Enabling Edge Computing In 5G Via Local Area Data Network: Implementation and Experiments [1]

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Abstract

The benefits of cloud computing are eclipsing when compared to other technologies, but the applications of cloud computing are very much cloud computing also has limitations due to its centralized architecture. The centralized cloud computing architecture gives rise to unnecessary delays which result in poor user experience. To avoid this, a decentralized cloud computing concept was introduced. In this concept computing and storage part of the cloud was to be moved as close to the user equipment as possible. By doing so the overall delays can reduce significantly which will enhance user experience. The decentralized approach is known as edge computing and is an integral part of 5G communication. Local Area Data Network (LADN) is a part of that architecture. The main purpose of LADN is to reduce the end to end delay that users experience while accessing data(audio/video/websites) from the Internet.

This thesis is based upon the implementation of the LADN in 5G communication. Our main focus is to reduce latency or response time of requests. If implemented properly the number of requests that will need a response from the Internet will be reduced and will be serviced locally at the edge cloud. The reason behind this decision was that the demand for video/visual traffic on the Internet is increasing exponentially. It is also predicted that this trend will only increase with time. That being said the LADN can be implemented on all kinds of traffic and is a perfectly scalable solution.

We implemented the LADN architecture by taking a Long-Term Evolution E-UTRAN Node B and connecting it with the Mobility Management entity server that hosted the 5G architecture inside its. Once we were able to access the Internet via the UE, we added a LADN server in the topology. We then connected the LADN server and the MME with the help of a switch. Then we tested if the LADN server was accessible via the UE. Once all this was set up, we performed the Ping, iPerf and traceroute tests to gather the data and to analyses the results.

The results from the experiment revealed that the implementation of LADN will lead to lower RTT for the user and a higher data rate. It was also established that the number of hops a request has to travel was also reduced significantly. Therefore, the establishment of LADN will be very beneficial.

Preface

Since our university is in close cooperation with Telenor Maritime and they use satellite communication to provide connectivity to their onboard customers. We all know that satellite communication always leads to huge end-to-end delays and is very costly as well. Therefore, if anything can be done to enhance the user experience while reducing the overall cost, it will be very beneficial for end users. Hence, we decided to work on the LADN solution.

This thesis project was a part of the subject IKT590, Master's Thesis. The duration of this project was from August 19th, 2019 to January 10th, 2020 The course contains 30 credits towards the degree of MSc ICT. The project topic was proposed by Dr. Frank Li in cooperation with Prof. Jyh-Cheng Chen and Dr. Sebastian Tan from National Chiao Tung University Taiwan. The work was done at the University of Agder Grimstad. The University of Agder provided the devices, which in this case was 1 5GC small cell (purchased from GEMTEC), one D-Link router and two stands Alone PC with Ubuntu OS. The 5GC software was provided by NCTU Taiwan.

From the University of Agder, I had Frank Li as my main supervisor. He provided constant assistance with his in-depth understanding of 5G systems and how to proceed with the test. A special thanks to the NCTU team and GEMTEC for providing remote assistance for troubleshooting whenever required.

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Abbreviations

Abbreviation	Description
AMF	Access and Mobility Management Function
CMP	Internet Control Message Protocol
CO server	Central Office Server
DHCP	Dynamics Host Configuration Protocol
DNS	Domain Name Server
EARFCN	E-UTRA Absolute Radio Frequency Channel Number
eNB	E-UTRAN Node B
EPC	Evolved Packet Core
GW	Gate Way
HSS	Home Subscriber Server
HTTP	Hypertext Transfer Protocol
IP	Internet Protocol
GEO	Geo-stationary earth orbit
L2	Layer 2 / MAC Layer
L3	Layer 3 / Network layer
LEO	Low earth orbit
LADN	Local Area Data Network
LAMP	Linux + Apache + MySQL + PHP/Perl/Python
LAN	Local Area Network
MEC	Mobile Edge Computing
MEO	Medium earth orbit
MME	Mobility Management Entity
NAT	Network Address Translation
NOC	Network Operation Center
OS	Operating System
PCF	Policy Control Function
PAT	Port Address Translation
POE	Power Over Ethernet
QoS	Quality Of Services
RA	Registration Area
RAN	Radio Access Network
RTT	Round Trip Time
SCTP	Stream Control Transmission Protocol
SMF	Session Management function
TA	Tracking Area
TAI	Tracking Area Identifier
TCP	Transmission Control Protocol
UE	User Equipment
UPF	User Plane Function

1 Introduction

In this chapter, we first describe several background factors and the problem statement of this thesis work followed by the motivation. After the research methodology is explained to highlight important methods that we used during the thesis work. The chapter ends by providing an outline of the next chapters.

