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Comparison of Reference Signal Received Power Measurements between Cell Phone and Scanning Receiver in LTE

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By

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The degree of
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ABSTRACT

Title: Comparison of Reference Signal Received Power Measurements between Cell Phone and Scanning Receiver in LTE

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In cellular technology, before giving service to customers, coverage estimation, network optimization, and maintenance rely on RSRP (Received Signal Reference Power) measurements that are collected in a given area. This measurement collection is called "drive test or drive testing" that is very common practical experiment for RF engineers. These measurements are usually recorded by a professional receiver or a professional phone with appropriate software and license. A scanning receiver, PCTEL SeeGull EX scanning Receiver in this thesis, is a common professional tool for RF engineers to collect data. A cell phone, HTC One M7 for this experiment, has an appropriate application created by a Ph.D. student at Florida Institute of Technology in order to record the measurements. There may be some difference between a given coverage area and the area customers experience. Because of that, the target of this thesis is to show that there is a significant difference between the scanning receiver and the cell phone in terms of customers' experience.

RSRP measurements were collected in Melbourne, FL with three different drive test from two devices at 700MHz in Long Term Evolution (LTE). These measurements were compared and presented in this thesis. Stochastic tools and theoretical analysis were utilized in order to understand the validity of this experiment.

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1 INTRODUCTION TO MOBILE NETWORKS AND DRIVE TESTING

1.1 Mobile Generation Networks

Mobile networks may be one of the most active areas last four decades. As it is seen in Figure 1, mobile subscribers are increasing every day. Because of that, new technologies and systems that make mobile networks more comfortable for customers have to be applied to this technology.

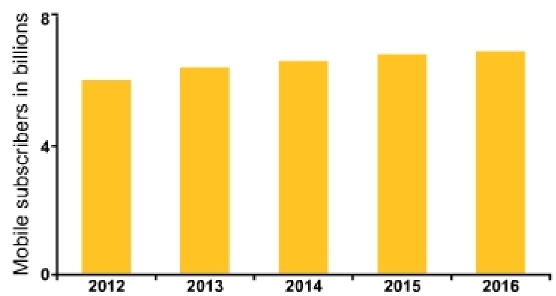

Figure 1: Mobile Subscribers [1]

Before 1973, mobile phones were placed to cars and other vehicles. In 1973, Motorola introduced a handheld mobile phone (Motorola DynaTAC 8000X, see Figure2) by Martin Cooper. It was 1.1 kg (2.42 lbs.), 23 cm long, 13 cm deep, 4.45 cm wide, and the prize of the phone was $3,995 in that time ($9600 in 2016). However, it was commercially available in 1983 in the USA and Europe.

Figure 2: Motorola DynaTAC 8000X [2]

Motorola DynaTAC 8000X was suitable for only voice calls. In this generation, Short Messaging Service (SMS) or any data was not available in those days. However, nowadays, it can be said that data is more important than voice. For customers, one of the most important application is data rate. Because of this, data rate in wireless communications systems has increased significantly since the deployment of smart phones. Since customers are looking for reliability, robustness and high performance, it is essential for operators to keep up with new technologies and keep their systems updated [3]. Therefore, there is need to satisfy the demands of the capacity improvements in wireless communications [4].

Due to these demands from customers, The International Telecommunication Union (ITU) launched the International Mobile Telecommunications (IMT-2000) as an initiative to cover high-speed, broadband, and Internet Protocol (IP)-based mobile systems featuring network-to-network interconnection, feature/service transparency, global roaming, and seamless services independent of location. IMT-2000 is intended to bring high-quality mobile multimedia telecommunications to a worldwide mass market by achieving the goals of increasing the speed and ease of wireless communications, responding to the problems faced by the increased demand to pass data via telecommunications, and providing “anytime, anywhere” services [5].

There are four generation networks less than four decades. Because of that, cellular network is the one of fastest growing technology in the world. In this technology, there have been many standards in order to satisfy the quality and demands. Two partnership organizations were born from the ITU-IMT-2000 initiative: The Third Generation Partnership project (www.3gpp.org) and the Third Generation Partnership Project 2 (www.3gpp2.org). The 3GPP and 3GPP2 developed their own version of 2G, 3G, and even beyond 3G mobile systems [5]. Figure 3 is an illustration of cellular generations.

Figure 3: Cell Phones with its Generations [6]

1.1.1 First Generation Mobile Network (1G)

First generation (1G) wireless networks denoted the voice only analog cellular systems with analogue circuit switched network architecture. Basic voice telephony, low capacity and limited local and regional coverage were the main challenges in this system [4].
In the late 1970s and early 1980s, various 1G cellular mobile communication systems were introduced. The first such system, the Advanced Mobile Phone System (AMPS), was introduced in the USA in the late 1970s. Other 1G systems include the Nordic Mobile Telephone System (NMT) and the Total Access Communications System (TACS) [5].
These Standards were operating in different frequency bands and different standards; therefore, if a person use a cell phone in the USA, that cell phone was not worked in different countries, e.g. Europe. This is why Second Generations had to be introduced to overcome these drawbacks.

1.1.2 Second Generation Mobile Network (2G)

The second-generation (2G) digital systems promised higher capacity and better voice quality than did their analog counterparts [5]. By utilizing digital system, the signal can be compressed much more efficiently than analog system. This means that effective encoding structure allows transmitting more packet into the same bandwidth and propagates with less power from user devices which were transmitting with an analogue signal before [4].

2G was introduced in 1990s. 2G cellular systems are GSM (Global System for Mobile Communications) formed by 3GPP and IS-95 CDMA (Code Division Multiple Access) formed by 3GPP2. These two standards was leading the market, GSM was common in Europe and all around the world while IS-95 CDMA was common in the USA.
Using circuit-switched for digital voice, and the cost of having cell phones made a rapid extension in cellular communication. Beside voice application, there was an application, SMS (Short Messaging Service). 2G mobile network was basically allocated frequency spectrums (800/900 & 1800/1900 MHz)

1.1.3 Third Generation Mobile Network (3G)

The third generation (3G) was introduced at the end of 20th century. 3G systems differed from 2G generation systems more in the ability to integrate voice and data applications [4]. In order to satisfy larger voice and data traffic, under 3GPP GSM systems have defined Universal Mobile Telecommunications System (UMTS) and 3GPP2 has launched CDMA2000. However, UMTS dominated over CDMA200 by using two different domain in order to traffic voice and data. For voice application, circuit-switched was used, and packet-switched was added without establishing any circuit for data traffic.
UMTS Terrestrial Radio Access Network (UTRAN) based on Wideband Code Division Multiple Access (WCDMA) radio technology since it is using 5 MHz bandwidth and GSM/EDGE Radio Access Network (GERAN) based on (GSM)-enhanced data rates. On the other hand, 3GPP2 implemented CDMA2000 under 1.25 MHz bandwidth which increased voice and data services and supported a multitude of enhanced broadband data applications, such as broadband Internet access and multimedia downloads [5]. There was also more frequency spectrum available up to 2100 MHz. Two standards was compatible to each other, which customers were satisfied with.

1.1.4 Fourth Generation Mobile Network (4G)

The ever increasing number of mobile broadband users requires the availability of enhanced data services. Long Term Evolution or LTE is the evolution of High Speed Packet

Access (HSPA), which was standardized by third generation partnership project (3GPP) Release 8 in order to meet the increasing demand of faster and more efficient mobile internet access today by supporting the larger bandwidth [7]. Although there was UMB (Ultra-Mobile Broadband) standard by 3GGP2, LTE was the only standard all around the world, and the deployment started around 2010.

The objective of 4G is to handle this rapidly increasing numbers of users without degrading the quality of service. However, scalability is not the only focus of 4G. It aims at providing a spectrally efficient system (in bit/s/Hz and bit/s/Hz/site) and a nominal data rate of 100 Mbit/s while the client physically moves at high speeds relative to the station, and 1 Gbit/s while client and station are in relatively fixed positions [1].

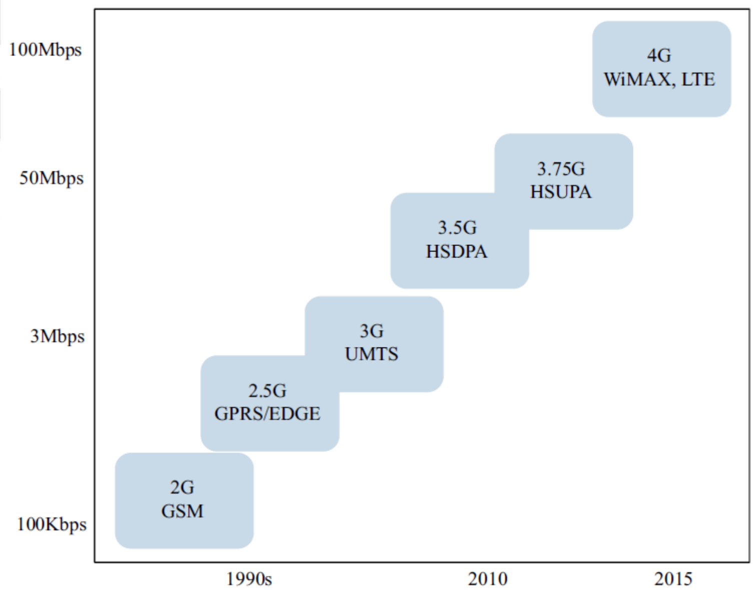

Figure 4: Evolution of global wireless technologies [4]

As it is shown in Figure 4, it can be seen that data rates versus wireless technologies. WiMAX and LTE systems are used in 4G, and UMB is not mentioned in fourth generation mobile network. Moreover, circuit-switched domain was removed in LTE, and now in LTE, voice and data are delivered over internet protocol (IP). It can be called VoIP (voice over internet protocol) or VoLTE (voice over LTE).

Table 1: Comparison of 3G and 4G systems [1]

	3G (including 2.5G, sub 3G)	4G
Major Requirement Driving Architecture	Predominantly voice driven - data was always add on	Converged data and voice over IP
Network Architecture	Wide area cell-based	Hybrid- integration of Wireless LAN (WiFi, Bluetooth) and wide area
Speeds	384 Kbps to 2 Mbps	20 to 100 Mbps in mobile mode
Frequency Band	Dependent on country or continent (1800-2400 Mhz)	Higher frequency bands (2-8 GHz)
Bandwidth	5 - 20 Mhz	100 Mhz (or more)
Switching Design Basis	Circuit and Packet	All digital with packetized voice
Access Technologies	W-CDMA, 1xRRT, Edge	OFDM and MC-CDMA (Multi Carrier CDMA)
Forward Error Correction	Convolution rate , 1/2, 1/3	Concatenated coding scheme
Component Design	Optimized antenna design, multi-band adapters	Smarter Antennas, software multiband and wideband radios
IP	A number of air link protocols, including IP 5.0	All IP (IP 6.0)

Faster wireless broadband connections enable wireless carriers to support higher level data services, including business applications, streamed audio and video, video messaging, video telephony, mobile TV, and gaming [5]. Numerous frequency band were allocated for 4G, and frequency bands were more than previous generations such as 1.4/3/5/10/15 and 20 MHz bandwidths. In order to understand basic differences between 3G and 4G, Table 1 is an example of this comparison.

1.1.5 Fifth Generation Mobile Network (5G)

Fifth generation (5G) is currently in development, the expectations for the deployment of 5G will be between 2020 and 2030. 5G will be the first generations which will not replace the previous generation because the goal of 5g is not mobile users. It targets vehicles, household devices and the Internet of Things (IoT) (see Figure 5). Because of IoT network, most of devices will use internet and wide range of data rates. As a result of that, wide frequency spectrum can be used such as 20/30/60 MHz.

Figure 5: 5G and IoT [8]

1.2 Drive Testing in LTE

All generations of cellular industry rely on measurements to monitor network performance. There are two types of testing for data collection, Drive Test and Walk Test. These tests are the test that records and measures RF metrics with their location (GPS) in a real world environment while driving or walking. RF engineers may theoretically model a program in order to see how RF signals perform; however, it is hard to wholly predict how User Equipment (UE) deals with the network. In terms of customers' experience, therefore, all generations of cellular industry rely on drive/walk test for data collection.

In LTE, drive testing is a part of the network deployment and management life cycle from the early onset. Drive testing provides an accurate real world capture of the RF environment under a particular set of network and environmental conditions. The main benefit of drive testing is that it measures the actual network coverage and performance that a user on the actual drive route would experience [9]. Driving test network life cycle may be described as Figure 6 shown.

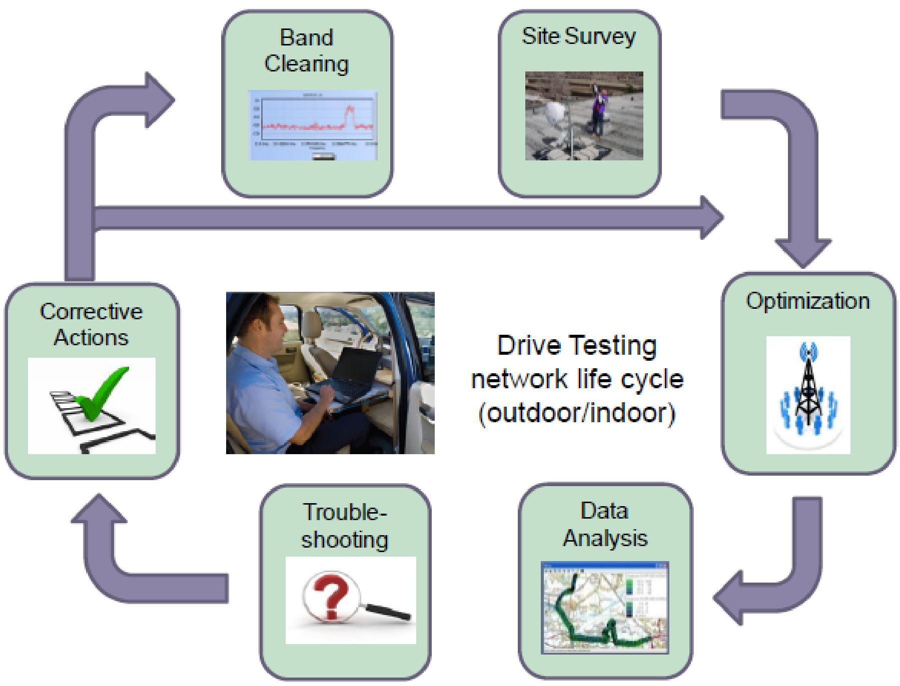

Figure 6: Network Planning Cycle [9]

Drive Test can be based on phone or receiver. Phone-based drive test records RF signals' information in phones or server which depend on their software, also it measures data with a carrier perspective. On the other hand, Receiver-based drive test saves data regardless carriers, and it can measure RF metrics in different frequencies, different bandwidths and different standards. In addition, it is for sure that Receivers has much more sophisticated systems than cell phones do.

Drive testing could be divided into four scenarios in order to perform a drive test in a given route. These are Pre-deployment, Network Benchmarking, Optimization and Troubleshooting, and Service Quality Monitoring. Pre-deployment is that before giving any service to customers, a carrier company measures RF signals' metrics to comprehend their coverage area. Network Benchmarking provides a way that compares different network technologies or carriers. Optimization and Troubleshooting usually focus on specific problems such as network issues, and aiming to solve problems. Service Quality Monitoring can be understood from its name that monitors the service quality.

2 OVERVIEW LTE SYSTEM

In this chapter, the LTE System is overviewed such as its architecture, its major features and its performance metrics.

