Performance Analysis of D2D Communication over LTE-A Network with Mode Switching

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ABSTRACT

In recent years, the global trend in mobile and smart devices with a wide range of multimedia application led to the rapid growth of data traffic in the cellular networks. Long Term Evolution - Advanced (LTE-A) as the enhanced mobile communication standard carries on a huge part of this requirement. In order to balance the uploading traffic from LTE-A, 3rd Generation Partnership Project (3GPP) introduced Device-to-Device (D2D) communication over LTE-A in its release 12. D2D communication enables users to send data packets to the receiver through a direct link which is called Side Link (SL) or users are able to communicate through the base station which is called Relay Path (RP). The communication can be switched between SL and RP during the communication by the base station. This switching between links is called Mode Switching (MS).

This thesis is attentive in measuring Quality of Service (QoS) in D2D and RP communications over LTE-A network using Voice over IP (VoIP) application. In order to simulate various conditions and different location distribution in the network, four scenarios are simulated in OMNET++. The examined performance results illustrate that D2D communication performs very well in short distances and also, by increasing distance between two mobiles, communication needs to change its path from the SL to the RP. In addition, this dissertation demonstrates how employing MS in a suitable state can improve the QoS of communication in LTE-A and utilize advantages of both D2D and RP communications.

Keywords: LTE-A, D2D, QoS, VoIP, MS, SL, RP

ÖZ

Son yıllarda, geniş bir multimedya uygulamasına sahip mobil ve akıllı cihazlardaki küresel eğilim, hücresel ağlarda veri trafiğinin hızlı bir şekilde artmasına neden olmuştur. Uzun Süreli Evrim - Gelişmiş mobil iletişim standardı olan Gelişmiş (LTE-A) bu gereksinimin büyük bir bölümünü taşıyor. Yükleme trafiğini LTE-A'dan dengelemek için, 3. Nesil Ortaklık Projesi (3GPP), piyasaya sürülmesi sırasında LTE-A üzerinden Cihazdan Cihaza (D2D) haberleşmeyi başlattı. Side Link (SL) veya kullanıcılar olarak adlandırılan bir doğrudan bağlantı, kullanıcılar, Röle Yolu (RP) adı verilen baz istasyonu üzerinden iletişim kurabilir. İletişim, baz istasyonu tarafından iletişim sırasında SL ve RP arasında değiştirilebilir. Bu bağlantılar arasında geçiş yapmak Mod Değiştirme (MS) olarak adlandırılır.

Bu tez, D2D'deki Servis Kalitesinin (QoS) ve IP üzerinden Ses (VoIP) uygulamasını kullanarak LTE-A ağı üzerinden RP iletişiminin ölçülmesinde özenlidir. Ağdaki çeşitli koşulları ve farklı konum dağılımını simüle etmek için OMNET ++ 'da dört senaryo simüle edilmiştir. İncelenen performans sonuçları, D2D iletişiminin kısa mesafelerde çok iyi performans gösterdiğini ve ayrıca iki cep telefonu arasındaki mesafeyi artırarak, iletişimin SL'den RP'ye olan yolunu değiştirmesi gerektiğini göstermektedir. Ek olarak, bu tez, MS'in uygun bir durumda kullanılmasının, LTE-A'da QoS iletişimini nasıl geliştirebileceğini ve hem D2D hem de RP iletişim avantajlarını nasıl kullanabileceğini göstermektedir.

Anahtar kelimeler: LTE-A, D2D, QoS, VoIP, MS, SL, RP

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3GPP	3rd Generation Partnership Project
5G	5th Generation
AM	Acknowledge Mode
AS	Access Stratum
BS	Base Station
CoMP	Coordinative Multiple Point
CQI	Channel Quality Indicator
D2D	Device-to-Device
DL	DownLink
EDGE	Enhanced Data GSM Evolution
eNB	evolved NodeBs
EPC	Evolved Packet Core
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communication
HARQ	Hybrid Automatic Repeat Request
HSPA	High Speed Packet Address
HSS	Home Subscriber Server
IMS	IP Multimedia Subsystem
IMT-A	International Mobile Telecommunication-Advanced
IoT	Internet of Things
IP	Internet Protocol

LTE-A	Long Term Evolution – Advanced
MAC	Medium Access Control
MIMO	Multi-Input Multi-Output
MME	Mobility Management Entity
MOS	Mean Opinion Service
MS	Mode Switching
MT	Mobile Termination
NAS	Non-Access Stratum
NIC	Network Interface Card
OFDM	Orthogonal Frequency Division Multiplexing
PAPR	Peak-to-Average Power Ratio
PDCP	Packet Data Conversion Protocol
PDN	Packet Data Networks
PDN-GW	Packet Data Network Gateway
PDU	Protocol Data Unit
ProSe	Proximity Services
QoE	Quality of Experience
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RLC	Radio Link Control
RN	Relay Node
ROHC	Robust Header Compression
RP	Relay Path
RRC	Radio Resource Control

SC-FDMA	Single Carrier Frequency Division Multiple Access
SDU	Service Data Unit
S-GW	Serving Gateway
SIM	Subscriber Identity Module
SINR	Signal-to-Interference-Plus-Noise Ratio
SL	Side Link
TB	Transmission Block
TCP	Transmission Control Protocol
TDD	Time Division Duplex
TM	Transparent Mode
TTI	Transmission Time Interval
UDP	User Datagram Protocol
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	UpLink
UM	Unacknowlege Mode
UMTS	Universal Mobile Telecommunication System
USIM	User Services Identity Module
VoIP	Voice over IP

Chapter 1

INTRODUCTION

1.1 Introduction

With increasing functionality of mobile devices in the concept of the connected world, smart cities, Internet of Things (IoT) and many innovative application services, cellular networks have been going through phenomenal fast evolution in recent years. This rapid growth of data traffic led 3rd Generation Partnership Project (3GPP) to introduce Long Term Evolution (LTE) network in 2009 in its release 8 which was a Packet-Based network [1]. 3GPP changed its path from circuit-switch to packet-switch network by using Internet Protocol (IP) as the central protocol for the transmission of all services by employing Evolved Packet Core (EPC). Architecture design of EPC decreased the number of elements in the network core, therefore the latency time of packets in the network was reduced significantly [2].

LTE-Advanced (LTE-A) which is also known as LTE release 10 has improved LTE criteria and has implemented much superior data rate, coverage, and throughput. Technologies such as Carrier aggregation, Multi-Input Multi-Output (MIMO), Upper link spatial multiplexing and Coordinative Multiple Point (CoMP) led LTE-A to fulfill International Mobile Telecommunication-Advanced (IMT-A) requirements [3].

Today, the fast growth in the number of mobile device users and smartphone application services like Voice over IP (VoIP), video traffic, gaming has increased the data traffic demand at an exponential rate. However, all of this amount of data is just the tip of the iceberg. Cisco in its last Global Mobile Data Traffic Forecast Update [4] stated: “Monthly global mobile data traffic will be 49 exabytes (1000^6 bytes) by 2021, and mobile will represent 20 percent of total IP traffic by 2021”. Consequently, in spite of low latency in the latest LTE-A network technologies, it has been necessary to decrease incoming traffic load into the cellular networks by employing another type of communication. Thereupon, in 2014, 3GPP decided to add Proximity Service (ProSe) to its release 12 to exploit Device to Device (D2D) communication in terms of Quality of Service (QoS) of communications and also high-capacity transmission technique in networks for public safety [5, 6].

D2D communication technology is presently passing examination and enhancement steps in the LTE-A network, and it can be a big part of 5th Generation (5G) network systems in the future. In the traditional cellular networks, packets were only transmitted between User Equipments (UEs) and base stations, that are denoted as enhanced NodeB (eNB). This transmission is called *Relay Path* (RP). In RP communication, two UEs only were able to communicate via a two-hope path. On the other hand, D2D communication allows devices to share data packets directly to each other without sending data-packets via eNB that, this connection is called *Side Link* (SL). During the communication, eNB can switch data traffic's path from RP to SL without service discontinuity. This change in data’s path is entitled *Mode Switching* (MS) and it is expected to decrease uploading data traffic to the EPC, reduce latency and reduce power consumption of eNBs and network elements [7].

Although there have been many studies on resource allocation on D2D communication in recent years, there is no comprehensive study of how D2D communication should be recognized in LTE-A protocol stack and how to choose the best time and condition for performing MS process. Since MS operation causes a complex signaling conversation as explained in [8] and may lead some packet loss as described in [9], decreasing the number of MS and at the same time keeping the performance of communication by proposing a threshold for MS becomes an important issue. In other words, the performance of communication can be improved by employing a suitable MS process.

1.2 Aim of the Research

The major aim of developing LTE network and invention of D2D communication is to ensure QoS of transmission. Also, as mentioned to the Cisco forecast [4] earlier, more than 78 percent of the global mobile data traffic will be video based on UDP by 2021, proper execution of services (especially real-time applications) must be guaranteed. The amount of requested traffic by low tolerance multimedia services which are currently running in a various number of smart mobiles and tablets increases the call for requirements in QoS performances criteria such as delay time, delivery ratio, bit error rate, and throughput.

This thesis aims to investigate the QoS of VoIP data traffic over RP and over D2D communication underlay LTE-A network. The focus of the investigation is on the D2D communication performance with various performance metrics to examine the best time for performing MS. Different network scenarios are employed to simulate and investigate D2D communication to find a suitable threshold for the distance for switching the mode from D2D mode to RP mode.

We employed OMNET++ simulation environment which has became one of the most popular frameworks for network field simulations [10]. For the purpose of investigating the QoS performance of VoIP application in D2D communication over LTE-A network, we employed Simulte framework which works on top of INET framework in OMNET++.

1.3 Thesis Outline

Thesis consists of 5 chapters and 4 appendices which are organized as follow: Chapter 1 performs a short introduction of the thesis motivation, aims, and methodology. Chapter 2 contains the background of LTE-A network, Evolved Packet Core entities, LTE-A protocol stack layer, and D2D communication. Chapter 3 describes the methodology, OMNET++ units, simulation parameters, and designed scenarios. And also, the results of simulations are discussed in Chapter 4. Conclusion and further works are presented in Chapter 5.

Chapter 2

AN OVERVIEW OF LTE-A NETWORK

2.1 LTE and LTE-A Background

The evolution of cellular networks started from Advanced Mobile Phone System (AMPS) and came up to LTE-A and 5G. The earliest wireless evolution standard was AMPS which utilized an analog system. Later, by employing digital communication system for the first time in the early 1990s, Global System for Mobile Communication (GSM) was born which is also known as 2G standard. Afterward, in the second half of the 90s, General Packet Radio Service (GPRS) and Enhanced Data GSM Evolution (EDGE) brought 3G into the market. Then Universal Mobile Telecommunication System (UMTS) which is identified as the full-dress 3G standard continued the evolution for better connectivity, carrier aggregation, and higher data rates. The movement from 3G to 4G started with High Speed Packet Address (HSPA), an IP-Based network which introduced 14 Mbps data rate and this is known as 3.5 Generation. Hence, LTE is generally known as the start point of 4G level [11, 12].

LTE's improved spectrum efficiency led to a better performance in terms of high data rates, low latency, more flexibility and seamless integration with other wireless networks. Furthermore, supporting both Time-Division Duplex (TDD) and Frequency-Division Duplex (FDD) and using adopted uprising technologies like

Orthogonal Frequency Division Multiplexing (OFDM) and MIMO made LTE the core technology of cellular networks [13].

The initial release of LTE in 2009 supported a peak rate of 300 Mb/s and provided time delay of less than 5 ms in radio-network [1]. LTE design is based on Evolved Packet System (EPS) which consists of the Radio Access Network (RAN) known as Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) and an IP-based core network known as EPC. All applications included VoIP can be integrated over a flat architecture to prepare seamless connectivity between operators subscribers [14].

In 2011, the next version of LTE, known as LTE-A was released. LTE-A inherited the advantage of LTE. By utilizing advanced wireless technologies namely Carrier Aggregation, Enhanced MIMO, Coordinative Multiple Point (CoMP) and Relay Node (RN) enhanced its properties in terms of coverage, bandwidth, peak rate, delay time, throughput, user experience, etc. [15].

- *Carrier Aggregation:* In carrier aggregation, it is possible to utilize more than one carrier to present wider bandwidths in UpLink (UL) and DownLink (DL) transmissions [16].
- *Enhanced MIMO:* LTE-A standardized increasing the number of layers in MIMO from 4 × 4 to 8 × 8 layers at DL and from 2 × 2 to 4 × 4 layers at UL to improve entirely bit rate in transmission of the all data streams in multiple antennas [17].
- *CoMP:* In CoMP different base stations which are geographically separated are able to coordinate dynamically on transmission and reception in order to improve the system performance and edge service quality.

- *RN:* RN technology enabled heterogeneous networks to plan their data and integrate with large cell networks such as Base Station (BS). This technology purposes to convert the received signal to inter-cell interference plus noise power ratio and improve throughput. In this manner, radio signals are able to be propagated more expeditiously, which can cause enhanced coverage and improved end-user throughput at cell edge [16].

2.2 LTE-A Architecture

LTE-A architecture was designed based on packet switching services in a flat IP connected and perfectly interconnected with heterogeneous wireless networks. This environment provided a seamless communication between UEs and Packet Data Networks (PDN) with lowest interference or discontinuity even during mobility [18].

As shown in Figure 2.1, LTE-A network consists of the radio access network, E-UTRAN, and EPC. EPC is completely an IP-based and packet-switched network core. LTE-A architecture connects the voice service which was known as a circuit-switched network [19].

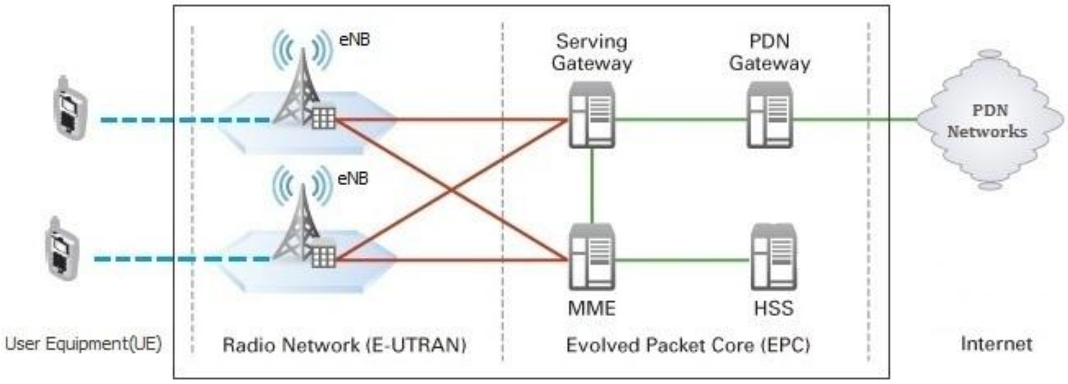


Figure 2.1: LTE/LTE-A Architecture [20]

2.2.1 User Equipment (UE)

In LTE-A architecture, the name "UE" represents a mobile terminal which is armed with a mobile broadband adapter such as a hand-held cellular mobile phone, laptop computer, LTE-enabled tablets or any IoT or vehicular device which is capable of transmission and reception of data through eNB in LTE networks. UE's structure consists of application, transport, network layers and also LTE Network Interface Card (NIC) as is illustrated in Figure 2.2. Moreover, it utilized Subscriber Identity Module (SIM) to store information about the user such as home network identity, phone number, and the security keys. Data traffic after passing all the layers procedures in UE are sent to the network by E-UTRAN which is the radio access network in LTE-A network [18, 21].

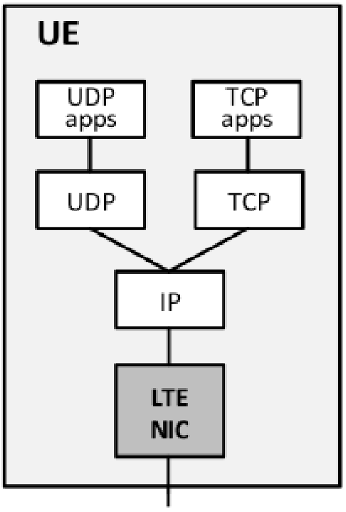


Figure 2.2: UE structure in LTE/LTE-A network

2.2.2 Radio Access Network E-UTRAN

E-UTRAN used in LTE-A as its radio access network, which is derived from the 3GPP UTRAN. E-UTRAN has the functionality of the connection between UEs and EPC. E-UTRAN consists of multiple eNBs which are connected to each other and to EPC. To be able to forward data packets to the destination UE, the eNB needs to have access to the headers of layers (i.e. deriving source and destination IP address from IP header). Therefore, eNBs include the same layers as UEs layers which are shown in Figure 2.2. eNBs are generally responsible for radio resource management, connection to the EPC entities, paging users and also, managing required signaling for the establishment and maintenance of the connections.

2.2.3 Evolved Packet Core (EPC)

EPC is the core of LTE network and it runs network traffic control and security. 3GPP had decided to have a "*flat architecture*" [23]. This architecture is designed to improve performance and reduce the cost of data transmission. Also, handling of the payload is accomplished by a few network elements. It is been tried to avoid complex signaling conversation. Figure 2.1 shows EPC network elements: Mobility Management Entity (MME), Serving Gateway (S-GW), Home Subscriber Server (HSS), and Packet Data Network Gateway (PDN-GW) [22, 23].

Home Subscriber Server (HSS): HSS is the central database of the network which maintains information related to the subscriber and users. Mostly, it provides the required information for implementing functions such as call and session establishment, mobility management, authentication and authorization of users and their access.

Packet Data Network Gateway (PDN-GW): The PDN is known as the gate of the network which connects the EPC to the external IP networks as shown in Figure 2.1. These external IP networks are called Packet Data Networks (PDN) such as the Internet, SIP-based IMS networks. PDN-GW routes packets from/to the PDNs. It also supports other functions including hosting IP address, IP prefix allocation, IP tunneling charging and policy control. PDN-GW is responsible for allocating the IP address to all the UEs in the network and routing packets to the correspondent S-GW, while GTP-CU is used as the tunneling protocol between PDN-GW and S-GW [21]. The utilized protocols for each layer in PDN-GW are as below:

- Transport Layer: UDP, TCP
- Tunneling:
    - GTPv2-C(Signaling Channel), GTPv1-U (Data Channel)
    - PMIPv6: GRE or IP-in-IP
- Network Layer: IPv4, IPv6
- Data Link Layer: ARP
- Physical Layer: Ethernet

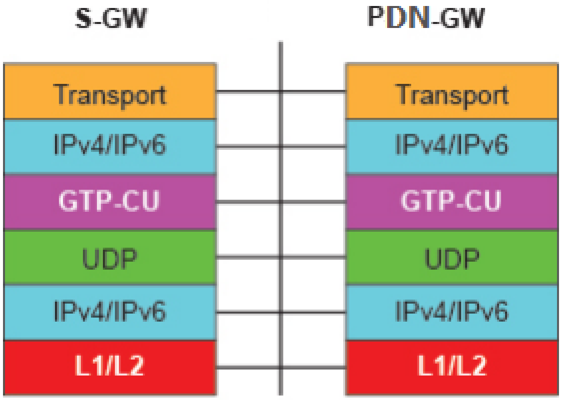


Figure 2.3: PDN-GW and S-GW supported protocols [24]

Serving Gateway (S-GW): The S-GW is the point of interconnection between the Radio Access Network (RAN) and EPC. It serves UEs by routing and forwarding the arrival and outgoing IP packets. S-GW runs the data plane of the network and it is the local mobility anchor which means routing and forwarding data traffic between PDN-GW and proper eNB in the RAN. It means when UE changes its location and moves to the neighbor eNB’s coverage area, packets need to change their path to the current location’s eNB. This switching is performed by S-GW by coordinating with the MME [22].

Mobility Management Entity (MME): MME is the major control entity in the radio access network and it is responsible for bearer management which evolves signal procedure for UE session setup and arranging corresponding QoS parameters, and also intra-3GPP mobility management. It routes the S-GW's data packets to the current location of UE [14]. MME is tightly interconnected with HSS and gains the required information to implement its functions included Non-Access Stratum (NAS) signaling, Access Stratum (AS), handling the idle state mobility, bearer control, authentication, etc. In terms of handover, HSS needs to see all mobilities and have all the last updated information about the UE. In order to limit the incoming traffic to the HSS, MME architecture is designed to hide these mobilities and serves as the proxy entity for the HSS [26].

2.3 LTE-A Protocol Stack Layers

The purpose of this section is to explain LTE-A protocol stack layers in NIC, that LTE compatible UEs and eNBs are equipped with, and also, their effects on the packets and data flow with particular emphasis on details of duties of each layer.

All the UEs and eNBs in LTE-A networks must be equipped by LTE NIC module. All generated packets by application layer after being processed in transport layer by TCP or UDP protocol and afterward in the network layer (IP), will enter into NIC which includes the sublayers that are known as LTE-A protocol stack layers [16]. 3GPP decided to separate transmission in LTE into two independent parts, which are known as control plane and data plane. In the data plane, data packets are produced by applications in UEs and are processed by network protocols like UDP, TCP, and IP, while in the control plane the Radio Resource Control (RRC) layer generates the signaling messages which are used for coordination between UE and eNB. Figure 2.4

illustrates the LTE-A protocol stack layers obsoleted in control and data plane, where RRC controls all the data plane layers' parameters and also the layers in the data plane are responsible for managing data transmission.

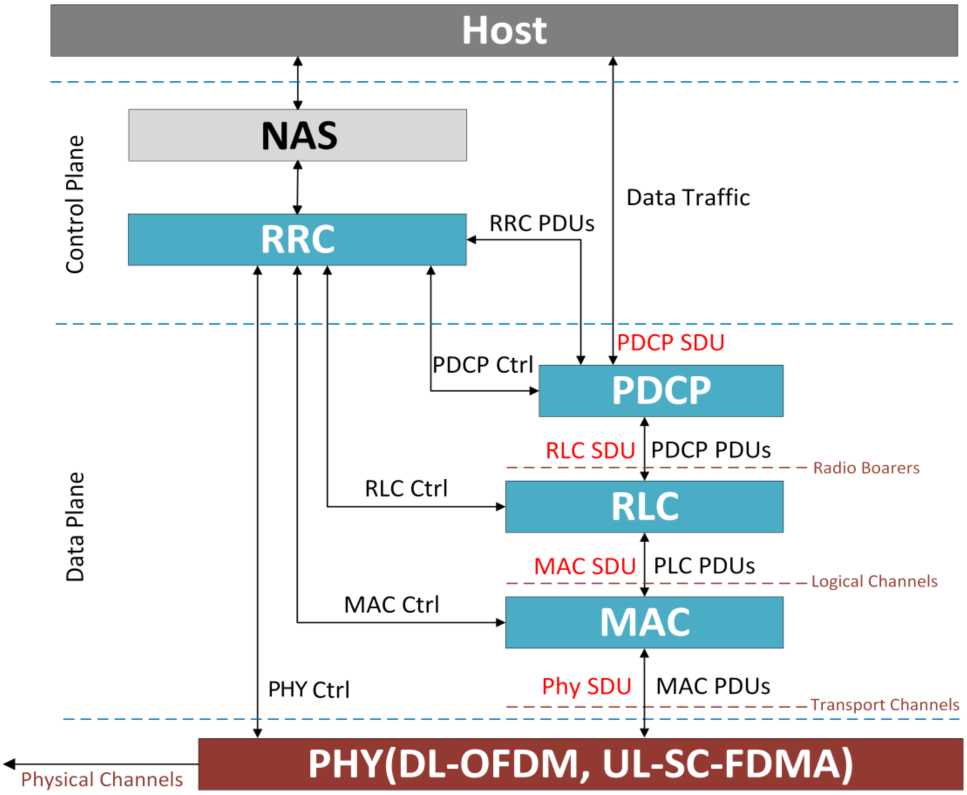


Figure 2.4: Life of an LTE packet in the protocol stack layers

As shown in Figure 2.4, when a data packet is going from PDCP to PHY layer, at the exit point of source sublayer it is called Packet Data Unit (PDU) and at the entrance point of the next sublayer, it is called Service Data Unit (SDU). For instance, the packet which came out from the PDCP layer and is moving to RLC layer is called PDCP PDU and also is called RLC SDU at the same time.

2.3.1 Radio Resource Control (RRC)

RRC which is the most vital entity in the control plane is responsible for broadcasting system information related to NAS and UEs. Also, RRC controls the connection between UEs and eNBs. RRC connection establishment is necessary before sending any data packet to the network. In order to establish a connection between UE and the eNB, first UE’s RRC establishes an RRC link with the peer entity of the eNB or vice versa.

In addition, RRC controls the transition mode which can be *idle mode* or *connected mode*. When a UE does not have an RRC active connection, it is recognized as in *idle mode* and when its RRC connection is active it is called *connected mode*. When there is no data transmission in a specific period of time for a given UE, the RRC layer of the eNB leads RRC link release for the UE and leads it to the idle state in order to save UE’s battery and interface resource [2].

After establishing the RRC connection between the UE and the eNB, RRC sublayer of the UE as the coordinator controls all the data sublayer via independent links PDCP Ctrl, RLC Ctrl, MAC Ctrl and PHY Ctrl as is illustrated in Figure 2.4. And also, configuring the performed measurements of the channel quality and reporting them by UE are other functions of RRC control sublayer. All UEs must do many types of measurements such as intra-frequency and inter-frequency measurements. All of these measurements are configured in UEs by the eNB’s RRC. And finally, the eNB’s RRC takes handover related decision according to the reports [28]. MS process from RP to D2D or vice versa is controlled by eNB’s RRC and measurements configuration of UEs. RRC also performs some security functions including security key management and security algorithm selection.

2.3.2 Non-Access Stratum (NAS)

This layer is in control plane and performs similar duty with RRC. It runs a utilized protocol between UE and MME to manage the establishment of the connection and maintaining the connection while UEs have mobility. Also, it performs some other function such as tracking area update, paging, authentication, EPS bearer management and PDN connectivity procedure [23].

Figure 2.5 shows the control plane architecture in LTE-A network and the signaling communication between the control sublayers of the UE and eNB and MME nodes. NAS layer of UE is communicating with NAS layer of MME directly, while other layers are connected to their peers in eNB.

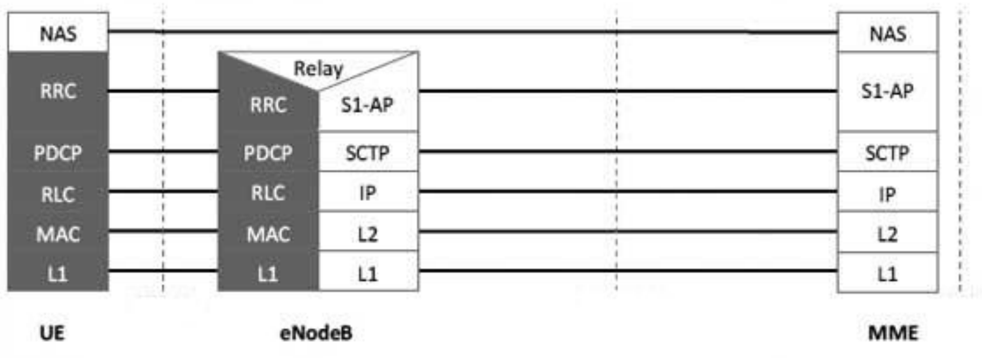


Figure 2.5: LTE-A Control Plane Architecture [31]

2.3.3 Packet Data Convergence Protocol (PDCP)

The first sublayer of data plane in NIC is PDCP. The first task of PDCP is header compression and decompression by Robust Header Compression (ROHC) standardized method [2]. Maintenance of PDCP sequence numbers and assigning PDCP sequence number to each packet before sending to RLC is its second task. And finally ciphering PDCP SDUs to enable only peering PDCP entity to recover original SDUs is its third task [27].

2.3.4 Radio link control (RLC)

Since the packets sizes of data traffic are variable e.g. VoIP’s payload is small but in case of video streaming, the data part is quite big, and also changing radio conditions and changing the number of UEs in the coverage area of an eNB cause available bandwidth on the interface keeps on changing frequently, therefore RLC has to segment or concatenate the transmission packets dynamically regarding the available bandwidth on the interface. Also, RLC is designed in three modes: Acknowledge Mode (AM), Unacknowledge Mode (UM), and Transparent Mode (TM). The service type of arriving packets specifies the RLC mode e.g. UDP packets lead RLC to UM and TCP triggers AM. RLC behavior is determined by the required mode, for example, in the case of UM PDU, RLC does not do retransmission procedure, or in case of TM does not add any preamble to SDUs. [28]

At the receiving side, RLC is responsible for the reassembly of the received segments. And also, RLC performs reordering of data PDUs in case of AM and UM data transfers. Because of multiple retransmission, received packets can arrive out of order. Therefore, RLC must reorder them and then send to the PDCP layer [29].

2.3.5 Media Access Control (MAC)

Prioritization between different data flows for a UE is one of the most important duties of MAC sublayer. Different flows are given various priority regarding their type, e.g. VoIP packets are one of the highest priority if available bandwidth can not effort all the transmission flows. MAC sublayer sends the higher priority stream selectively [30].