1.1 Background and Motivation

Since the Internet is mostly used for entertainment purposes nowadays, therefore the requirement of connectivity has been changed significantly. The users want to be online even if he is traveling by sea or by air, hence it can be said the users need for connectivity can no longer be bounded by location or time. Although the conventional wired network is very reliable it does not support the level of mobility which is needed by the users. Even pure cellular networks cannot overcome the limitation of location since we can get cellular connectivity while we are traveling by air or by sea. To provide connectivity in these scenarios we need satellite communication to connect with our cellular or wired network.

Hence a hybrid approach needs to be adopted that will lead towards the integration of various types of communication networks under a single umbrella. With 5G this can be achieved, and the user will get highly reliable connectivity with ultra-low latency.

Now the connectivity problem is solved but satellite links are very expensive and lead to significantly higher delays. Both of which will degrade the user experience. Have you ever tried to watch/download a movie online while you are on a cruise ship? If you have then you know how painful this experience is, hence something has to be done to improve the user experience.

We think that this issue can be solved by Multi-access Edge Computing or Mobile Edge Computing (MEC). Since the biggest hurdle in utilizing the cloud computing was the enormous delays that the user has to suffer. MEC introduced a distributed cloud concept where the cloud will be placed as close to the user as possible. "Edge computing is acknowledged as one of the key pillars for meeting the demanding Key Performance Indicators (KPIs) of 5G, especially as far as low latency and bandwidth efficiency are concerned" [1, p. 4]. MEC opens network edges for application and services as it acts as a small distributed data center or cloud. This way all computing can be done as close to the cloud as possible and result in low latency and better bandwidth utilization. Local Area Data Network (LADN) act as enabler of MEC in 5G" [1, p. 5].

Videos trending on the internet and movies will be stored locally on the ship. Now, whenever a user sends a request it will first search its internal database and if a match is found the user will watch the video on the LAN. On the other hand, if the video is not found on the local database only then the request will be forwarded to the external network over the Satellite link. the Ship will update its database whenever it reaches a mobile services coverage area to keep it up to date. While in open waters the entire ship act as LADN service area where each request will be responded by the MEC located on the ship.

The main motivation behind this thesis was to enhance the user experience and make their traveling experience more delightful by finding out that how much RTT can be reduced with MEC as compared to public internet and satellite internet. We will also find out how much throughput can be achieved while using MEC as compare to using public internet and satellite internet. Will this lead to optimal utilization of resources by reduction of traffic on the external link. The later can be achieved once the LADN is fully implemented.

1.2 Problem Statement

To address this problem 5G introduced the concept of LADN which will reduce the traffic volume on the satellite links. Our main problem statement was to design a network that will result in a significant reduction in RTT experiences by the user while accessing the videos on the satellite link. The main aim is to enhance user experience but if that also leads to traffic volume reduction on the satellite link it will be a huge bonus.

The main motivation behind this master thesis is as follow:

- Reduce RTT while accessing the entertainment
- Reduce the traffic load on the satellite link
- Provide in-house on-demand Mobile entertainment during traveling

In LADN a large number of user quires can be responded by the LADN servers and hence the traffic over the internet reduces. Since the LADN server is located as close to the edge as possible hence the RTT will also be improved.

1.3 Research Methodology

Our first step will be to set up the lab and connect all its components LADN server, Mobility management entity (MME), User equipment (UE), E-UTRAN Node B (eNB LTE small cell) and D-links router with each other. Then we will configure them as per the required topology. Now we can check if UE can access the internet via eNB. Once these steps are established, we can move to our next stage which is the testing and result gathering phase.