2.1 LTE Architecture

The overall architecture has two distinct components: the access network and the core network. The access network is the Evolved Universal Terrestrial Radio Access Network (E-UTRAN). The core network is called the Evolved Packet Core (EPC) [5]. Figure 7 shows overall LTE architecture, even though there is a User Equipment (UE) such as a cell phone or laptop in Figure 7, UE is not a part of the System Architecture Evolution (SAE); however, it will be explained in this section. Additionally, as it is known, the Evolved Packet System (EPS) consists of E-UTRAN and EPC.

The evolved UMTS terrestrial radio access network (E-UTRAN) is responsible for all management of mobile equipped EPC`s radio communication which replaces the UTRAN that was part of previous architecture. EPC comprises of a Mobility Management Entity (MME), a Serving Gateway (S-GW) that interfaces with the E-UTRAN, and a PDN Gateway (P-GW) that interfaces to external packet data networks [7].

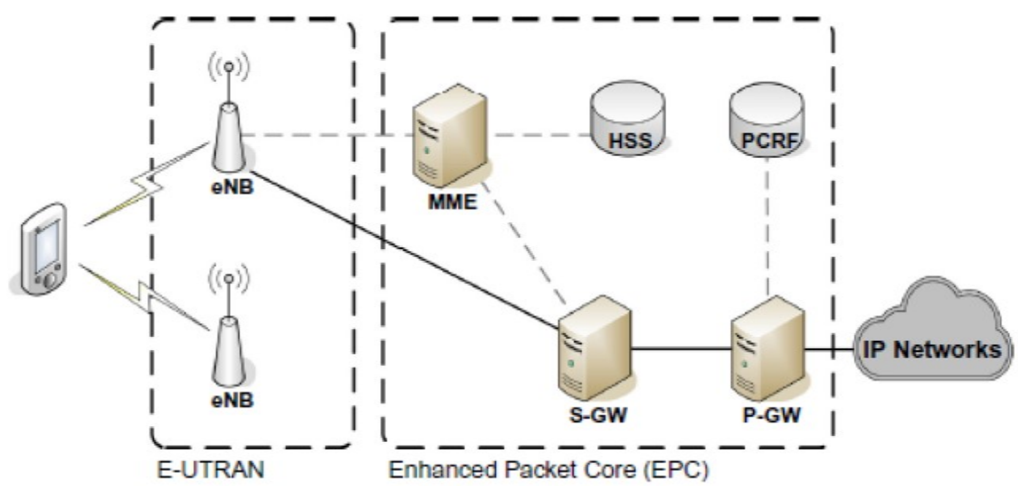

Figure 7: Overall LTE Architecture [7]

2.1.1 The Evolved Universal Terrestrial Radio Access Network

E-UTRAN is the air interface of 3GPP's Long-Term Evolution (LTE) upgrade path for mobile networks. It is a radio access network standard meant to be a replacement of the UMTS, HSDPA, and HSUPA technologies specified in 3GPP releases 5 and beyond. LTE's E-UTRAN is an entirely new air interface system, which provides higher data rates and lower latency and is optimized for packet data [5].

The E-UTRAN in LTE architecture consists of a single node (evolved NodeB, eNB or eNodeB) that interfaces with the UE. The aim of this simplification is to reduce the latency of all radio interface operations. eNBs are connected to each other with X2 interface, and they are connected to the S-GW and to the MME with S1 interface (see Figure 8), more specifically to the MME via S1-MME, and to the S-GW via S1-U. The E-UTRAN uses OFDMA for Downlink transmission and SC-OFDMA for Uplink transmission, which are explained in the section, LTE Major Features.

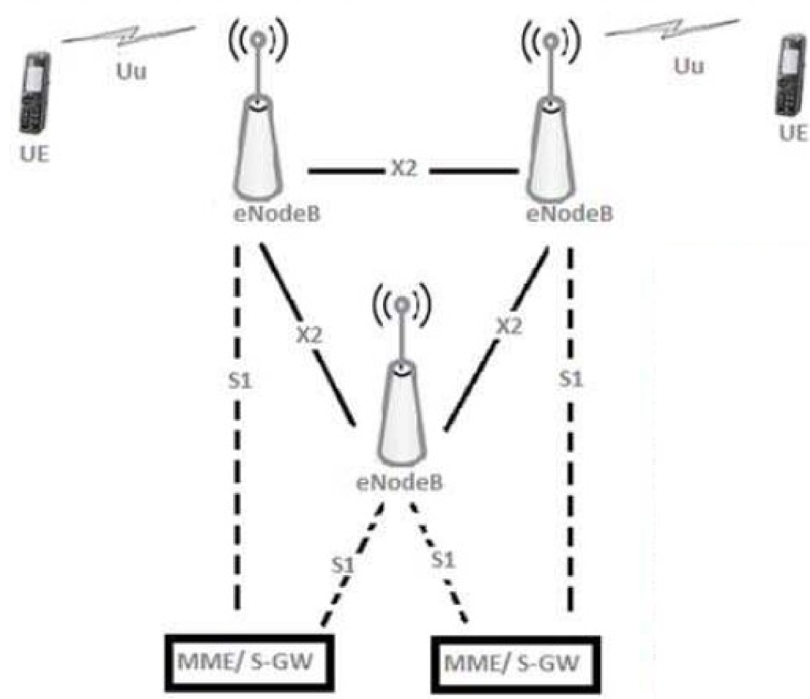

Figure 8: E-UTRAN Architecture [10]

eNBs are basically base stations, and they are responsible for managing multiple cells. Unlike some of the previous second- and third-generation technologies, LTE integrates the radio controller function into the eNodeB. This allows tight interaction between the different protocol layers of the radio access network (RAN); thus, reducing latency and improving efficiency [11]. X2 interface is used for handover information, and load & interference management.S1-U (S1 user plane) is defined between eNB and the S-GW for delivering data. On the other hand, S1-MME is defined as an interface between the MME and eNB, and it is responsible for signaling and paging procedure.

2.1.2 Evolved Packet Core

The architecture in GSM is based on circuit-switching, it provides voice and short messages. Later, in GPRS in order to transfer data without establishing circuits, packet-switching is added, so that the architecture of in GPRS consists of two domains circuit and packet (see Figure 9).

The 3GPP community decided to use IP (Internet Protocol) as the key protocol to transport all services. It was therefore agreed that the EPC would not have a circuit-switched domain anymore and that the EPC should be an evolution of the packet-switched architecture used in GPRS/UMTS [12].

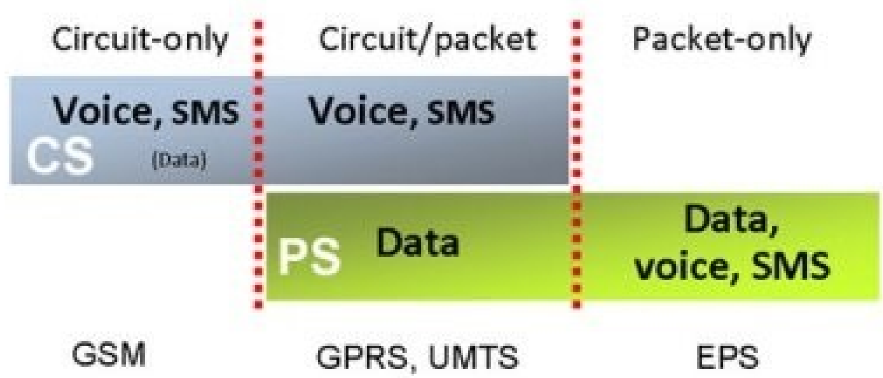

Figure 9: Circuit and Packet Domains [12]

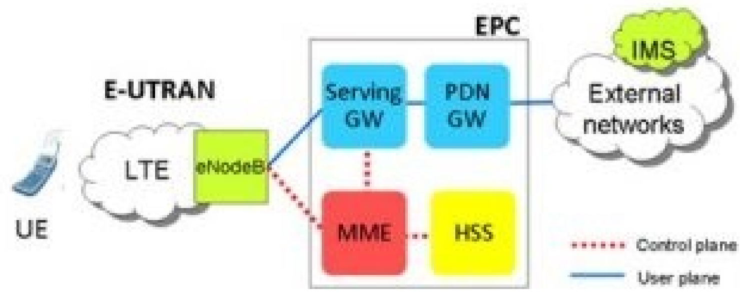

Figure 10: Basic EPS Architecture [12]

It can be said that the main part of the EPS is the EPC, and it basically has 4 elements: the S-GW, the MME, the PDN-GW, and the HSS as shown in Figure 10.

The Serving gateway: The S-GW routes and forwards user data packets, while also acting as the mobility anchor for the user plane during inter-eNodeB handovers and as the anchor for mobility between LTE and other 3GPP technologies. For idle state UEs, the S-GW terminates the downlink data path and triggers paging when downlink data arrives for the UE. It manages and stores UE contexts, e.g., parameters of the IP bearer service and network internal routing information. It also performs replication of the user traffic in case of lawful interception [5].

The Mobility Management Entity: This unit is the brain of the EPC, as it resides in its control plane, and is responsible for the session status management, paging, authentication, mobility in 3GPP, 2G and 3G nodes, Barrier management functions, roaming [13].

The Packet Data Network Gateway: The PDN-GW is the point of interconnect between the EPC and the external IP networks which are called PDN (Packet Data Network). The PDN-GW routes packets to and from the PDNs. The PDN GW also performs various functions such as IP address / IP prefix allocation or policy control and charging [12].

The Home Subscriber Server: Basically, the HSS (for Home Subscriber Server) is a database that contains user-related and subscriber-related information. It also provides support functions in mobility management, call and session setup, user authentication and access authorization [12].

2.1.3 User Equipment (UE)

User equipment is a device that is utilized by an end-user to connect with eNodeB, and user equipment can be any devices such as cell phones or laptops. For cell phones, there is a card which is known as the SIM (Subscriber Identity Module) card. This card executes an application called the Universal SIM (USIM) that stores specific user data, such as home network identity and phone number. The LTE supports all devices that use USIM releases 99 and beyond, but it does not support earlier releases of GSM that used the Subscriber Identity Module (SIM) [13].

LTE has categorized user equipment in order to allow eNodeBs to communicate with User Equipment. For all devices, LTE-Release 8 has 5 categories, and after Category 5, there are Category 6 and up to Category 12, which are for LTE-Advanced, Release 10 and beyond. Table 2 shows Release 8 UE's categories and their features.

Table 2: Release 8 User Equipment Categories and Features [14]

<table>
<tr><th colspan="2">Category</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th></tr>
<tr><td rowspan="2">Peak rate Mbps</td><td>DL</td><td>10</td><td>50</td><td>100</td><td>150</td><td>300</td></tr>
<tr><td>UL</td><td>5</td><td>25</td><td>50</td><td>50</td><td>75</td></tr>
<tr><td colspan="7">Capability for physical functionalities</td></tr>
<tr><td colspan="2">RF bandwidth</td><td colspan="5">20MHz</td></tr>
<tr><td rowspan="2">Modulation</td><td>DL</td><td colspan="5">QPSK, 16QAM, 64QAM</td></tr>
<tr><td>UL</td><td colspan="4">QPSK, 16QAM</td><td>QPSK, 16QAM, 64QAM</td></tr>
<tr><td colspan="7">Multi-antenna</td></tr>
<tr><td colspan="2">2 Rx diversity</td><td colspan="5">Assumed in performance requirements.</td></tr>
<tr><td colspan="2">2x2 MIMO</td><td>Not supported</td><td colspan="4">Mandatory</td></tr>
<tr><td colspan="2">4x4 MIMO</td><td colspan="4">Not supported</td><td>Mandatory</td></tr>
</table>

QPSK and 16-QAM can be used as modulation schemes for uplink until Category 4, but Category 5 devices can use three different modulation for uplink transmission. Moreover, Category 1 devices do not support Multiple Input Multiple Output (MIMO), which is an antenna technology using multiple antennas at transmitter and receiver side in order to increase data rate, and to reduce the errors. On the other hand, 4x4 MIMO is only used for Category 5 in LTE-Release 8.

2.2 LTE Major Features

In this section, it is discussed some significant features for LTE system that deserve to be mentioned such as its modulation scheme, its multiple access technique, and its bandwidth. Table 3 shows these features for LTE Release 8 as major parameters.

Table 3: LTE Release 8 major parameters [5]

Parameter	Values
Access Scheme UL	SC-OFDMA
Access Scheme DL	OFDMA
Bandwidth	1.4, 3, 5, 10, 15, and 20 MHz
Minimum TTI	1 ms
Subcarrier spacing	15 kHz
Cyclic prefix short	4.7 μs
Cyclic prefix long	16.7 μs
Modulation	QPSK, 16 QAM, 64 QAM
Spatial multiplexing	Single layer for UL per UE, up to four layers for DL per UE, MU-MIMO supported for UL and DL

2.2.1 Multiple Access in LTE

There are mainly two types of Multiple Access Techniques which are Frequency Division Multiple Access (FDMA) and Time division Multiple Access (TDMA) (see Figure 11). In FDMA that was used by the first generation analogue systems, analogue filters were used by the UEs to differentiate their own carrier frequencies from other carriers. In this technique guard bands were used to separate adjacent carriers to minimize the interference between the two. On the other hand, in TDMA all mobile devices receive information on the same carrier frequency but at different times [13].

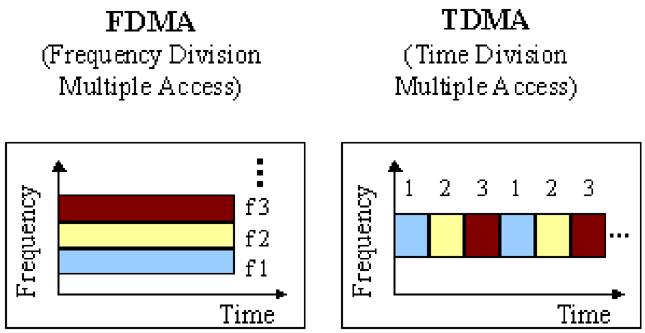

Figure 11: Multiple Access Techniques [15]

Multiple access schemes allow many mobile users to share simultaneously a finite amount of radio spectrum. The sharing of spectrum is done in order to achieve high capacity by simultaneously allocating the available bandwidth (or the available amount of channels) to multiple users (see Figure 12). For high quality communications, this must be done without severe degradation in the performance of the system [1].

