),'euclidean'));
```

```
d = dist/2 + simulation_data.LTE_config.map_resolution;
rad = (d/NumberOfRegions);
set(handles.edit2,'String', num2str(rad));
r(1:7) = rad;
theta= 0:pi/3:2*pi;
theta = theta + pi/2;
phx(1:7) = 0;
phy(1:7) = 0;
for Region = 1:NumberOfRegions
   polar(theta,r*Region);
   hx(1:7) = 0;
   hy(1:7) = 0;
   for j = 1:7
       hx(j) = r(j)*Region*cos(theta(j));
       hy(j) = r(j)*Region*sin(theta(j));
   end
   Index = 1;
   for Counter = 1:length(UE_pos)
            x = UE_pos(Counter,1);
            y = UE_pos(Counter,2);
            if((inpolygon(x,y, hx, hy))&&(~inpolygon(x,y, phx,
phy))&&(~completely_disabled_UEs(Counter)))
                ang=0:0.01:2*pi;
                xp=20*cos(ang);
                yp=20*sin(ang);
                plot(x+xp,y+yp, 'Color',[0,1,0]);
                UEsInRegion(Region, Index) = Counter;
                Index = Index + 1;
            end
   end
   NumberOfUEs(Region) = Index - 1;
   phx(1:7) = hx(1:7);
   phy(1:7) = hy(1:7);
end

set(handles.listbox4, 'String', '');
i = 1;
while(i <= size(UEsInRegion, 1))

    j = 1;
    while(UEsInRegion(i, j) > 0)
        j = j + 1;
    end
    UEs_to_plot_lin2 = UEsInRegion(i, 1:j-1);
    to_average2                   =
[the_UE_traces(UEs_to_plot_lin2).average_throughput_Mbps];
    to_average2                   =
to_average2(isfinite(to_average2));
    h_mean_average_throughput   = mean(to_average2);
    to_average2                   =
[the_UE_traces(UEs_to_plot_lin2).average_spectral_efficiency_bit_per
_cu];
    to_average2                   =
to_average2(isfinite(to_average2));
    h_mean_average_spectral_eff = mean(to_average2);
    str = sprintf('Region[%d]',i);
    additemtolistbox(handles.listbox4, str);
    str = sprintf('Number of UEs: %d', NumberOfUEs(i));
    additemtolistbox(handles.listbox4, str);
    str = sprintf('Avg UE throughput: %3.2f Mb/s',
h_mean_average_throughput);
```

```
    additemtolistbox(handles.listbox4, str);
    str = sprintf('Avg UE spectral eff.: %3.2f bit/cu',
h_mean_average_spectral_eff);
    additemtolistbox(handles.listbox4, str);
    i = i + 1;
end


i = 1;
j = 1;
Index = 1;
set(handles.listbox3, 'String', '');
while(i <= size(UEsInRegion, 1))
    if(UEsInRegion(i, j) > 0)
        str = sprintf('Region[%d]: %d  T: %3.2f Mb/s  SE: %3.2f
bit/cu', i, UEsInRegion(i, j), the_UE_traces(UEsInRegion(i,
j)).average_throughput_Mbps, the_UE_traces(UEsInRegion(i,
j)).average_spectral_efficiency_bit_per_cu);
        additemtolistbox(handles.listbox3, str);
        Index = Index + 1;
    end
    j = j + 1;
    if(UEsInRegion(i, j) == 0)
        j = 1;
        i = i + 1;
    end
end

hold off;
```

For the uniform distribution

```
R=288;
N=10; % No of users
V=[]; % Locations
fname='uniform20_10.mat';

L = linspace(0,2.*pi,7); xv = cos(L)'*R;yv = sin(L)'*R;
xv = [xv ; xv(1)]; yv = [yv ; yv(1)];
xv1=cos(L)'*(R-57.6); yv1=sin(L)'*(R-57.6);
xv1=[xv1;xv1(1)];yv1=[yv1;yv1(1)];
xv2=cos(L)'*(R-115.2); yv2=sin(L)'*(R-115.2);
xv2=[xv2;xv2(1)];yv2=[yv2;yv2(1)];
xv3=cos(L)'*(R-172.8); yv3=sin(L)'*(R-172.8);
xv3=[xv3;xv3(1)];yv3=[yv3;yv3(1)];
xv4=cos(L)'*(R-230.4); yv4=sin(L)'*(R-230.4);
xv4=[xv4;xv4(1)];yv4=[yv4;yv4(1)];

n=0; i=0;
while (m<M) % uniform
    x=randi([-500 500],1); y=randi([-500 500],1);
    if inpolygon(x, y, yv, xv)&&~inpolygon(x,y,yu,xu)
        V=[V; x y];
        m=m+1;
    end
end
figure;
plot(yv,xv,yv1,xv1,yv2,xv2,yv3,xv3,yv4,xv4,V(:,1), V(:,2),'*')
save(fname,'V');
```

For the hybrid distribution

```
clc
close all force
rand('state',sum(100*clock))

R=280; %rad for region
r=70; %rad for cluster
A=20; %Number of all users to be deployed
N=ceil(0.7*(A)); % No of users to form cluster
M=ceil(A-N); %No of users in other locations
V=[]; % Locations
W=[]; % Location of clustered UEs
fname='clustered20_10.mat';

L = linspace(0,2.*pi,7); xv = cos(L)'*R;yv = sin(L)'*R;
xv = [xv ; xv(1)]; yv = [yv ; yv(1)];

xu = cos(L)'*r;yu = sin(L)'*r; xu = [xu ; xu(1)]; yu = [yu ; yu(1)];
n=0; i=0;
sigma=50; % Determines the degree of clustering
while (n<N) %Clustered users
    x=round(sigma*randn(1)); y=round(sigma*randn(1));
    if inpolygon(x, y, yu, xu)
        W=[W; x y];
        n=n+1;
    end
end
figure
plot(yu,xu,'w',W(:,1), W(:,2),'*')
hold on
m=0; j=0;
sigma=5000; % Determines the degree of clustering
while (m<M) % non clustered
    x=round(sigma*randn(1)); y=round(sigma*randn(1));
    if inpolygon(x, y, yv, xv)&&~inpolygon(x,y,yu,xu)
        V=[V; x y];
        m=m+1;
    end
end
plot(yv,xv,V(:,1), V(:,2),'+')
V=[V;W];
save(fname,'V');
```

For the clustered scenario

```
rand('state',sum(100*clock))

R=288;
N=20; % No of users
V=[]; % Locations
fname='clustered20_10.mat';
```

```
L = linspace(0,2.*pi,7); xv = cos(L)'*R;yv = sin(L)'*R;
xv = [xv ; xv(1)]; yv = [yv ; yv(1)];

n=0; i=0;
sigma=40; % Determines the degree of clustering
while (n<N)
    x=round(sigma*randn(1)); y=round(sigma*randn(1));
    if inpolygon(x, y, yv, xv)
        V=[V; x y];
        n=n+1;
    end
end
figure
plot(yv, xv,V(:,1), V(:,2),'+')
save(fname,'V');
```