MAC encapsulates SDUs in MAC Transmission Blocks (TBs), which is the transmission unit in MAC. The TBs are organized into sub-frames with Transmission Time Interval (TTI) 1ms.

MAC and RLC sublayers are tightly interconnected in order to perform error detection and correction. Hybrid Automatic Repeat reQuest (HARQ) scheme in the MAC [2] is an error correction technique that is utilized from UMT and leads retransmissions of the corrupted transmission blocks and thereby recover most of the transmission errors.

2.3.6 Physical Layer

The physical layer is responsible for receiving TBs from the MAC and adding Cyclic Redundancy Check (CRC) bits to it. This task is performed in order to check errors through the air interface path. Another task of physical layer is loading TBs within the eNB's granted RBs. RBs are the smallest unit of resources that can be devoted to a UE on the air interface [16].

Data has to pass through the encoding process before modulation in the Physical layer. This process is needed to enable the receiver peer entity to detect any error in the packet bits which may occur during the transportation on the air interface. Therefore, at the receiver side, the physical layer is able to correct data in case of the presence of corruption, by decoding the CRC bits.

Also, channel quality measurement is another vital job of physical layer in both sides (at the sender and the receiver), in order to report the channel quality state to the eNB.

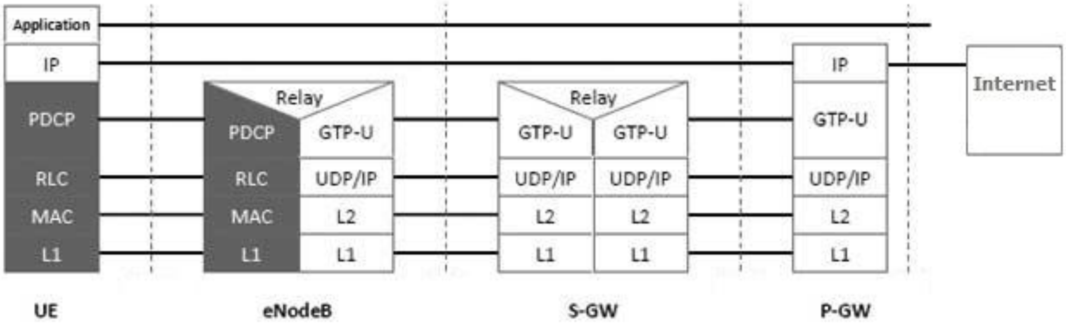


Figure 2.6: LTE-A Data Plane Architecture [31]

Figure 2.6 illustrates the involved nodes in the data transmission procedure and the connected layers and sublayers in UE, eNB, S-GW, and PDN-GW in the data plane to transmit data packets in LTE-A network.

2.4 LTE-A Network Modulation Technologies

LTE-A uses two different multiplexing techniques in order to utilize the shared channel, namely FDD and TDD [33]. And also, OFDM is utilized as the signal bearer and relevant access schemes, Single Carrier Division Multiple Access (SC-FDMA). Basically, LTE-A benefits OFDMA for DL transmission and SC-FDMA for UL transmission which supplies an enhanced Peak-to-Average Power Ratio (PAPR) that triggers more power-efficient terminal[2]. Utilization of these standards makes LTE-A able to benefit these multiple carrier techniques' advantages such as high flexibility, multiuser diversity, robustness in communication and efficient spectrum utilization and resistance to frequency selective fading [32].

2.4.1 OFDMA

In the OFDM modulation format, the original bandwidth is split into multiple subcarriers. These subcarriers can be shared between different users within a transmission interval since OFDM supports multi-user access. In LTE, OFDMA is employed with time domain, therefore the basic unit of resource allocated to one user consists of a subset of subcarriers for a particular time period. This basic unit in LTE is RB, which is an addressable and the smallest unit of resource for data transmission. One RB consists of 12 sequential subcarriers with 15 KHz channel bandwidth for a duration of 1ms (one slot) and overall provides a bandwidth of 180 KHz [33].

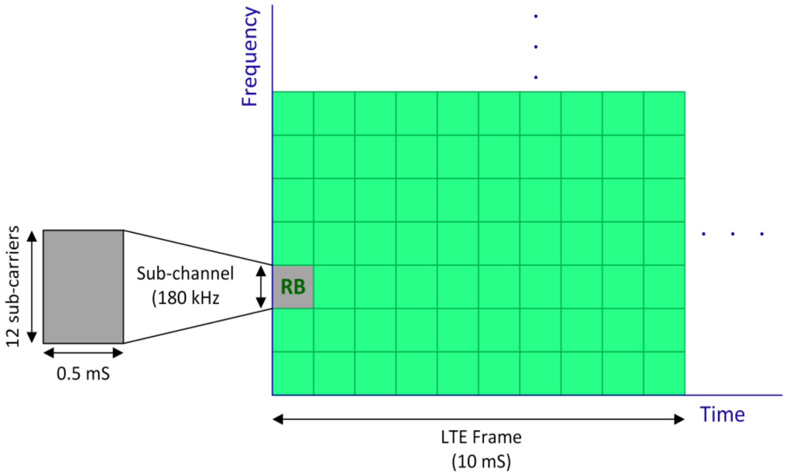


Figure 2.7: An OFDMA frame

The radio frame has a duration of 10 ms and this frame is built by 10 subframes where each subframe has the equal duration of 1ms and consists of two slots, each of length 0.5ms, and each subframe is composed of 14 OFDM symbols.

2.4.2 SC-FDMA

The main goal of design SC-FDMA for UL direction in LTE is to reduce the effect of high PAPR which is the ratio between maximum power and the averaged power. Although SC-FDMA signals seem like a single carrier, it is carrying data in a multi-carrier process similar to OFDMA [34]. Figure 2.8 illustrates the concept of OFDMA and SC-FDMA in the axes of frequency and time.

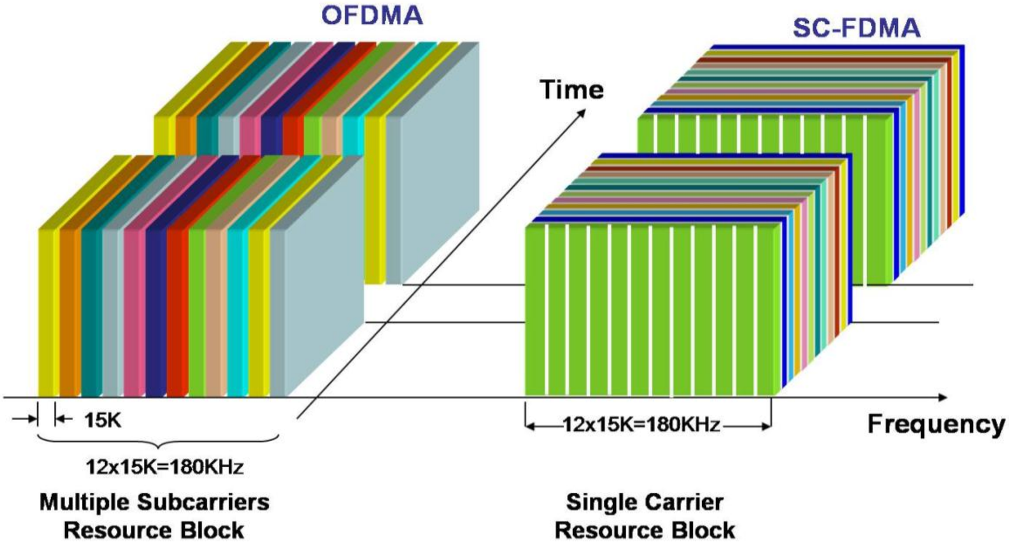


Figure 2.8: OFDMA and SC-FDMA structures

While LTE-A utilized OFDMA for DL and SC-FDMA for UL, D2D communication reuses the UL resource because of its low PAPR.

2.5 D2D Communication

3GPP has introduced D2D communication in LTE release 12 under the name of ProSe in 2014 [35] in order to respond to the fast growth of data traffic especially on the commercial part, e.g. social networking and shop advertising, and public safety positioning such as ambulance and police. It is predictable that D2D communication will play a vital role in the future of 5G technology. Controlled D2D communication in LTE-A enables users to communicate directly to the destination without sending data packets through the eNB that makes the expectations of lower latency and lower energy consumption at the eNB [37].

The RRC of the eNB, as the controller of the D2D communication, is responsible for establishing and controlling the D2D connection between endpoints. The direct link between two D2D UEs is called Side Link (SL). Figure 2.9 shows SL and normal two-hop path.

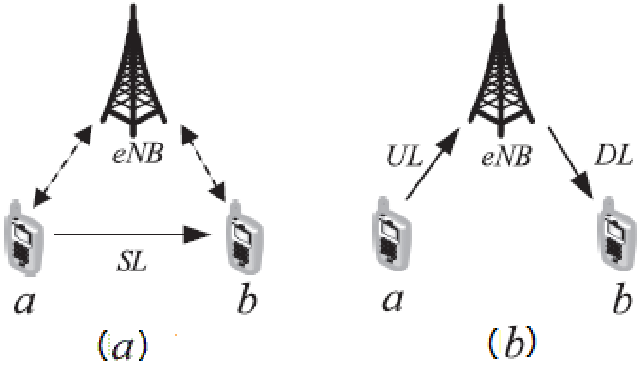


Figure 2.9: D2D connection through SL(a) and traditional two-hop connection(b) [36]

To achieve a proper network-controlled D2D communication, there is a need to address several difficulties. The first one is *discovery* which pairs of UEs are permitted for D2D communication, in terms of proximity and possibility of hearing each other. And the second difficulty is *Resource allocation* which has two aspects: *Mode switching* and *Packet scheduling* in the MAC layer (e.g which RBs be assigned to which data flows) [37].

2.5.1 Discovery of the UE

The defined ProSe in 3GPP has two main functions: discovery and data transmission have been defined in [38] and all the possible scenarios are illustrated in Figure2.10. This thesis focuses on D2D communication between two devices within the same eNB coverage area which is illustrated in scenario (a) in Figure 2.10.

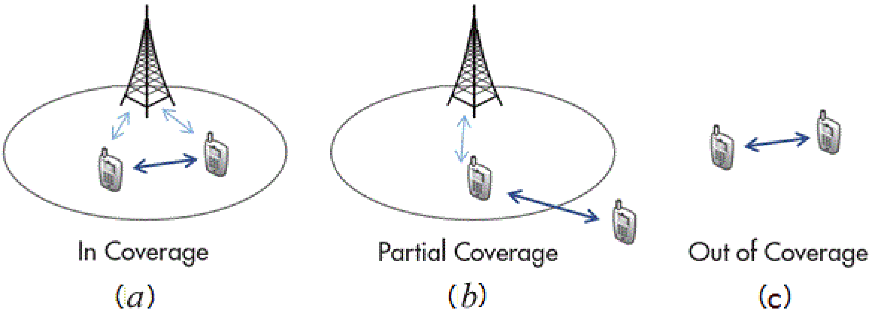


Figure 2.10 Possible scenarios of D2D communication [39]

In order to D2D peers be able to communicate directly with each other through the SL, they must assure that they are close enough to establish the D2D communication. Hence, different ProSe discovery methods have been introduced in the 3GPP technical report [38] and all these methods can be categorized into the following two classes:

- *Network core-assisted discovery:* Users update their location information in the central servers MME and HSS, then MME server broadcasts the updated information to other users. The RRC of the eNB checks with the MME to recognize two UEs are in the hearing range of each other. This mechanism is also called *Open Discovery* (Hey! I’m here!)
- *Direct discovery:* One UE asks for a specific user. In this method, ProSe-enabled UEs announce and/or monitor the granted radio resource to realize each other’s presence. This mechanism is also called *Strict Discovery* (Who is there?!). This is mostly applied when the file size is large or transferred file needs to be shared between two users in the same locality [6, 40].

2.5.2 Resource Allocation

In order to gain required RB from the shared radio resource, UE needs to start the standard handshake procedure in the UL with the eNB. It forwards a Random ACcess (RAC) demand to the eNB, then the eNB replies to the RAC request by adjusting a small grant in the next TTI. TxUE is now able to send its buffer size which is equal to its RLC buffer size, via sending Buffer Status Report (BSR) in order to inform the eNB about its upcoming data size. Then eNB allocates its required grant in the next TTI if it is available. Figure 2.11 summarizes the standard handshake procedure.

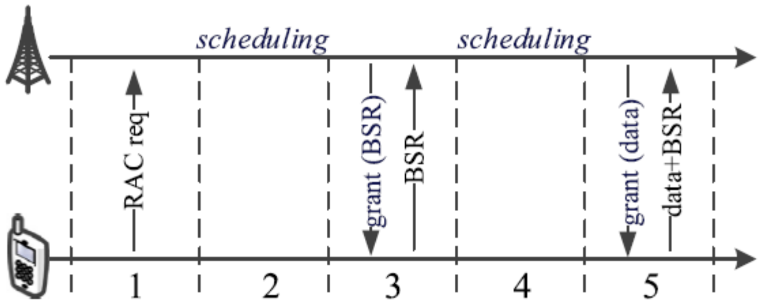


Figure 2.11 Standard Handshaking Procedure between UE and eNB [9]

The eNB is responsible for resource allocation in both UL and DL. In order to grant the resource to UEs, it tells the UEs to where to send/listen for their packets. The eNB can target both UEs at the same time, having one transmit on the same RBs where another one is told to listen and receive its data packets [37].

Since the UE's transmitting power is low, spatial reuse is able to be performed. Consequently, D2D communication used UL spectrum for transmission over SL, while the UL subframes are likely to be lower loaded than DL subframes because of the well-known traffic asymmetry and it gives more preferable Signal-to-Interference-Plus-Noise Ratio (SINR) in the SL [41]. Therefore, UEs must be equipped with SC-FDMA in order to receive a transmission packet from the SL [35].

2.5.3 Mode Switching (MS)

Mainly, eNB is the essential entity to perform coordination between transmitter UE and receiver UE. In D2D communication, the eNB establishes the communication between two UEs and controls its stability by signaling via the control plane. The eNB triggers the MS process which enables it to redirect communication from the RP to the SL and vice versa, to achieve efficient resource utilization without interrupting the communication or harming the QoS. The eNB is responsible for deciding about when and how MS must take place by monitoring the reported measurement of channel quality (CQI) by UEs. The final decision of the eNB is not certainly the same. It may consist of one or different measured metrics, such as the represented data rate that can be efforted by channel, SINR, and also UE receiver properties [34].

D2D Communication Establishment Steps: D2D communication establishment steps are listed below:

i. A session is initiated by one of the UEs' request.

ii. The source and destination's IP addresses are detected by the gateways. It must be recognized that both UEs are in the same eNB's coverage area or in the neighborhood area of each other.

iii. If SL is able to effort certain criteria of QoS, two UEs will be devoted as potentially D2D communication UEs by the eNB.

iv. The eNB then asks UEs to measure SL quality and then receive the sent CQI by the UEs.

v. If both UEs support D2D communication and also SL offers higher performance e.g. higher throughput, the eNB may establish D2D communication.

vi. After D2D communication establishment, the eNB continues as a bearer between UEs and gateway. Moreover, it controls the radio resources between UEs and also performs the MS, if it is necessary.

Chapter 3

IMPLEMENTATION

Most of the current researches in D2D communication area have often focused on resource allocation. This thesis targeted to improve the performance in D2D communication and RP communication by investigation of the MS process between two communication modes. The UEs are placed in different locations in order to obtain various performance of network. Therefore, different scenarios are used and their various results are collected and presented. This chapter consists of related work, the contribution of the performance examination, OMNET++ design, performance metrics, and scenarios description. In the beginning, a general overview of data flow in D2D communication is stated to bring to light data traffic journey to bearer on air interface in the RP, SL, and MS procedure.

3.1 Data flows in the stack protocols of LTE-A Network Interface

In the sender side, generated packets will arrive at the stack protocol sublayers through the application, transport, and network layer, respectively. Obviously, each layer attaches its own header to the packets. The packets are called PDCP SDUs at the moment of entering the PDCP layer as shown in Figure 3.1. PDCP allocates a sequence number per SDU and compresses its IP header, then these SDUs are ciphered and sent to RLC as the PDCP PDU packets [6, 9].

RLC accepts PDCP PDUs and buffers them until the lower sublayer (MAC) sends a request for transmission PDUs that includes the MAC TB size. If an RLC SDU size is larger than the announced TB size, segmentation will be performed and if it is smaller than TB size, concatenation will be performed. Then RLC PDUS are sent to the MAC sublayer. All the operations in RLC layer are performed regarding RLC mode (AM, UM, and TM). The most of approaches are employed UM RLC for D2D communication, because of its appropriate signaling feature [9].

Thereupon, MAC performs multiplexing on MAC SDUS from different data flows and encapsulates them in the MAC TBs and sends them to the physical layer. During the traveling of data packets through the layers and sublayers, all of the layers and sublayers add their own header to the SDUs [2] (Figure 3.1).

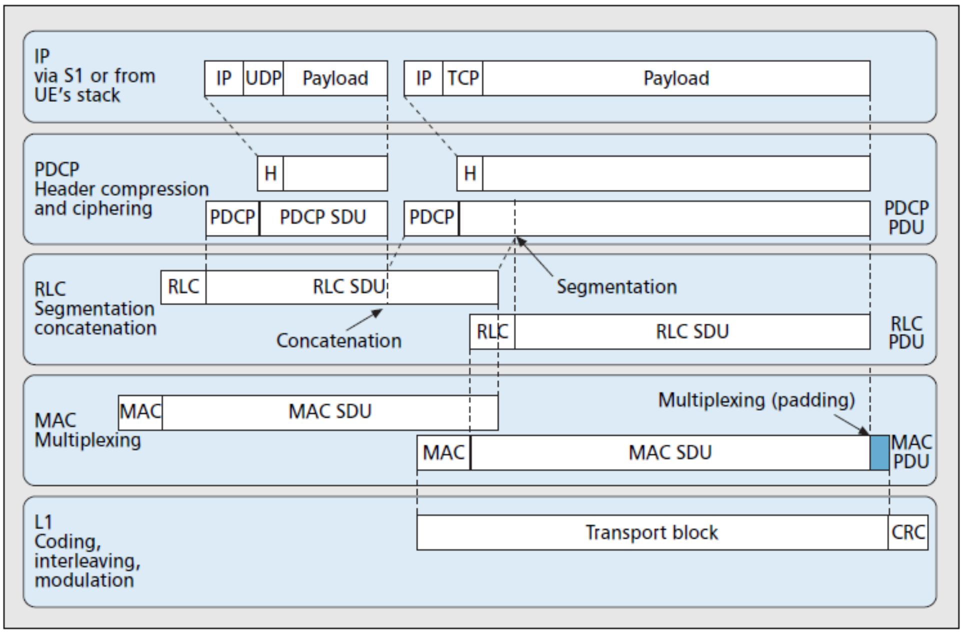


Figure 3.1: Data flow in the stack protocol layers [2]

In the physical layer, the Received TBs are inserted into RBs. These RBs which are arranged with 1ms (1 TTI) interval are sent to the channel. The size of TBs and RBs will vary regarding the channel quality. Therefore, monitoring the air interface is one of the most important tasks of Physical layers in the eNB and UEs in order to measure the channel quality. Since the mobility of UEs and various noise on the air interface lead available bandwidth changes frequently, these measurements are needed periodically. The eNB uses these measurements to decide about the size of RBs and TBs for data transmission. And also, in MS these measurements play a vital role in terms of decision making by the eNB [6]. It is worth to mention the CQI of channel quality is varied by changing distance between UEs.

3.2 Related Work

With the fast development of communication technologies in mobile networks, D2D communication assures a huge commercial interest and research value. Thereby growing effort in the scientific world that try to address running difficulties and problems by creating new methods and finding new research challenges on present technologies. The performance issue of D2D communication underlying LTE-A network has become one of the most attractive research areas in recent years because of its advantages compared to other heterogeneous networks [42]. It is significant to know which data transmission should be switched between D2D and RP modes and when is the best time for a MS.

In [42], the D2D communication performance is compared with other heterogeneous networks such as WiFi direct, Zigbee, Bluetooth, and etc. Also, it demonstrated that D2D technology covers more maximum transmission distance and supports significantly more data rate. The authors concluded that through a suitable MS and interference management, D2D communication can enhance the throughput of network and access rate remarkably without harming QoS by reducing signaling overhead for collecting channel quality state reports.

In [43], researchers investigated Quality of Experience (QoE) of D2D communication utilizing VoIP traffic and considering 5-point MOS parameter. The authors explored the QoE of D2D communication by monitoring MOS and throughput with different number of UEs in the cell coverage area and the various distance between D2D peers. Their simulation results showed how MOS performance improved by MS on D2D communication. Although their study acknowledged the enhanced QoE of D2D communication, it is by no means supported by other performance parameters such as delay time, loss ratio and etc.

Work [9] focused on the data plane in D2D communication and explained when the MS is performed, the receiver's address in the sender PDCP entity is changed. Therefore all the data packets under the PDCP layer at the sender cannot be received by its first-hop receiver. Accordingly, the packets will be dropped and packet loss may occur as a result of MS. The authors proposed an auxiliary map to stay informed about the RLC PDUs and receive their acknowledgment in order to address this problem. The number of MS could be decreased by choosing the best time for MS which lead a better performance with lower packet loss ratio.

In [44], key measurements in QoS in transport protocols, TCP and UDP in LTE-A network are investigated. These measurements were performed by simulating different performance conditions in the LTE protocol stack. Simulation results showed that when UEs took place at the cell edge, the signal power decreased because of distance, and SINR dropped and throughput was reduced and also delay increased remarkably for both TCP and UDP traffics. Moreover, the results showed that although UDP traffic obtained a small amount of throughput more than TCP, faced a significant amount of packet loss. In addition, the authors brought to light that Transport layer is very sensitive to control plane errors, due to increasing PDU loss in case of utilizing RLC AM. All the measurements in this paper are performed only on RP in LTE-A network.

And also, [37] proposed a framework to determine which communication should switch the mode between D2D and RP and when. They also presented how to allocate resources to D2D and RP UEs. Moreover, they stated that MS and packet scheduling should occur at completely independent time scales. They also challenged the same problem as [9] which is packet loss due to MS and illustrated how short period and frequently MS processes increase the packet loss. Their proposed framework managed the coexistence of D2D and RP flows in the UL subframes.

In [45] authors discussed how TCP packets behave during the MS procedure. The results showed TCP is significantly more sensitive to losses when MS is performed. This packet loss is interpreted as the congestion signaling during MS.

Also, [46] proposed a D2D bearer control architecture for D2D communication to handle offloading data traffic on the SL in LTE-A network. However, the proposed architecture just covered control plane scheme without defining data flow in PDCP and RLC layers.

Authors in [47] discussed MS and resource allocation problems for D2D unicast communication and proposed a method that involves estimation of MS metrics. Also, [48] studied the optimal MS in multi eNBs systems. However, both of these works are by no means covered the QoS of communication with MS and the effects of MS on the performance of D2D communication.

Although MS process between D2D and RP modes in LTE-A network has been highly investigated by the research society during the last years, the effects of MS on the communication performance and the QoS of communication with MS are not covered appropriately. Table 3.1 represents the summary of related works.

Table 3.1: Survey of D2D communication studies

Source	Method	Simulator	Parameter	Value(s)	Metrics
[42]	Optimal, Rayleigh, Lognormal, Rayleigh-lognormal	NaN	NaN	NaN	Throughput Access rate
[43]	QoE-driven management techniques, QoE Hand	LTE-Sim	eNB's TX power	43 dBm	MOS Throughput
			Cellular UEs' TX power	23 dBm	
			D2D UEs' TX power	-19 dBm	
			Traffic load per UE	1 VoIP	
			Packet size	20 bytes	
			Channel bandwidth	5 MHz	
			Duplex mode	FDD	
			Path loss model	L = 128.1+37.6 log10d	
[9]	Standard, transmission, IP relaying, RLC tunneling	**OMNET++**	Carrier frequency	2 GHz	Packet loss Throughput
			Bandwidth	5 MHz (25RBs)	
			Path loss model	Urban Macro	
			Macro eNB Tx Power	46 dBm	
			UE Tx Power	26 dBm	
			eNB Antenna gain	18 dB	
			UE Antenna gain	0 dB	
			Noise figure	5 dB	
			Cable loss	2 dB	
			Simulation time	50 s	
[44]	AM RLC, UM RLC	NS-3 (LENA)	Transmission power	46 dBm	Throughput Congestion windows size
			Carrier Frequency for downlink	2.1GHz	
			Carrier Frequency for uplink	1.9GHz	
			Bandwidth	50 RBs (10 MHz)	
			Traffic Pattern	Backlogged	
[45]	TCP traffic peformance D2D-RP	**OMNET++**	Carrier frequency	2 GHz	Packet loss Throughput
			Bandwidth	10 MHz	
			Path loss model	ITU urban macro	
			Fading model	Jakes	
			eNB Tx power	40 dBm	

			UE Tx Power	20 dBm	
			eNB antenna gain	18 dB	
			Noise figure	5 dB	
			Cable loss	2 dB	
			Simulation time	500 s	
[37]	Best Fit PS, Optimal PS	**OMNET++**	Carrier frequency	2 GHz	Packet loss Throughput
			Bandwidth	5 MHz	
			Path loss model	ITU urban macro	
			Fading model	Jakes	
			eNB Tx power	40 dBm	
			eNB antenna gain	18 dB	
			Noise figure	5 dB	
			Cable loss	2 dB	
			Simulation time	30 s	
[46]	D2D Bearer Control Architecture	**NaN**	**NaN**	**NaN**	**NaN**
[47]	Greedy heuristic	**NaN**	Carrier Frequency	2 GHz	Percentage gains
			Max Transmit Power of UE	23 dBm	
			UE Antenna Gain	0 dBi	
			UE Noise Figure	9 dB	
			BS Antenna Gain	14 dBi	
			BS Noise Figure	5 dB	
			Fast Fading Model	Rayleigh Fading Model (3Kmph)	
			Path Loss Model	HataUrban Macro	
[48]	“dual-based algorithm”, “weighted bipartite graph”	**NaN**	Number of eNBs	4	Throughput
			Number of UEs	50	
			Fast Fading Model	Rayleigh Fading Model	
			Path Loss Model	Large scale-fading (exp=4)	

3.3 Contributions

This work is an investigation of the effect of various distances and locations of UEs on the performance of communication over RP and SL connections. The weak performance of the D2D communication in long distances triggers MS procedure. We focused on D2D and RP communication performances to understand the best mode for data transmission and the suitable time for performing the MS process during communication. In order to perform these analyses, four scenarios are simulated. In all the scenarios two UEs are performing sending and receiving which are in the cell coverage area of the same eNB. These UEs are able to communicate through normal RP or SL. The mobility state of the two UEs is static, (i.e. they do not have any mobility during the simulation running). The simulations are performed for each specific distance between two UEs and the eNB. The distance between the UEs is increased by changing the location of UEs after collecting the results of the simulated set. The distance is increased by a 10 m interval. Since the simulations are performed to compare the performance metrics between D2D and RP communications, the maximum distance is selected based on the maximum distance that D2D communication can effort.

This study investigates how different distances and locations of UEs affect communication performance using some important metrics. By studying the performance of RP and D2D modes, the best moment for MS implementation will be recognized according to the channel quality of each mode. The examination method is quantitative, using one-to-one communication between two UEs in a single cell of the LTE-A.

Since testbeds are hardly available (especially to academia), we need to simulate the designed scenarios in simulators. OMNET++ which has become one of the reference frameworks in wireless communication in recent years [36] has been employed as the simulator in this dissertation.

3.4 OMNET++ Design

OMNET++ is an open source discrete event simulator written in C++, using the simulation class library, which can be utilized in diverse problem domains, such as wired and wireless communication in large scales. And also, it includes a large number of simulation models. INET and SimuLTE are employed for D2D communication simulation. These models work based on OMNET++ as Figure 3.2 (conceptualized form). This study employed OMNET++ version 5.1, INET-3.6.4 and SimuLTE branch-MASTER for simulating the proposed scenarios [49].

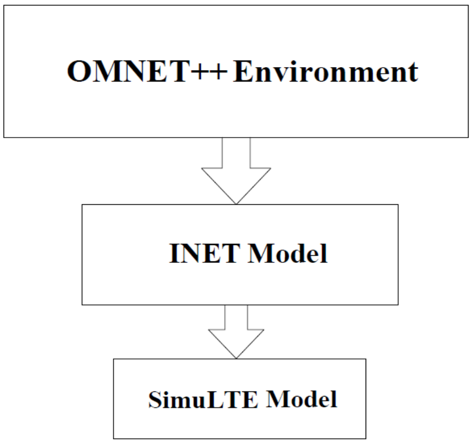


Figure 3.2: INET and SimuLTE work based on OMNET++

The architecture of the simulated networks in OMNET++ is composed of the following elements:

- Simple Module: A single component which allows us to define the algorithm for a specific purpose e.g UDP layer.
- Compound Module: Compound module consists of one or several simple modules which are connected to each other via gates.
- Channel: Nodes communicate with each other by sending messages through a configurable channel. (e.g. configurable propagation delay, bandwidth, etc.)

Figure 3.3 shows the connection of simple modules and compound modules.