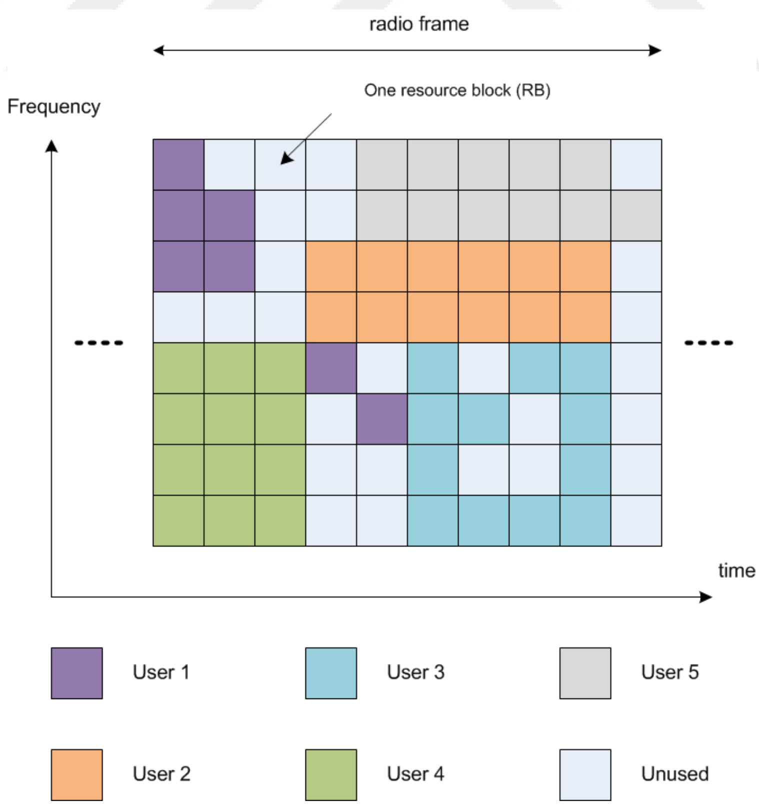

Figure 12: OFDMA Resource Allocation [6]

In LTE, OFDMA (Orthogonal Frequency Division Multiple Access) is an air interface in order to manage users in two domain. In OFDMA, one resource block is 1ms in time domain, 15 kHz in frequency domain. It means that every 1ms, it is decided how much bandwidths will be given to users based on their demands. In order to use efficiently bandwidth, this technique is very dynamic in terms of power because every millisecond it changes users' carrier. These carriers are seen overlapped in frequency domain but they are orthogonal in vector domain, which means that carriers do not interface each other. In other words, all carriers' power are zero at specific frequency except one of them has power.

2.2.2 Transmission in LTE

3GPP-LTE introduces the air interface access technologies from the use of orthogonal frequency division multiplexing (OFDM), multiple antenna technologies as well as modifications to the network architecture. OFDM is used in the downlink transmission, and Single Carrier FDMA (Frequency Division Multiple Access) technology is applied in the uplink transmission [16].

2.2.2.1 Downlink Transmission

If the dot product of two deterministic signals is equal to zero, these signals are said to be orthogonal to each other. Orthogonality can also be viewed from the standpoint of stochastic processes. If two random processes are uncorrelated, then they are orthogonal [5]. Radio resources in LTE are divided into frequency domain and time domain. Each LTE downlink frame has 10ms duration and further divided into sub-frames (10 sub frames) each of which has 1ms duration, known as Transmission Time Interval (TTI) and each TTI consists of two time slots of 0.5ms duration [10] as shown in Figure 13.

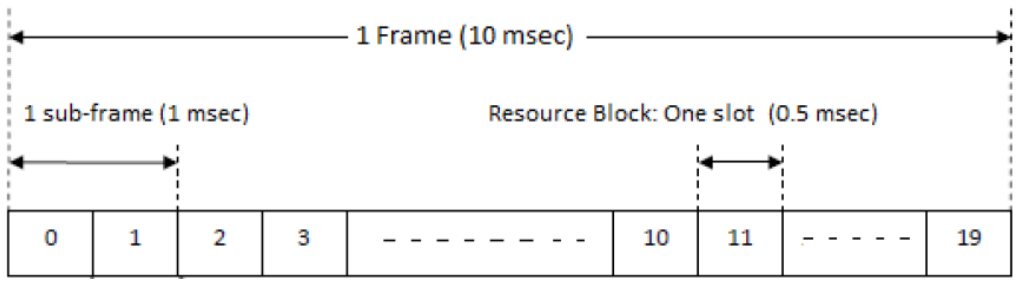

Figure 13: Time domain frame structure [10]

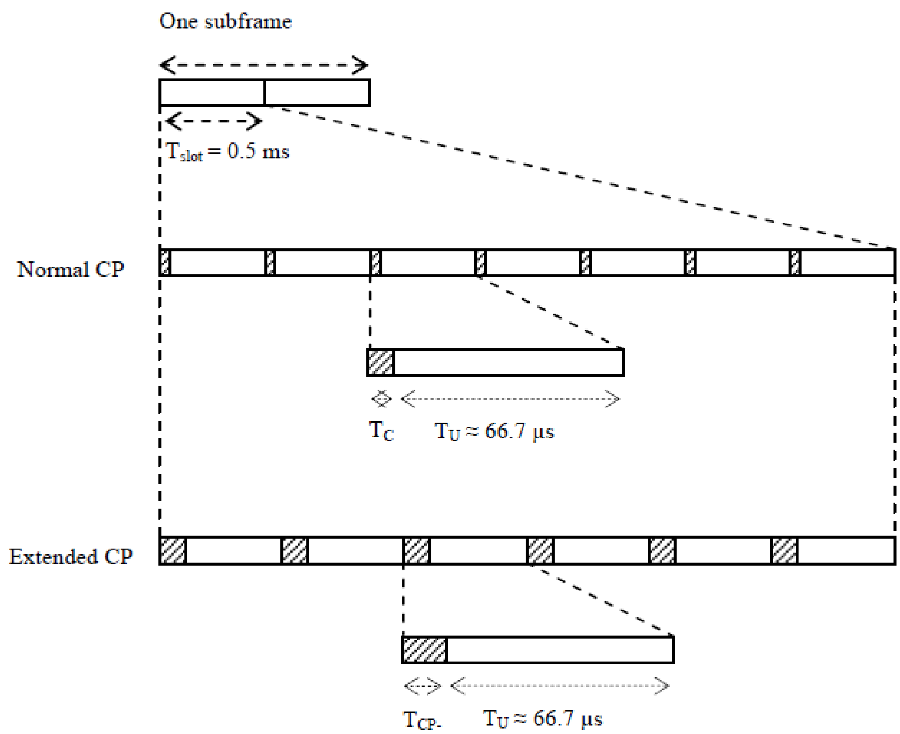

Figure 14: LTE sub frame and slot structure [16]

The number of OFDM symbols per sub-frame is 7 for normal cyclic prefix and 6 for extended cyclic prefix in the time domain (Figure 14) and length of 12 consecutive sub-carriers (180 kHz) in the frequency domain [5] (Figure 15 and Figure 16). To provide consistent and exact timing definitions, different time intervals within the LTE radio access specification can be expressed as multiples of a basic time unit

$Ts = \frac{1}{30720000}$ sec. Therefore T_{frame} and $T_{subframe}$ can be expressed as (307200.Ts) and (30720.Ts) respectively [16].

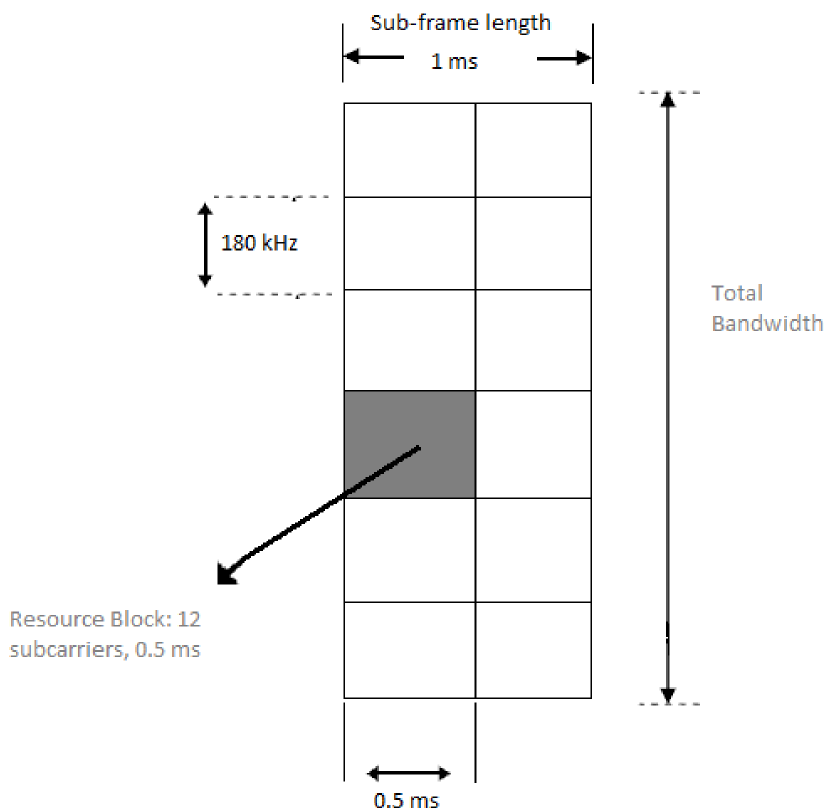

Figure 15: Resource Block grid in frequency domain [10]

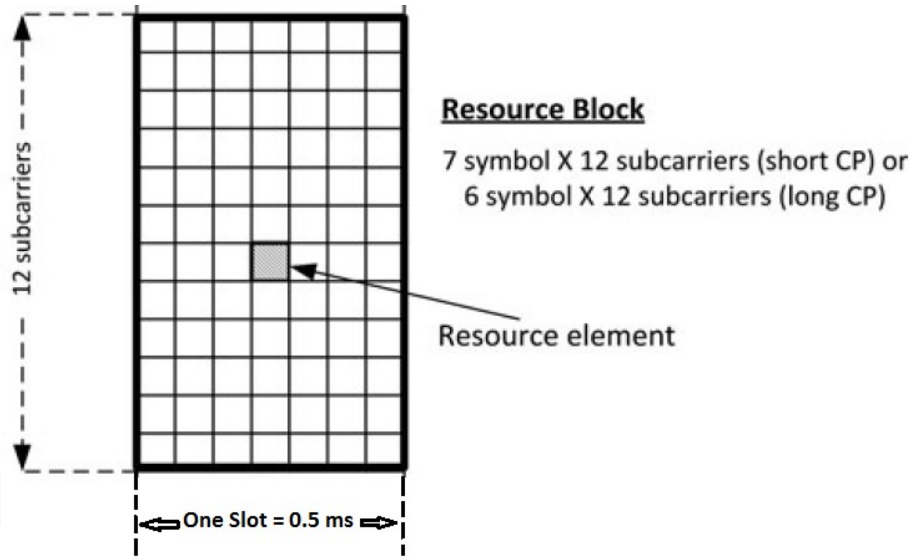

Figure 16: Resource Block Structure [5]

The total number of available subcarriers depends on the overall transmission bandwidth of the system [5]. There are 12 resource blocks as it is seen In Figure 15 with, and each resource block has 12 subcarriers (Figure 16). Therefore, it means that there are 72 subcarriers, and the total bandwidth is 1.4 MHz that means each subcarrier spacing is 15 kHz. System bandwidths parameters which depends on the LTE specifications is defined in Table 4.

Table 4: Downlink OFDM modulation parameters [5]

Parameter	1.4	3	5	10	15	20
Sub-frame duration	1.0 ms					
Subcarrier spacing	15 kHz					
Sampling frequency (MHz)	1.92	3.84	7.68	15.36	23.04	30.72
FFT size	128	256	512	1,024	1,536	2,048
No. of occupied subcarriers	72	180	300	600	900	1,200
CP length normal (μs)	4.69 × 6, 5.21 × 1					
CP length extended (μs)	6.16					

2.2.2.2 Uplink Transmission

Single carrier FDMA (SC-FDMA) which utilizes single carrier modulation at the transmitter and frequency domain equalization at the receiver is a technique that has similar performance and essentially the same overall structure as those of an OFDMA system. SC-FDMA has been adopted as the uplink multiple access scheme in 3GPP Long Term Evolution (LTE) mainly due to its low peak-to-average power ratio (PAPR) which greatly improves the transmit power efficiency [17].

SC-FDMA is a single carrier transmission based on DFT-spread OFDM where a block of N modulation symbols is applied to N-point DFT. The DFT spreads data symbols between all available subcarriers, combined with pilot symbols in time division multiplexing (TDM) and then mapped to proper subcarriers. After the Npoint DFT, a size of M-point IDFT is applied to the signal, where M > N and the unused inputs of the IDFT equals to zero. At the receiver, the process is the opposite way in which after the M-point DFT is applied, the signal is frequency domain equalized and then the signal is finally converted into time domain using N-point IDFT. A comparison of SC-FDMA and OFDMA is drawn in Figure 17 which summarizes the difference in block diagram [16].

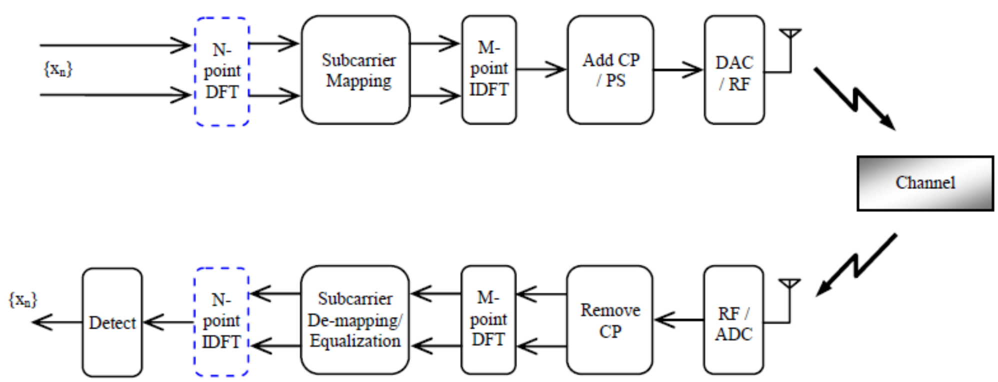

Figure 17: A block diagram of SC-FDMA and OFDMA [16]

2.2.3 Modulation Scheme in LTE

Modulation for analog transmission of digital data is a way to covert digital data (zeros and ones) into analog waveforms in order to transmit the information. Theoretically, square pulls are used to represent zeros and ones; however, sine or cosine function are used in practical experiments for the representation of digital data due to the fact that producing square pulls are required to use high frequencies.

There are three type of modulation from digital to analog, these are ASK (Amplitude Shift keying), FSK (Frequency Shift Keying), and PSK (Phase shift Keying). QAM (Quadrature Amplitude Modulation) is the combination of ASK and PSK. Additionally, there are three types of modulation scheme used in LTE, these are QPSK (Quadrature Phase Shift Keying), 16-QAM (16 Quadrature Amplitude Modulation), and 64-QAM (64 Quadrature Amplitude Modulation).

With QPSK, 4 symbols are send at a time, and each symbol consist of 2 bits as it is seen in Figure 18, M is the number of symbols, and Ɛ is the energy of a symbol. For 16-QAM, 16 symbols are transmitted at a time, for each symbol consists of 4 bits. On the other hand, 64-QAM modulation scheme has 64 symbols and each symbol has 6 bits. For QAM constellation points in vector domain, Figure 19 is presented.