We divided the entire process into following three stages,

I. Installation/configuration of real-life testbed and gathering test results (Chapter 3)

II. Installation/configuration of simulation and gathering test results (Chapter 4)

III. Feasibility of LADN(Stage I and II) VS Satellite link, and will also comparing the test results (Chapter 5)

First, we start with the installation of Lab setup and then configure the equipment as per the desired topology. Once it is done, we can start with tests. The main tests will be to run ping [2], traceroute [3] and i-Perf [4] . Ping will find the end to end latency while i-Perf will be used to find out data rate that can be achieved on the local link and since we need to simulate ideal conditions hence to find out the number of hops required to reach the google DNS and YouTube server, we will need the traceroute command. The reason behind using ping is to find out RTT and Traceroute to find out the number of hops the traffic will travel to get a request serviced. While i-Perf is the only test that provides you data rate in terms of TCP and UDP traffic that can be achieved on a network segment. In i-Perf, we will denote the LADN server as the i-Perf server that will generate some TCP or UDP traffic. The UE will act as an i-perf client and will download that traffic on it. In this way, we can find out what will be data rate in terms of TCP and UDP traffic on the LADN.

Second, now we can create a simulation. Since a simulation is an approximate imitation of the operation of a process or system. Therefore, the simulation will use the same Lab topology. We will use cisco's packet tracer as simulator and will repeat the above experiment in ideal conditions but with two different core configurations. We state ideal conditions as there will be no external traffic with which the UEs will have to compete. we will run the same ping test with two different routing protocols and find out the RTT of LADN VS Google domain name server (DNS). The no. of hops will be the same as listed in the traceroute test of the real-life testbed stage.

The results from all these three scenarios will be compared with each other and we will find out the difference of RTT between LADN and the internet in these different scenarios.

1.4 Thesis Outline

This thesis consists of 6 chapters, where:

- Chapter 1 will be the introduction of the LADN solution.
- Chapter 2 will cover earlier work and enabling technologies for LADN implementation.
- Chapter 3 and Chapter 4 will take more focus on implementation and experiments on LADN solutions. Chapter 3 will be based upon a real-life testbed-based solution while Chapter 4 will lean towards simulation setup for LADN solutions.
- In Chapter 5 we will discuss the feasibility of LADN for satellite communication and finally, Chapter 6 will describe the conclusion and future works.

2 Enabling Technologies

In this chapter, we will discuss the concept of the LADN, and previous studies done on it. We will also discuss the use of cases of LADN and enabling technologies

2.1 Edge Computing

The concept of cloud computing is widely known and implemented. The implementation of cloud computing provided universal access, this is of prime importance for a project-based organization with geographically distributed resources. It also provides more storage spaces, automatic updates, simple configuration and is very cost-effective. Since the computing is done on the cloud you can run heavy-duty applications on simple low-cost computers. Since most of the maintenance is done at the operator side the Operational cost is also reduced significantly. Although these benefits were sufficient for clients' needs, but the emergence of new applications require faster response time. Some changes need to be made in the conventional cloud computing concept. If the cloud is located at a centralized location, then the distance between the cloud and the user dictates the response time. But with the emergence of IoT and interactive video streaming the conventional response time is not suitable.

Therefore, to reduce the response time it was proposed that resources at the cloud are to be moved closer to user location creating a decentralized cloud. This is known as edge computing. Now the latency-sensitive application can be processed at the edge. The edge should be placed as close to the user location as possible to avoid unnecessary delays. Figure 2-1 shows the concept of edge computing.