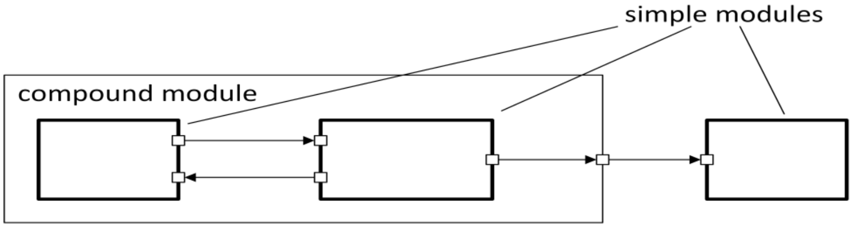


Figure 3.3: Simple and compound modules

In order to configure simple module's properties, and also define the topology model, parameters are used. Topology model parameters define which modules are used in the simulation network and how to connect them to each other. Parameters can accept numeric, string or boolean values. The simple modules used in the simulation consists of algorithms as C++ functions. The flexibility and other advantages of C++ language can be used in OMNET++ models by OMNET++ simulation class library.

The configuration of network topology, algorithms of modules, channel configuration, and parameters are performed in three types of files where users can create a new one or edit the existing one in the OMNET++ folders. These three files are *.ini*, *.cc* and *NED*.

- *NED file:* The structure of the simulated network is defined in the Network Description (NED) file. The user can declare needed modules and specify their connection in the proposed model. NED language has two views: Source and Design views. Figure 3.4 represents the Source view which includes a simplified NED file for one of the UE modules in the performed scenario. The module consists of parameters, gates, and connections. Figure 3.5 displays design view of NED file.

```
// User Equipment Module
module Ue
{
parameters:
@networkNode();
@display("i=device/pocketpc;bgb=400,518");
//# Node specs
string nodeType = "UE";
gates:
mobility: <mobilityType> like IMobility {
@display("p=50,175;is=s");
}
tcpApp[numTcpApps]: <> like ITCPApp {
@display("p=155.556,33.408,row");
}
tcp: TCP if numTcpApps>0 {
@display("p=175,150");
}
udpApp[numUdpApps]: <> like IUDPApp {
@display("p=354.96,33.408,row");
}
udp: UDP if numUdpApps>0 {
@display("p=325,150");
}
lteNic: <nicType> like ILteNic {
nodeType = nodeType;
d2dCapable = d2dCapable;
@display("p=250,407");
}
networkLayer: <networkLayerType> like INetworkLayer {
parameters:
@display("p=250,258");
}
connections allowunconnected:
udp.ipOut --> networkLayer.transportIn++ if numUdpApps>0;
udp.ipIn <-- networkLayer.transportOut++ if numUdpApps>0;
lteNic.radioIn <-- radioIn;
}
```

Figure 3.4: Source view of the NED file of UE module

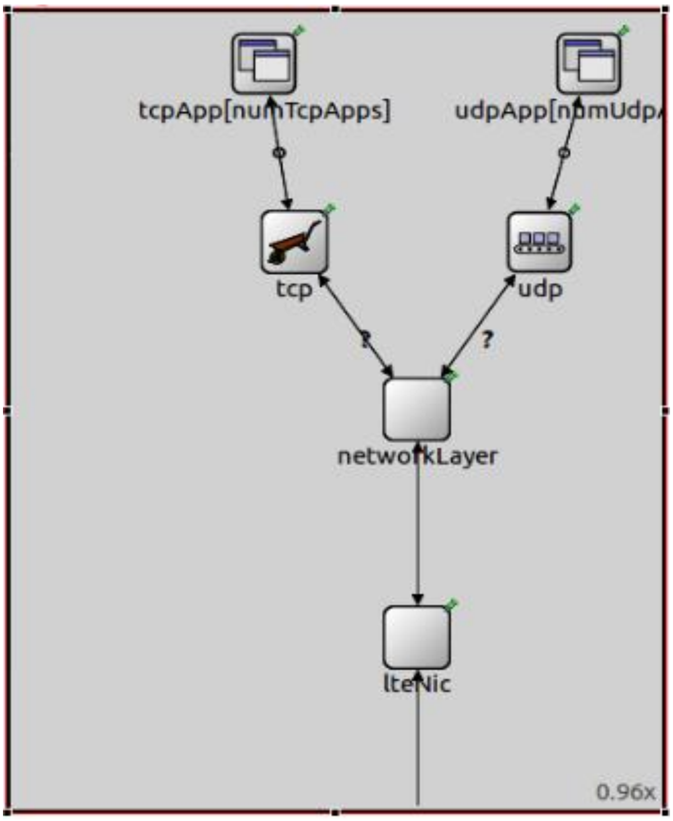
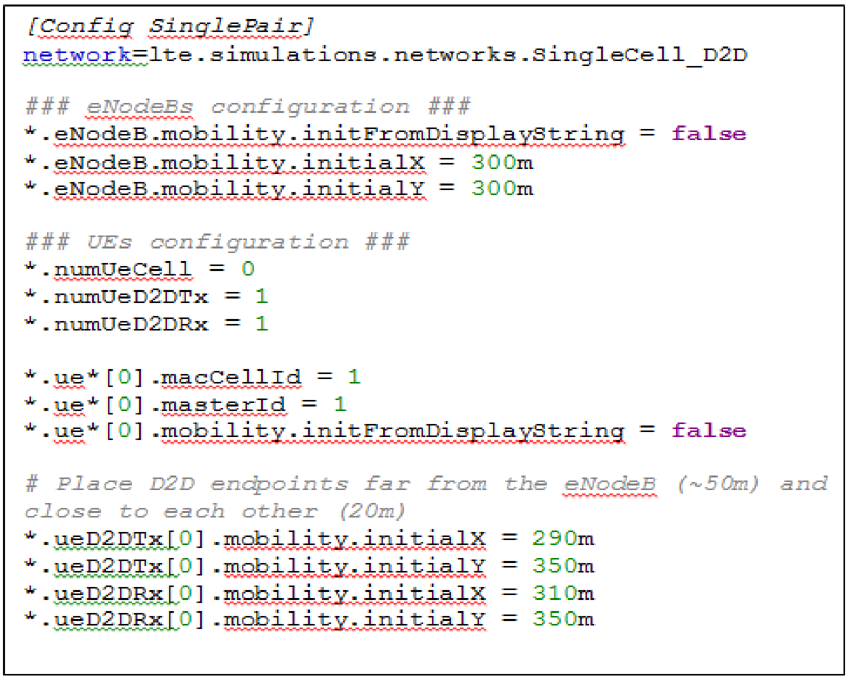


Figure 3.5: Design view of the NED file of UE

- *C++ files (.cc):* The simulation algorithms are implemented by means of C++ functions. These classes are located in .cc files. After creating the NED file, the simulation program needs to contain .cc files in order to execute the proposed network algorithm.
- *ini file(.ini):* It is the assumption that the defined parameters in NED files are fixed. However, some parameters need to be changed regarding different experiments. For example, in the proposed scenarios, UE's location needs to be changed in order to experience different distance with the eNB. Hence, the parameters can be saved individually in the *.ini* file, in order to change their default values. Figure 3.6 represents the relevant parameters to the eNB and UEs in the *omnet.ini* file, such as the number of UEs and eNB, locations, and the mobility state of UEs.



```
[Config SinglePair]
network=lte.simulations.networks.SingleCell_D2D

### eNodeBs configuration ###
*.eNodeB.mobility.initFromDisplayString = false
*.eNodeB.mobility.initialX = 300m
*.eNodeB.mobility.initialY = 300m

### UEs configuration ###
*.numUeCell = 0
*.numUeD2DTx = 1
*.numUeD2DRx = 1

*.ue*[0].macCellId = 1
*.ue*[0].masterId = 1
*.ue*[0].mobility.initFromDisplayString = false

# Place D2D endpoints far from the eNodeB (~50m) and
close to each other (20m)
*.ueD2DTx[0].mobility.initialX = 290m
*.ueD2DTx[0].mobility.initialY = 350m
*.ueD2DRx[0].mobility.initialX = 310m
*.ueD2DRx[0].mobility.initialY = 350m
```

Figure 3.6: Parameters in the *.ini* file

3.4.1 INET

INET framework which is a member of OMNET++ family and is executed under OMNET++ environment, includes a large number of simulation models, such as protocols for internet (UDP, TCP, IPv4, IPv6, etc.) different protocols in MAC and physical layer, mobility supports and a huge number of protocols and models. Several simulations frameworks utilize INET as a basis and develop it towards desired direction [49]. In this work, SimuLTE is employed based on INET-3.6.4 to simulate D2D communication underlying LTE-A network model.

3.4.2 SimuLTE

The data plane of LTE-A network is fully supported by SimuLTE framework. The key element of SimuLTE is its NIC implementation. D2D communication is supported by SimuLTE and consists of several example scenarios in the last version, SimuLTE branch-Master which is utilized in the performed simulations in this dissertation. The performed simulations are based on SingleCell-D2D scenario located in the SimuLTE file.

As discussed earlier, simulation models are built by composing different modules that communicate with other entities by sending messages. Figure 3.7 shows the eNB and the UE structure which consist of LTE NIC compound module and upper layers modules (application, transport, and network layers). The upper layers module are derived from INET libraries. eNBs can be connected to each other through *X2* interface and also, are connected to the Internet via *PPP* module.

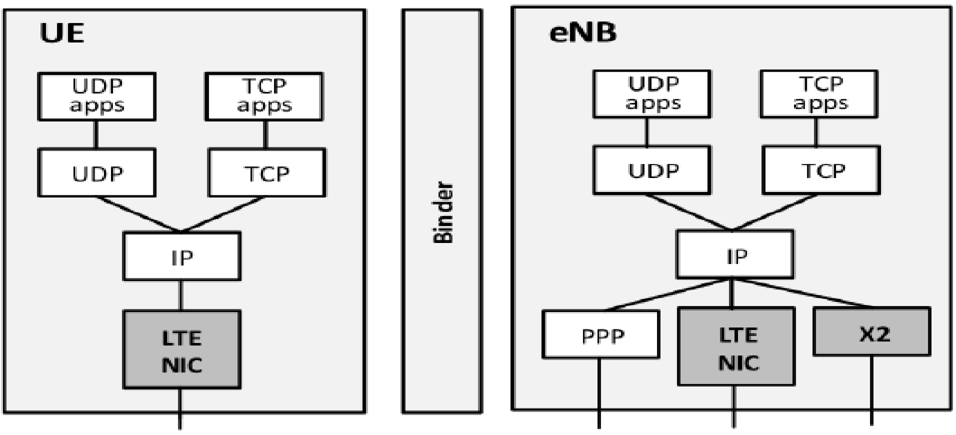


Figure 3.7: SimuLTE architecture

ChannelModel class: The wireless link between LTE NICs in two nodes is simulated by the *ChannelModel* class which supports the physical layer parameters. *ChannelModel* calculates the SINR observed by the UE nodes. In order to calculate SINR, *ChannelModel* gains information about utilized RBs from the binder entity. Moreover, *ChannelModel* is in charge of calculating and reporting the CQI in the UEs. These reported CQIs are used by the eNB for resource allocation and MS implementation [36].

The *ChannelModel* as the interface specifies two important functions, getSINR() which returns the SINR and error() which checks if packets bit include errors. The implementation of the ChannelModel interface in OMNET++ is called *Realistic Channel Model.* The SINR is calculated as:

$$\mathrm{SINR} = \frac{P_{Rx}^{eNB}}{\sum_i P_{Rx}^{i} + N} \tag{3.1}$$

where P_{Rx}^{eNB} is the received power from the eNB, P_{Rx}^{i} is the received interference power from the eNB_i , and N is the Guassian noise. Also, P_{RX} is calculated as:

$$\mathrm{P}_{Rx} = \mathrm{P}_{Tx} - \mathrm{P}_{loss} - F - S \tag{3.2}$$

where, P_{Tx} is the transmission power, P_{loss} is the path loss, F and S are the attenuation by fast and slow fading respictively [10].

The P_{loss} changes regarding the distance and frequency as:

$$P_{loss} = 22.0\ log_{10}\,(d) + 28.0 + 20\ log_{10}\,(fc) \tag{3.3}$$

Where d is distance in meter and fc is the center frequency in Hz where, fc is calculated based on carrier frequency [51].

In the designed scenarios, different distances between the sender and the receiver are adjusted. The difference in the distances lead to different $\mathrm{P}_{loss}, \mathrm{P}_{Rx}$ and SINR which let us to simulate the effect of these parameters on the performance metrics in RP and SL. The channel implementation codes are represented in Appendix B.

D2D communication Configuration: Figure 3.8 shows the entities of D2D communication scenario in a single cell, where *ueD2DTx*[0] and *ueD2DRx*[0] presents the transmitter and the receiver of the data traffic, respectively. The *eNodeB* represents the eNB in the data plane. Since OMNET++ just supports the data plane of LTE-A and does not include EPC entities for performing control plane, it utilized other entities in order to carry on the control plane signaling. *pgw* and *router* carry the responsibility of the S-GW and PDN-GW in LTE-A network and perform routing and IP addressing. *Binder* which is shown in Figure 3.7, is the Oracle module in SimuLTE performs resource allocation and monitors RBs and has the full visibility of all nodes and can be reached by every entity in order to achieve shared information [36]. *ChannelControl* is responsible to establish the communication channel as is configured in *ChannelModel class,* and monitor the channel state during the simulation. *Configurator* and *RoutingRecorder* are two other entities which OMNET++ utilized for signaling in the control plane of LTE-A network. And *SingleCell_D2D* is the name of the simulated scenario in the OMNET++

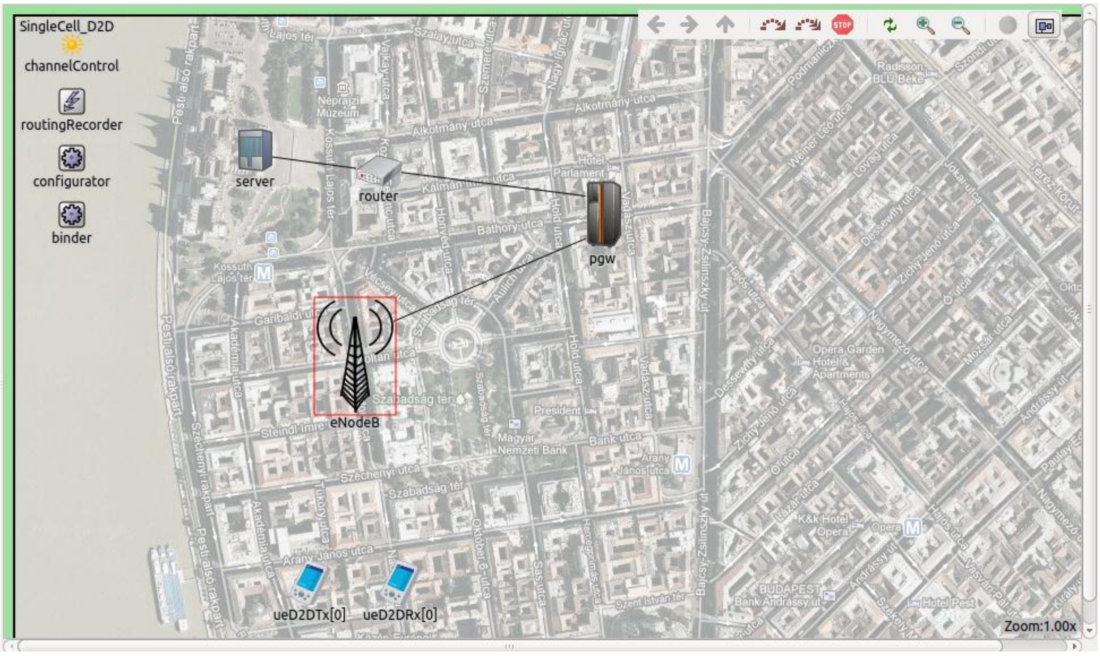


Figure 3.8: Simulation running screen

In order to enable D2D communication for two UEs, several parameters must be modified in the *.ini* file. Figure 3.9 represents these parameters and a brief description of their functions, while Figure 3.10 illustrates the parameters for enabling RP communication.

```
# Enable D2D for the eNodeB and the UEs involved in direct commulteNications
*.eNodeB.d2dCapable = true
*.ueD2D*[*].d2dCapable = true
**.amcMode = "D2D"

# --- Set the D2D peering capabilities ---#
*.ueD2DTx[0].lteNic.d2dPeerAddresses = "ueD2DRx[0]"
*.ueD2DRx[0].lteNic.d2dPeerAddresses = "ueD2DTx[0]"
```

Figure 3.9: The configured parameters for providing the D2D communication

```
# Enable D2D for the eNodeB and the UEs involved in direct commulteNications
*.eNodeB.d2dCapable = false
*.ueD2D*[*].d2dCapable = false
**.amcMode = "AUTO"
```

Figure 3.10: The configured parameters for providing the RP communication

To enable the reporting of CQIs, the parameter *enableD2DCqiReporting* must be modified as illustrated in Figure 3.11. Since in the designed scenarios, the CQI value will change regarding various distances or positions, we need to set CQI parameter to the dynamic mode. In order to disable fixed CQI and utilize dynamic CQI, the parameter *usePreconfiguredTxParams* must be defined as false.

```
# --- Select CQI for D2D transmissions --- #
*.eNodeB.lteNic.phy.enableD2DCqiReporting = true
**. usePreconfiguredTxParams = false
```

Figure 3.11: Enabling dynamic CQI and CQI reporting

3.4.3 Data Collection Methods

OMNET++ has two main ways to collect results:

- Collectors
- Signals

Collector is a classical method of collecting data in C++. The collector needs to be hardcoded in the C++ codes and it is able to define one type of statistics (scalar, vector or histogram).

Signal is a more organized method for collecting the data and results. This method lets us gather data in time by time mode. This means a series of data $S = x_t$ where x_t is the data at time *t* will be produced. The function *emit(S,value)* utilized to collect desired data where *value* presents x_t. *Signals* are defined in corresponding NED file and *emit* function is called in the coresponding .cc file. The signal which is used in terms of throughput collection in the MAC layer is shown in Figure 3.12. This study just utilized *Signals* as the data collection methods and results are shown in Appendix B.

```
@signal[macThroughputVector];
@statistic[macThroughputVector](title="D2DTHrOuPutRX"; unit="";
source="macThroughputVector"; record=mean,vector);

emit(macThroughput , tputSample);
```

Figure 3.12 Definition of the signal of the throughput vector and its collector function

3.5 Performance Metrics

This thesis is interested in the performance evaluation of VoIP data traffic in mobile communication through the traditional RP and SL. During the communication between two UEs, the eNB might switch between these two links. This work analyzed QoS of communication and realized the best state for MS implementation between RP and SL. And also, we attempted to show how VoIP traffic reacts during the simulation by examining the following metrics:

End-to-End Delay: This is the amount of time that a packet spends in its journey from the sender endpoint to the receiver endpoint. In the performed simulation this metric is calculated in the application layer and considered departure time as the time that packet is sent from the application layer at the sender node and arrival time as the arrival time of the packet in the application layer at the receiver node.

$$End-to-End\ Delay=\frac{1}{N}\sum_{k=1}^{N} Arrival\ Time-Departure\ Time \qquad (3.4)$$

where N is the number of packets in a simulation run.

Packet Loss Ratio: Packet loss might happen during the travel of packets between the nodes. This loss ratio can be calculated as:

$$Packet\ Loss\ Ratio=\frac{(Number\ of\ sent\ packets-Numbr\ of\ received\ packets)}{Number\ of\ sent\ packets} \qquad (3.5)$$

Throughput: Mostly, throughput in network communication is calculated at the end of transmission by dividing the total received bytes/bits by simulation time, and calculated as:

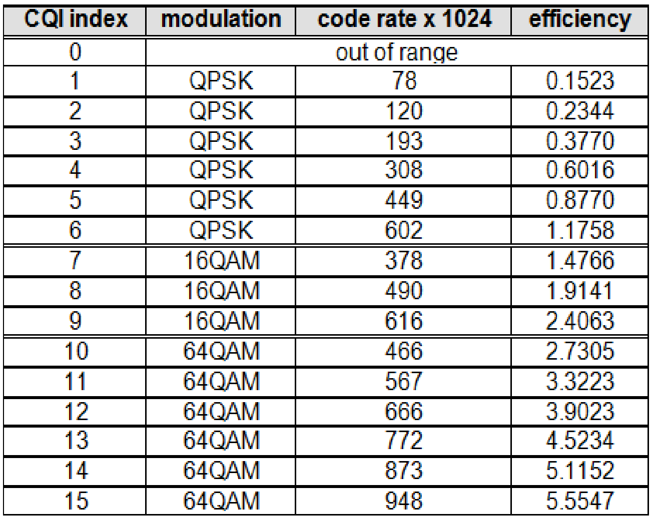
$$Throughput=\frac{Total\ received\ bits}{simulation\ time} \qquad (3.6)$$

Bit Error Rate: Because of movement and variety of the number of UEs in the cell, the signal power in the air interface is changing during the transmission time and it can make some error in the transmitted bits on their path to the receiver. The formula below shows how it is calculated:

$$Bit\ error\ ratio=\frac{Number\ of\ bit\ errors}{Total\ number\ of\ received\ bits} \qquad (3.7)$$

Channel Quality Indicator (CQI): The CQI bears information sent by UEs to the eNB in UL direction to suggest an appropriate transmission data rate for the best possible Modulation and Coding Scheme (MSC) value. CQI is a 4-bit integer number and is based on sensed SINR at the UE. CQI carries a discrete value from 0 to 15. The algorithms of CQI calculation are numerous. UEs perform SINR-CQI mapping to determine what SINR maps to what CQI [50]. Table 3.2 which is drawn from 3GPP TS 36.213 [51] presents the appropriate code rate and modulation scheme (QPSK, 16QAM, or 64 QAM) for each CQI. The code rate means the number of real data bits that can be present out of every 1024 sent bits, for instant, when CQI reports 10, only 466 data bits would be received out of 1024 sent bits. Also, the efficiency column represents the related efficiency of CQI's values (high CQI value = good efficiency).

Table 3.2 CQI Modulation Scheme Table [51]



CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Mean Opinion Service (MOS): In cellular communication, MOS is a ranking of the QoS for VoIP and Video streams. Basically, MOS is obtained from experts assessment and observation that is affected by packet loss ratio and packet size and it is calculated as [52]:

$$MOS = \ln(packet\ loss\ ratio) - 0.1\ln(packet\ size) \tag{3.8}$$

The values of MOS mean as follow:

5 - Perfect

4 – Good

3 – Fair

2 – Weak

1 - Bad

3.6 Simulation Parameters

All the designed scenarios in this study are set up and simulated with the mentioned parameters in Table 3.3 without any changes during the simulation. These settings are selected based on the related works results in Table 3.1.

Table 3.3 General Parameters of Simulation

LTE-A Network Parameter	Assigned Value
Carrier Frequency	2 GHz
Channel Bandwidth	5 MHz (25 RBs)
Path Loss Model	ITU-R, Urban Macro [51]
eNB Tx Power	46 dBm
UE Tx Power	24 dBm
Cable Loss	2 dB
Fading Model	JAKES
eNB Antenna Gain	18 dB
UE Antenna Gain	0 dB
UE Noise Figure	7 dB
eNB Noise Figure	5 dB
Thermal Noise	-104.5 dBm

Mobility Model	Stationary (OMNET++ Model)
Simulation Time	50 seconds(s)

In addition, UM RLC is employed and the RLC PDU (TB) size is set to 40 Bytes(B) by default, however, it can vary dynamically according to TB size depending on the channel quality. This is observed in the simulation by changing the distance. The generated traffic type is VoIP and is sent by 172 bytes application packets with 20 miliseconds(ms) interval, then after passing through the transport and network layers the size becomes 200B (8B UDP header + 20B IP header). The simulations are performed on a system with an Intel(R) Core(TM) i5 at 2.30 GHz, and 8GB RAM with a Linux Ubuntu 16.04 LTS operating system using OMNET++ version 5.1.

3.7 Simulation Scenarios

3.7.1 Scenario 1: Changing the distance between UEs in the horizontal direction

This scenario consists of 2 different simulations. In the first one, UEs are communicating through RP. In the second one, they are communicating through a direct link (SL). Initially, two UEs are located with 0 m distance from each other and 0 m distance from the eNB (in both modes). Then the distance between UEs is increased by 10 m, which means that each UE is located 5m far away from the eNB (in horizontal direction) and 10 m from each other. Accordingly, by increasing the distance with 10 m steps, the distance between two UEs is reached up to 120 m. In the case of RP, the measurements are done up to 200 m. Since D2D communication is not feasible in long distances (more than 120 m), the simulation is done up to 120 m, in the case of D2D communication. Figure 3.13 presents the network configuration for this scenario.

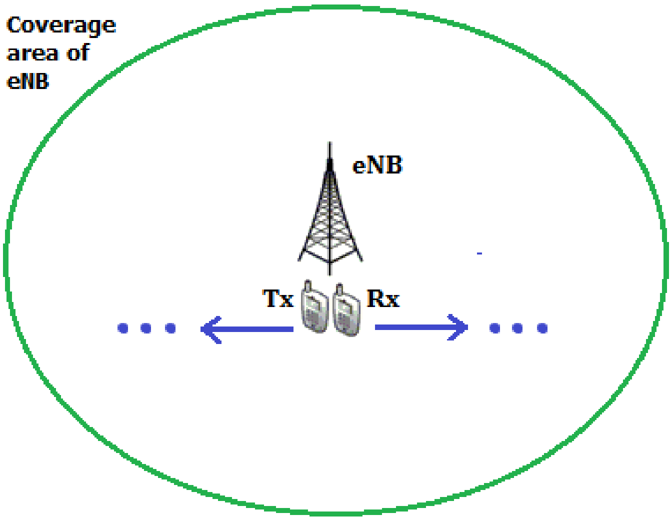


Figure 3.13: Initial state of scenario 1 network configuration

3.7.2 Scenario 2: Changing the distance between eNB and UEs in the vertical direction

In this scenario, two UEs are located at a constant distance to each other (20 m) and their distances from the eNB is increased in each step by 10 m interval with starting 0 m distance. This scenario is simulated when two mobile devices are close to each other and moving farther away from the eNB. Similar to Scenario1, both RP and D2D modes are simulated individually in all distances. Moreover, for both modes simulations are performed up to 200 m. Figure 3.14 shows the initial state and movement direction of two UEs.

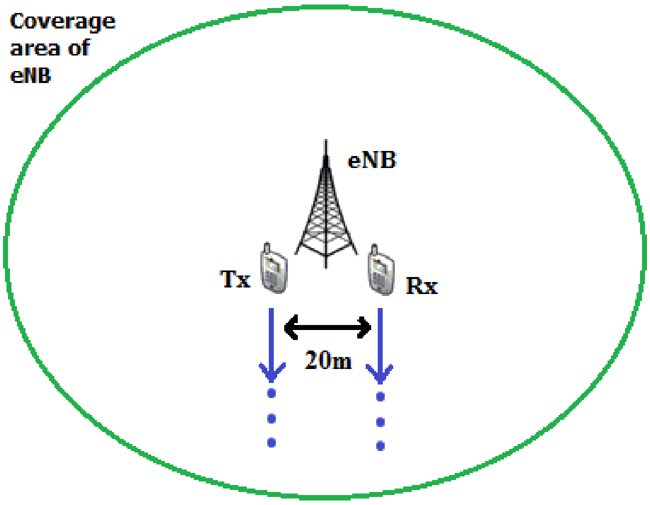


Figure 3.14: Initial state of Scenario 2 network configuration

3.7.3 Scenario 3: Changing distance between UEs in the horizontal direction with 50 m and 150 m initial distance from the eNB

This scenario is only performed in D2D mode in order to cover various conditions of D2D communication. In the first configuration, the initial distance of two UEs from the eNB is set to 50 m, and in the second one, the initial distance of UEs is set to 150 m far away from the eNB. Also, the initial distance between two UEs is set to 0 m in both D2D configurations. In each step of the simulation, the distance between the two UEs increased by 10m. Figure 3.15 describes the locations of the nodes in Scenario 3.

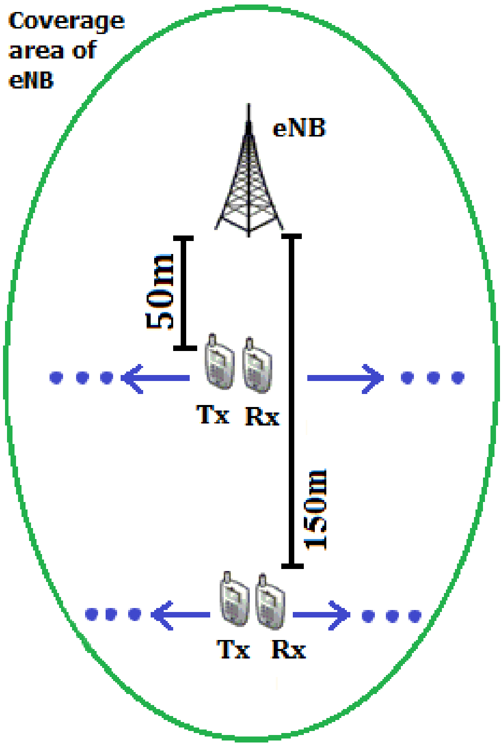


Figure 3.15: Initial state of Scenario 3 network configuration

3.7.4 Scenario 4: MS employment

The locations of the UEs are the same as Scenario 1 as shown in Figure 3.13. The D2D mode is used when UEs are close to each other as the initial communication mode. The transmitter node sends its VoIP traffic via SL from 0 m up to 50 m. And then, after 50 m MS is employed and RP is used as the communication between two UEs.