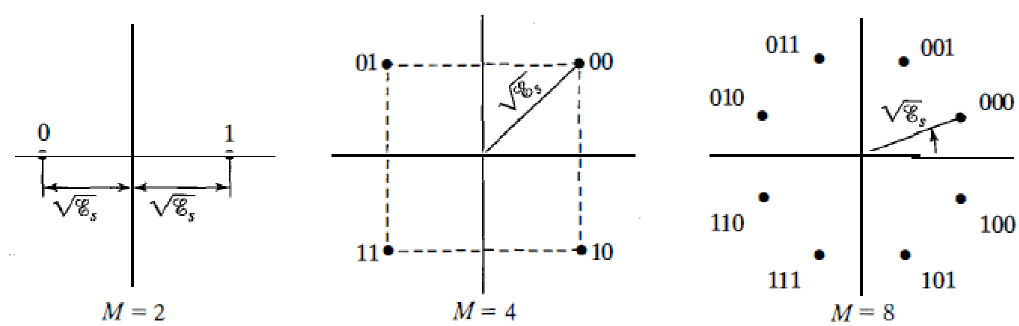

Figure 18: PSK Signal Constellations [18]

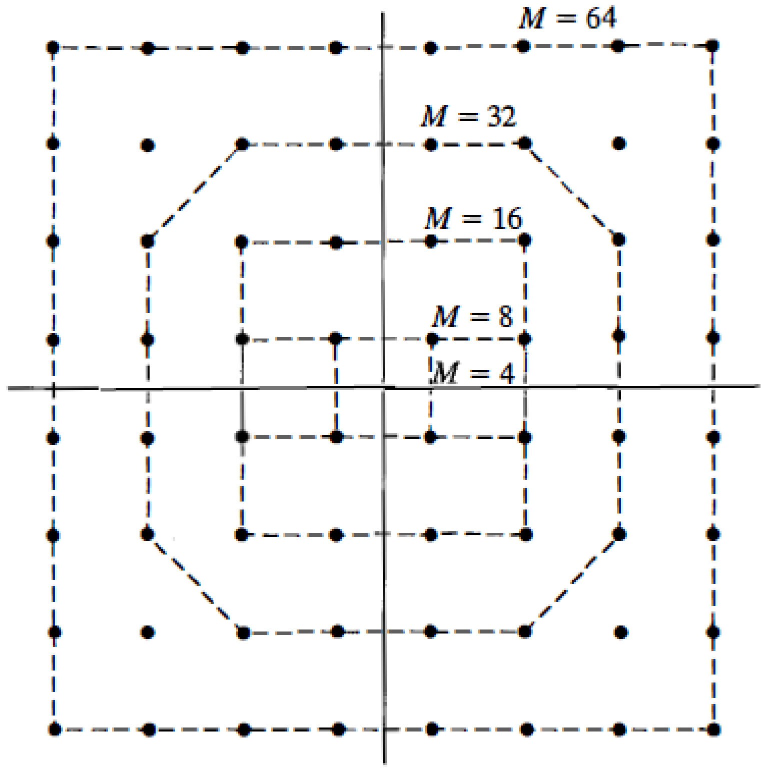

Figure 19: Constellation for QAM [18]

2.2.4 Channel Bandwidth in LTE

In LTE, there are 6 different channels bandwidths, which are 1.4, 3, 5, 10, 15, and 20MHz. The bandwidths can be max 100MHz with carrier aggregation (see Figure 20). Carrier aggregation is a way to combine different LTE carriers in order to increase peak data rate.

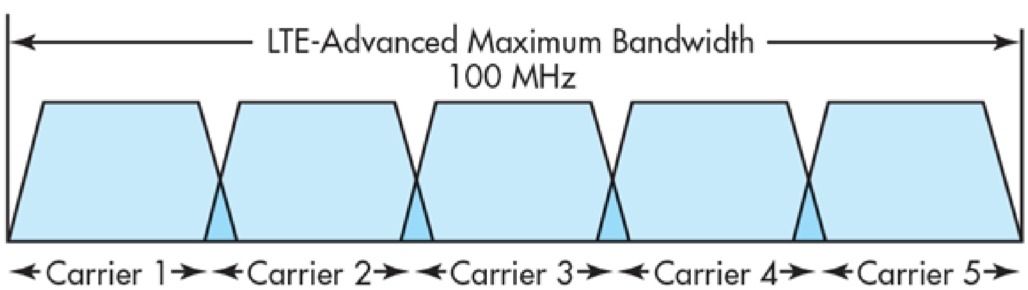

Figure 20: Max Bandwidth with Carrier Aggregation [19]

2.2.5 Physical Cell Identity (PCI)

The Physical Cell Identity (PCI) is the identifier of a cell within the physical layer of the LTE network [20]. In LTE, there are 504 numbers in order to identify base stations. These are carefully set up by network designers to avoid close reuse. The PCI distribution needs to be planned such that two cells with the same PCIs are separated by a considerable physical distance to prevent the cells from interfering with each other [3].

UE can understand where the base station is exactly by using Primary Synchronization Signal and Secondary Synchronization Signal. The PCI is calculated by adding two different down link synchronization signals, the primary synchronization signal (PSS) and the secondary synchronization signal (SSS) [20].

2.3 Performance Metrics in LTE

There are many performance metrics that can be taken into consideration. However, RSRP and RSRQ are key metrics in LTE network in order to make a selection and reselection for a cell when a UE moves from a cell to another cell.

2.3.1 RSRP

RSRP (Reference Signal Received Power) is a key parameter for evaluating the coverage of the network. The base station 24hours transmits a constant power to say "I am here." Based on this constant received power, a UE chooses the best cell to communicate with an eNB. 3GPP defines RSRP values with 1 dB steps (see Table 5), reported value means that a UE reports a measured RSRP value to the eNB in order to utilize that cell. Additionally, RSRP is not affected by number of users, it is always there. As a result of that, RSRP provides the coverage area of eNodeBs.

Table 5: RSRP Measurement Report Mapping [21]

Reported value	Measured quantity value	Unit
RSRP_00	RSRP < -140	dBm
RSRP_01	-140 ≤ RSRP <-139	dBm
RSRP_02	-139 ≤ RSRP <-138	dBm
…	…	…
RSRP_95	-46 ≤ RSRP <-45	dBm
RSRP_96	-45 ≤ RSRP <-44	dBm
RSRP_97	-44 ≤ RSRP	dBm

2.3.2 RSRQ

RSRQ is a parameter that determines the quality of received signal, and it is important to make a reliable handover and reselection a cell by providing additional information because RSRP is not very efficient to decide which cell will be used. RSRQ (Received Signal Received Quality) is unlike RSRP affected by number of users, demands, interference, and noise. Moreover, 3GPP defines RSRP reported values with 0.5 dB steps (see Table 6).

Table 6: RSRQ Measurement Report Mapping [21]

Reported value	Measured quantity value	Unit
RSRQ_00	RSRP < -19.5	dB
RSRQ_01	-19.5 ≤ RSRP <-19	dB
RSRQ_02	-19 ≤ RSRP <-18.5	dB
…	…	…
RSRQ_32	-4 ≤ RSRP < -3.5	dB
RSRQ_33	-3.5 ≤ RSRP < -3	dB
RSRQ_34	-3 ≤ RSRP	dB

3 STOCHASTIC TOOLS FOR STASTICAL ANALYSIS OF MEASUREMENTS

In this section, it is explained how to calculated the mean, standard deviation, variance, cumulative distribution function (CDF) and probability density function (PDF) of any data. Moreover, it is also mentioned how data binning's idea is applied to measurements, and the Vehicle Penetration Loss (VPL) is described based on previous experiments.

With formulas, RSL (Received Signal Level), RSRP (Reference Signal Received Power), SNR (Signal to Noise Ratio) or FSPL (Free Space Path Loss) can be calculated; however, it is very hard to calculate exactly these parameters due to the fading, weather conditions or the VPL. Figure 21 is an illustration of complex environment for mobile communication channels. Therefore, RF signals are subject to fast fading and other propagation phenomenon, which requires stochastic tools to define them.

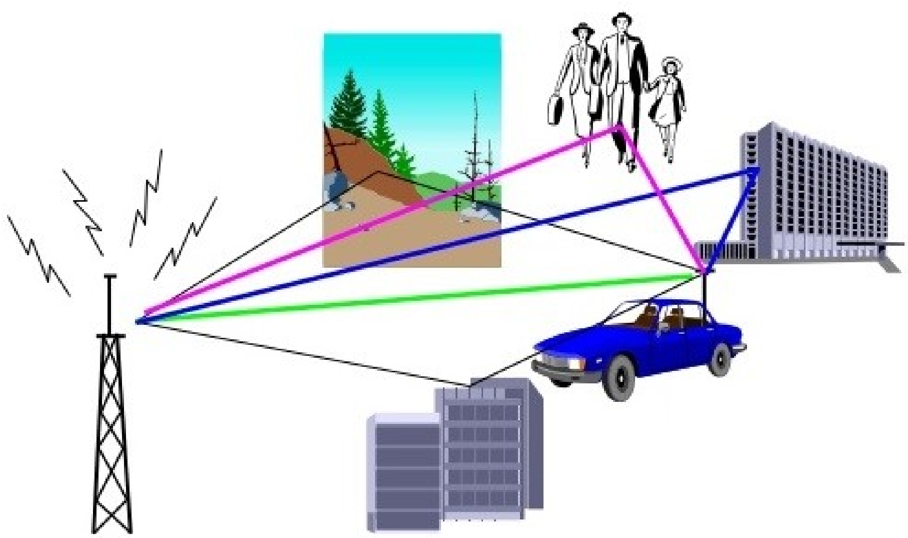

Figure 21: Sources of fading and Path Loss [22]

As it is understood, RF signals are not deterministic signals, which means that they cannot completely be determined as a function of time. Therefore, they are random signals, which are usually sourced from nature. Basically, RF signals are generated by machines, which have periodic signals waveforms that make them deterministic signals at transmitter side, but due to real world environments, they become random signals at receiver side. In order to describe random signals, stochastic signals in Math, these signals have to be ruled by probability theory. As a result of this, before going deep into the mean, median, standard deviation, there is a term, *Random Variable,* which needs to be defined.

A *random variable* is a mapping from the sample space to the set of real numbers. In other words, a random variable is an assignment of real numbers to the outcomes of a random experiment [18] (See Figure 22). There are different type of random variables such as exponential random variables, or log-normal random variables. RSRP is defined as a log-normal random variable, which is normally distributed in logarithmic domain.

$\Omega: \{\omega_1, \omega_2, \omega_3, \ldots\} \rightarrow X: \{x_1, x_2, x_3, \ldots\}$

Ω: sample space (the set of all possible event outcomes)

ω: individual outcomes

X: Random variable

x*: real numbers that correspond to outcomes*

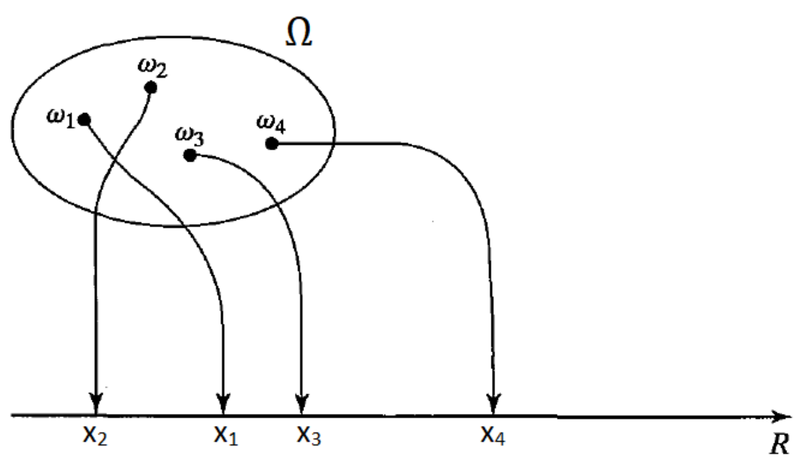

Figure 22: A random variable as a mapping from Ω to R *[18]*

3.1 Mean

The Mean is the average of the total numbers or data. Basically, it is calculated that you sum up all numbers and divide by how many numbers there are. However, it should take into account how many times a number occurs in statistical analysis, which means that the probability of the numbers are very significant. In that case, the Mean is also known as the *Expected Value*, which shows a central tendency of a random variable. It is calculated as the sum of all possible random variable values multiplied by their probabilities.

Let $X: \Omega \rightarrow \{x_1, x_2, x_3, \dots\}$ be a random variable with distribution $P\{X = x_k\} = p_k$

The probability and the mean are calculated with the following formulas:

$$P\{X = x_k\} = p_k = \frac{the\ number\ of\ \mathrm{xk}\ event\ happens}{total\ number\ of\ events}$$

$$E(x) = \mu = \sum_k x_k p_k$$

Where P is probability operator, X is a random variable, x_k is the k^{th} event that corresponds an outcome, *E(X) or* μ is average value of all measurements, and p_k is the probability of k^{th} event.

We also call μ the *first moment* of random variable X [23].

If the random variable of X is equally distributed, and the total number of points are N, we can denote the mean

$$E(X) = \mu = \sum_{k=1}^{N} x_k \frac{1}{N} = \frac{x_1 + x_2 + \dots + x_N}{N} \quad (3.1)$$

Where: E(X) or µ is average value of all measurements

X_k is the k^{th} measurements in the population

N is the total number of measurements

In this thesis, we assume that probability of each RSRP measurements are equally probable, so that when the mean is calculated, equation 3.1 is utilized.

3.2 Median

The Median is the number that is the middle number in the sorted list of measurements if the total number of measurements are odd. If measurements are even, the Median is the number that is the mean of the two central numbers.

The Median is more reliable a measure of central tendency than the Mean in case of significant outliers. In an example, it is found the Mean and the Median because the median and the mean can be compared. If these result are not close enough each other, it may indicate that there is a data corruption.

__Example:__ Calculate the Mean and the Median for following data,

In a given bin, there are 10 RSRP measurements which are:

-90 dBm	-50 dBm	-95 dBm	-91 dBm	-93 dBm
-93 dBm	-60 dBm	-89 dBm	-99 dBm	-100 dBm

__Solution:__ The mean is equal, $E(x) = \frac{-90-93-50-60-95-89-91-99-93-100}{10} =$ -86 dBm

-50 dBm -60 dBm -89 dBm -90 dBm ***-91 dBm*** ***-93 dBm*** -93 dBm -95 dBm -99 dBm -100 dBm

When it is reordered from maximum to minimum measurements or vice-versa, -91 dBm and -93 dBm are two central numbers. Thus, the Median is equal -92 dBm.

As a result of these calculation, the difference between the mean and median is 6 dB (4 times in linear domain), which is very significant difference.

3.3 Standard deviation

Before the explanation of standard deviation, it has to be defined what the *Variance* of random variable. Variance in probability theory measures what is the range of a data set, or variance is a measure that quantifies data variation around the mean.

Standard deviation is a measure that define the amount of variation of measurements (data), and Standard deviation is the square root of the variance. Higher variance indicates wider spread in measured data.

Let X be a numerically valued random variable with expected value $\mu = E(X)$. Then the *variance* of X, denoted by V(X), is

$$V(X) = E((X - \mu)^2)$$

$V(X) = \sum_{x}(x - \mu)^2 . m(x)$, where m(x) is the distribution function of X.

If X is any random variable with $E(X) = \mu$, then

$$V(X) = E(X^2) - \mu^2$$

(3.2)

Proof. We have

$$
\begin{aligned}
V(X) &= E((X- \mu)^2)) = E(X^2 - 2\mu X + \mu^2) \\
&= E(X^2) - 2\mu E(X) + \mu^2 \\
&= E(X^2) - \mu^2.
\end{aligned}
$$

The *standard deviation* of X, denoted by D(X), is $D(X) = \sqrt{V(X)}$. We often write σ for D(X) and σ^2 for V (X) [24].

3.4 CDF and PDF

In probability theory and statistics, CDF (Cumulative Distribution Function) is the function that calculates the probability of a random variable being less than or equal to the argument. CDF ranges between zero and one, and it is non-decreasing function.

On the other hand, PDF (Probability Density Function) is a function that gives the probability of each measurements, and shows the probability distribution of a random variable. From this distribution, it can be easily seen what the probability of each measurements is. Additionally, if X is discrete random variable, it is defined Probability Mass Function (PMF) instead of probability density function (PDF).