This scenario keep the performance of the communication at an appropriate level successfully, by employing MS. Advantages of D2D mode in short distances and the advantages of RP in long distances let Scenario 4 to employ better performance with MS.

Chapter 4

RESULTS AND DISCUSSIONS

This chapter describes the results of the given scenarios in Chapter 3 and compares the simulation results of RP, D2D communications and MS in LTE-A network. It is worth to mention that scenarios 1, 2, and 3 which consist of two modes of communication, are compared in the different distances and the behavior of the results are demonstrated in the figures.

As the performance metrics CQI, end-to-end delay, throughput, MOS, packet loss ratio and bit error rate are employed to support the analysis of the QoS performance of the simulated scenarios. Scenario 1, 2 and 3 present RP and SL communication results by changing distance between two UEs and between UEs and the eNB. The investigations of the first three scenarios are used to construct Scenario 4 which employed both SL and RP communications. In order to obtain reliable results, each step is simulated 5 times independently, and the average of the results are computed.

The obtained numeric results for each run of simulations are tabulated in the prepared tables in Appendix D, and the average results of relative runs for each scenario are tabulated in the tables of Appendix C.

4.1 Results and Analysis of Scenario 1

Scenario 1 attempted to accomplish various conditions for both RP and SL locating two UEs in different distances from the eNB and from each other. As a result of each movement horizontally, the distances of UEs from the eNB is half of the D2D distance. For example, when the D2D distance is 20 m, it means horizontally the distances of UEs from the eNB is 10 m. Initial locations and movement directions of UEs are as illustrated in Figure 3.13.

CQI Results: When UEs move further away from the eNB, the received power changes regarding the equation (3.2), which leads to change of SINR. Accordingly, CQI changes also [1, Tables 7.2.3-1, 7.2.3-2].

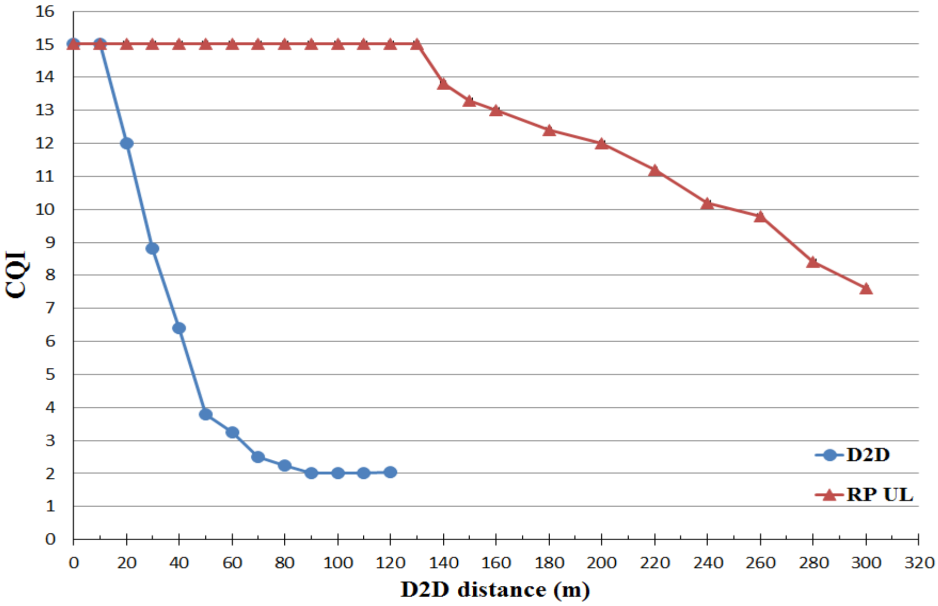


Figure 4.1: CQI for D2D and RP communication modes

As shown in Figure 4.1, while the distance is increased the CQI decrease. The CQI of RP stabilizes up to 130 m and then descends lightly. On the other hand, the D2D CQI has a speed descend after 10 m and it lies down on value 2 after 80 m that is not a good feasibility level of D2D communication (Only 78 bits are received out of every 1024 sent bits, see Table 3.2). The observations illustrate the RP is performing better at long distances. Figure 4.2 illustrates the behavior of D2D CQI results is similar to the results in [53].

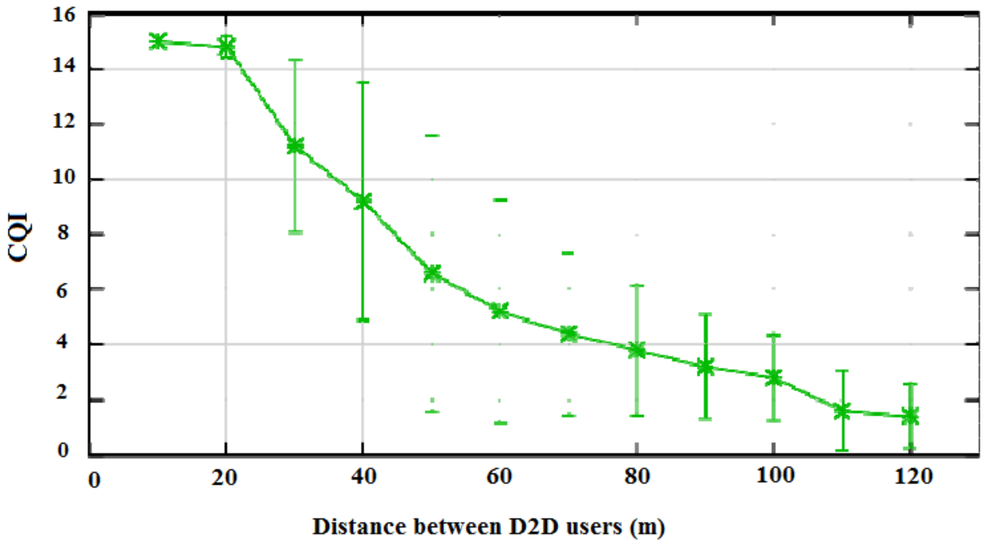


Figure 4.2: CQI results for D2D communication in [53]

End-to-End Delay Results: As shown in Figure 4.3, at low distances end-to-end delay related to RP is remarkably higher than D2D, which confirms lower delay advantages of the D2D communication (up to 100 m). Since in D2D communication, packets are sent directly to the destination, they need less time to arrive. On the other hand, in RP mode, packets are sent to the eNB and after assembling packets in the eNB's NIC layers as is described in [9], need to be sent to the receiver node, which causes longer distance and longer time for the packets to be received by the receiver.

The number of assigned bits to RBs are defined according to the channel quality state. Hence, when UEs are located in further distances which are faced with lower SINR, the RBs' capacities decrease. Accordingly, packets need to be sent in more number of RBs, which needs more time to carry all the data traffic. This is the reason for increasing the end-to-end delay of D2D mode by increasing distance, while RP end-to-end delay is remained stable up to 300 m. It is clear that the end-to-end delay in D2D communication is significantly lower than RP for short distances (the distances less than 100 m) as depicted in Figure 4.3.

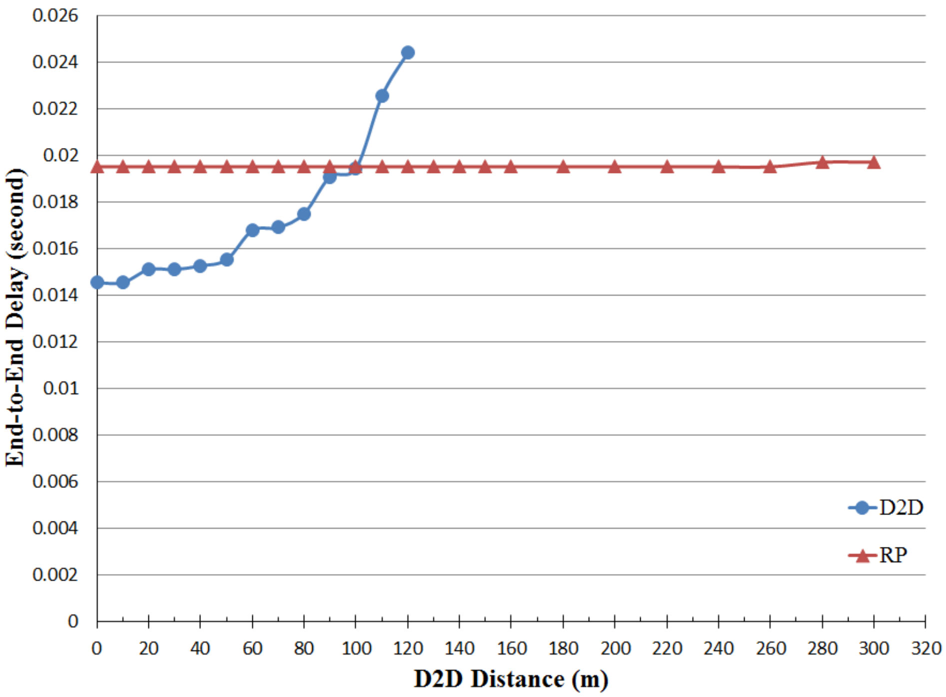


Figure 4.3: End-to-End delay in D2D and RP communication modes

Since D2D communication is not possible over long distances, we considered 120 m as the maximum simulated distance for D2D mode.

Throughput Results: One of the most important metrics of QoS parameters is throughput which presents the amount of successfully transmitted data from the sender to the receiver in a slot of given time. As shown in Figure 4.4, D2D throughput starts with higher performance when comparing with the RP throughput at low distances. Although it descends with a fast slope, it is still higher than RP throughput up to 30 m. Afterward, it continues descending almost with the same gradient up to 50 m. But from 50 m to 60 m it loses approximately 30% of its performance and performs 21744 bps at 60 m. On the other hand, RP throughput performs less than D2D until 30 m but remains same up to 220 m.

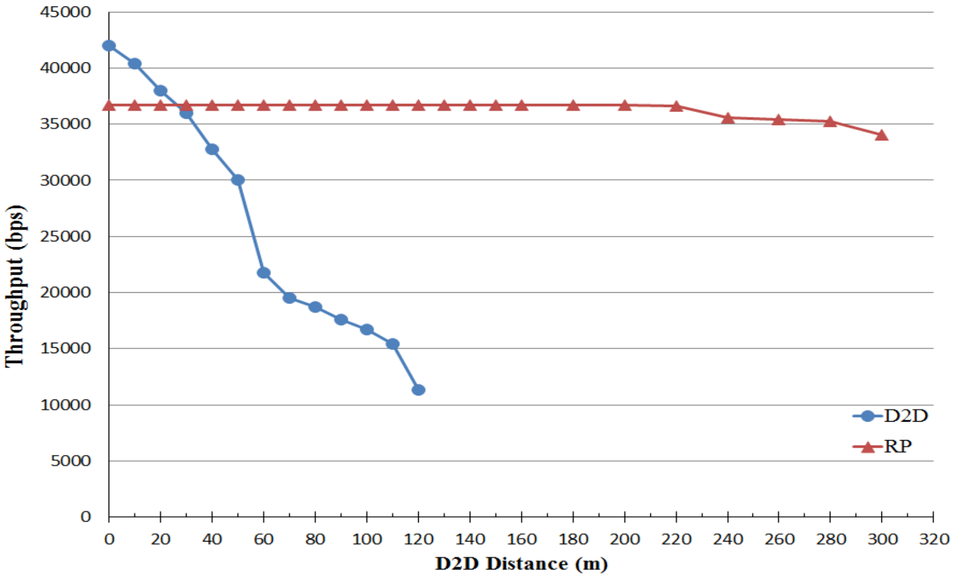


Figure 4.4: Throughput in D2D and RP communication modes

Throughput is behaving the same for RP and D2D as throughput results in [54] as represented in Figure 4.5.

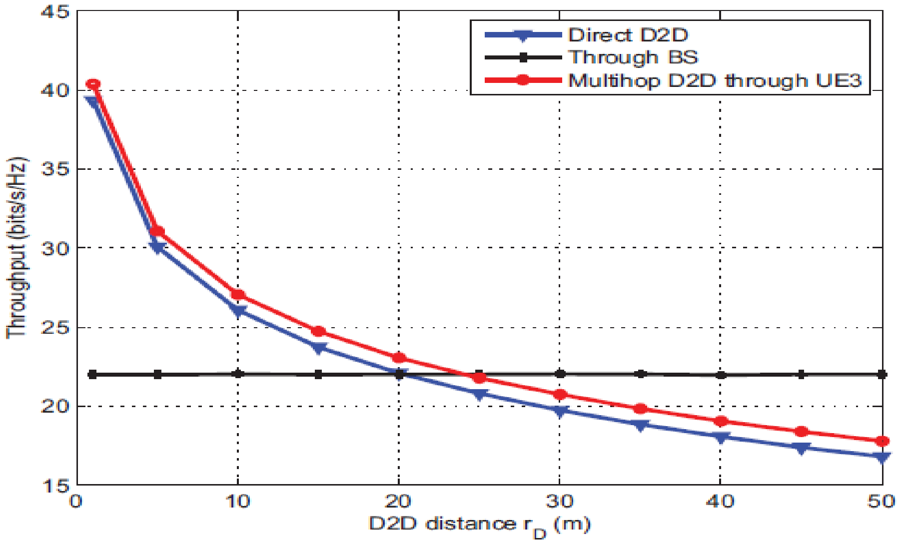


Figure 4.5: Throughput results in D2D and RP communication of [54]

MOS Results: Figure 4.6 demonstrates that the highest value of MOS in D2D communications is 4.41. As shown in the figure, D2D MOS remains at the highest level and declines with a deep slope after 50 m. On the other hand, the MOS of RP performs well without any change for a long distance up to the maximum simulated distance which is 300 m. D2D communication delivered high quality similar to RP in the short distances up to 50 m. And also, the behavior of our D2D MOS simulation results are similar to the results in [43], as represented in Figure 4.7 (the drastic descent after 50 m).

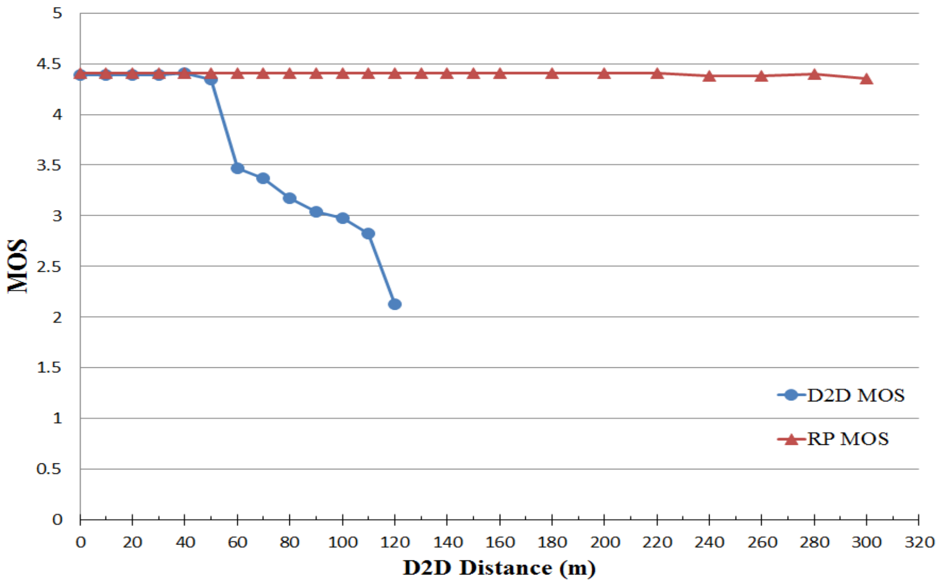


Figure 4.6: MOS performance in D2D and RP communication modes

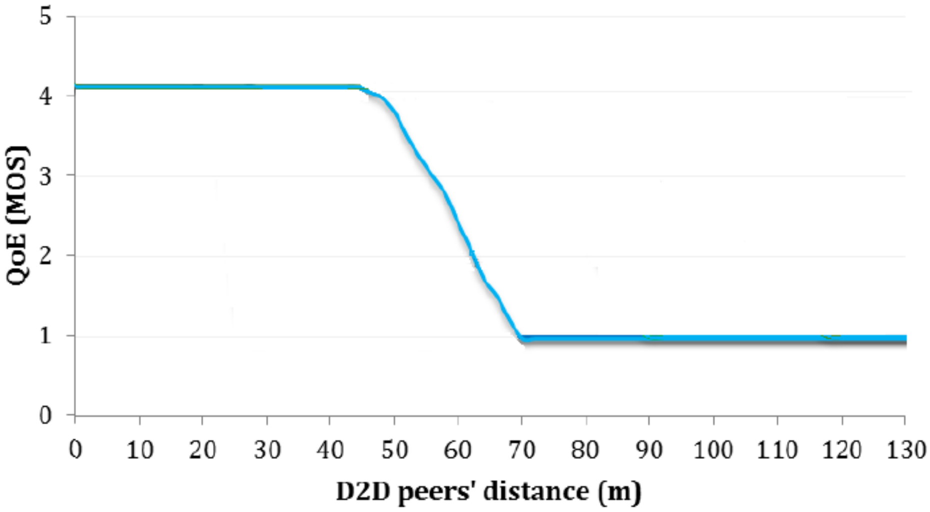


Figure 4.7: MOS Performance results of D2D communication in [43]

Packet Loss Ratio Results: As illustrated in Figure 4.8, the packet loss ratio stabilizes around zero up to 50 m, which is the same as the RP packet loss ratio. Then it jumps to 0.2 loss ratio at 60 m which is a high ratio for packet loss, even for loss-tolerant services like VoIP [52]. This jump takes place after 50 m, this behavior of packet loss ratio is the same as the behavior of throughput as shown in Figure 4.3 and MOS behavior as shown in Figure 4.4. Packet loss ratio remains constant at 0.2 from 60 m to 100 m then suddenly jumps up to 0.4 at 120 m.

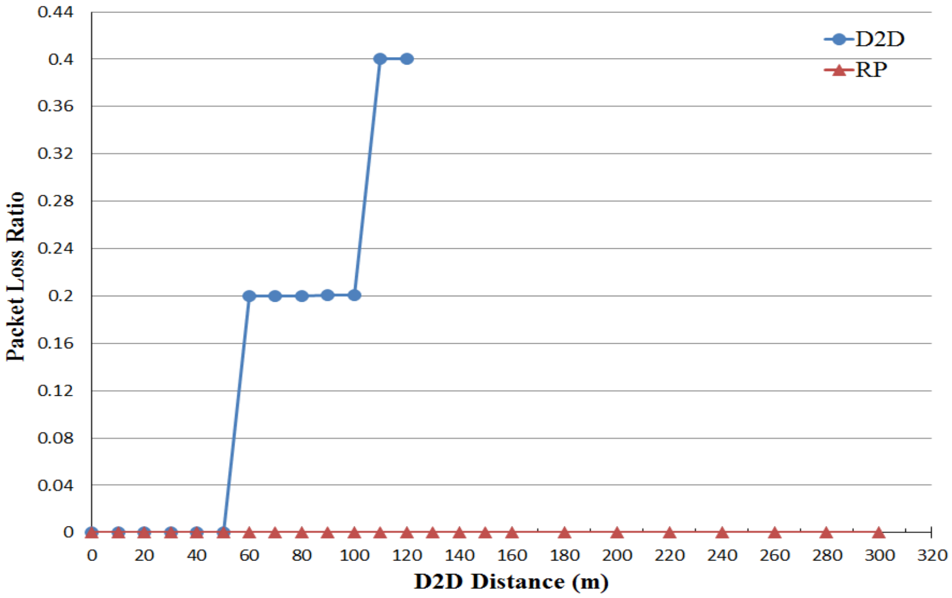


Figure 4.8: Packet Loss Ratio in D2D and RP communication modes

Bit Error Rate Results: The rate of error bit is calculated by equation (3.7) and as represented in Figure 4.9, after 50 m the bit error rate dramatically increases to 0.2 which advocates the trends in the other investigated metrics in this scenario. Differently, the bit error rate in the RP remains zero until the distance between two UEs arrives 220 m, and then extremely slightly increases.

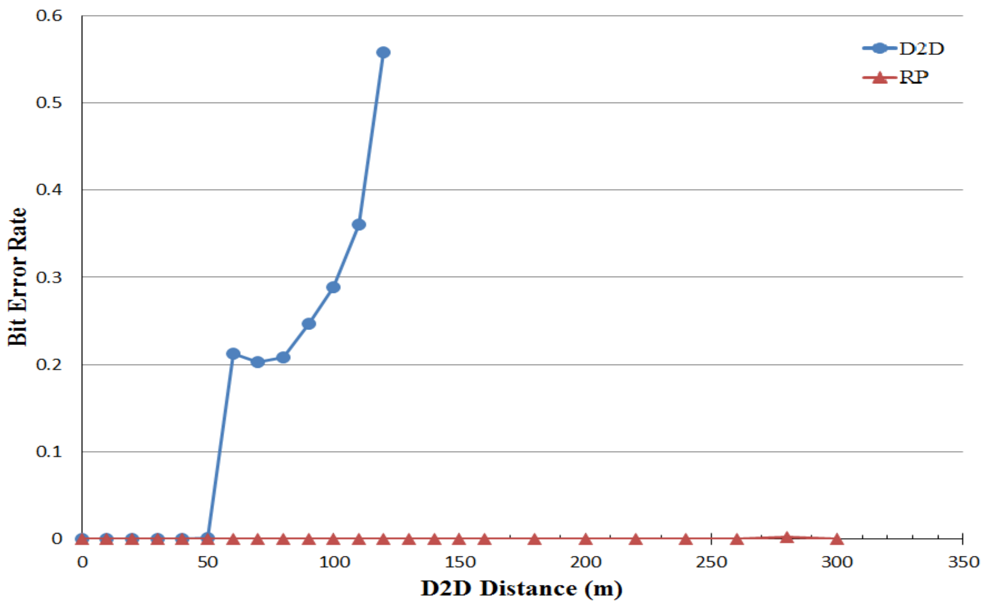


Figure 4.9: Bit Error Rate in D2D and RP communication modes

4.2 Results and Analysis of Scenario 2

In order to cover different possibilities of UEs' distribution in the eNB's cell coverage area, Scenario 2 is employed. Figure 3.14 described the initial location and configuration of the scenario. Indeed, this scenario is designed to examine the behavior of D2D communication performance metrics when the UEs are close to each other (electromagnetically) but moving farther away from the eNB.

CQI Results: As demonstrated in Figure 4.10, D2D CQI remains on level 15 which is interpreted as perfect channel quality. Since the UEs stays close to each other the power of the signal is kept in a suitable amount with low path attenuation. However, the RP CQI starts falling after 50 m and keeps its descend to touch level 2 at 200 m. These examinations provide pieces of proves that D2D communication has higher performance than RP when UEs are close to each other and go farther away from the eNB.

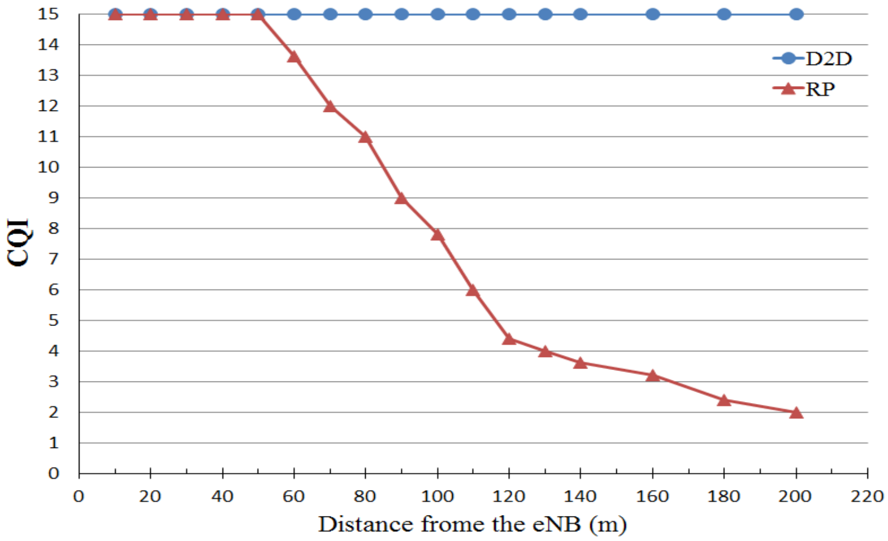


Figure 4.10: CQI in D2D and RP communication modes

End-to-End Delay Results: The results in Figure 4.11 indicate how the end-to-end delay in the D2D communication is performed better than RP communication. It is recognizable that, data packets need a shorter time to be delivered in D2D than RP mode with all distances. In addition, RP end-to-end delay starts a gradient increase after 110 m, which demonstrates the QoS for VoIP traffic through D2D is a better choice in such cases.

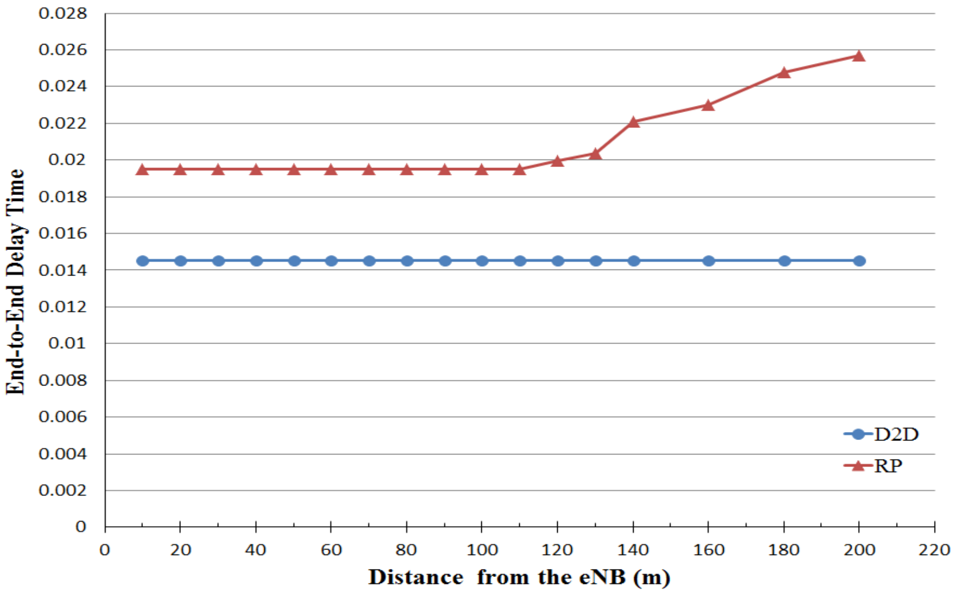


Figure 4.11: End-to-end delay in D2D and RP communication modes

Throughput Results: As represented in Figure 4.12, D2D throughput gains more amount than RP throughput and remains in the high value in all distances. On the other hand, RP throughput stays at a high level up to 110 m and then starts to move downward with a steep slope. The throughput results show how D2D communication mode performs better than RP in all the distances.

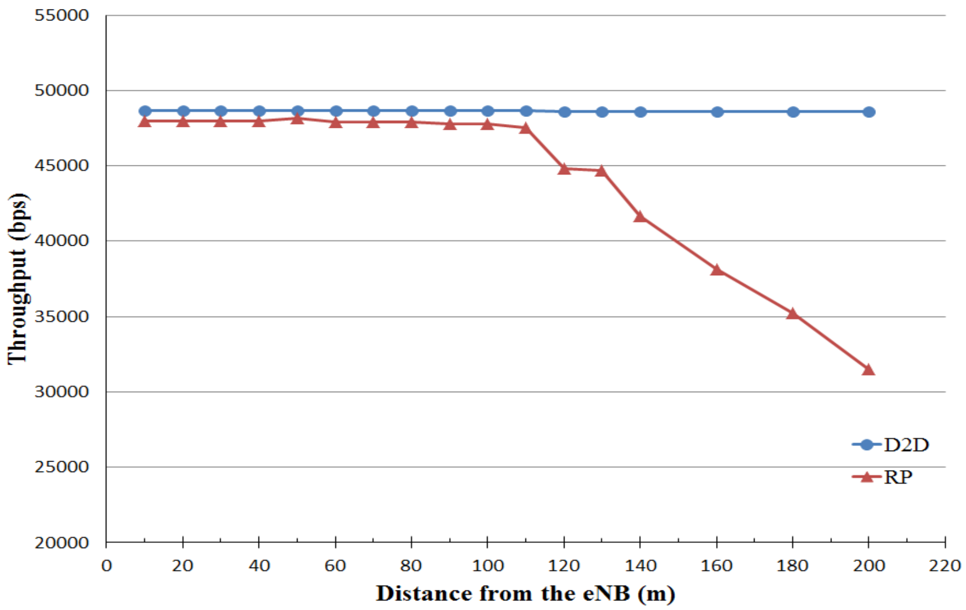


Figure 4.12: Throughput in D2D and RP communication modes

MOS Results: Also, MOS results of both communication models behave in the same way as other examined metrics in this scenario, as it is demonstrated in Figure 4.13. The obtained results approve when UEs are close to each other, D2D communication has better performance than RP in all distances from the eNB.

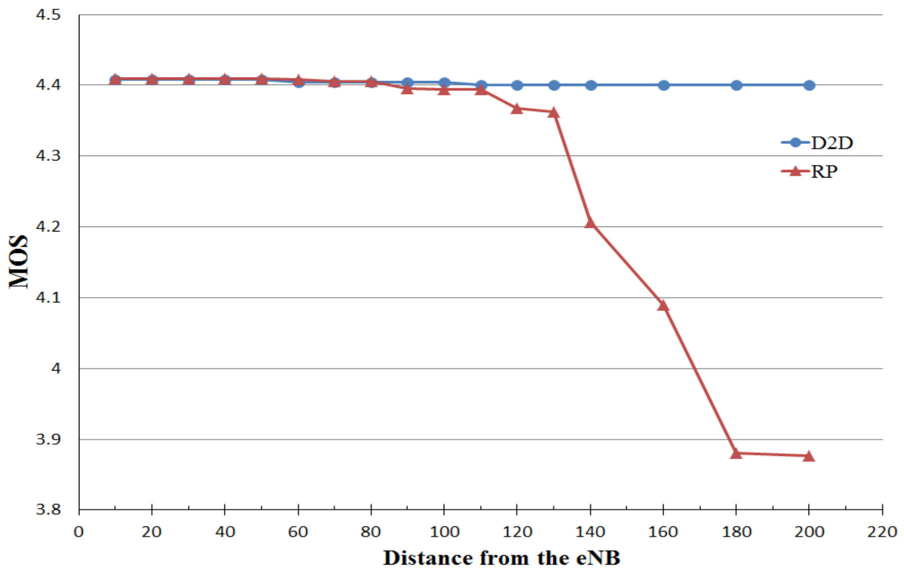


Figure 4.13: MOS in D2D and RP communication modes

Packet Loss Ratio Results: Packet loss ratio which is one of the most important QoS metrics in VoIP performance is shown in Figure 4.14. The D2D packet loss ratio remains at a lower level than the RP packet loss ratio starting from the short distances. RP packet loss ratio increases sharply after 140 m. Also, the monitored packet loss ratio ratifies the D2D communication efficiency in terms of its enhanced advantages in this scenario cases.

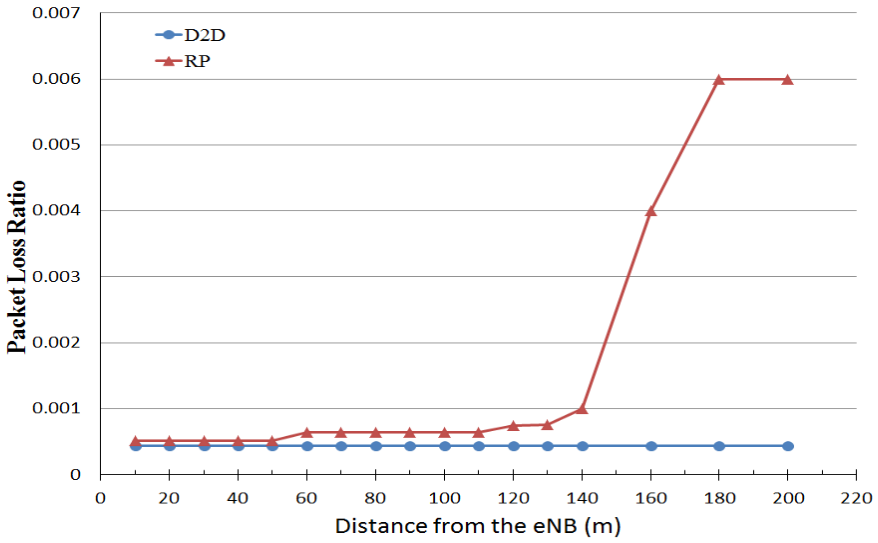


Figure 4.14: Packet Loss Ratio in D2D and RP communication modes

Bit Error Rate Results: As it is expected, in the RP mode, the bit error rate which has a direct effect on the packet loss ratio, starts to climb after 130 m similar to the packet loss ratio. On the other hand, the bit error rate of D2D mode remains at the best level in all distances.

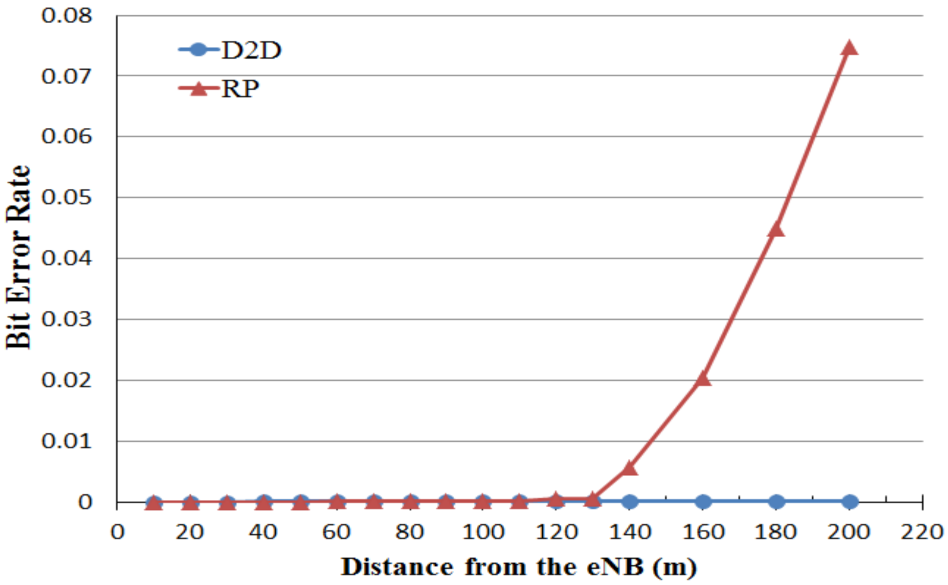


Figure 4.15: Bit Error Rate in D2D and RP communication modes

From simulation results, it is observed that when two mobile devices are close to each other but far away from the eNB, D2D communication is the best choice for communication. The UEs have a good D2D communication performance in around edge of cell coverage area while path loss of long distance from the eNB harms RP communication quality. And also, as results of Scenario 1 and 2, RP communication performance remains at a high level without any significant change when UEs have maximum 110 m distance from the eNB. Since RBs content size is defined regarding the channel quality and RP quality does not have significant change, it can be concluded that UL RBs have the same content size up to 110 m distance.

4.3 Results and Analysis of Scenario 3

The purpose of this scenario is to examine different possible conditions in D2D communication. Hence, only D2D communication performance is investigated in this section. In this scenario, three D2D network configurations are considered. In the first D2D configuration two UEs are located as same as UEs' location in Scenario 1, while in the second D2D configuration, two UEs are settled 50 m far away from the eNB. In the third configuration, UEs' initial positions are located 150 m far away from the eNB. The directions (in the horizontal) and the distance interval of the movements of the UEs in different D2D configurations are the same. Also, the initial distance between UEs is set to 0 m for all configurations. The distances between UEs in all steps is increased by 10 m interval in the horizontal direction as described in Figure 3.15. Which means when the distance between the UEs increases, the distance from the eNB changes, accordingly. Related results of all configurations are tabulated in Appendix C.

CQI Results: The graph in Figure 4.16 shows when UEs are located further away from the eNB and are close to each other, the CQI of communication decreases slightly. In the third D2D configuration when UEs are 150 m far away from the eNB, the CQI results have a deep dive from 13 to 9 level from 10 m to 20 m distance, while the other D2D configurations start their fast decrease at 30 m. However, when the distance between UEs became more than 30 m the CQI results of all three communications behave almost the same and their values are close to each other. Overall, the performance of CQI of the UEs which have 0 m initial distance from the eNB is slightly better than other D2D configurations which are located further away from the eNB, especially in the short distances.

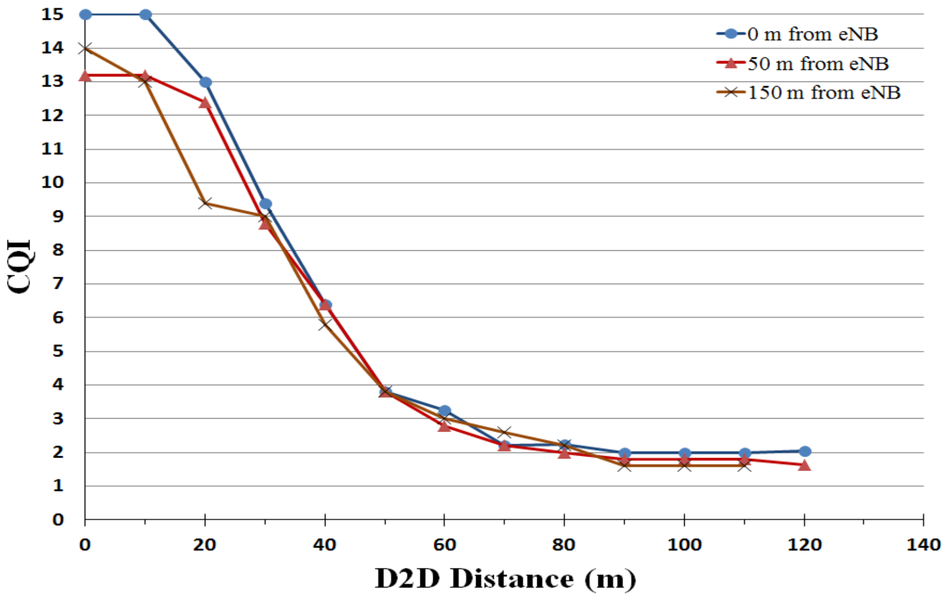


Figure 4.16: CQI of the D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

End-to-End Delay Results: In this section, we are interested in analyzing the end-to-end delay in three D2D configurations. As Figure 4.17 represents, the VoIP packets need almost the same time to arrive at the destination in all D2D configurations.

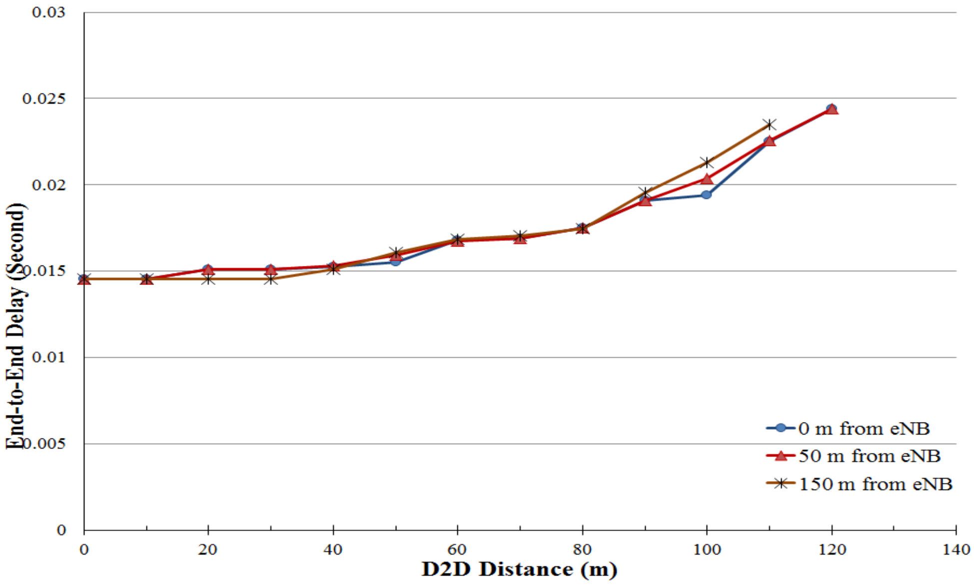


Figure 4.17: End-to-End Delay of D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

Throughput Results: D2D communication reuses UL RBs and UL RBs have the same quality up to 110 m (as observed in the previous scenarios). Hence, D2D configurations with distances less than 110 m, must have almost the same performance. Throughput results in Figure 4.18 show D2D configurations with 0 m and 50 m distances have the same behavior, while D2D communication with 150 m distance from the eNB performs a lower level of throughput in all distances.

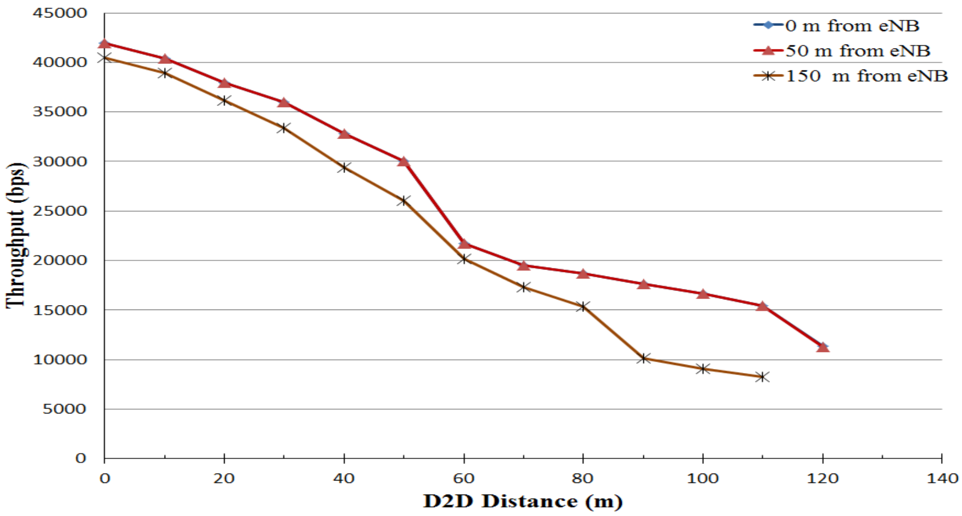


Figure 4.18: Throughput of D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

MOS Results: As shown in Figure 4.19, MOS results for D2D configuration with 150 m distance have almost the same value as the other two D2D configurations. However, after 80 m MOS demonstrates a lower performance than other D2D configurations.

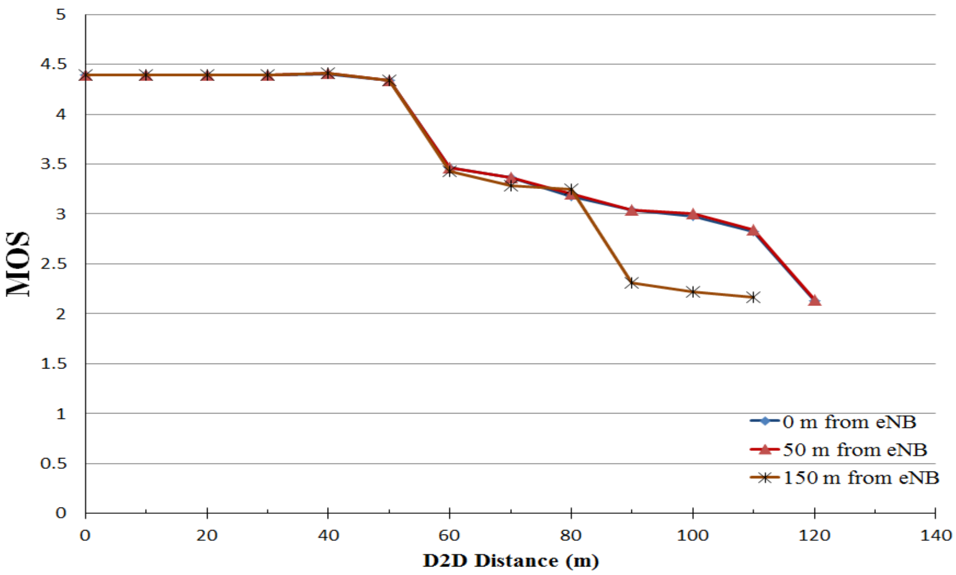


Figure 4.19: MOS of D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

Packet Loss Ratio Results: Packet loss ratio results of all D2D configurations are shown in Figure 4.20. D2D communication with 150 m distance from the eNB behaves similar to other D2D communication up to 80 m. And then, it touches 0.4 packet loss ratio at 90 m, which is 20 m earlier than packet loss ratio in 0 m and 50 m D2D configurations.

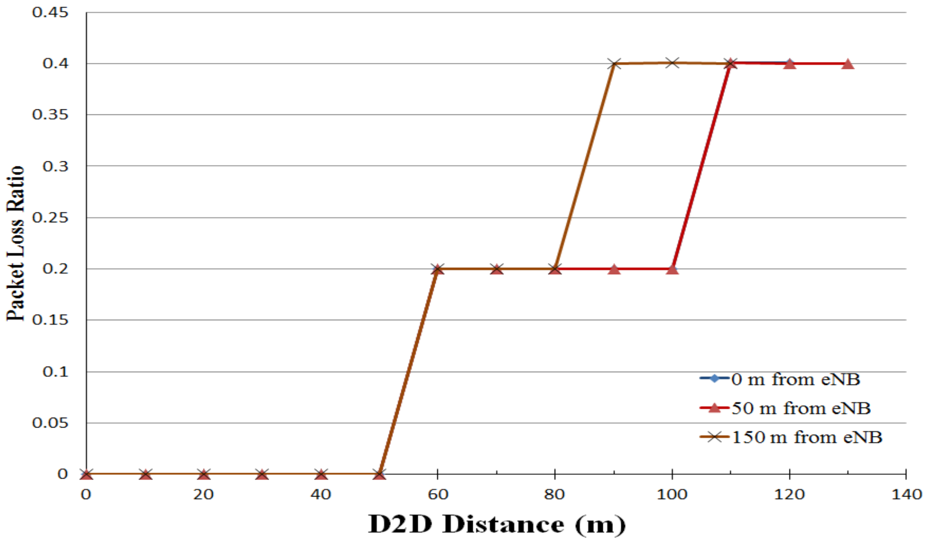


Figure 4.20: Packet Loss Ratio of D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

Bit Error Rate Results: All the bit error rate results have the same trends up to 80 m. But bit error rate result of 150 m D2D configuration trends similar to its packet loss ratio and after 80 m it increases more than 0.4 rates, while in the other two D2D configurations increase with the lower rate and behave similar to each other, as shown in Figure 4.21.

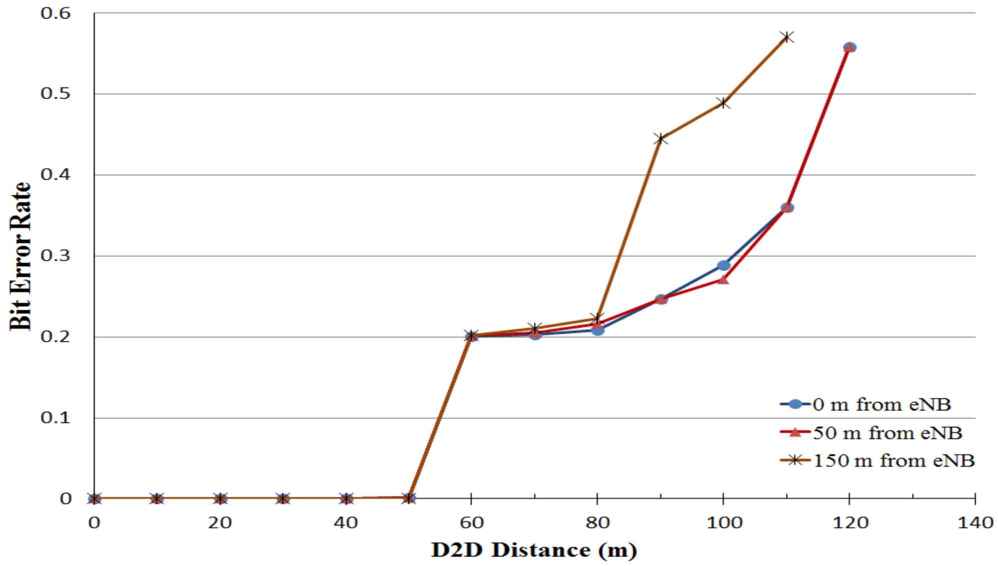


Figure 4.21: Bit Error Rate of D2D communication mode with different distances from the eNB (0 m, 50 m, 150 m)

As shown from the figures of this section, the presented results of the D2D configurations are nearly close to each other and have similar trends in short distances. And generally, 150 m D2D configuration performance decreases, especially after 80 m. This performance reduction is due to the reduction of RBs' content size after 110 m distance from the eNB. The average results for all D2D configurations are tabulated in Appendix C.

On the basis of the observed results of this scenario and also based on the results of Scenarios 1 and 2, the LTE-A network RP performance retains at a high level up to 110 m away from the eNB (220 m D2D distance). It can be concluded that, since the radio resources have almost the same quality, accordingly the D2D communication with less than 110 m distances performs a high QoS.

4.4 Results and Analysis of Scenario 4

The previous three scenarios investigated the performance metrics of VoIP traffic, by adjusting the UEs in the various locations by changing the distance between them and the distance between the UEs and the eNB. Based on equation (3.1, 3.2 and 3.3) these various distances bring various SINR and path loss in a specific order, that affect the measured results. The observed results led us to choose 50 m as the distance threshold between two UEs, in terms of the best distance for performing MS. This threshold is selected based on the simulated network scenarios with the specific parameters as shown in Table 3.3, while different parameters settings can trigger different distance threshold value.

Scenario 4 is designed in a way that both D2D and RP communication modes are performed, respectively. In this scenario, in the first 50 m data packets are sent through SL and afterward, packets are sent over RP (i.e. from 60 m up to 160 m). Two UEs are located as same as in Scenario 1 which is described in Figure 3.13. And also, the movement directions and distance interval for each step are also same as in Scenario 1, which are horizontal and 10 m interval, respectively.

In order to examine how the monitored performance metrics will behave when the communication is switched from the D2D communication to the traditional RP communication, the data packets are routed from the SL to RP after 50 m distance. The simulated results of this scenario are illustrated in the following figures while the red line (the vertical line) presents the point of the MS implementation.

CQI Results:

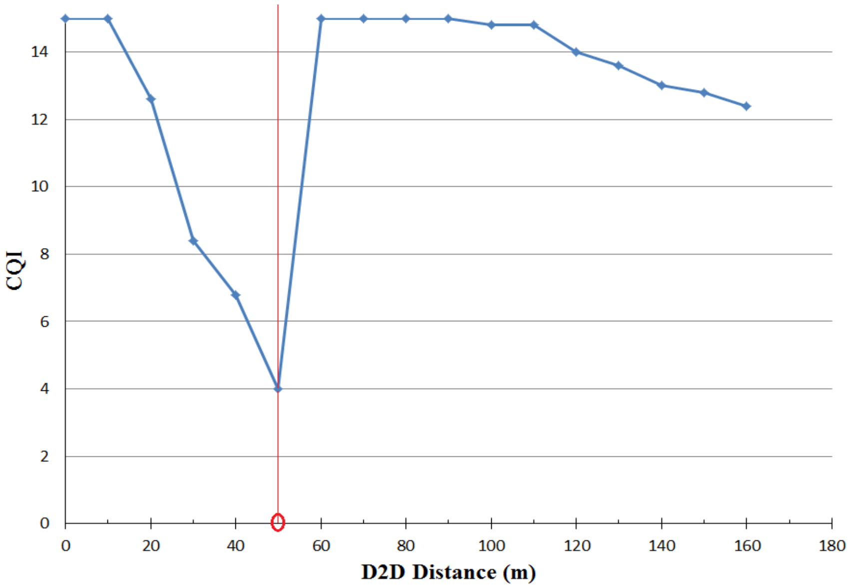


Figure 4.22: CQI with the MS

As shown in Figure 4.22, the CQI of D2D mode behaves similarly to the corresponding CQI results in scenarios 1 and 3. However, after performing MS it suddenly moves up from 4 to the high level of RP CQI in 60 m which still remains in level 15. The improvement of CQI results after MS implementation (after 50 m) is significant.

End-to-End Delay Results: Based on Figure 4.23, the average of the end-to-end delay is improved compared with the end-to-end delay in Scenario 1 and Scenario 3. This improvement is because of employing the MS at a suitable distance.

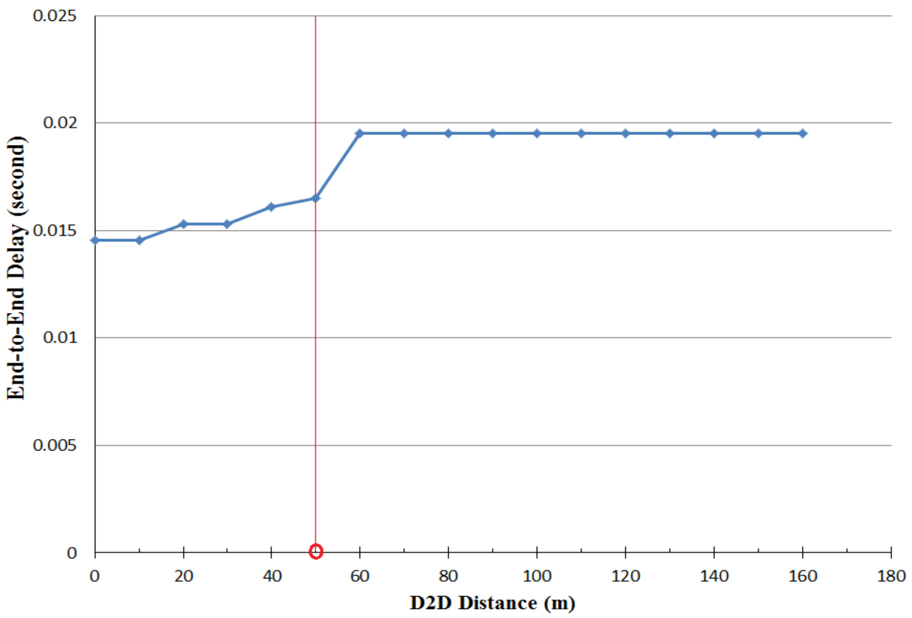


Figure 4.23: End-to-End Delay with the MS

Throughput Results: Figure 4.24 shows that initially the throughput is at a high level which is close to 4900 bps. By increasing the distance, it demonstrates an almost dip falling in D2D communication which loses roughly 27% of its value, after MS it roses suddenly to a higher 45000 bps level.

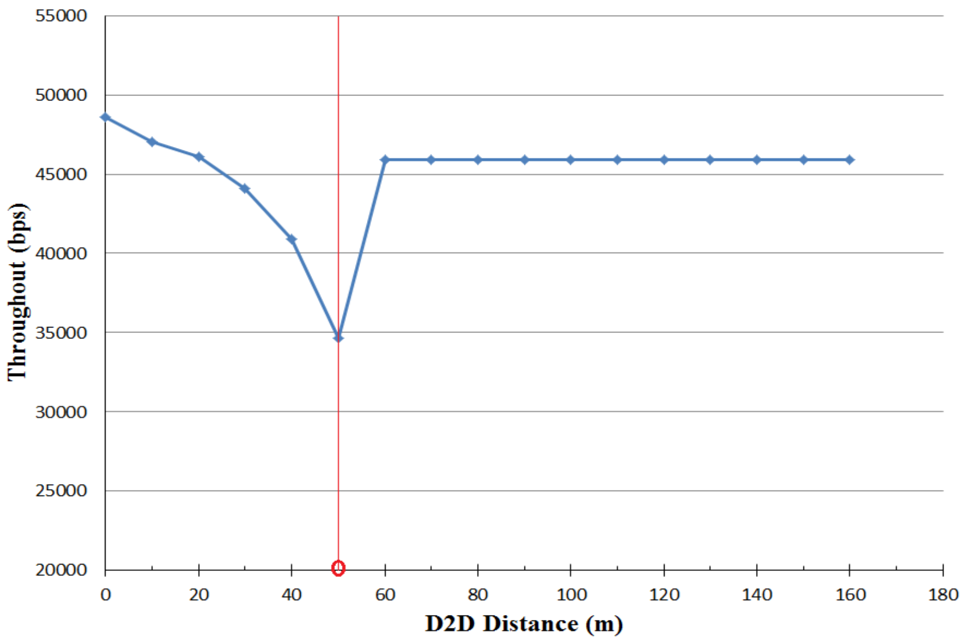


Figure 4.24: Throughput with the MS

MOS Results: The behavior of MOS before and after the MS is illustrated in Figure 4.25. Once MOS has a dip decline from 4.4 level to nearly 3.7 at 50 m, the MS implementation triggered an uprising to the high level. Overall, MOS remains at a high level during the communication by MS employment.