In statistical analysis, CDF and PDF are usually plotted instead of calculation to see measurements' behavior in the form of a histogram. Moreover, F(x) is the cumulative distribution function of X in math, and f(x) is the probability density function of X. however, in electrical engineering, Cumulative Distribution Function of X, and Probability Density Function of X is written as CDF(X) and PDF(X) respectively.

Let X be a continuous random variable. Then the CDF of X is defined by the equation

$$F_X(x) = CDF(x) = P(X \leq x)$$

P is probability operator

$$P(X \leq x) = \frac{The\ number\ of\ measurements\ smaller\ than\ x}{The\ total\ number\ of\ measurements}$$

CDF (+∞) is equal one, CDF (-∞) is equal zero

Let X be a continuous random variable with density function f(x). Then the function defined by

$F(x) = \int_{-\infty}^{x} f(t)\, dt$ is the CDF of X.

Furthermore, we have

$\frac{d}{dx}F(x) = f(x)$ [24], where f(x) is probability density function of X.

For discrete random variables, the calculation of PMF depends on the type of distribution such as Binomial distribution, or Poisson distribution.

3.5 Data binning

Data Binning is a method that averages measurements into geographical bins. As it is seen in Figure 23, numbers of data are averaged and placed in a specified area as if there is only one points in that area. The bin resolution in cellular communication industry is usually between 1m and 100m. Higher resolution typically leads to increased accuracy; however, inadequate averaging may reduce the accuracy at extremely fine resolution. Bin resolution adopted in this study has been 50 X 50m (164 by 164 feet). In every bins, it has been counted the number of measurements, which their PCIs also took into consideration, as it is calculated from equation (3.1). Moreover, the area can be considered as a matrix that has 193 rows and 149 columns, Figure 24 shows the drive route and bin grids.

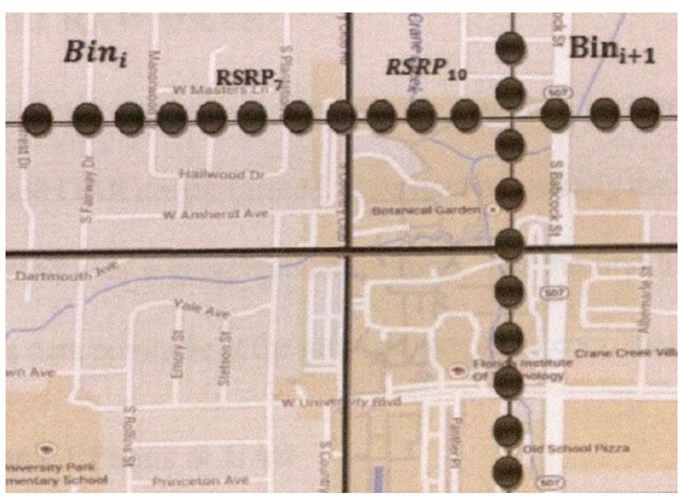

Figure 23: Binning Concept [25]

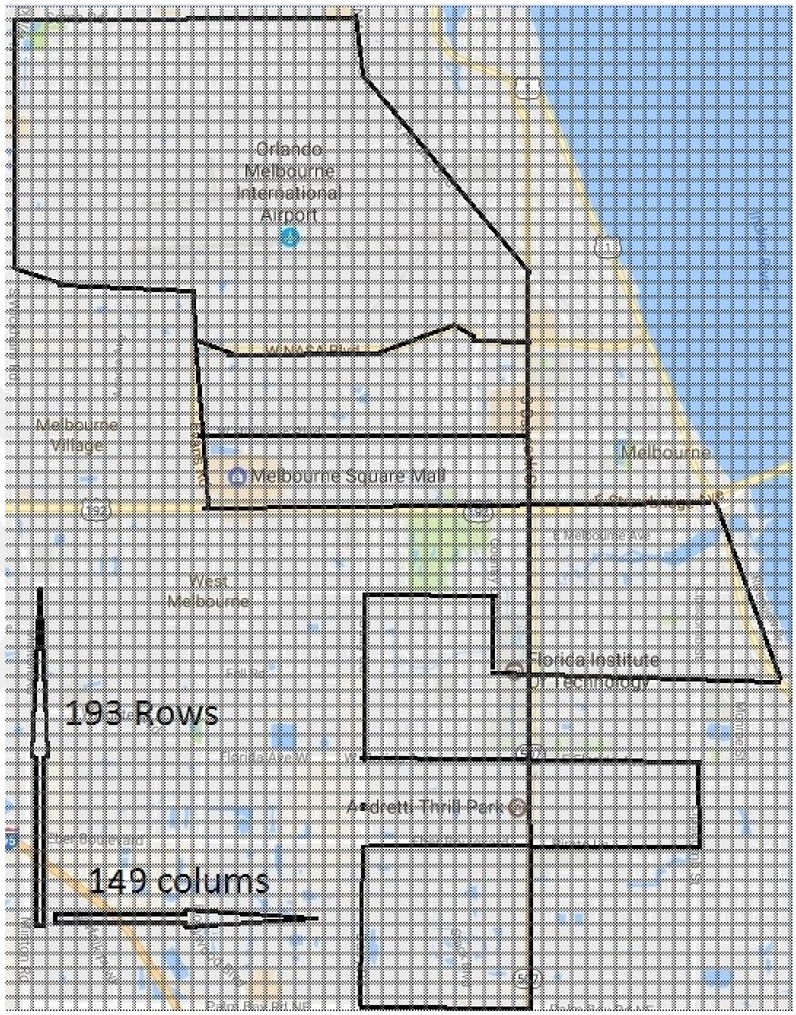

Figure 24: Drive Testing Road with Bin Grids

For further calculation, as it is known, the distance between each degree of latitude is around 111 km while the distance between each degree of longitude is 111 km in only equator. However, the distance between two longitudes in Melbourne (28.08360 N 80.60810 W) 98 km.

From these information, 50 meter can be written as a conversion factors 0.00051 degree for longitudes' angular distance, and 0.00045 degree for latitudes' angular distance. For drive testing route, the maximum and minimum longitudes is respectively -80.59715 and -

80.67256 whereas the maximum and minimum latitudes is respectively 28.12166 and 28.03524.

When the measurements are collected, RF metrics are saved with their locations such as longitudes and latitudes, so that for simplicity it has been converted to small bins, and these bins are named as a row index and column index i.e. 30^{th} row 43^{th} column. This conversion is calculated with following formula:

$$I = \frac{Lon - minLon}{0.00051} + 1 \qquad J = \frac{Lat - minLat}{0.00045} + 1$$

I : column index

J : row index

Lon : a measurement's longitude in degree

Lat : a measurement's latitude in degree

minLon : the minimum longitude of the drive testing area in degree

minLat : the minimum latitude of the drive testing area

0.00051 & 0.00045: conversion factors between Lat/Lon angular distance and 50m bin size

3.5 Vehicle Penetration Loss

The Vehicle Penetration Loss (VPL) is the received power reduction between the antenna outside of the vehicle and the antenna inside of the vehicle. The VPL has to be calculated in order to calculate the link budget of the system. The VPL is calculated as it seen in equation (3.3).

$$VPL[dB] = 10\log(\frac{P_{out}}{P_{in}}) \quad (3.3)$$

VPL : vehicle penetration loss expressed in dB

P_{out} : the power of the signal coming from the antenna mounted outside of the vehicle

P_{in} : the power of the signal coming from the internal antenna [26].

In the thesis, the Vehicle Penetration Loss has not been calculated due to the fact that the VPL has been measured earlier at 800 MHz, and the results of that experiment is shown in Table 4. These published results were applied to current measurements collected at 700 MHz. The experiment which the VPL were measured and the measurements in this thesis are almost at the same frequency. As it is known, the more frequencies increase the more received powers decrease. It can be understood that the VPL at 700 MHz will be less than 7.26 dB in this case.

Table 7: Summary of the VPL Measurement for the Full Size Car [26]

Type of Environment	Position of the Antenna	Mean [dB]	Standard Deviation [dB]
Urban	Attached to Drivers Hat	8.98	2.26
Urban	Placed on the Passenger Seat	8.64	3.89
Suburban	Attached to Drivers Hat	8.86	3.13
Suburban	Placed on the Passenger Seat	7.26	2.94

3.6 ANOVA (Analysis of Variation)

ANOVA is a stochastic tool that provides the difference between groups whether their means are equal or not by calculating the amount of variation between groups and within groups. Because of that, there have to be at least two groups in order to compare their means.

There is a table called "ANOVA Table." Before calculating the parameters of this table, the hypotheses are defined such as H_0 *is Null Hypothesis* which means the means of groups are equal, and H_1 *is Alternative Hypothesis* which means the means of groups are not equal. After defining our hypotheses, the parameters of the table are calculated (see Table 8). Although the parameters can be calculated, there are many anova functions, which make this analysis easier, in MATLAB. Result of that, it will be decided if the means are equal, which means whether *Null Hypothesis* is rejected or not.

The decision is based on whether F is greater than *critical value* or not. The critical value is found from F-Table, which can be found in Appendix. F-Table is different based on alpha (α) level. Alpha can be 10%, 5%, or 1%. However, it is usually 0.05.

Table 8: ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns (Between, Treatments)	SS_B	a-1	MS_B = SS_B/(a-1)	MS_B/MS_W	p
Error (within)	SS_W	N-a	MS_W = SS_W/(N-a)		
Total	SS_T	N-1			

SS: Sum of Squares

SS_B: Sum of square between groups

SS_W: Sum of square within groups

SS_T: Total sum of squares

df: Degree of freedom

a: number of groups

N: Total number of measurements (data)

MS: Mean square

MS_B: Mean square between groups

MS_W: Mean square within groups

4 MEASUREMENT PROCEDURE

In this chapter, we can understand where and under which circumstances data measurements were collected. Moreover, it is explained how equipment were setup in the car, and how software were setup into the devices.

4.1 Equipment Setup

The car, which is utilized during data collection and which is shown in Figure 25, was 2001 Hyundai Elantra. The cell phone was placed on the front passenger seat while the receiver antenna was on the car roof. The scanning receiver was placed back seats of the car while the laptop was placed on the front passenger. The GPS and the RF antenna were mounted on the car roof. Cables were connected properly, the power for the scanning receiver was from the car itself while the laptop and the cell phone always had full battery.

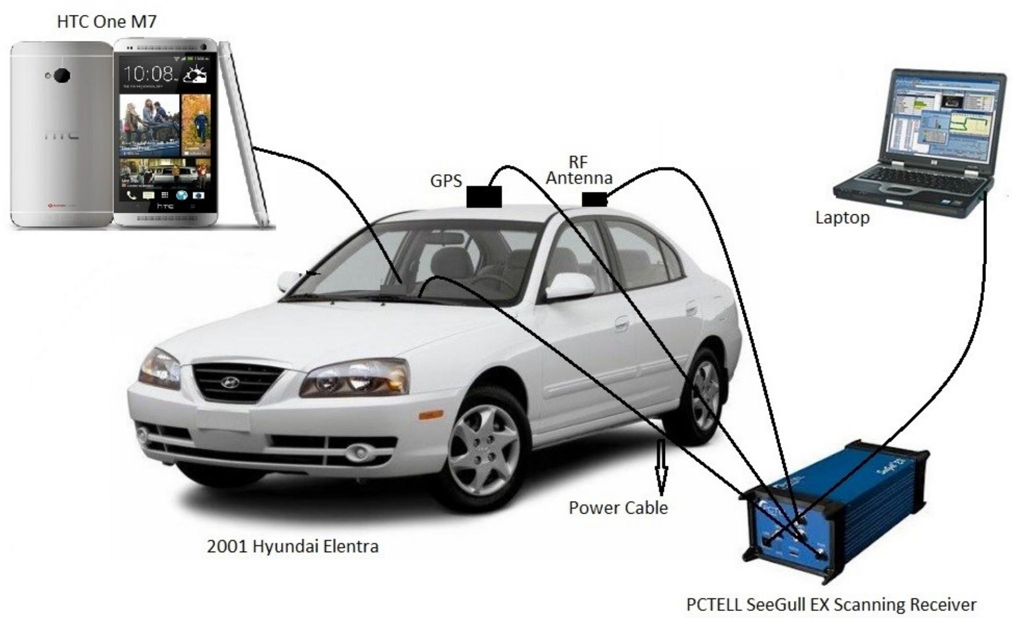

Figure 25: Equipment Setup

4.1.1 Phone-based Drive Testing Equipment Setup

Phone-based drive testing systems are useful for evaluating basic network performance and are essential to characterizing the end-user experience while using the network. Phone-based systems address the need to verify network settings such as cell selection and re-selection boundaries and to measure the voice and data application performance in the live network [9]. In this thesis, HTC One M7 was used as a cell phone for measuring and recording the data. Additionally, it was utilized AT&T as a carrier in HTC One M7. In Figure 26, its specifications are given.

Figure 26: Network Specifications for HTC ONE M7 [27]

In order to collect measurements with a cell phone while drive testing, you need either a professional software and license or an application. An application is much cheaper than a professional tools, and also it provides a view that a UE has experienced. Because of that, LTE Measurement application is developed for the android platform. This application is used to measure and save radio frequency (RF) signals each second. This application saves the values of the parameters such as RSSI, RSRP and RSRP at each instant for later use and analysis [28]. The application easy to install and use (see Figure 27).

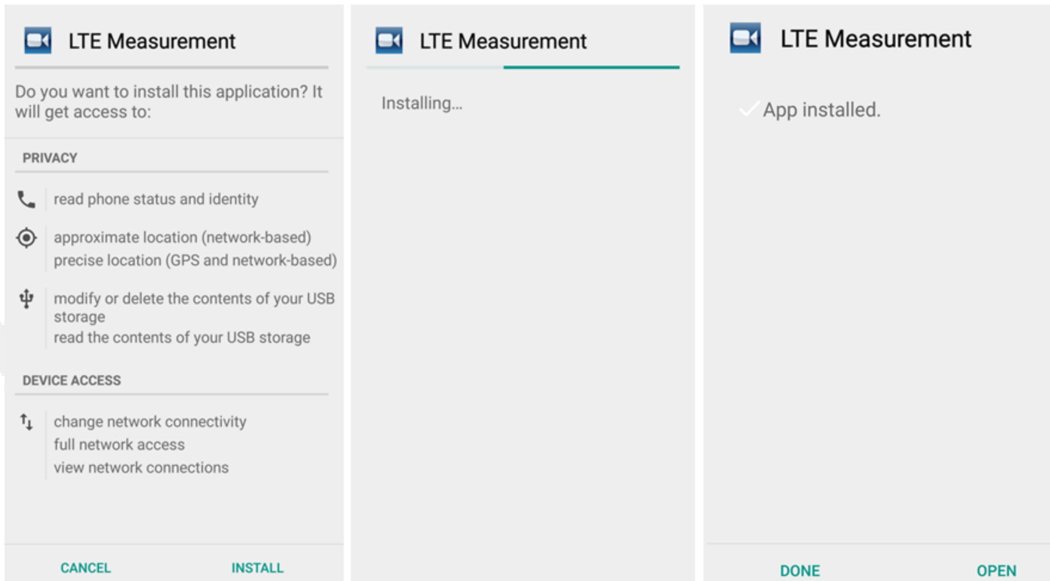

Figure 27: Application Setup

This application was created as fulfilling in part the requirements for the degree of doctor of philosophy in Electrical Engineering at Florida Institute of Technology in 2015. This application was recording data such as RSRP or SNR at given location without PCI (Physical Cell Identity). When a UE moves, the cell phone has been surrounded with many sites, some of them are close, and some of them are far away from the cell phone. The cell phone decides which site is available at that time, so that it is very important which site is being used by the cell phone at that moment and location; because of this, the application has been updated in 2017. Therefore, the application now records data parameters with its PCI, which makes the statistical analysis more reliable. In Figure 28, it is shown the main screen of the application, and when 'start recording' button is pressed, the information of RF signal will be recorded at the phone as a NetInfo.txt file.