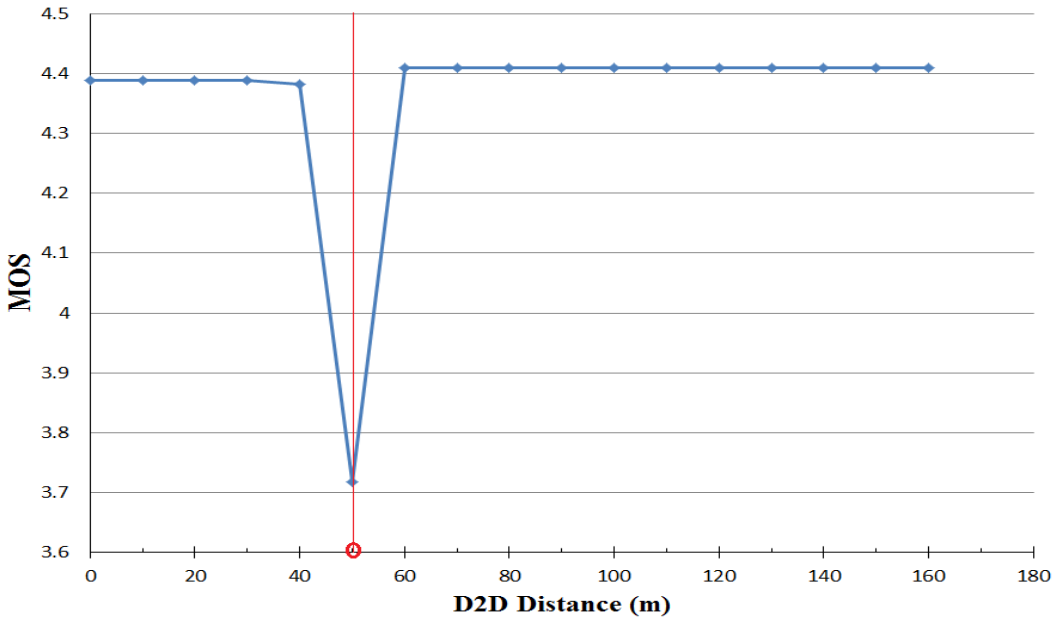


Figure 4.25: MOS with the MS

Packet Loss Ratio Results:

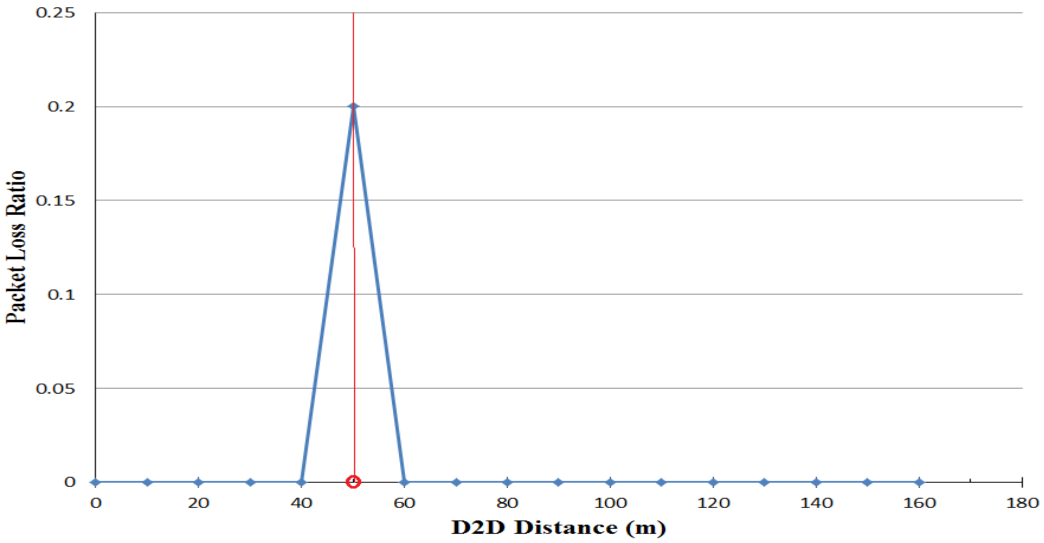


Figure 4.26: Packet loss ratio with the MS

Figure 4.26 represents packet loss ratio is perfectly down at zero levels from the beginning up to 40 m. Once packet loss happens which leads the loss ratio increases to the high level 0.2 at 50 m, the MS implementation changes the path of data packets to the RP. This path switch brings down the packet loss ratio at the same level as before 40 m which is a suitable low packet loss ratio.

Bit Error Rate Results:

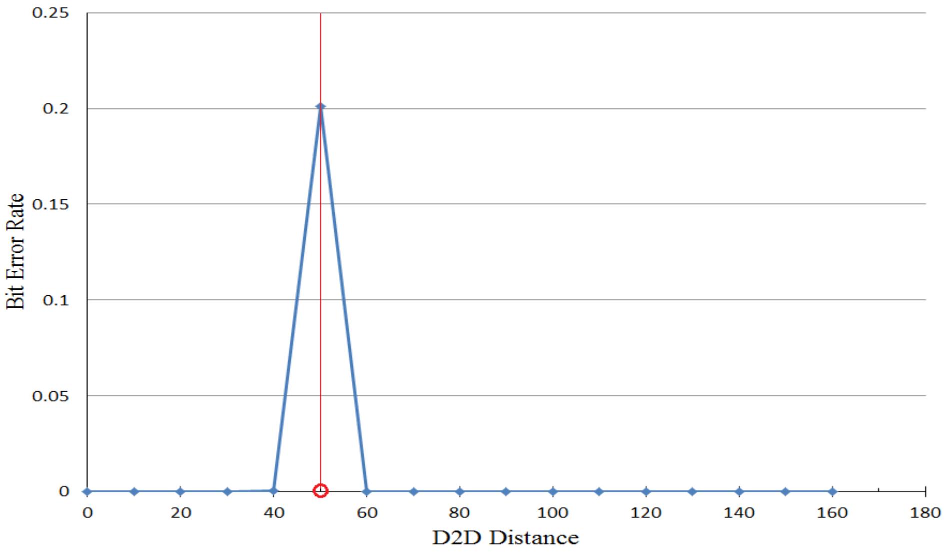


Figure 4.27: Bit error rate with the MS

As depicted in Figure 4.27, the bit error rate has a similar trend like packet loss ratio in Figure 4.26. The bit error rate experiences a sharp increase after 40 m and MS takes place after 50 m distance and causes a low bit error rate at 60 m.

We went further and simulated distances between 40 m and 50 m with a 2 m distance interval in order to discover more accurate distance that the communication metrics change their behavior significantly, e.g. jumping the packet loss ratio from 0 to 0.2. The results are demonstrated by relevant graphs in the following Figures 4.28 – 4.31.

Throughput Results:

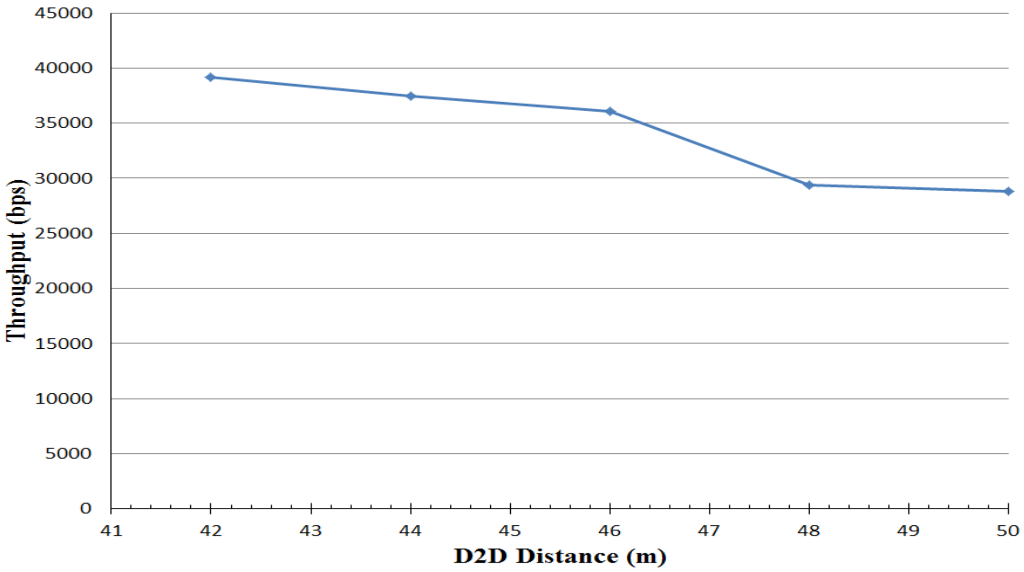


Figure 4.28: D2D Throughput (with a distance interval 2m)

MOS Results:

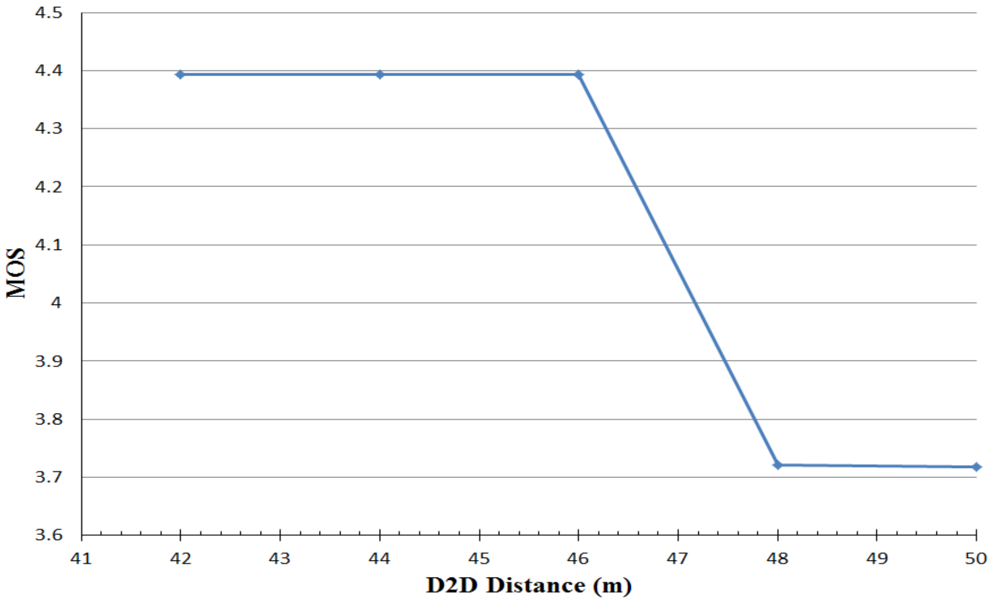


Figure 4.29: D2D MOS (with a distance interval 2m)

Packet Loss Ratio Results:

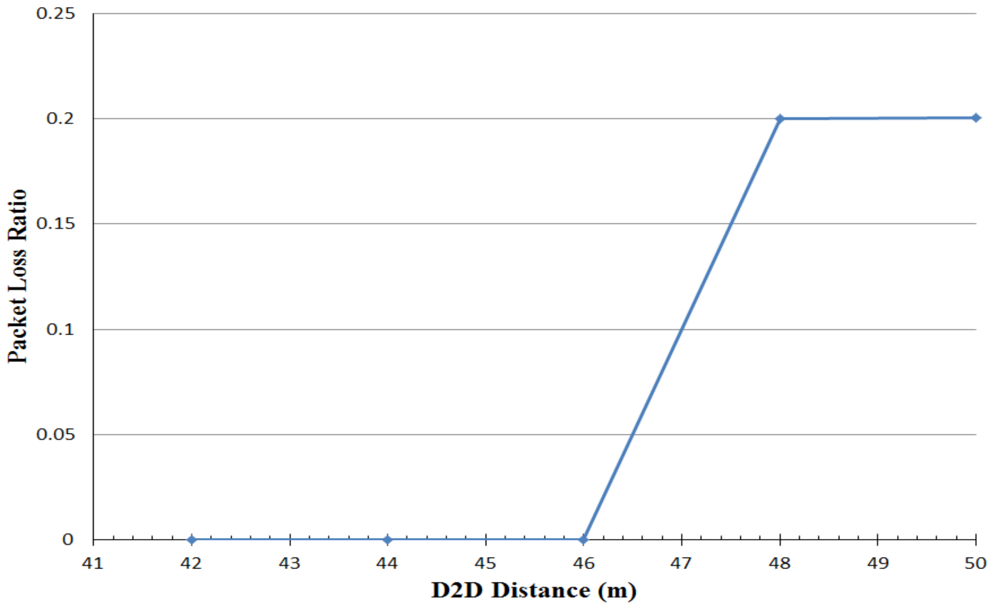


Figure 4.30: D2D Packet Loss Ratio (with a distance interval 2m)

Bit Error Rate Results:

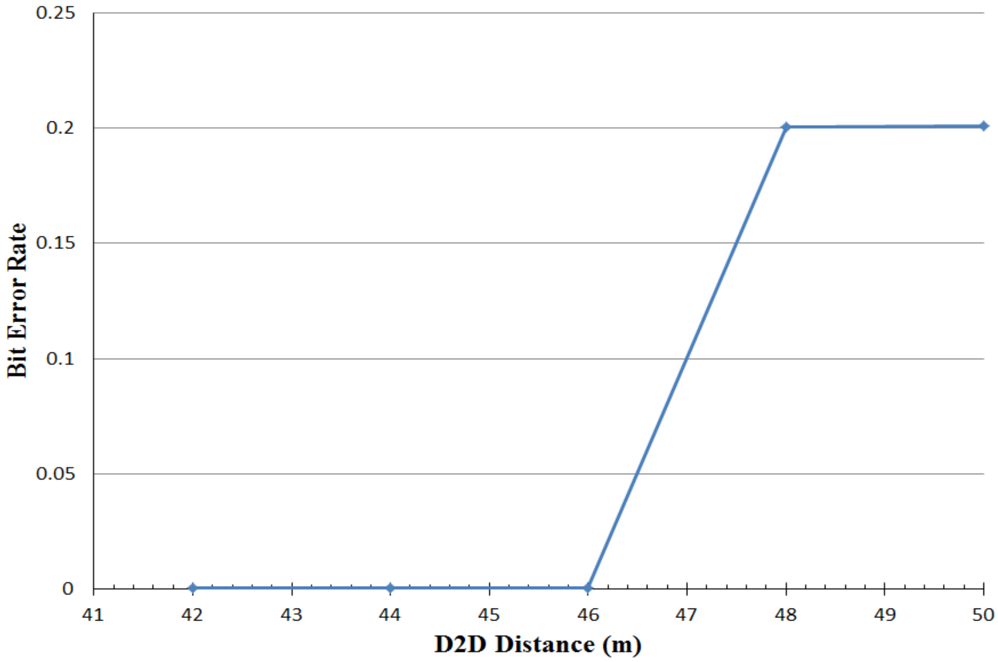


Figure 4.31: D2D Bit Error Ratio (with a distance interval 2m)

According to Figures 4.28 – 4.31, the significant loss of communication performance occurs at the 48 m distance. Figure 4.30 and 4.31 illustrates how the packet loss ratio and the bit error rate grow strikingly at 48 m from 0 to 0.2 which is the high rate for both metrics.

In Scenario 4, we utilized the MS after 50 m distance, which is after the significant performance loss, to show how the MS implementation can recover and reclaim the quality of the communication. Based on the detailed simulations results, the accurate threshold could be 47 m. In order to avoid the significant performance loss in the D2D communication, the MS implementation needs to be adjusted before 48 m, in terms of maximum utilization of D2D communication and avoiding its performance reduction in the longer distances.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In this thesis, we have conducted some scenarios to examine the performance of D2D communication (SL) over LTE-A network and the traditional two-hops path communication through eNB (RP) in LTE-A network by utilizing VoIP packets as the application data. In order to improve the quality of communication and profit the advantages of both type communications, the MS process is employed to enable users to send data traffic through the eNB or a direct link(SL) to the receiver.

We conducted four scenarios in OMNET++ to simulate various conditions of UEs' distribution and accordingly channel quality in both D2D communication and RP communication. Therefore, each scenario is simulated several times with different distances. In order to simulate the scenarios in LTE-A network, SimuLTE version of branch-MASTER version which is based on OMNET++ environment and works over INET model version 3.6.4 is used.

From simulation results, it is observed that when two mobile devices are close to each other but far away from the eNB, D2D mode is the best choice for communication. The UEs have a good D2D communication performance in around edge of cell coverage area while path loss of long distance from the eNB harms RP communication quality. On the other hand, D2D communication in long distances between the UEs shows a low-quality performance, while RP communication delivers a good QoS.

In addition to this, in short distances (up to 30 m) between two mobile devices, D2D communication performance is remarkably superior to RP. Also, it is illustrated that after 30 m distance D2D throughput is lower than RP throughput while the calculated end-to-end delay of the D2D mode is significantly shorter than end-to-end delay time in RP mode. The results of the designed scenarios demonstrate that D2D communication faces an unpleasant packet loss ratio and bit error rate when D2D distance is more than 48m. Therefore RP mode is the best alternative for communication before facing the performance decline in D2D communication. Our last scenario demonstrates how a suitable MS can recover a harmed communication and how by adjusting MS at an appropriate distance can utilize the advantages of both communication modes.

5.2 Future Work

In the research procedure of this thesis, we found plenty of improvements that could be done in order to achieve better performance in D2D communication field. MS triggers some packet loss during the communication since the destination address is changed in the sender’s PDCP layer, the packets under the PDCP layer are sent to the destination before MS operation. Solving the packet loss problem in MS and also, the effect of packet size in D2D communication performance are the open issues in D2D communication.

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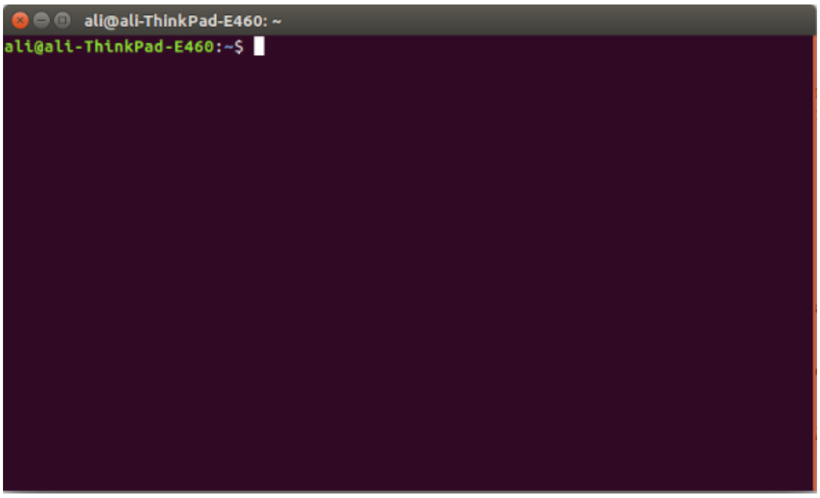
APPENDICES

Appendix A: OMNET++ Installation and Running Guidance

A.1 Installing the Prerequisite Packages:

1- Before beginning the installation, we need to update the exist packages in the system. Enter the following code in Ubuntu terminal:

```
$ sudo apt-get update
```



```
ali@ali-ThinkPad-E460:~$
```

Figure A.1: The Terminal of Linux Ubuntu

Then enter the following codes in the terminal:

```
$ sudo apt-get install build-essential gcc bison g++ flex \
python python3 libqt5opengl5-dev tcl-dev tk-dev
```

In order to active Geographical view, Install the following development components:

build-essential, g++, libwebkitgtk-3.0-0 flex, perl, qt5-default, tcl-dev, tk-dev, libxml2-dev,

A.2 Installing OMNET++:

* Find omnetpp-5.1-src.tgz. file from http://omnetpp.org. Assure you choose the correct version of the archive to download,

* Copy the downloaded file to the folder that you wish to setup OMNET++. Normally, it is your home folder, /home/<user name>, then in the terminal by entering the bellow code you can extract the downloaded file:

```
$ tar xvfz omnetpp-5.1-src.tgz
```

- OMNeT++ must be located in the directory. In order to add it in bin directory for the moment, go to the OMNeT++ path in the terminal and origin the *setenv* script by:

```
$ cd omnetpp-5.1
$ . setenv
```

- In addition, the software attaches the subfolder to *LD_LIBRARY_PATH*. To adjust the simulation variables forever, change *.bashrc* in your OMNET++ directory by editing *.bashrc* file.

```
$ gedit ~/.bashrc
```

- Write below code at the end of *.bashrc* file, and save it and then reopen the terminal:

```
export PATH=$HOME/omnetpp-5.1/bin:$PATH,
```

A.3 Configuring and Building OMNeT++:

Type in the terminal:

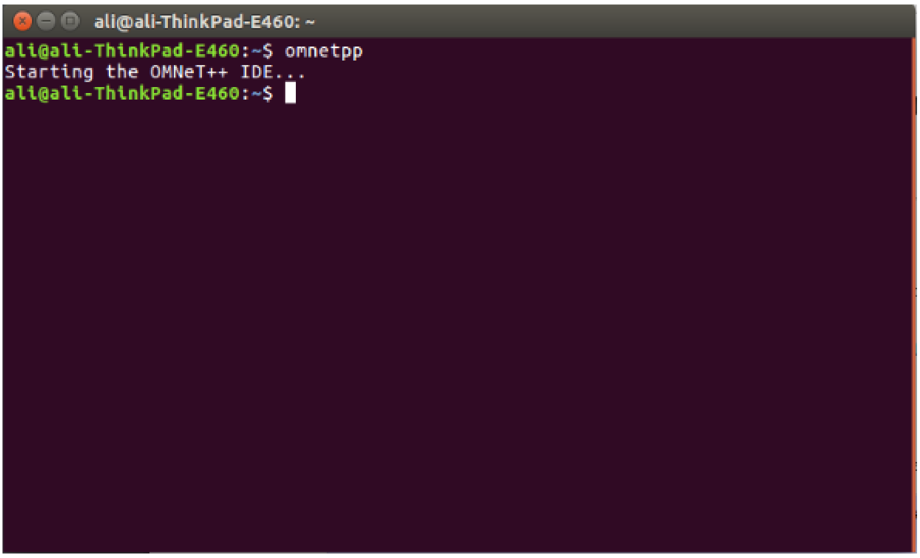
```
$ ./configure
$ make
```

The configure script recognize setup software and configuration of your system. It adds the results into the Makefile.inc file, that will be read by the *makefiles* during the build process.

A.4 Starting the IDE:

Type in the terminal :

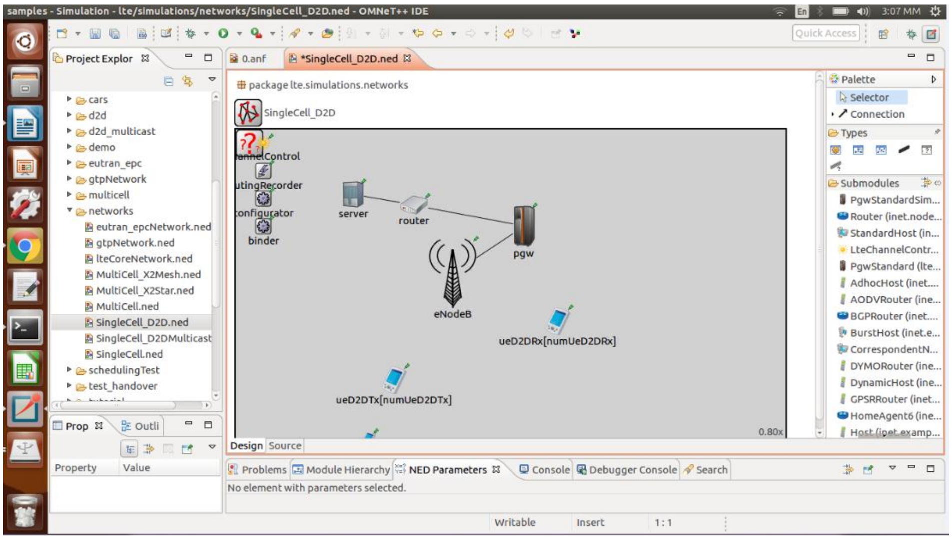
```
$ omnetpp
```



```
ali@ali-ThinkPad-E460:~$ omnetpp
Starting the OMNeT++ IDE...
ali@ali-ThinkPad-E460:~$ 
```

Figure A.2: Running OMNET++ via terminal

A.5 OMNET++ IDE:



No element with parameters selected.

Figure A.3: OMNET++ IDE

Appendix B: Utilized Codes

B.1 Modified parameters in omnetpp.ini:

```
[General]

image-path=../../images
tkenv-plugin-path = ../../../inet/etc/plugins
output-scalar-file-append = true
debug-on-errors = false
tkenv-default-config =
sim-time-limit=50s
warmup-period=0s

**.routingRecorder.enabled = false

############### Statistics ##################
output-scalar-file = ${resultdir}/${configname}/${repetition}.sca
output-vector-file = ${resultdir}/${configname}/${repetition}.vec
seed-set = ${repetition}
**.vector-recording = true

**.scalar-recording= true
debug-statistics-recording=true

################ Channel parameters #####################
**.channelControl.pMax = 10W
**.channelControl.alpha = 1.0
**.channelControl.carrierFrequency = 2100e+6Hz

################ PhyLayer parameters #####################
**.lteNic.phy.channelModel=xmldoc("config_channel.xml")
**.feedbackComputation = xmldoc("config_channel.xml")

################ Mobility parameters #####################
**.mobility.constraintAreaMinZ = 0m
**.mobility.constraintAreaMaxZ = 0m

################# Deployer parameters #######################
# UEs attached to eNB
**.fbDelay = 1

############### AMC MODULE PARAMETERS ###############
**.rbAllocationType = "localized"
**.deployer.numRbDl = 25
**.deployer.numRbUl = 25
**.numBands = 25

[Config SinglePair]
network=lte.simulations.networks.SingleCell_D2D

### eNodeBs configuration ###
*.eNodeB.mobility.initFromDisplayString = false
*.eNodeB.mobility.initialX = 300m
*.eNodeB.mobility.initialY = 300m

### UEs configuration ###
```

```
*.numUeCell = 0
*.numUeD2DTx = 1
*.numUeD2DRx = 1

*.ue*[0].macCellId = 1
*.ue*[0].masterId = 1
*.ue*[0].mobility.initFromDisplayString = false

# Place D2D endpoints far from the eNodeB (~50m) and close to each other (20m)
*.ueD2DTx[0].mobility.initialX = 276m
*.ueD2DTx[0].mobility.initialY = 300m
*.ueD2DRx[0].mobility.initialX = 324m
*.ueD2DRx[0].mobility.initialY = 300m



[Config SinglePair-UDP-D2D]
extends=SinglePair-UDP-Infra
repeat=10
# Enable D2D for the eNodeB and the UEs involved in direct commulteNications
*.eNodeB.d2dCapable = true
*.ueD2D*[*].d2dCapable = true
**.amcMode = "D2D"

# --- Set the D2D peering capabilities ---#
#
# For each D2D-capable UE, write a list of UEs (separated by blank spaces)
# representing the possible peering UEs. Note that this relationship is unidirectional.
# Here, ueD2DTx[0] --> ueD2DRx[0]
*.ueD2DTx[0].lteNic.d2dPeerAddresses = "ueD2DRx[0]"

# --- Select CQI for D2D transmissions --- #

*.eNodeB.lteNic.phy.enableD2DCqiReporting = true
**.usePreconfiguredTxParams = false

### Traffic configuration ###
*.ueD2D*[0].numUdpApps = 1

# Traffic between UEs (ueD2DTx[0] --> ueD2DRx[0])
# Transmitter
*.ueD2DTx[0].udpApp[*].typename = "VoIPSender"
*.ueD2DTx[0].udpApp[*].localPort = 3088+ancestorIndex(0)
*.ueD2DTx[0].udpApp[*].startTime = uniform(0s,0.02s)
*.ueD2DTx[0].udpApp[*].destAddress = "ueD2DRx[0]"
*.ueD2DTx[0].udpApp[*].destPort = 1000
*.ueD2DTx[0].udpApp[*].PacketSize = 172

# Receiver
*.ueD2DRx[0].udpApp[*].typename = "VoIPReceiver"
*.ueD2DRx[0].udpApp[*].localPort = 1000
```

B.2 MAC Layer Data Collectors codes:

LteMac.ned: LTE MACBASE

```
@signal[macDelayDl];
        @statistic[macDelayDl](title="Delay at the MAC layer UL", unit="s", source="macDelayDl", record=mean,vector);
        @signal[macThroughputDl];
        @statistic[macThroughputDl](title="Throughput at the MAC layer DL", unit="Bps", source="macThroughputDl", record=mean);
        @signal[macDelayUl];
        @statistic[macDelayUl](title="Delay at the MAC layer UL", unit="s", source="macDelayUl", record=mean,vector);
        @signal[macThroughputUl];
        @statistic[macThroughputUl](title="Throughput at the MAC layer UL", unit="Bps", source="macThroughputUl", record=mean);
        @signal[macDelayD2D];
        @statistic[macDelayD2D](title="Delay at the MAC layer D2D", unit="s", source="macDelayD2D", record=mean,vector);
        @signal[macThroughputD2D];
        @statistic[macThroughputD2D](title="Throughput at the MAC layer D2D", unit="Bps", source="macThroughputD2D", record=mean);
        @signal[macCellThroughputUl];
        @statistic[macCellThroughputUl](title="Cell Throughput at the MAC layer UL", unit="Bps", source="macCellThroughputUl", record=mean);
        @signal[macCellThroughputDl];
        @statistic[macCellThroughputDl](title="Cell Throughput at the MAC layer DL", unit="Bps", source="macCellThroughputDl", record=mean);
        @signal[macCellThroughputD2D];
        @statistic[macCellThroughputD2D](title="Cell Throughput at the MAC layer D2D", unit="Bps", source="macCellThroughputD2D", record=mean);
        @signal[macCellPacketLossDl];
        @statistic[macCellPacketLossDl](title="Mac Cell Packet Loss", unit="", source="macCellPacketLossDl", record=mean);
        @signal[macCellPacketLossUl];
        @statistic[macCellPacketLossUl](title="Mac Cell Packet Loss", unit="", source="macCellPacketLossUl", record=mean);
        @signal[macCellPacketLossD2D];
        @statistic[macCellPacketLossD2D](title="Mac Cell Packet Loss D2D", unit="", source="macCellPacketLossD2D", record=mean);
        @signal[macPacketLossUl];
        @statistic[macPacketLossUl](title="Mac Packet Loss", unit="", source="macPacketLossUl", record=mean);
        @signal[macPacketLossDl];
        @statistic[macPacketLossDl](title="Mac Packet Loss", unit="", source="macPacketLossDl", record=mean);
        @signal[macPacketLossD2D];
        @statistic[macPacketLossD2D](title="Mac Packet Loss D2D", unit="", source="macPacketLossD2D", record=mean);
        @signal[macBufferOverFlowDl];
```

```
@statistic[macBufferOverFlowDl](title="Mac buffer overflow as function of time", unit="Byte/s", source="macBufferOverFlowDl", record=mean);
@signal[macBufferOverFlowUl];
@statistic[macBufferOverFlowUl](title="Mac buffer overflow as function of time", unit="Byte/s", source="macBufferOverFlowUl", record=mean);
@signal[macBufferOverFlowD2D];
@statistic[macBufferOverFlowD2D](title="Mac buffer overflow as function of time", unit="Byte/s", source="macBufferOverFlowD2D", record=mean);
@signal[harqErrorRateUl];
@statistic[harqErrorRateUl](title="Harq Error Rate Dl", unit="", source="harqErrorRateUl", record=mean,vector);
@signal[harqErrorRateDl];
@statistic[harqErrorRateDl](title="Harq Error Rate Dl", unit="", source="harqErrorRateDl", record=mean,vector);
@signal[harqErrorRateD2D];
@statistic[harqErrorRateD2D](title="Harq Error Rate D2D", unit="", source="harqErrorRateD2D", record=mean,vector);
@signal[harqErrorRate_1st_Ul];
@statistic[harqErrorRate_1st_Ul](title="Harq Error Rate Dl", unit="", source="harqErrorRate_1st_Ul", record=mean,vector);
@signal[harqErrorRate_1st_Dl];
@statistic[harqErrorRate_1st_Dl](title="Harq Error Rate Dl", unit="", source="harqErrorRate_1st_Dl", record=mean,vector);
@signal[harqErrorRate_1st_D2D];
@statistic[harqErrorRate_1st_D2D](title="Harq Error Rate D2D", unit="", source="harqErrorRate_1st_D2D", record=mean,vector);
@signal[harqErrorRate_2nd_Ul];
@statistic[harqErrorRate_2nd_Ul](title="Harq Error Rate Dl", unit="", source="harqErrorRate_2nd_Ul", record=mean,vector);
@signal[harqErrorRate_2nd_Dl];
@statistic[harqErrorRate_2nd_Dl](title="Harq Error Rate Dl", unit="", source="harqErrorRate_2nd_Dl", record=mean,vector);
@signal[harqErrorRate_2nd_D2D];
@statistic[harqErrorRate_2nd_D2D](title="Harq Error Rate D2D", unit="", source="harqErrorRate_2nd_D2D", record=mean,vector);
@signal[harqErrorRate_3rd_Ul];
@statistic[harqErrorRate_3rd_Ul](title="Harq Error Rate Dl", unit="", source="harqErrorRate_3rd_Ul", record=mean,vector);
@signal[harqErrorRate_3rd_Dl];
@statistic[harqErrorRate_3rd_Dl](title="Harq Error Rate Dl", unit="", source="harqErrorRate_3rd_Dl", record=mean,vector);
@signal[harqErrorRate_3rd_D2D];
@statistic[harqErrorRate_3rd_D2D](title="Harq Error Rate D2D", unit="", source="harqErrorRate_3rd_D2D", record=mean,vector);
@signal[harqErrorRate_4th_Ul];
@statistic[harqErrorRate_4th_Ul](title="Harq Error Rate Dl", unit="", source="harqErrorRate_4th_Ul", record=mean,vector);
@signal[harqErrorRate_4th_Dl];
@statistic[harqErrorRate_4th_Dl](title="Harq Error Rate Dl", unit="", source="harqErrorRate_4th_Dl", record=mean,vector);
```

```
        @signal[harqErrorRate_4th_D2D];
        @statistic[harqErrorRate_4th_D2D](title="Harq Error Rate D2D", unit="",
source="harqErrorRate_4th_D2D", record=mean,vector);
        @signal[receivedPacketFromUpperLayer];

@statistic[receivedPacketFromUpperLayer](source="receivedPacketFromUpperLay
er", record=count,"sum(packetBytes)","vector(packetBytes)", interpolationmode=none);
        @signal[receivedPacketFromLowerLayer];

@statistic[receivedPacketFromLowerLayer](source="receivedPacketFromLowerLay
er", record=count,"sum(packetBytes)","vector(packetBytes)", interpolationmode=none);
        @signal[sentPacketToUpperLayer];
        @statistic[sentPacketToUpperLayer](source="sentPacketToUpperLayer",
record=count,"sum(packetBytes)","vector(packetBytes)", interpolationmode=none);
        @signal[sentPacketToLowerLayer];
        @statistic[sentPacketToLowerLayer](source="sentPacketToLowerLayer",
record=count,"sum(packetBytes)","vector(packetBytes)", interpolationmode=none);
        @signal[measuredItbs];
        @statistic[measuredItbs](title="TBS index", unit="", source="measuredItbs",
record=mean,vector);
        @signal[macThroughputVector];
        @statistic[macThroughputVector](title="D2DTHrOuPutRX", unit="",
source="macThroughputVector", record=mean,vector);
        @signal[mmmacThroughputVector];
        @statistic[mmmacThroughputVector](title="D2DTHrOuPutRX", unit="",
source="mmmacThroughputVector", record=mean,vector);
```

B. 3 LTE MAC UE:

```
@signal[cqiDlSiso0];
        @statistic[cqiDlSiso0](title="Average cqi siso band 0", unit="cqi",
source="cqiDlSiso0", record=mean);
        @signal[cqiDlSiso1];
        @statistic[cqiDlSiso1](title="Average cqi siso band 1", unit="cqi",
source="cqiDlSiso1", record=mean);
        @signal[cqiDlSiso2];
        @statistic[cqiDlSiso2](title="Average cqi siso band 2", unit="cqi",
source="cqiDlSiso2", record=mean);
        @signal[cqiDlSiso3];
        @statistic[cqiDlSiso3](title="Average cqi siso band 3", unit="cqi",
source="cqiDlSiso3", record=mean);
        @signal[cqiDlSiso4];
        @statistic[cqiDlSiso4](title="Average cqi siso band 4", unit="cqi",
source="cqiDlSiso4", record=mean);

        @signal[cqiDlSpmux0];
        @statistic[cqiDlSpmux0](title="Average cqi Spmux band 0", unit="cqi",
source="cqiDlSpmux0", record=mean);
        @signal[cqiDlSpmux1];
```

```
    @statistic[cqiDlSpmux1](title="Average cqi Spmux band 1", unit="cqi", source="cqiDlSpmux1", record=mean);
    @signal[cqiDlSpmux2];
    @statistic[cqiDlSpmux2](title="Average cqi Spmux band 2", unit="cqi", source="cqiDlSpmux2", record=mean);
    @signal[cqiDlSpmux3];
    @statistic[cqiDlSpmux3](title="Average cqi Spmux band 3", unit="cqi", source="cqiDlSpmux3", record=mean);
    @signal[cqiDlSpmux4];
    @statistic[cqiDlSpmux4](title="Average cqi Spmux band 4", unit="cqi", source="cqiDlSpmux4", record=mean);

    @signal[cqiDlTxDiv0];
    @statistic[cqiDlTxDiv0](title="Average cqi TxDiv band 0", unit="cqi", source="cqiDlTxDiv0", record=mean);
    @signal[cqiDlTxDiv1];
    @statistic[cqiDlTxDiv1](title="Average cqi TxDiv band 1", unit="cqi", source="cqiDlTxDiv1", record=mean);
    @signal[cqiDlTxDiv2];
    @statistic[cqiDlTxDiv2](title="Average cqi TxDiv band 2", unit="cqi", source="cqiDlTxDiv2", record=mean);
    @signal[cqiDlTxDiv3];
    @statistic[cqiDlTxDiv3](title="Average cqi TxDiv band 3", unit="cqi", source="cqiDlTxDiv3", record=mean);
    @signal[cqiDlTxDiv4];
    @statistic[cqiDlTxDiv4](title="Average cqi TxDiv band 4", unit="cqi", source="cqiDlTxDiv4", record=mean);

    @signal[cqiDlMuMimo0];
    @statistic[cqiDlMuMimo0](title="Average cqi MuMimo band 0", unit="cqi", source="cqiDlMuMimo0", record=mean);
    @signal[cqiDlMuMimo1];
    @statistic[cqiDlMuMimo1](title="Average cqi MuMimo band 1", unit="cqi", source="cqiDlMuMimo1", record=mean);
    @signal[cqiDlMuMimo2];
    @statistic[cqiDlMuMimo2](title="Average cqi MuMimo band 2", unit="cqi", source="cqiDlMuMimo2", record=mean);
    @signal[cqiDlMuMimo3];
    @statistic[cqiDlMuMimo3](title="Average cqi MuMimo band 3", unit="cqi", source="cqiDlMuMimo3", record=mean);
    @signal[cqiDlMuMimo4];
    @statistic[cqiDlMuMimo4](title="Average cqi MuMimo band 4", unit="cqi", source="cqiDlMuMimo4", record=mean);
```

B. 4 Channel Implementation

```
<?xml version="1.0" encoding="UTF-8"?>
<root>
            <!-- Channel Model Type (REAL, DUMMY) -->
        <ChannelModel type="REAL">
            <!-- Enable/disable shadowing -->
            <parameter name="shadowing" type="bool" value="true"/>
            <!-- Pathloss scenario from ITU -->
            <parameter name="scenario" type="string"
value="RURAL_MACROCELL"/>
            <!-- eNodeB height -->
            <parameter name="nodeb-height" type="double"
value="25"/>
            <!-- Building height -->
            <parameter name="building-height" type="double"
value="20"/>
            <!-- Carrier Frequency (GHz) -->
            <parameter name="carrierFrequency" type="double"
value="2"/>
            <!-- Target bler used to compute feedback -->
            <parameter name="targetBler" type="double"
value="0.001"/>
            <!-- HARQ reduction -->
            <parameter name="harqReduction" type="double"
value="0.2"/>
            <!-- Rank indicator tracefile -->
            <parameter name="lambdaMinTh" type="double"
value="0.02"/>
            <parameter name="lambdaMaxTh" type="double"
value="0.2"/>
            <parameter name="lambdaRatioTh" type="double"
value="20"/>
            <!-- Antenna Gain of UE -->
            <parameter name="antennaGainUe" type="double"
value="0"/>
            <!-- Antenna Gain of eNodeB -->
            <parameter name="antennGainEnB" type="double"
value="18"/>
            <!-- Antenna Gain of Micro node -->
            <parameter name="antennGainMicro" type="double"
value="5"/>
                  <!-- Thermal Noise of Bandwidth -->
            <parameter name="thermalNoise" type="double" value="-
104.5"/>
            <!-- Ue noise figure -->bh
            <parameter name="ue-noise-figure" type="double"
value="7"/>
            <!-- eNodeB noise figure -->
            <parameter name="bs-noise-figure" type="double"
value="5"/>
            <!-- Cable Loss -->
            <parameter name="cable-loss" type="double" value="2"/>
            <!-- If true enable the possibility to switch
dinamically the LOS/NLOS pathloss computation -->
            <parameter name="dynamic-los" type="bool"
value="false"/>
            <!-- If dynamic-los is false this parameter, if true,
compute LOS pathloss otherwise compute NLOS pathloss -->
            <parameter name="fixed-los" type="bool" value="false"/>
            <!-- Enable/disable fading -->
```

```
            <parameter name="fading" type="bool" value="true"/>
            <!-- Fading type (JAKES or RAYGHLEY) -->
            <parameter name="fading-type" type="string"
value="JAKES"/>
            <!-- If jakes fading this parameter specify the number
of path (tap channel) -->
            <parameter name="fading-paths" type="int" value="6"/>
                  <!-- if true, enables the inter-cell interference
computation -->
            <parameter name="extCell-interference" type="bool"
value="true"/>
                  <!-- if true, enables the multi-cell interference
computation -->
            <parameter name="multiCell-interference" type="bool"
value="true"/>
            <!-- if true, enables the in-cell D2D interference
computation -->
            <parameter name="inCellD2D-interference" type="bool"
value="true"/>
        </ChannelModel>

        <!-- Feedback Type (REAL, DUMMY) -->
        <FeedbackComputation type="REAL">
             <!-- Target bler used to compute feedback -->
             <parameter name="targetBler" type="double"
value="0.001"/>
             <!-- Rank indicator tracefile -->
             <parameter name="lambdaMinTh" type="double"
value="0.02"/>
             <parameter name="lambdaMaxTh" type="double"
value="0.2"/>
             <parameter name="lambdaRatioTh" type="double"
value="20"/>
        </FeedbackComputation>
</root>
```

Appendix C: Average Results of the Scenarios

Table C.1: Scenario 1, RP average results

Distance (m)	Loss Ratio	UL CQI	Delay	Error Rate	MOS	Throughput
0	0.00014	15	0	0	4.41	36697.6
10	0.00014	15	0	0	4.41	36697.6
20	0.00014	15	0	0	4.41	36697.6
30	0.00014	15	0	0	4.41	36697.6
40	0.00014	15	0	0	4.41	36697.6
50	0.00014	15	0	0	4.41	36697.6
60	0.00014	15	0	0	4.41	36697.6
70	0.00014	15	0	0	4.41	36697.6
80	0.00014	15	0	0	4.41	36697.6
90	0.00014	15	0	0	4.41	36697.6
100	0.00014	15	0	0	4.41	36697.6
110	0.00014	15	0	0	4.41	36697.6
120	0.00014	15	0	0	4.41	36697.6
130	0.00014	15	0	0	4.41	36697.6
140	0.00014	13.8	0	0	4.41	36697.6
150	0.00014	13.3	0	0	4.41	36680
160	0.00014	13	0	0	4.41	36673.6
180	0.00014	12.4	0	0	4.41	36673.6
200	0.00014	12	0	0	4.41	36662.4
220	0.00014	11.2	0	0	4.406	36641.6
240	0.00026	10.2	0.0001	0	4.376	35612.8
260	0.00028	9.8	0.00022	0	4.376	35450.4
280	0.00036	8.4	0.0024	0	4.394	35240
300	0.0005	7.6	0.0003	0	4.35	34011

Table C.2: Scenario 1, D2D Average Results

Distance (m)	Loss Ratio	D2D CQI	Delay	Error Rate	MOS	Throughput
0	0.0001	15	0.01454	0	4.388	41969.6
10	0.0001	15	0.01454	0	4.388	40356.8
20	0.0001	13	0.0151	0	4.388	37972.8
30	0.0001	9.4	0.0151	0	4.388	36012.8
40	0.00036	6.4	0.01526	0.00022	4.404	32782.4
50	0.00014	3.8	0.01552	0.00104	4.342	30043.2
60	0.20024	3.25	0.016775	0.2124	3.466	21744
70	0.20012	2.2	0.0169	0.20312	3.366	19550.4
80	0.20028	2.25	0.0175	0.20838	3.176	18724.8
90	0.20038	2	0.019075	0.2466	3.044	17616
100	0.20036	2.00075	0.019425	0.2892	2.98	16678.4
110	0.40048	2.00075	0.022525	0.36	2.822	15440
120	0.4005	2.0533	0.0244	0.558	2.126	11332.8

Table C.3: Scenario 2, RP Average Results

Distance (m)	**Loss Ratio**	**UL CQI**	**Delay**	**Error Rate**	**MOS**	**Throughput**
10	0.00052	15	0.01952	0	4.41	47961.6
20	0.00052	15	0.01952	0	4.41	47961.6
30	0.00052	15	0.01952	0	4.41	47961.6
40	0.00052	15	0.01952	0	4.41	47961.6
50	0.00052	15	0.0195	0	4.41	48172
60	0.00064	13.6	0.0195	0.00004	4.408	47910.4
70	0.00064	12	0.0195	0.00004	4.406	47884.8
80	0.00064	11	0.0195	0.00004	4.406	47876.8
90	0.00064	9	0.0195	0.00008	4.396	47787.2
100	0.00064	7.8	0.01952	0.00012	4.394	47766.4
110	0.00064	6	0.01952	0.00016	4.394	47521.6
120	0.00075	4.4	0.01998	0.00054	4.368	44817.6
130	0.00076	4	0.02038	0.00052	4.362	44691.2
140	0.001	3.6	0.02208	0.00556	4.206	41648
160	0.004	3.2	0.02302	0.02038	4.09	38129.6
180	0.006	2.4	0.02476	0.045	3.88	35252.8
200	0.006	2	0.02568	0.0748	3.876	31523.2

Table C.4: Scenario 2, D2D Average Results

Distance (m)	Loss Ratio	D2D CQI	Delay	Error Rate	MOS	Throughput
10	0.00044	15	0.01452	0	4.408	48664
20	0.00044	15	0.01452	0	4.408	48664
30	0.00044	15	0.01452	0	4.408	48664
40	0.00044	15	0.01452	0.0001	4.408	48664
50	0.00044	15	0.01452	0.0001	4.408	48664
60	0.00044	15	0.01452	0.0001	4.404	48664
70	0.00044	15	0.01452	0.0001	4.404	48664
80	0.00044	15	0.01452	0.0001	4.404	48664
90	0.00044	15	0.01452	0.0001	4.404	48664
100	0.00044	15	0.01452	0.0001	4.404	48664
110	0.00044	15	0.01452	0.0001	4.4	48664
120	0.00044	15	0.01452	0.0001	4.4	48619.2
130	0.00044	15	0.01452	0.0001	4.4	48619.2
140	0.00044	15	0.01452	0.0001	4.4	48619.2
160	0.00044	15	0.01452	0.0001	4.4	48619.2
180	0.00044	15	0.01452	0.0001	4.4	48619.2
200	0.00044	15	0.01452	0.00016	4.4	48619.2

Table C.5: Scenario 3, D2D 50m average results

Distance (m)	**Loss Ratio**	**D2D CQI**	**Delay**	**Error Rate**	**MOS**	**Throughput**
0	0.0001	13.2	0.01454	0	4.388	41969.6
10	0.0001	13.2	0.01454	0	4.388	40356.8
20	0.0001	12.4	0.0151	0	4.388	37972.8
30	0.0001	8.8	0.0151	0	4.388	36012.8
40	0.00036	6.4	0.0153	0.00022	4.406	32782.4
50	0.00014	3.8	0.01592	0.00104	4.342	30043.2
60	0.20012	2.8	0.01675	0.20132	3.462	21712
70	0.20012	2.2	0.0169	0.2049	3.364	19545.6
80	0.20014	2	0.0175	0.21618	3.2	18721.6
90	0.20038	1.8	0.019075	0.2466	3.04	17603.2
100	0.20034	1.8	0.020375	0.2712	3	16665.6
110	0.40036	1.8	0.02255	0.36	2.84	15420.8
120	0.40018	1.62	0.0244	0.558	2.14	11312
130	0.4001	1.632	0.026267	0.578	2.02	10328

Table C.6: Scenario 3, D2D 150m average results

Distance (m)	**Loss Ratio**	**D2D CQI**	**Delay**	**Error Rate**	**MOS**	**Throughput**
0	0.00026	14	0.01454	0	4.388	40481.6
10	0.00026	13	0.01454	0	4.388	38912
20	0.00026	9.4	0.01454	0	4.388	36180.8
30	0.00026	9	0.01454	0	4.388	33372.8
40	0.00026	5.8	0.0151	0.00012	4.406	29355.2
50	0.00014	3.8	0.0161	0.00054	4.338	26020.8
60	0.20028	3	0.016825	0.20184	3.432	20161.6
70	0.20014	2.6	0.017075	0.21012	3.284	17310.4
80	0.20036	2.2	0.017475	0.22238	3.25	15329.6
90	0.40026	1.6	0.019533	0.4446	2.314	10113.6
100	0.40038	1.6	0.0213	0.4892	2.224	9096
110	0.40024	1.6	0.0235	0.57	2.168	8235.2

Table C.7: Scenario 4, MS Employment

Distance (m)	Loss Ratio	CQI	Delay	Error Rate	MOS	Throughput
0	0.0001	15	0.01454	0	4.388	48572.8
10	0.0001	15	0.01454	0	4.388	47012.8
20	0.0001	12.6	0.01532	0	4.388	46083.2
30	0.0001	8.4	0.01532	0	4.388	44070.4
40	0	6.8	0.0161	0.0004	4.382	40875.2
50	0.2003	4	0.016475	0.20104	3.718	34662.4
60	0.00016	15	0.0195	0	4.41	45937.6
70	0.00016	15	0.0195	0	4.41	45937.6
80	0.00016	15	0.0195	0	4.41	45937.6
90	0.00016	15	0.0195	0	4.41	45937.6
100	0.00016	14.8	0.0195	0	4.41	45937.6
110	0.00016	14.8	0.0195	0	4.41	45937.6
120	0.00016	14	0.0195	0	4.41	45937.6
130	0.00016	13.6	0.0195	0	4.41	45937.6
140	0.00016	13	0.0195	0	4.41	45937.6
150	0.00016	12.8	0.0195	0	4.41	45937.6
160	0.00016	12.4	0.0195	0	4.41	45937.6

Table C.8: Scenario 4, 2m interval (40m-50m)

Distance (m)	Loss Ratio	CQI	Delay	Error Rate	MOS	Throughput
42	0	5.6	0.01608	0.0004	4.394	39190.4
44	0	5.4	0.01608	0.0004	4.394	37472
46	0	4.4	0.0161	0.0005	4.394	36086.4

Appendix D: Results of all Runs

Table D.1: Scenario 1, RP Results

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	UL CQI	Error Rate	Delay	MOS	Throughput (Byte)
10	1336	1335	0.0007	15	0	0.0194	4.41	4898
10	1513	1513	0	15	0	0.0196	4.41	4012
10	1360	1360	0	15	0	0.0195	4.41	4317
10	1342	1342	0	15	0	0.0196	4.41	4852
10	1679	1679	0	15	0	0.0194	4.41	4865
20	1336	1335	0.0007	15	0	0.0194	4.41	4898
20	1513	1513	0	15	0	0.0196	4.41	4012
20	1360	1360	0	15	0	0.0195	4.41	4317
20	1342	1342	0	15	0	0.0196	4.41	4852
20	1679	1679	0	15	0	0.0194	4.41	4865
30	1336	1335	0.0007	15	0	0.0194	4.41	4898
30	1513	1513	0	15	0	0.0196	4.41	4012
30	1360	1360	0	15	0	0.0195	4.41	4317
30	1342	1342	0	15	0	0.0196	4.41	4852
30	1679	1679	0	15	0	0.0194	4.41	4865

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
40	1336	1335	0.0007	15	0	0.0194	4.41	4898
40	1513	1513	0	15	0	0.0196	4.41	4012
40	1360	1360	0	15	0	0.0195	4.41	4317
40	1342	1342	0	15	0	0.0196	4.41	4852
40	1679	1679	0	15	0	0.0194	4.41	4865
50	1336	1335	0.0007	15	0	0.0194	4.41	4898
50	1513	1513	0	15	0	0.0196	4.41	4012
50	1360	1360	0	15	0	0.0195	4.41	4317
50	1342	1342	0	15	0	0.0196	4.41	4852
50	1679	1679	0	15	0	0.0194	4.41	4865
60	1336	1335	0.0007	15	0	0.0194	4.41	4898
60	1513	1513	0	15	0	0.0196	4.41	4012
60	1360	1360	0	15	0	0.0195	4.41	4317
60	1342	1342	0	15	0	0.0196	4.41	4852
60	1679	1679	0	15	0	0.0194	4.41	4865

Distance (m)	**Num of sent Packet**	**Num of received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
70	1336	1335	0.0007	13	0	0.0194	4.41	4898
70	1513	1513	0	11	0	0.0196	4.41	4012
70	1360	1360	0	15	0	0.0195	4.41	4317
70	1342	1342	0	15	0	0.0196	4.41	4852
70	1679	1679	0	15	0	0.0194	4.41	4865
80	1336	1335	0.0007	11	0	0.0194	4.41	4869
80	1513	1513	0	9	0	0.0196	4.41	4010
80	1360	1360	0	15	0	0.0195	4.41	4317
80	1342	1342	0	15	0	0.0196	4.41	4855
80	1679	1679	0	15	0	0.0194	4.41	4865
90	1336	1335	0.0007	9	0	0.0194	4.41	4869
90	1513	1513	0	8	0	0.0196	4.41	4010
90	1360	1360	0	15	0	0.0195	4.41	4317
90	1342	1342	0	15	0	0.0196	4.41	4855
90	1679	1679	0	15	0	0.0194	4.41	4865

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
100	1336	1335	0.0007	8	0	0.0194	4.41	4845
100	1513	1513	0	7	0	0.0196	4.41	4000
100	1360	1360	0	15	0	0.0195	4.41	4317
100	1342	1342	0	15	0	0.0196	4.41	4832
100	1679	1679	0	15	0	0.0194	4.41	4865
110	1336	1335	0.0007	8	0	0.0194	4.41	4836
110	1513	1513	0	6	0	0.0196	4.41	3978
110	1360	1360	0	14	0	0.0195	4.41	4317
110	1342	1342	0	14	0	0.0196	4.41	4819
110	1679	1679	0	14	0	0.0194	4.39	4823
120	1336	1335	0.0007	6	0	0.0194	4.41	4836
120	1513	1513	0	4	0	0.0196	4.41	3922
120	1360	1360	0	13	0	0.0195	4.41	4286
120	1342	1342	0	15	0	0.0196	4.41	4819
120	1799	1798	0.0006	13	0.0005	0.0194	4.39	4823

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
130	1336	1335	0.0007	6	0	0.0194	4.41	4818
130	1260	1260	0	4	0.0005	0.0196	4.39	3922
130	1360	1360	0	13	0	0.0195	4.41	4286
130	1342	1341	0.0007	15	0	0.0196	4.41	4810
130	1710	1710	0	11	0.0006	0.0195	4.26	4819
140	1336	1335	0.0007	4	0	0.0194	4.41	4789
140	1558	1557	0.0006	3	0.0009	0.0205	4.35	3878
140	1360	1360	0	10	0	0.0195	4.41	4286
140	1342	1342	0	15	0	0.0196	4.41	4810
140	1834	1833	0.0005	10	0.0003	0.0195	4.39	4819
150	1336	1335	0.0007	4	0	0.0194	4.41	4756
150	1762	1761	0.0006	2	0.001	0.0205	4.27	3820
150	1416	1415	0.0007	8	0.0002	0.0195	4.4	4286
150	1342	1342	0	15	0	0.0196	4.41	4768
150	1834	1833	0.0005	9	0.0003	0.0195	4.26	4752

Table D.2:Scenario 1, D2D Results

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
0	1881	1880	0.0005	15	0	0.0146	4.41	6032
0	1430	1430	0	15	0	0.0145	4.41	5042
0	1440	1440	0	15	0	0.0146	4.41	5711
0	1536	1536	0	15	0	0.0145	4.41	4536
0	1402	1402	0	15	0	0.0145	4.3	4910
10	1881	1880	0.0005	15	0	0.0146	4.41	6032
10	1430	1430	0	15	0	0.0145	4.41	4722
10	1440	1440	0	15	0	0.0146	4.41	5312
10	1536	1536	0	15	0	0.0145	4.41	4536
10	1402	1402	0	15	0	0.0145	4.3	4621
20	1881	1880	0.0005	15	0	0.0146	4.41	5762
20	1430	1430	0	13	0	0.0145	4.41	4532
20	1589	1589	0	7	0	0.0174	4.41	5111
20	1536	1536	0	15	0	0.0145	4.41	4230
20	1402	1402	0	15	0	0.0145	4.3	4098

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
40	1881	1880	0.0005	6	0	0.0146	4.41	4987
40	1444	1443	0.0007	3	0	0.0154	4.4	3916
40	1648	1647	0.0006	2	0.0005	0.0174	4.4	4515
40	1536	1536	0	8	0	0.0145	4.41	3282
40	1604	1604	0	13	0.0006	0.0144	4.4	3789
50	1527	1527	0	3	0.001	0.0156	4.4	4381
50	1371	1370	0.0007	2	0.0002	0.0154	4.4	3368
50	1765	1765	0	2	0.004	0.0176	4.2	4196
50	1536	1536	0	4	0	0.0145	4.41	3215
50	1604	1604	0	8	0	0.0145	4.3	3617
60	1761	1760	0.0006	2	0.06	0.0177	4.2	4023
60	1638	1637	0.0006	2	0.002	0.0174	4.32	3160
60	1590	0	1	nan	1	NaN	0	0
60	1830	1830	0	2	0	0.0176	4.41	3215
60	1604	1604	0	7	0	0.0144	4.4	3192