Figure 28: Main Screen for LTE Measurement application

4.1.2 Receiver-based Drive Testing Equipment Setup

Receiver-based systems are used to obtain a ''raw'' view of the environment. They can measure the entire spectrum and are not constrained by network operator settings. These systems are useful for activities such as band clearing and general coverage estimation, but they cannot give a true measure of customer experience because they do not physically interact with the network under test [9]. The scanner based drive testing system has four basic components which are scanner, a laptop with the software for collecting data, and external GPS and RF antennas.

In this experiment, the PCTEL SeeGull EX Scanner was used (see Figure 29 for its front view). It is very common for RF engineers to perform drive tests and optimize the wireless network through analysis of measurement. The PCTEL SeeGull EX Scanner supports multiple protocols and different frequency ranges to evaluate spectrum performance. The scanner that is used is capable of measuring data pertaining to two technologies, LTE and UMTS [20]. For LTE systems, it can scan channels bandwidth 1.4, 3, 5, 10, 15, and 20 MHz. Moreover, during drive testing, the scanning receiver was set up at 700 MHz frequency and 10 MHz bandwidth, and channel 5110 was used as well.

Figure 29: Front View of SeeGull EX Receiver [13]

For more detail specifications of the PCTEL SeeGull EX Scanner, it can be seen in Appendix. From its specifications, the measurements rate at 10 MHz is 50/sec for LTE-FDD in the LTE section. From this information, it has to be extracted what the speed of the car should be. Additionally, Lee Criteria says that for 1 dB accuracy and 90% probability, 50 measurements has to be taken over 40 λ (wavelength). Thus, the car speed cannot be more than 40mph (65km/h) in order to satisfy the Lee criteria.

Before driving, the software has to be ready for data collection in the laptop. As it is seen in Figure 30, after all cables are connected properly, the steps that are explained can be followed:

- Click “Detect Devices”
- Wait for the message “All devices are detected” at “Message Log”
- Click “UMTS LTE”
- Go to “EB 12 US Lower 700 A/B/C Blocks DL”
- Go to “Top N Signal 10 MHz”
- Click properties of “Top N Signal 10 MHz”
- Select “Selected Channels : 5110”
- Click “Bar Charts” in order to see RSRP Measurements while driving

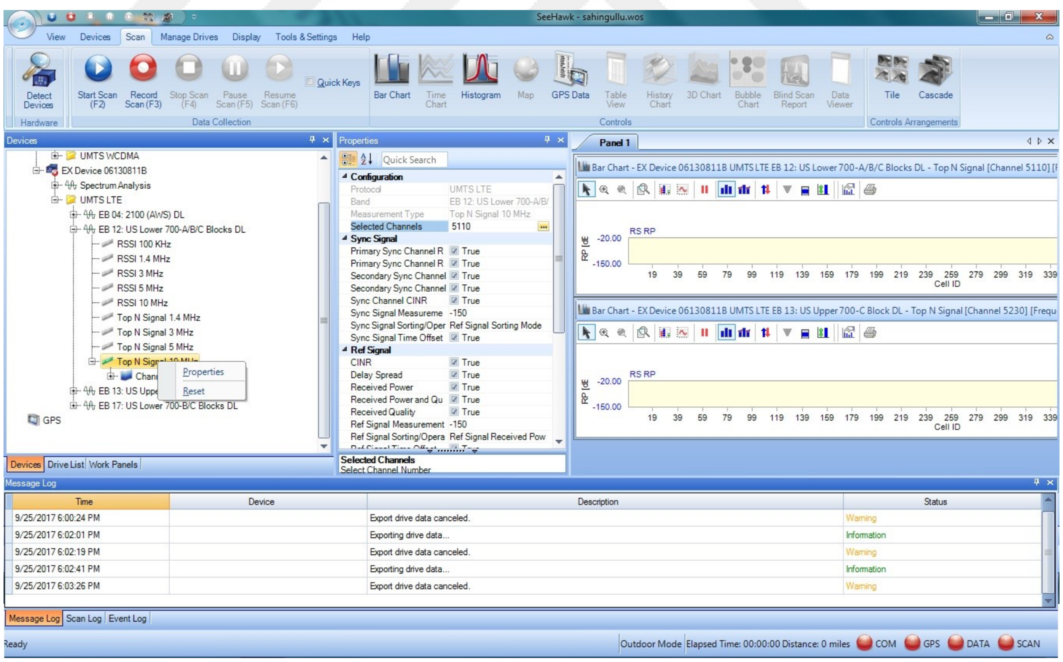

Figure 30: Software Setup before Drive Testing

After driving, the steps that are explained can be followed in order to export measurements for statistical analysis (see Figure 31):

- Click “Drive List”
- Go to the section list which you have driven
- Go to “Export”
- Chose file type “CSV” for an excel file
- Click “Next”, and
- Chose the “Channel” which you want to export, and/or RF signal metrics

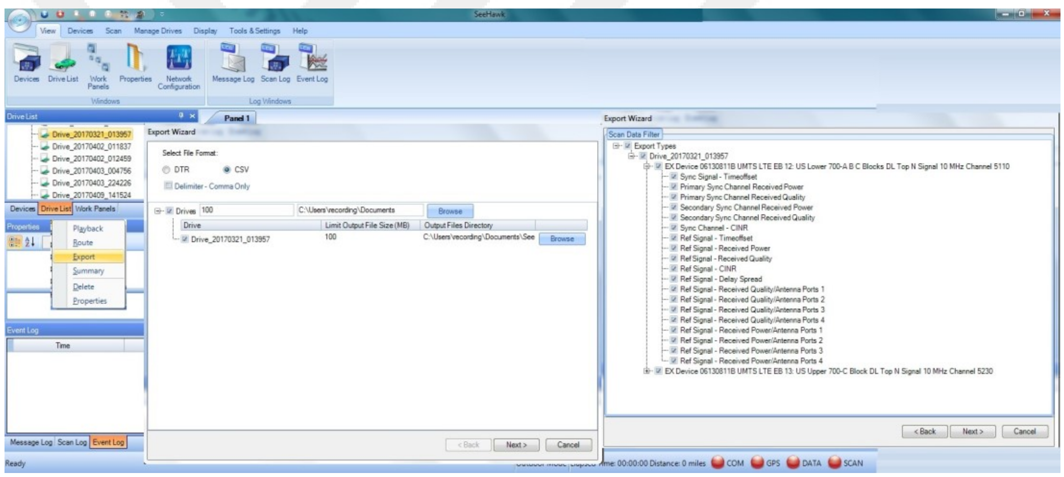

Figure 31: Exporting Data after Drive Testing

4.2 Drive Testing Area

The drive testing area in Melbourne, Florida and it is around Florida Tech. The area can be classified as a suburban area, it is shown in Figure 32. The road used is approximately 30 miles (50km), the area is around 31.48 square mile (81.54 square kilometer). The speed of the car was between 20mph and 40mph (30 – 65 km/h). The measurements were collected in three times during the month of April 2017. The data were measured at night after 11pm. While collecting data, the weather was clear, and the temperature was around 80 F^0 ($27C^0$).

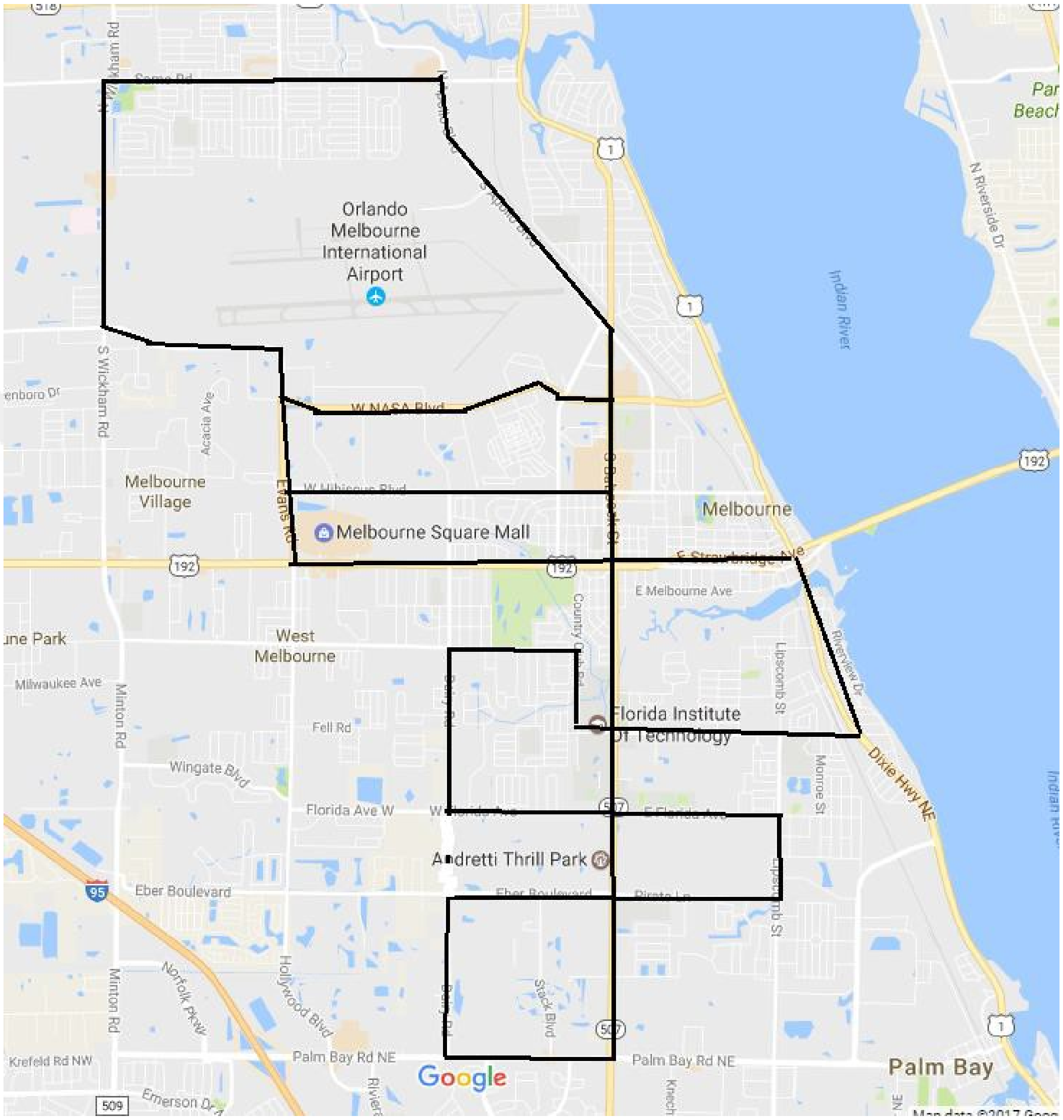

Figure 32: Drive Testing Area

5 MEASUREMENTS COMPARISON

For measurements' statistical analysis, RSRP was taken into account. For more understanding of measurements comparison, Box and whiskers, Histogram, CDF and PDF of measurements were plotted as descriptive charts.

Figure 33 shows that between the phone and Scanning Receiver have similar sequence measurements at the same bins. As it is expected, Scanning Receiver has better RSRP measurements than the phone does. From this graph, it also can be understand that Phone RSRP measurements can drop up to -120 dBm while the scanning receiver could not.

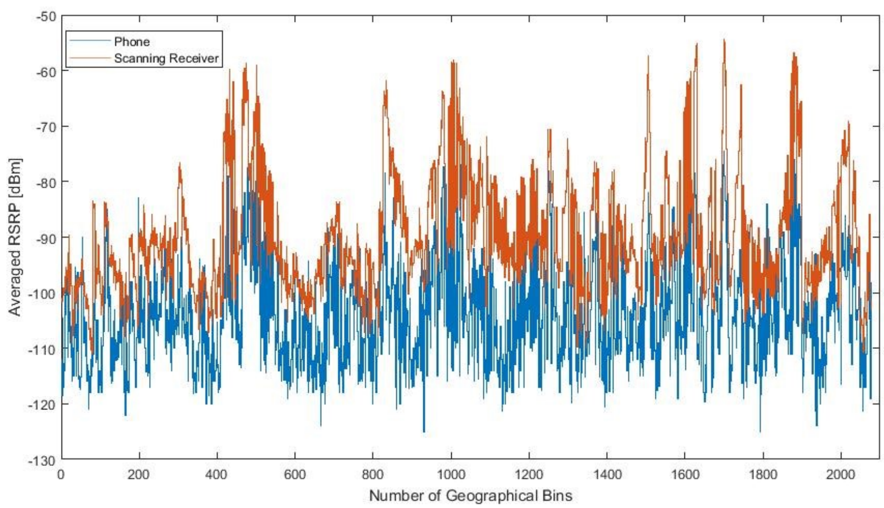

Figure 33: Averaged RSRP measurements of the Scanning Receiver and Phone for geographical bins

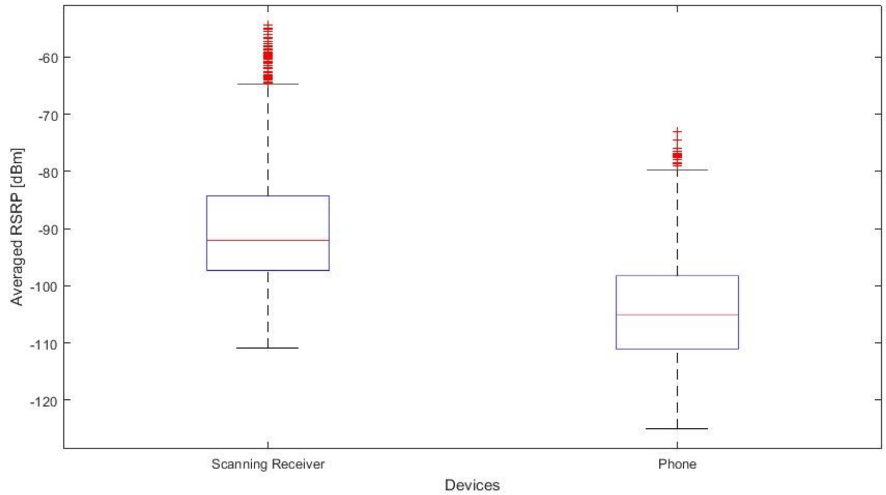

Figure 34: Box Representation of the Scanning Receiver and Phone's Averaged RSRP measurements

In Figure 34, it can be seen that the scanning receiver's averaged RSRP value is around -90 dBm although HTC One M7 has approximately -105 dBm. In addition, the scanning receiver's RSRP is closed the lower bound, it means that the distribution of the scanning receiver is not exactly normal distribution; however, Phone 1's distribution is close to Gaussian distribution. Moreover, the minimum and maximum values of the scanning receiver is around -110 dBm and -65 dBm respectively, the RSRP of Phone differs between -80 dBm and -125 dBm as well. We also can see that 75 percent of the time, the scanning receiver's RSRP is below -85 dBm, Phone's RSRP is below -100 dBm.