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
70	1825	1825	0	2	0.008	0.0177	4.2	3174
70	1732	1731	0.0006	2	0.001	0.0179	3.9	2987
70	1590	0	1	1	1	NaN	0	0
70	1785	1785	0	2	0.0006	0.0175	4.4	3051
70	1627	1627	0	4	0.006	0.0145	4.33	3007
80	1326	1325	0.0008	2	0.02	0.0185	3.75	2989
80	1412	1412	0	2	0.001	0.0181	3.86	2802
80	1590	0	1	NaN	1	NaN	0	0
80	1658	1658	0	2	0.0009	0.0176	4.36	3051
80	1550	1549	0.0006	3	0.02	0.0158	3.91	2861
90	1550	1549	0.0006	2	0.1	0.0203	3.5	2780
90	1527	1527	0	2	0.06	0.019	3.71	2616
90	1590	0	1	NaN	1	NaN	0	0
90	1741	1740	0.0006	2	0.003	0.0177	4.27	2999
90	1393	1392	0.0007	2	0.07	0.0193	3.74	2615

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
100	955	955	0	2	0.17	0.0203	3.67	2611
100	1608	1607	0.0006	2.003	0.15	0.019	3.55	2593
100	1590	0	1	NaN	1	NaN	0	0
100	1605	1604	0.0006	2	0.006	0.0177	4.18	2786
100	1805	1804	0.0006	2	0.12	0.0207	3.5	2434
110	1676	1674	0.0012	2	0.28	0.0248	3.38	2400
110	1608	1607	0.0006	2.003	0.27	0.0242	3.56	2387
110	1590	0	1	NaN	1	NaN	0	0
110	1665	0	1	2	0.02	0.018	3.97	2786
110	1540	1539	0.0006	2	0.23	0.0231	3.2	2077
120	1123	1121	0.0018	2.06	0.4	0.0281	3.47	2389
120	1843	0	1	NaN	1	NaN	0	0
120	1590	0	1	NaN	1	NaN	0	0
120	1352	1351	0.0007	2	0.04	0.0185	3.86	2617
120	1271	1271	0	2.1	0.35	0.0266	3.3	2077

Table D.3: Scenario 2, RP results

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
10	1406	1405	0.0007	15	0	0.0195	4.41	5989
10	1746	1745	0.0006	15	0	0.0194	4.41	6065
10	1518	1518	0	15	0	0.0196	4.41	6247
10	1703	1702	0.0007	15	0	0.0195	4.41	6525
10	1651	1650	0.0006	15	0	0.0196	4.41	6075
20	1406	1405	0.0007	15	0	0.0195	4.41	5989
20	1746	1745	0.0006	15	0	0.0194	4.41	6065
20	1518	1518	0	15	0	0.0196	4.41	6247
20	1703	1702	0.0007	15	0	0.0195	4.41	6525
20	1651	1650	0.0006	15	0	0.0196	4.41	6075
30	1406	1405	0.0007	15	0	0.0195	4.41	5989
30	1746	1745	0.0006	15	0	0.0194	4.41	6065
30	1518	1518	0	15	0	0.0196	4.41	6247
30	1703	1702	0.0007	15	0	0.0195	4.41	6525
30	1651	1650	0.0006	15	0	0.0196	4.41	6075

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
40	1406	1405	0.0007	15	0	0.0195	4.41	5989
40	1746	1745	0.0006	15	0	0.0194	4.41	6065
40	1518	1518	0	15	0	0.0196	4.41	6247
40	1703	1702	0.0007	15	0	0.0195	4.41	6525
40	1651	1650	0.0006	15	0	0.0196	4.41	6075
50	1406	1405	0.0007	14	0	0.0195	4.41	5989
50	1746	1745	0.0006	15	0	0.0194	4.41	6065
50	1518	1518	0	15	0	0.0196	4.41	6247
50	1703	1702	0.0007	15	0	0.0195	4.41	6525
50	1651	1650	0.0006	15	0	0.0196	4.41	6075
60	1406	1405	0.0007	11	0	0.0195	4.41	5983
60	1746	1745	0.0006	15	0	0.0194	4.41	6065
60	1616	1615	0.0006	13	0.0002	0.0195	4.4	6221
60	1703	1702	0.0007	15	0	0.0195	4.41	6525
60	1651	1650	0.0006	15	0	0.0196	4.41	6075

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	UL CQI	Error Rate	Delay	MOS	Throughput (Byte)
70	1406	1405	0.0007	9	0	0.0195	4.4	5976
70	1746	1745	0.0006	15	0	0.0194	4.41	6065
70	1616	1615	0.0006	9	0.0002	0.0195	4.4	6212
70	1703	1702	0.0007	15	0	0.0195	4.41	6525
70	1651	1650	0.0006	15	0	0.0196	4.41	6075
80	1406	1405	0.0007	8	0	0.0195	4.4	5976
80	1746	1745	0.0006	15	0	0.0194	4.41	6065
80	1616	1615	0.0006	8	0.0002	0.0195	4.4	6212
80	1703	1702	0.0007	13	0	0.0195	4.41	6522
80	1651	1650	0.0006	13	0	0.0196	4.41	6073
90	1406	1405	0.0007	7	0	0.0195	4.4	5974
90	1746	1745	0.0006	13	0.0002	0.0194	4.36	6019
90	1616	1615	0.0006	7	0.0002	0.0195	4.4	6211
90	1703	1702	0.0007	11	0	0.0195	4.41	6519
90	1651	1650	0.0006	11	0	0.0196	4.41	6069

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
100	1406	1405	0.0007	6	0	0.0195	4.4	5972
100	1746	1745	0.0006	11	0.0002	0.0194	4.36	6016
100	1616	1615	0.0006	6	0.0002	0.0195	4.4	6209
100	1703	1702	0.0007	10	0.0002	0.0196	4.4	6519
100	1651	1650	0.0006	9	0	0.0196	4.41	6063
110	1406	1405	0.0007	4	0	0.0195	4.4	5970
110	1746	1745	0.0006	9	0.0004	0.0195	4.36	6012
110	1616	1615	0.0006	4	0.0002	0.0194	4.4	6209
110	1703	1702	0.0007	8	0.0002	0.0196	4.4	6373
110	1651	1650	0.0006	8	0	0.0196	4.41	6062
120	1312	1312	0	3	0.0009	0.0206	4.37	5113
120	1572	1571	0.0006	8	0.0004	0.0195	4.36	6011
120	1437	1437	0.0006	3	0.001	0.0206	4.3	5375
120	1562	1562	0.0006	8	0.0004	0.0196	4.4	6375
120	1464	1463	0.0006	8	0	0.0196	4.41	6062

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
130	1793	1792	0.0006	2	0.0008	0.0206	4.3	5226
130	1572	1571	0.0006	8	0.0004	0.0195	4.36	6011
130	1407	1406	0.0005	2	0.001	0.0226	4.34	5187
130	1575	1574	0	8	0.0002	0.0196	4.4	6372
130	1651	1650	0.0007	7	0.0002	0.0196	4.41	6061
140	1520	1519	0.0005	2	0.007	0.0277	4.06	4934
140	1572	1571	0.0007	6	0.0004	0.0195	4.36	6011
140	1489	1489	0	2	0.02	0.024	3.8	4322
140	1562	1562	0	4	0.0004	0.0196	4.4	5627
140	1651	1650	0.0006	6	0	0.0196	4.41	6061
160	1496	1496	0	2	0.02	0.0273	3.87	4871
160	1265	1264	0.0007	3	0.0002	0.0204	4.27	4712
160	1325	1323	0.0015	2	0.08	0.025	3.57	4220
160	1698	1696	0.0012	2	0.001	0.0228	4.33	5321
160	1419	1419	0	3	0.0007	0.0196	4.41	5632

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	UL CQI	Error Rate	Delay	MOS	Throughput (Byte)
180	1667	1667	0	2	0.06	0.0285	3.31	4502
180	1323	1322	0.0007	2	0.002	0.0224	4.27	4555
180	1236	1236	0	2	0.16	0.0277	3.47	3981
180	1561	1561	0	2	0.002	0.0227	4.14	5160
180	1336	1335	0.0006	2	0.001	0.0225	4.21	4760
200	1691	1691	0	2	0.09	0.0299	3.43	3963
200	1679	1679	0	2	0.006	0.0226	4.12	3687
200	1636	1635	0.0008	2	0.27	0.0305	3.65	3581
200	1709	1708	0.0015	2	0.006	0.0227	3.95	5007
200	1409	1409	0	2	0.002	0.0227	4.23	4389

Table D.4: Scenario 2, D2D results

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
10	1317	1316	0.0008	15	0	0.0146	4.41	4345
10	1470	1469	0.0008	15	0	0.0144	4.41	4988
10	1847	1847	0	15	0	0.0146	4.41	6970
10	1842	1842	0	15	0	0.0144	4.4	7131
10	1881	1880	0.0006	15	0	0.0146	4.41	6981
30	1317	1316	0.0008	15	0	0.0146	4.41	4345
30	1470	1469	0.0008	15	0	0.0144	4.41	4988
30	1847	1847	0	15	0	0.0146	4.41	6970
30	1842	1842	0	15	0	0.0144	4.4	7131
30	1881	1880	0.0006	15	0	0.0146	4.41	6981
40	1317	1316	0.0008	15	0	0.0146	4.41	4345
40	1470	1469	0.0008	15	0	0.0144	4.41	4988
40	1847	1847	0	15	0	0.0146	4.41	6970
40	1842	1842	0	15	0.0005	0.0144	4.4	7131
40	1881	1880	0.0006	15	0	0.0146	4.41	6981

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
60	1317	1316	0.0008	15	0	0.0146	4.41	4345
60	1470	1469	0.0008	15	0	0.0144	4.41	4988
60	1847	1847	0	15	0	0.0146	4.41	6970
60	1842	1842	0	15	0.0005	0.0144	4.38	7131
60	1881	1880	0.0006	15	0	0.0146	4.41	6981
80	1317	1316	0.0008	15	0	0.0146	4.41	4345
80	1470	1469	0.0008	15	0	0.0144	4.41	4988
80	1847	1847	0	15	0	0.0146	4.41	6970
80	1842	1842	0	15	0.0005	0.0144	4.38	7131
80	1881	1880	0.0006	15	0	0.0146	4.41	6981
100	1317	1316	0.0008	15	0	0.0146	4.41	4345
100	1470	1469	0.0008	15	0	0.0144	4.41	4988
100	1847	1847	0	15	0	0.0146	4.41	6970
100	1842	1842	0	15	0.0005	0.0144	4.38	7131
100	1881	1880	0.0006	15	0	0.0146	4.41	6981

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
120	1317	1316	0.0008	15	0	0.0146	4.41	4345
120	1470	1469	0.0008	15	0	0.0144	4.38	4988
120	1847	1847	0	15	0	0.0146	4.41	6970
120	1918	1917	0	15	0.0005	0.0144	4.39	7103
120	1881	1880	0.0006	15	0	0.0146	4.41	6981
140	1317	1316	0.0008	15	0	0.0146	4.41	4345
140	1470	1469	0.0008	15	0	0.0144	4.38	4988
140	1847	1847	0	15	0	0.0146	4.41	6970
140	1918	1917	0	15	0.0005	0.0144	4.39	7103
140	1881	1880	0.0006	15	0	0.0146	4.41	6981
160	1317	1316	0.0008	15	0	0.0146	4.41	4345
160	1470	1469	0.0008	15	0	0.0144	4.38	4988
160	1847	1847	0	15	0	0.0146	4.41	6970
160	1918	1917	0	15	0.0005	0.0144	4.39	7103
160	1881	1880	0.0006	15	0	0.0146	4.41	6981

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
180	1317	1316	0.0008	15	0	0.0146	4.41	4345
180	1470	1469	0.0008	15	0	0.0144	4.38	4988
180	1847	1847	0	15	0	0.0146	4.41	6970
180	1918	1917	0	15	0.0005	0.0144	4.39	7103
180	1881	1880	0.0006	15	0	0.0146	4.41	6981
200	1317	1316	0.0008	15	0	0.0146	4.41	4345
200	1470	1469	0.0008	15	0.0003	0.0144	4.38	4988
200	1847	1847	0	15	0	0.0146	4.41	6970
200	1918	1917	0	15	0.0005	0.0144	4.39	7103
200	1881	1880	0.0006	15	0	0.0146	4.41	6981

Table D.5: Scenario 3, D2D 50m distance results

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
0	1881	1880	0.0005	15	0	0.0146	4.41	6032
0	1430	1430	0	15	0	0.0145	4.41	5042
0	1440	1440	0	6	0	0.0146	4.41	5711
0	1536	1536	0	15	0	0.0145	4.41	4536
0	1402	1402	0	15	0	0.0145	4.3	4910
10	1881	1880	0.0005	15	0	0.0146	4.41	6032
10	1430	1430	0	15	0	0.0145	4.41	5042
10	1440	1440	0	6	0	0.0146	4.41	5711
10	1536	1536	0	15	0	0.0145	4.41	4536
10	1402	1402	0	15	0	0.0145	4.3	4910
20	1881	1880	0.0005	15	0	0.0146	4.41	6032
20	1430	1430	0	15	0	0.0145	4.41	5042
20	1440	1440	0	2	0	0.0174	4.41	5896
20	1536	1536	0	15	0	0.0145	4.41	4536
20	1402	1402	0	15	0	0.0145	4.3	4910

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	D2D CQI	Error Rate	Delay	MOS	Throughput (Byte)
30	1881	1880	0.0005	9	0	0.0146	4.41	6032
30	1430	1430	0	7	0	0.0145	4.41	5042
30	1589	1589	0	2	0	0.0174	4.41	5896
30	1536	1536	0	11	0	0.0145	4.41	4536
30	1402	1402	0	15	0	0.0145	4.3	4910
40	1881	1880	0.0005	6	0	0.0146	4.41	6032
40	1444	1443	0.0007	3	0	0.0154	4.41	4903
40	1648	1647	0.0006	2	0.0005	0.0175	4.41	6004
40	1536	1536	0	8	0	0.0145	4.41	4536
40	1604	1604	0	13	0.0006	0.0145	4.3	4969
50	1527	1527	0	3	0.001	0.0156	4.41	4972
50	1371	1370	0.0007	2	0.0002	0.0174	4.41	5414
50	1765	1765	0	2	0.004	0.0176	4.41	6153
50	1536	1536	0	4	0	0.0145	4.41	4536
50	1402	1402	0	8	0	0.0145	4.3	4910

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
60	1760	1760	0	2	0.004	0.0177	4.2	6855
60	1638	1637	0.0006	2	0.002	0.0174	4.3	5874
60	1590	0	1	1	1	NaN	0	0
60	1830	1830	0	2	0	0.0175	4.41	6945
60	1604	1604	0	7	0.0006	0.0144	4.4	4969
70	1825	1825	0	2	0.008	0.0177	4.2	7214
70	1732	1731	0.0006	2	0.01	0.0179	3.92	6502
70	1590	0	1	1	1	NaN	0	0
70	1785	1785	0	2	0.0005	0.0175	4.4	6924
70	1627	1627	0	4	0.006	0.0145	4.3	5558
80	1326	1325	0.0007	2	0.03	0.0185	3.8	6308
80	1412	1412	0	2	0.02	0.0181	3.9	5239
80	1590	0	1	1	1	NaN	0	0
80	1658	1658	0	2	0.0009	0.0176	4.4	5949
80	1550	1549	0	3	0.03	0.0158	3.9	5175

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
90	1550	1549	0.0006	2	0.1	0.0203	3.5	4384
90	1527	1527	0	2	0.06	0.019	3.7	6137
90	1590	0	1	1	1	NaN	0	0
90	1741	1740	0.0006	2	0.003	0.0177	4.3	6005
90	1393	1392	0.0007	2	0.07	0.0193	3.7	7090
100	955	955	0	2	0.17	0.022	3.7	3121
100	1608	1607	0.0006	2	0.06	0.0212	3.6	5744
100	1590	0	1	1	1	NaN	0	0
100	1605	1604	0.0006	2	0.006	0.0176	4.2	6183
100	1805	1804	0.0005	2	0.12	0.0207	3.5	7138
110	1676	1674	0.0012	2	0.28	0.0248	3.4	6996
110	1616	1615	0.0006	2	0.27	0.0242	3.6	6349
110	1590	0	1	1	1	NaN	0	0
110	1644	1644	0	2	0.02	0.018	4	6193
110	1666	0	1	2	0.23	0.0232	3.2	308

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	D2D CQI	Error Rate	Delay	MOS	Throughput (Byte)
120	1123	1121	0.0009	2	0.4	0.0281	3.5	4220
120	1843	0	1	1	1	NaN	0	0
120	1590	0	1	1	1	NaN	0	0
120	1352	1351	0	2	0.04	0.0185	3.9	4613
120	1271	1271	0	2.1	0.35	0.0266	3.3	6131
130	1930	1929	0.0005	2.06	0.48	0.0307	3.6	4135
130	1843	0	1	1	1	NaN	0	0
130	1590	0	1	1	1	NaN	0	0
130	1632	1632	0	2	0.06	0.0193	3.4	4613
130	1271	1271	0	2.1	0.35	0.0288	3.1	5526

Table D.6: Scenario 3, D2D 150m distance results

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	D2D CQI	Error Rate	Delay	MOS	Throughput (Byte)
0	1881	1880	0.0005	15	0.0146	0	4.41	6032
0	1430	1430	0	15	0.0145	0	4.41	5042
0	1536	1536	0	15	0.0145	0	4.41	4536

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
0	1402	1402	0	15	0.0145	0	4.3	4910
0	1317	1316	0.0008	15	0.0146	0	4.41	4781
10	1881	1880	0.0005	15	0.0146	0	4.41	6032
10	1430	1430	0	15	0.0145	0	4.41	4722
10	1536	1536	0	15	0.0145	0	4.41	4536
10	1402	1402	0	15	0.0145	0	4.3	4601
10	1317	1316	0.0008	15	0.0146	0	4.41	4429
20	1881	1880	0.0005	8	0.0146	0	4.41	5698
20	1430	1430	0	6	0.0145	0	4.41	4490
20	1536	1536	0	9	0.0145	0	4.41	4189
20	1402	1402	0	15	0.0145	0	4.3	3987
20	1317	1316	0.0008	9	0.0146	0	4.41	4249
30	1881	1880	0.0005	8	0.0146	0	4.41	5490
30	1430	1430	0	6	0.0145	0	4.41	4128
30	1536	1536	0	9	0.0145	0	4.41	3811

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	D2D CQI	Error Rate	Delay	MOS	Throughput (Byte)
30	1402	1402	0	13	0.0145	0	4.3	3604
30	1317	1316	0.0008	9	0.0146	0	4.41	3825
40	1881	1880	0.0005	4	0.0146	0	4.41	4862
40	1287	1287	0	2	0.0174	0	4.41	3742
40	1536	1536	0	6	0.0144	0	4.41	3415
40	1604	1604	0	11	0.0145	0.0006	4.39	3227
40	1317	1316	0.0008	6	0.0146	0	4.41	3101
50	1770	1770	0	2	0.0176	0.001	4.34	3961
50	1371	1370	0.0007	2	0.0174	0.0002	4.4	3498
50	1779	1779	0	3	0.0154	0.0006	4.4	3069
50	1533	1533	0	9	0.0145	0.0006	4.35	2995
50	1533	1533	0	3	0.0156	0.0003	4.2	2740
60	1466	1464	0.0007	2	0.0178	0.005	4.16	3723
60	1508	1507	0.0007	2	0.0175	0.003	4.24	3156
60	1830	1830	0	2	0.0175	0.0006	4.41	2960

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
60	1533	1533	0	8	0.0145	0.0006	4.35	2762
60	1995	0	1	1	NaN	1	0	0
70	1395	1395	0	2	0.0182	0.03	3.78	2986
70	1487	1486	0.0007	2	0.0179	0.016	3.94	2811
70	1785	1785	0	2	0.0175	0.0006	4.39	2410
70	1581	1581	0	6	0.0147	0.004	4.31	2612
70	2039	0	1	1	NaN	1	0	0
80	1958	1957	0.0005	2	0.0193	0.06	3.71	2508
80	1678	1677	0.0007	2	0.0184	0.036	3.9	2463
80	1658	1658	0	2	0.0176	0.0009	4.36	2246
80	1690	1689	0.0006	4	0.0146	0.015	4.28	2364
80	1792	0	1	1	NaN	1	0	0
90	1466	1465	0.0007	2	0.0215	0.15	3.6	2146
90	1493	0	1	1	NaN	1	0	0
90	1741	1740	0.0006	2	0.0177	0.003	4.27	2076

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
90	1652	1652	0	2	0.0194	0.07	3.7	2099
90	1234	0	1	1	NaN	1	0	0
100	1457	1456	0.0007	2	0.0247	0.28	3.32	1992
100	1678	0	1	1	NaN	1	0	0
100	1605	1604	0.0006	2	0.0176	0.006	4.18	1970
100	1663	1662	0.0006	2	0.0216	0.16	3.62	1723
100	1537	0	1	1	NaN	1	0	0
110	1472	1472	0	2	0.0277	0.39	3.42	1868
110	1843	0	1	1	NaN	1	0	0
110	1644	1644	0	2	0.018	0.18	3.97	1769
110	1679	1677	0.0012	2	0.0248	0.28	3.45	1510
110	1649	0	1	1	NaN	1	0	0

Table D.7: Scenario 4, MS employment results

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
0	1881	1880	0.0005	15	NaN	0	0.0146	4.41	6981
0	1430	1430	0	15	NaN	0	0.0145	4.41	5835
0	1440	1440	0	15	NaN	0	0.0146	4.41	6609
0	1536	1536	0	15	NaN	0	0.0145	4.41	5250
0	1402	1402	0	15	NaN	0	0.0145	4.3	5683
10	1881	1880	0.0005	15	NaN	0	0.0146	4.41	6357
10	1430	1430	0	15	NaN	0	0.0145	4.41	5835
10	1440	1440	0	15	NaN	0	0.0146	4.41	6258
10	1536	1536	0	15	NaN	0	0.0145	4.41	5250
10	1402	1402	0	15	NaN	0	0.0145	4.3	5683
20	1881	1880	0.0005	15	NaN	0	0.0146	4.41	6212
20	1430	1430	0	10	NaN	0	0.0145	4.41	5835
20	1576	1576	0	8	NaN	0	0.0185	4.41	5822
20	1536	1536	0	15	NaN	0	0.0145	4.41	5250
20	1402	1402	0	15	NaN	0	0.0145	4.3	5683

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
30	1881	1880	0.0005	8	NaN	0	0.0146	4.41	5917
30	1430	1430	0	6	NaN	0	0.0145	4.41	5835
30	1576	1576	0	4	NaN	0	0.0185	4.41	5111
30	1536	1536	0	9	NaN	0	0.0145	4.41	4998
30	1402	1402	0	15	NaN	0	0.0145	4.3	5683
40	1553	1553	0	6	NaN	0.001	0.0146	4.4	5514
40	1220	1220	0	6	NaN	0.0003	0.0185	4.3	5313
40	1655	1655	0	2	NaN	0.0001	0.0185	4.41	4475
40	1536	1536	0	6	NaN	0	0.0145	4.41	4833
40	1604	1604	0	14	NaN	0.0006	0.0144	4.39	5412
50	1295	1294	0.0008	2	NaN	0.003	0.0185	4.4	5288
50	1240	1240	0	2	NaN	0.0002	0.0185	4.4	5230
50	1590	0	1	2	NaN	1	NaN	1	0
50	1536	1536	0	4	NaN	0	0.0145	4.41	5250
50	1548	1547	0.0007	10	NaN	0.002	0.0144	4.38	5896

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
60	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
60	1513	1513	0	NaN	15	0	0.0196	4.41	6069
60	1360	1360	0	NaN	15	0	0.0195	4.41	4569
60	1342	1342	0	NaN	15	0	0.0196	4.41	5100
60	1679	1679	0	NaN	15	0	0.0194	4.41	6965
70	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
70	1513	1513	0	NaN	15	0	0.0196	4.41	6069
70	1360	1360	0	NaN	15	0	0.0195	4.41	4569
70	1342	1342	0	NaN	15	0	0.0196	4.41	5100
70	1679	1679	0	NaN	15	0	0.0194	4.41	6965
80	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
80	1513	1513	0	NaN	15	0	0.0196	4.41	6069
80	1360	1360	0	NaN	15	0	0.0195	4.41	4569
80	1342	1342	0	NaN	15	0	0.0196	4.41	5100
80	1679	1679	0	NaN	15	0	0.0194	4.41	6965

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
90	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
90	1513	1513	0	NaN	15	0	0.0196	4.41	6069
90	1360	1360	0	NaN	15	0	0.0195	4.41	4569
90	1342	1342	0	NaN	15	0	0.0196	4.41	5100
90	1679	1679	0	NaN	15	0	0.0194	4.41	6965
100	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
100	1513	1513	0	NaN	14	0	0.0196	4.41	6069
100	1360	1360	0	NaN	15	0	0.0195	4.41	4569
100	1342	1342	0	NaN	15	0	0.0196	4.41	5100
100	1679	1679	0	NaN	15	0	0.0194	4.41	6965
110	1336	1335	0.0008	NaN	15	0	0.0194	4.41	6008
110	1513	1513	0	NaN	14	0	0.0196	4.41	6069
110	1360	1360	0	NaN	15	0	0.0195	4.41	4569
110	1342	1342	0	NaN	15	0	0.0196	4.41	5100
110	1679	1679	0	NaN	15	0	0.0194	4.41	6965

Distance (m)	Num of sent Packet	Num received Packets	Loss Ratio	D2D CQI	UL CQI	Error Rate	Delay	MOS	Throughput (Byte)
120	1336	1335	0.0008	NaN	14	0	0.0194	4.41	6008
120	1513	1513	0	NaN	11	0	0.0196	4.41	6069
120	1360	1360	0	NaN	15	0	0.0195	4.41	4569
120	1342	1342	0	NaN	15	0	0.0196	4.41	5100
120	1679	1679	0	NaN	15	0	0.0194	4.41	6965
130	1336	1335	0.0008	NaN	13	0	0.0194	4.41	6008
130	1513	1513	0	NaN	10	0	0.0196	4.41	6069
130	1360	1360	0	NaN	15	0	0.0195	4.41	4569
130	1342	1342	0	NaN	15	0	0.0196	4.41	5100
130	1679	1679	0	NaN	15	0	0.0194	4.41	6965
140	1336	1335	0.0008	NaN	11	0	0.0194	4.41	6008
140	1513	1513	0	NaN	9	0	0.0196	4.41	6069
140	1360	1360	0	NaN	15	0	0.0195	4.41	4569
140	1342	1342	0	NaN	15	0	0.0196	4.41	5100
140	1679	1679	0	NaN	15	0	0.0194	4.41	6965

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**UL CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
150	1336	1335	0.0008	NaN	10	0	0.0194	4.41	6008
150	1513	1513	0	NaN	9	0	0.0196	4.41	6069
150	1360	1360	0	NaN	15	0	0.0195	4.41	4569
150	1342	1342	0	NaN	15	0	0.0196	4.41	5100
150	1679	1679	0	NaN	15	0	0.0194	4.41	6965
160	1336	1335	0.0008	NaN	9	0	0.0194	4.41	6008
160	1513	1513	0	NaN	8	0	0.0196	4.41	6069
160	1360	1360	0	NaN	15	0	0.0195	4.41	4569
160	1342	1342	0	NaN	15	0	0.0196	4.41	5100
160	1679	1679	0	NaN	15	0	0.0194	4.41	6965
140	1679	1679	0	NaN	15	0	0.0194	4.41	6965

Table D.8: Scenario 4, MS employment, 2m interval (40m-50m)

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
42	1553	1553	0	4	0.001	0.0145	4.4	5214
42	1220	1220	0	2	0	0.0185	4.41	4936
42	1655	1655	0	2	0.0004	0.0185	4.36	4269
42	1536	1536	0	6	0	0.0145	4.41	4678
42	1604	1604	0	14	0.0006	0.0144	4.39	5397
44	1553	1553	0	4	0.001	0.0145	4.4	5101
44	1220	1220	0	2	0	0.0185	4.41	4811
44	1655	1655	0	2	0.0004	0.0185	4.36	4012
44	1536	1536	0	6	0	0.0145	4.41	4187
44	1604	1604	0	13	0.0006	0.0144	4.39	5309
46	1553	1553	0	3	0.001	0.0146	4.4	4911
46	1220	1220	0	2	0	0.0185	4.41	4678
46	1655	1655	0	2	0.0009	0.0185	4.36	3896
46	1536	1536	0	4	0	0.0145	4.41	3896
46	1604	1604	0	11	0.0006	0.0144	4.39	5173

Distance (m)	**Num of sent Packet**	**Num received Packets**	**Loss Ratio**	**D2D CQI**	**Error Rate**	**Delay**	**MOS**	**Throughput (Byte)**
48	1553	1553	0	3	0.001	0.0146	4.4	4879
48	1220	1220	0	2	0	0.0185	4.41	4529
48	1655	0	1	1	1	NaN	1	0
48	1536	1536	0	4	0	0.0145	4.41	3860
48	1604	1604	0	11	0.0006	0.0144	4.39	5100