It is usually sketched the histogram of measurements instead of PDF of them. The CDF and PDF of both devices are shown in Figure 35 and 36, from these two descriptive charts, the scanning receiver has more measurements around its mean while Phone's measurements has spread. It can be said that the scanning receiver has more constant power that Phone does. The RSRP values for Phone one is accumulated between -75 dBm and -125 dBm while the scanning receiver is accumulated between -69 dBm and -110 dBm. It can be seen that 50 percent of the time, Phone has weak signal while the scanning receiver has good signal. "Good signal" or "weak signal" can be interpreted better than or worse than -100 dBm. We also can say that that 90 percent of the time, the receiver has RSRP measurements below -75 dBm while Phone's measurements has below -90 dBm.

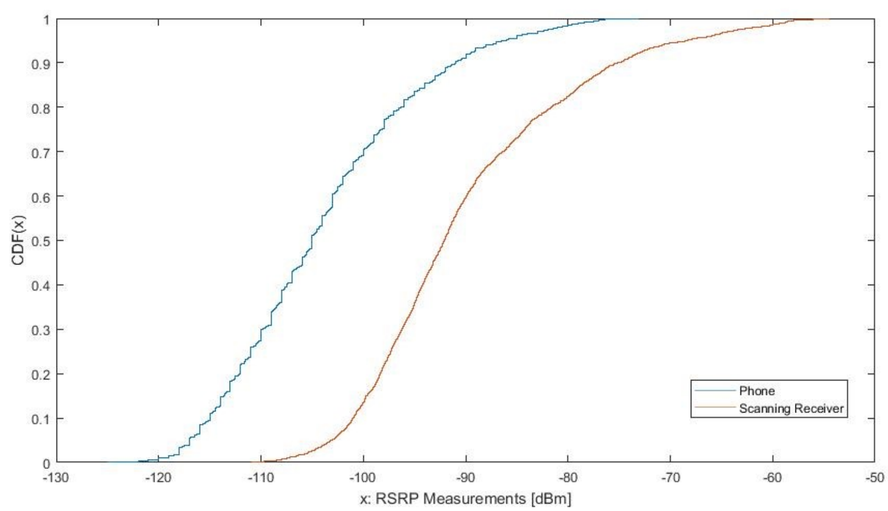

Figure 35: CDF of both the Scanning Receiver and Phone

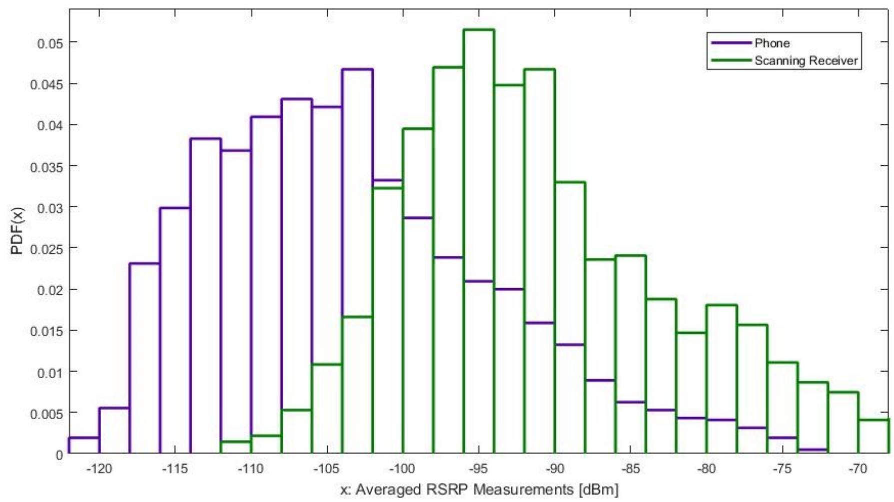

Figure 36: Histogram (PDF) of both the Scanning Receiver and Phone at the same geographical bins

From ANOVA Table of measurements (see Table 9), the F value is 2104.9 by using α level of 0.05, and the critical value, F (1, 4152), is 3.8415 (see Table 13 in Appendix). Since the F value is much larger than the critical value, the Null Hypothesis is rejected, which means the mean of both devices are different. It is concluded that there is a statistically significant difference among the measurements means of two devices.

Table 9: ANOVA Table for Measurements

Source	SS	df	MS	F	Prob>F
Columns	205386	1	205386	2104.9	0
Error	405125.8	4152	97.6		
Total	610511.7	4153			

6 CONCLUSION AND FUTURE WORK

It is seen that the mean and median of three measurements (Phone, Scanning Receiver and Their difference) are close enough in Table 10. They are not exactly the same due to some outliers, but these outliers are not significant. 1 or 2 dB is not significant difference in linear domain.

Table 10: Comparison of Devices

Devices	The Mean	The Median	Standard Deviation
Phone	-103.93dBm	-105dBm	9.29dB
Scanning Receiver	-89.87dBm	-92.06dBm	10.44dB
Difference	14.06dB	14.17dB	7.82dB

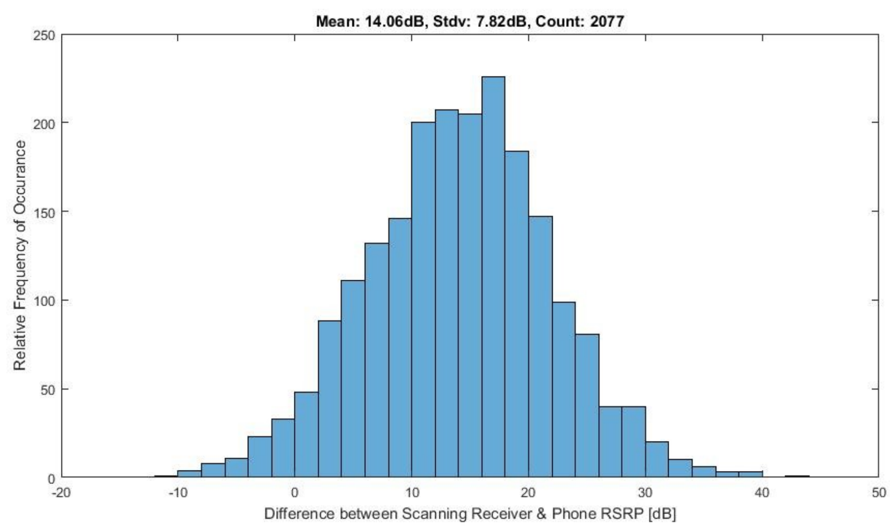

Figure 37: Histogram of the difference between the scanning receiver and phone RSRP measurements

The average RSRP difference between the scanning receiver and Phone is 14.06 dB. There is also the Vehicle Penetration Loss around 7 dB in this experiment, which is explained in Chapter 3. Therefore, in given area the scanning receiver's received power is around 5 times better than Phone in linear domain. It shows that given RSRP measurements, or coverage area, or voice or data traffic is significantly different what a UE experiences. It means that the carrier uses bandwidth or spectrum inefficiently, and also the decision made for given bandwidth to UE is not efficient. It may refer to some software or hardware problem for either cell phones or operators. As it is seen in Figure 37, most of the time, the difference is more than zero dB, in some bins Phone has better RSRP measurements than the receiver does, and the difference's distribution is similar to Normal Distribution. Due to either inexpensive hardware of the cell phone or the carrier, customers do not have what they are supposed to from their perspective while they drive.

As a conclusion, it has been shown that there is a significant difference between the scanning receiver and the cell phone in terms of customers' experience. This result are also similar to a conference paper, "Comparison of Receive Signal Level Measurement Techniques in GSM Cellular Networks." As it is seen in Figure 38 in Appendix, this results are almost the same. Therefore, it can be considered that the data analysis in Chapter 4 are reasonable [15].

For future work, cell phones can be chosen the same model and different carriers, or vice versa, which means that at least they should have a common point. As a result of that, the comparison between two or more cell phones will be more reliable. Furthermore, in this thesis, the comparison between devices is based on their RSRP measurements, so that the next experiment can be based on the difference between their SINR (Signal to Interference Noise Ration). Additionally, the future work could be Network Benchmarking or Optimization and Troubleshooting instead of Service Quality Monitoring. The next future work also may be creating a new application that records RF information for cell phones, and the applications also can be compared. I believe that these future work help those students who are willing to work in private companies, but also they can help those who consider to continue their academic career at universities.

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APPENDIX

Table 11: Specifications of PCTEL SeeGull EX Scanning Receiver [29]

LTE FDD and TD-LTE	Measurement Modes	Top N Synchronization Channel (P-SCH/S-SCH), Reference Signal, and Resource Block (Wideband, Subband)
	Data Modes	RSRP, RSRQ, CINR, Cyclic Prefix, Time Offsets, Delay Spread, Averaging (LTE FDD only)
	Channel Bandwidths	1.4 / 3 / 5 / 10 / 15 / 20 MHz
	Transmit Antenna Configurations	1, 2, 4
	Measurement Rates @ 10 MHz: Top N Sync Channel RS	LTE FDD: 50/sec; TD-LTE: 20/sec
	Dynamic Range (CINR) @ 20 MHz: P-SCH/S-SCH RS	-10 to +18 dB** -20 to +40 dB**
	Min. Detection Level: RSRP	-140 dBm (RSRP @ 10 MHz)
	Relative Accuracy (CINR): P-SCH/S-SCH RS	±1 dB ±1 dB
UMTS [WCDMA/HSPA(+)]	Measurement Modes	Top N Pilot
	Data Modes	Io, Ec/Io, Aggregate Ec/Io, SIR, Rake Finger Count, Time Offset, Delay Spread, Eps/Io, Ess/Io
	Channel Bandwidths	200 kHz / 3.84 MHz
	Measurement Rate	100/sec (High Speed Mode); 50/sec (High Dynamic Range Mode); 50/sec Pilots with Clarify® Option
	Top N CPICH Dynamic Range (Ec/Io)	-21.5 dB (High Speed Mode); -26 dB (High Dynamic Range Mode)**; -33 dB (High Dynamic Range) with Clarify® Option (via Post Processing)
	Min. Detection Level	-120 dBm (High Dynamic Range Mode)
	Relative Accuracy	±1 dB
TD-SCDMA	Measurement Modes	Top N Pilot
	Data Modes	Sync_DL: Ec/Io, Io, Time Offset, SIR Midamble: Ec/Io, Io, Time Offset, SIR, Midamble Code
	Channel Bandwidths	200 kHz / 1.28 MHz
	Measurement Rate	50/sec
	Top N PN Dynamic Range, Ec/Io	-20 dB**
	Min. Detection Level	-110 dBm
	Relative Accuracy	±1 dB
GSM	Measurement Modes	Color Code
	Data Modes	BSIC, C/I, RSSI
	Channel Bandwidths	30 kHz / 200 kHz
	Measurement Rate	Up to 190 BSIC Decodes/sec; 160 Decodes/sec BCCH with Clarify® Option
	Dynamic Range	+2 dB C/I @ 90% BSIC Detection with <0.1% False Detection Rate -18 dB C/I with Clarify® Option (via Post Processing)
	Min. BSIC Detection Level	-108 dBm
	Relative Accuracy	±1 dB
CDMA	Measurement Modes	Top N PN
	Data Modes	Ec, Io, Ec/Io, Aggregate Ec/Io, Pilot Delay, Delay Spread
	Channel Bandwidths	30 kHz / 1.25 MHz
	Measurement Rate	25/sec
	Top N PN Dynamic Range, Ec/Io	-28 dB**
	Min. PN Detection Level	-130 dBm
	Relative Accuracy	±1 dB
EV-DO	Measurement Modes	Top N PN
	Data Modes	Ec, Io, Ec/Io, Aggregate Ec/Io, Pilot Delay, Delay Spread
	Channel Bandwidths	30 kHz / 1.25 MHz
	Measurement Rate	18/sec
	Top N PN Dynamic Range, Ec/Io	-18.5 dB**
	Min. PN Detection Level	-120 dBm
	Relative Accuracy	±1 dB

Table 12: Specifications of PCTEL SeeGull EX Scanning Receiver [Continued] [29]

Power Measurements	**RSSI MEASUREMENTS**	
	Measurement Rate (Typical) LTE	10,000 ch/sec
	UMTS (WCDMA/HSPA(+))	7,000 ch/sec
	GSM	3,000 ch/sec
	CDMA	10,000 ch/sec
	EV-DO	10,000 ch/sec
	TD-SCDMA	10,000 ch/sec
	Dynamic Range	-120 to -20 dBm @ 30 kHz
	Absolute Accuracy	±1 dB (across Basic RF Input Power Range)
	ENHANCED POWER SCAN (EPS™) MEASUREMENTS	
	Channel Bandwidths	5 kHz to 20 MHz in 2.5 kHz Increments
	Measurement Rate	1,000 MHz/sec @ 5 MHz (Typical)
	Absolute Accuracy	±1 dB (across Basic RF Input Power Range)
	SPECTRUM ANALYSIS MEASUREMENTS	
	Measurement Range	>90 dB
	Measurement Rate (Single Sweep)	>400 MHz/sec
	Accuracy	±1 dB (across Basic RF Input Power Range)
	LTE POWER ANALYSIS MEASUREMENTS (Available for TD-LTE Only)	
	Channel Bandwidths	1.4 / 3 / 5 / 10 / 15 / 20 MHz
	Measurement Rate	50 msec @ 20 MHz
	Accuracy	±1 dB (across Basic RF Input Power Range)
RF Characteristics	Internally Generated Spurs	-102 dBm Max.
	Conducted Local Oscillator	-75 dBm Max.
	RF Operating Range: In-Band	-15 dBm Max.
	Desensitization: Adjacent Channel	>50 dB (CDMA/EV-DO)
	Adjacent Channel	>55 dB (All Other Technologies)
	Alternate Channel	>65 dB
	Safe RF Input Range	≤10 dBm
	Frequency Accuracy	±0.05 ppm (GPS Locked); ±0.1 ppm (GPS Unlocked)
GPS	Type	50 Channel Internal Receiver
	Position Accuracy	±2.5 meter
	Acquisition Time	Cold Start: <30 sec; Hot Start: <2 sec
	Sensitivity (Tracking)	>-150 dBm
Physical	Maximum Power (+8 to +16 VDC)	21W Max.; 17W Typical
	Size	8.7"D x 3.7"W x 2.7"H (221 mm D x 94 mm W x 68.5 mm H)
	Weight	1.6 lb (0.71 kg)
	Temperature Range	Operating: 0°C to +50°C; Storage: -40°C to +85°C
	Host Data Communications Interface	USB 2.0
	RF Input	RF: SMA Female (50Ω); GPS: Male (50Ω) SMB
	Safety (CE)	EN 60950-1
	EMC	EN 301 489-1
	Shock and Vibration	MIL-STD-810G, SAE J1455
	RoHS	Compliant (6/6)

Table 13: F Table [30]

α=0.005	**df_1=1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**12**	**15**	**20**	**24**	**30**	**40**	**60**	**120**	**∞**
df_2=1	161.4476	199.5000	215.7073	224.5832	230.1619	233.9860	236.7684	238.8827	240.5433	241.8817	243.9060	245.9499	248.0131	249.0518	250.0951	251.1432	252.1957	253.2529	254.3144
2	18.5128	19.0000	19.1643	19.2468	19.2964	19.3295	19.3532	19.3710	19.3848	19.3959	19.4125	19.4291	19.4458	19.4541	19.4624	19.4707	19.4791	19.4874	19.4957
3	10.1280	9.5521	9.2766	9.1172	9.0135	8.9406	8.8867	8.8452	8.8123	8.7855	8.7446	8.7029	8.6602	8.6385	8.6166	8.5944	8.5720	8.5494	8.5264
4	7.7086	6.9443	6.5914	6.3882	6.2561	6.1631	6.0942	6.0410	5.9988	5.9644	5.9117	5.8578	5.8025	5.7744	5.7459	5.7170	5.6877	5.6581	5.6281
5	6.6079	5.7861	5.4095	5.1922	5.0503	4.9503	4.8759	4.8183	4.7725	4.7351	4.6777	4.6188	4.5581	4.5272	4.4957	4.4638	4.4314	4.3985	4.3650
6	5.9874	5.1433	4.7571	4.5337	4.3874	4.2839	4.2067	4.1468	4.0990	4.0600	3.9999	3.9381	3.8742	3.8415	3.8082	3.7743	3.7398	3.7047	3.6689
7	5.5914	4.7374	4.3468	4.1203	3.9715	3.8660	3.7870	3.7257	3.6767	3.6365	3.5747	3.5107	3.4445	3.4105	3.3758	3.3404	3.3043	3.2674	3.2298
8	5.3177	4.4590	4.0662	3.8379	3.6875	3.5806	3.5005	3.4381	3.3881	3.3472	3.2839	3.2184	3.1503	3.1152	3.0794	3.0428	3.0053	2.9669	2.9276
9	5.1174	4.2565	3.8625	3.6331	3.4817	3.3738	3.2927	3.2296	3.1789	3.1373	3.0729	3.0061	2.9365	2.9005	2.8637	2.8259	2.7872	2.7475	2.7067
10	4.9646	4.1028	3.7083	3.4780	3.3258	3.2172	3.1355	3.0717	3.0204	2.9782	2.9130	2.8450	2.7740	2.7372	2.6996	2.6609	2.6211	2.5801	2.5379
11	4.8443	3.9823	3.5874	3.3567	3.2039	3.0946	3.0123	2.9480	2.8962	2.8536	2.7876	2.7186	2.6464	2.6090	2.5705	2.5309	2.4901	2.4480	2.4045
12	4.7472	3.8853	3.4903	3.2592	3.1059	2.9961	2.9134	2.8486	2.7964	2.7534	2.6866	2.6169	2.5436	2.5055	2.4663	2.4259	2.3842	2.3410	2.2962
13	4.6672	3.8056	3.4105	3.1791	3.0254	2.9153	2.8321	2.7669	2.7144	2.6710	2.6037	2.5331	2.4589	2.4202	2.3803	2.3392	2.2966	2.2524	2.2064

14	4.6001	3.7389	3.3439	3.1122	2.9582	2.8477	2.7642	2.6987	2.6458	2.6022	2.5342	2.4630	2.3879	2.3487	2.3082	2.2664	2.2229	2.1778	2.1307
15	4.5431	3.6823	3.2874	3.0556	2.9013	2.7905	2.7066	2.6408	2.5876	2.5437	2.4753	2.4034	2.3275	2.2878	2.2468	2.2043	2.1601	2.1141	2.0658
16	4.4940	3.6337	3.2389	3.0069	2.8524	2.7413	2.6572	2.5911	2.5377	2.4935	2.4247	2.3522	2.2756	2.2354	2.1938	2.1507	2.1058	2.0589	2.0096
17	4.4513	3.5915	3.1968	2.9647	2.8100	2.6987	2.6143	2.5480	2.4943	2.4499	2.3807	2.3077	2.2304	2.1898	2.1477	2.1040	2.0584	2.0107	1.9604
18	4.4139	3.5546	3.1599	2.9277	2.7729	2.6613	2.5767	2.5102	2.4563	2.4117	2.3421	2.2686	2.1906	2.1497	2.1071	2.0629	2.0166	1.9681	1.9168
19	4.3807	3.5219	3.1274	2.8951	2.7401	2.6283	2.5435	2.4768	2.4227	2.3779	2.3080	2.2341	2.1555	2.1141	2.0712	2.0264	1.9795	1.9302	1.8780
20	4.3512	3.4928	3.0984	2.8661	2.7109	2.5990	2.5140	2.4471	2.3928	2.3479	2.2776	2.2033	2.1242	2.0825	2.0391	1.9938	1.9464	1.8963	1.8432
21	4.3248	3.4668	3.0725	2.8401	2.6848	2.5727	2.4876	2.4205	2.3660	2.3210	2.2504	2.1757	2.0960	2.0540	2.0102	1.9645	1.9165	1.8657	1.8117
22	4.3009	3.4434	3.0491	2.8167	2.6613	2.5491	2.4638	2.3965	2.3419	2.2967	2.2258	2.1508	2.0707	2.0283	1.9842	1.9380	1.8894	1.8380	1.7831
23	4.2793	3.4221	3.0280	2.7955	2.6400	2.5277	2.4422	2.3748	2.3201	2.2747	2.2036	2.1282	2.0476	2.0050	1.9605	1.9139	1.8648	1.8128	1.7570
24	4.2597	3.4028	3.0088	2.7763	2.6207	2.5082	2.4226	2.3551	2.3002	2.2547	2.1834	2.1077	2.0267	1.9838	1.9390	1.8920	1.8424	1.7896	1.7330
25	4.2417	3.3852	2.9912	2.7587	2.6030	2.4904	2.4047	2.3371	2.2821	2.2365	2.1649	2.0889	2.0075	1.9643	1.9192	1.8718	1.8217	1.7684	1.7110
26	4.2252	3.3690	2.9752	2.7426	2.5868	2.4741	2.3883	2.3205	2.2655	2.2197	2.1479	2.0716	1.9898	1.9464	1.9010	1.8533	1.8027	1.7488	1.6906
27	4.2100	3.3541	2.9604	2.7278	2.5719	2.4591	2.3732	2.3053	2.2501	2.2043	2.1323	2.0558	1.9736	1.9299	1.8842	1.8361	1.7851	1.7306	1.6717
28	4.1960	3.3404	2.9467	2.7141	2.5581	2.4453	2.3593	2.2913	2.2360	2.1900	2.1179	2.0411	1.9586	1.9147	1.8687	1.8203	1.7689	1.7138	1.6541

29	4.1830	3.3277	2.9340	2.7014	2.5454	2.4324	2.3463	2.2783	2.2229	2.1768	2.1045	2.0275	1.9446	1.9005	1.8543	1.8055	1.7537	1.6981	1.6376
30	4.1709	3.3158	2.9223	2.6896	2.5336	2.4205	2.3343	2.2662	2.2107	2.1646	2.0921	2.0148	1.9317	1.8874	1.8409	1.7918	1.7396	1.6835	1.6223
40	4.0847	3.2317	2.8387	2.6060	2.4495	2.3359	2.2490	2.1802	2.1240	2.0772	2.0035	1.9245	1.8389	1.7929	1.7444	1.6928	1.6373	1.5766	1.5089
60	4.0012	3.1504	2.7581	2.5252	2.3683	2.2541	2.1665	2.0970	2.0401	1.9926	1.9174	1.8364	1.7480	1.7001	1.6491	1.5943	1.5343	1.4673	1.3893
120	3.9201	3.0718	2.6802	2.4472	2.2899	2.1750	2.0868	2.0164	1.9588	1.9105	1.8337	1.7505	1.6587	1.6084	1.5543	1.4952	1.4290	1.3519	1.2539
∞	3.8415	2.9957	2.6049	2.3719	2.2141	2.0986	2.0096	1.9384	1.8799	1.8307	1.7522	1.6664	1.5705	1.5173	1.4591	1.3940	1.3180	1.2214	1.0000

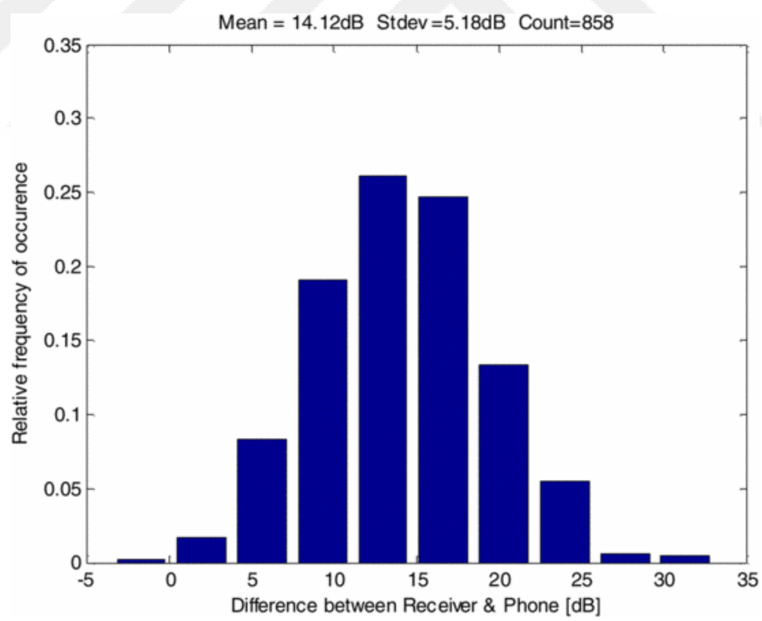

Figure 38: Histogram of the difference between the receiver and phone RSL measurements [31]

MATLAB CODES

After loading your measurements file as a table variable in MATLAB, you need to have 4 columns, which are longitude index, latitude index, and PCI and RSRP values. Converting geo-location to bin index is explained in Chapter 3 as I and J formula by using binning idea in excel, then the file is saved as a PATT which refers to PHONE and AT&T carrier. The same thing is done for the scanning receiver as well. Then, the calculation of averaged RSRP measurements of each bin based on their location and PCIs is coded in MATLAB by following:

```
binning_PATT = zeros (193,149,504);        % there are 193
latitudes,149 longtitude, and 504 PCIs create 3 dimension zero
matrix
count_PATT = zeros (193,149,504);          % create 3 dimension zero
matrix in order to find how many RSRP mearements there are in each
bins
binning_PATT_med = zeros (193,149,504);    % create 3 dimension zero
matrix in order to find median of each bin

for LON = 1 : 149
    idx1 = PATT.ILon_index~=LON;
% idx1,logical, is 1(one) where PATT.ILon_index is not equal LON
    j1 = PATT.jLat_index(~idx1);
      % find latitudes' indexs where idx1 is zero
    i1 = PATT.ILon_index(~idx1);
      % find longtitudes' index where idx1 is zero
    p1 = PATT.CellPCI (~idx1);
      % find PCIs where idx1 is zero
    rsrp1 = PATT.RSRP(~idx1);
      % find RSRP values where idx1 is zero
    a1 = unique(j1);
      % find how many different latitudes there are
    [row1,~] = size(a1);
      % find the length of a1
        for r1 = 1 :row1
            LAT = a1(r1);
            % find first elements of a1
            idx2 = j1~=LAT;
            % idx2,logical, is 1(one) where j1 is not equal LAT
            p2 = p1(~idx2);
            % find PCIs where idx2 is zero
            rsrp2 = rsrp1(~idx2);
            % find RSRP values where idx2 is zero
            a2 = unique(p2);
            % find how many different PCIs there are
```

```
            [row2,~] = size(a2);
            % find the length of a2
                for r2 = 1 : row2
                    PCI = a2(r2);
                    % find first elements of a1
                    idx3 = p2 ~= PCI;
                    % idx2,logical, is 1(one) where j1 is not equal
                  PCI
                    rsrp3 = rsrp2(~idx3);
                    % find RSRP values where idx3 is zero
                    points = length (rsrp3);
                    % find how many RSRP mearements there are
                    average = mean(rsrp3);
                    % find the Mean of RSRP measurements at
                  specific LON, LAT,and PCI
                    med = median (rsrp3);
                    count_PATT (LAT,LON,PCI) = points;
                    % place the number of RSRP mearements at 3
                  dimension matrix in specific points
                    binning_PATT(LAT,LON,PCI) = average;
                    % place the Mean at 3dimension matrix in
                  specific points
                    binning_PATT_med (LAT,LON,PCI) = med;
                end
        end
end
```

After calculation of averaged RSRP measurements of each bin, it needs to be reshape, and erase the bins that they are not matched, and erase zeros that created at the beginning of the code. This process can be done by following code:

```
%%  to find bins where phone and receiver have RSRP measuremnts
together
%   and make those bins zero where they do not have RSRP
measuremnts together
SIZE = 193*149*504;
DATT = binning_RATT - binning_PATT;
DATT (binning_RATT ==0) = 0;
DATT (binning_PATT ==0) = 0;

DATT_med = binning_RATT_med - binning_PATT_med;
DATT_med (binning_RATT_med ==0) = 0;
DATT_med (binning_PATT_med ==0) = 0;
```

```
binning_PATT (binning_RATT == 0) = 0;
binning_RATT (binning_PATT == 0) = 0;

binning_PATT_med (binning_RATT_med == 0)= 0;
binning_RATT_med (binning_PATT_med == 0)= 0;

count_PATT (count_RATT == 0) = 0;
count_RATT (count_PATT == 0) = 0;


%%  Reshape phone and receiver measurements, and remove zeros in
order to compare their RSRP
DATT_reshape = reshape(DATT,SIZE,1);
DATT_med_reshape = reshape(DATT_med,SIZE,1);
binning_RATT_reshape = reshape(binning_RATT, SIZE, 1);
binning_PATT_reshape = reshape(binning_PATT, SIZE, 1);
binning_RATT_med_reshape = reshape(binning_RATT_med, SIZE, 1);
binning_PATT_med_reshape = reshape(binning_PATT_med, SIZE, 1);
count_PATT_reshape = reshape(count_PATT, SIZE, 1);
count_RATT_reshape = reshape(count_RATT, SIZE, 1);

index = DATT_reshape==0;
DATT_NEW = DATT_reshape(~index);
DATT_med_NEW = DATT_med_reshape(~index);
binning_PATT_new = binning_PATT_reshape(~index);
binning_RATT_new = binning_RATT_reshape(~index);
binning_PATT_med_new = binning_PATT_med_reshape(~index);
binning_RATT_med_new = binning_RATT_med_reshape(~index);
count_PATT_new = count_PATT_reshape(~index);
count_RATT_new = count_RATT_reshape(~index);


%%  Find the Mean, Standard Deviation and total Number of points
%   Each Phone, Receiver and the difference
MEAN_DATT = round(mean(DATT_NEW), 2);
STDV_DATT = round(std(DATT_NEW), 2);
COUNT_DATT = numel(DATT_NEW);
MEAN_DATT_med = round(median(DATT_med_NEW), 2);
STDV_DATT_med = round(std(DATT_med_NEW), 2);

MEAN_RATT = round(mean(binning_RATT_new),2);
STDV_RATT = round(std(binning_RATT_new), 2);
COUNT_RATT = numel(binning_RATT_new);
MEAN_RATT_med = round(mean(binning_RATT_med_new),2);
STDV_RATT_med = round(std(binning_RATT_med_new), 2);

MEAN_PATT = round(mean(binning_PATT_new),2);
STDV_PATT = round(std(binning_PATT_new), 2);
COUNT_PATT = numel(binning_PATT_new);
MEAN_PATT_med = round(median(binning_PATT_med_new),2);
STDV_PATT_med = round(std(binning_PATT_med_new), 2);
```