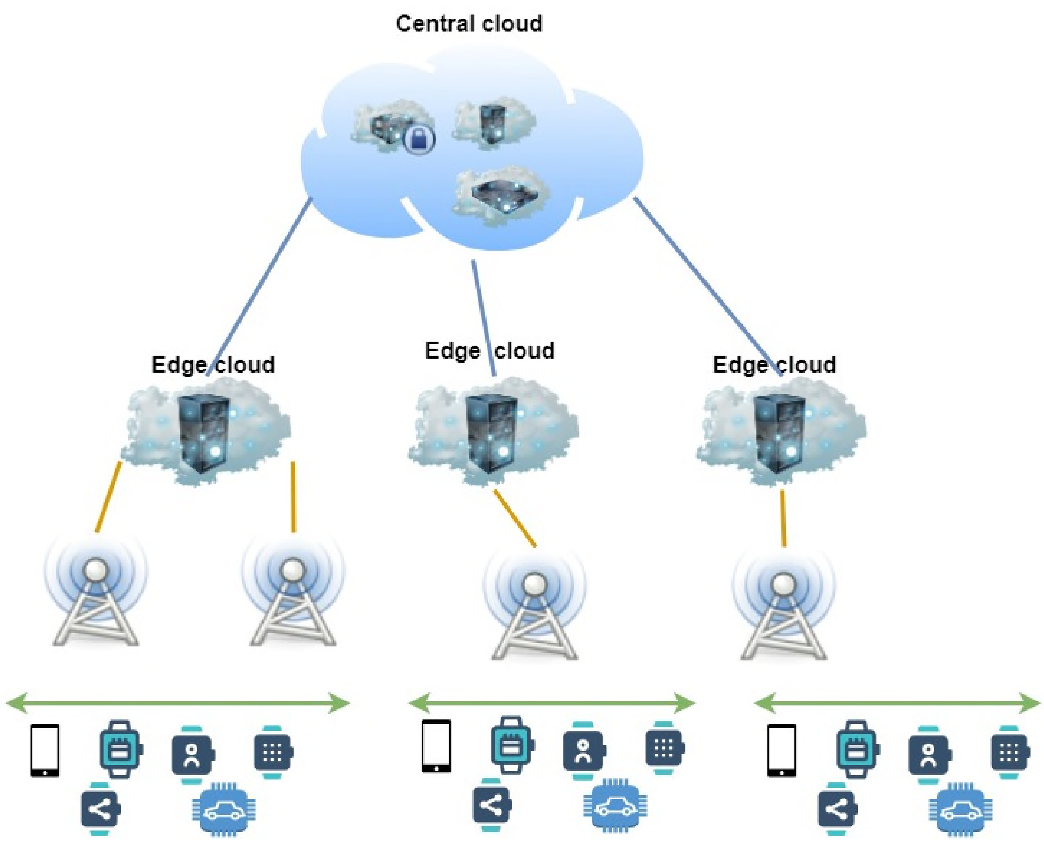

Figure 2-1 Edge Computing.

It can be seen in Figure 2-1 that edge cloud is placed closer to the User location while maintaining a connection with the central cloud. In this way, the resources intensive and latency-sensitive application can be processed by the edge cloud and the user can avoid unnecessary delays. Users can also enjoy resource-intensive applications on their mobile devices which was not possible before.

The Edge cloud provides real-time data processing, M2M communication, low latency, location awareness and user-defined security among other benefits that were not available in conventional cloud computing but are required by the current applications. Therefore, the utilization of edge-based cloud computing will enhance significantly.

2.2 MEC

mobile edge computing aka multi-access edge computing provides the edge computing platform at the radio access network (RAN) which is close to the end-users (mobile subscribers). This reduces latency and improves the user experience [5, p. 4].

To achieve this phenomenon the routing of applications traffic on the core network should be done based upon application requirement and available resources on the local network (Mobile edge) and external network. the 5G Core Network selects the traffic to be routed to the applications in the local Data Network [6, p. 127].

Due to the rapid growth in mobile traffic, it is also very beneficial if some requests can be processed by the MEC rather than sending them to centralize the cloud or data center to get processed. With the emergence of IoT and resource-intensive applications such as online gaming, graphical applications the conventional concept of the centralized cloud was unable to satisfy their delay requirement. But since the user wanted these applications on the go they mobile network needed to make some adjustments. The concept of MEC allowed these applications to be serviced in the RAN network which enhanced the user experience by satisfying applications delay requirement. Figure 2-2 shows a few market drivers for MEC. In this thesis, we will concentrate more on low latency in the technical integration portion of Figure 2-2.

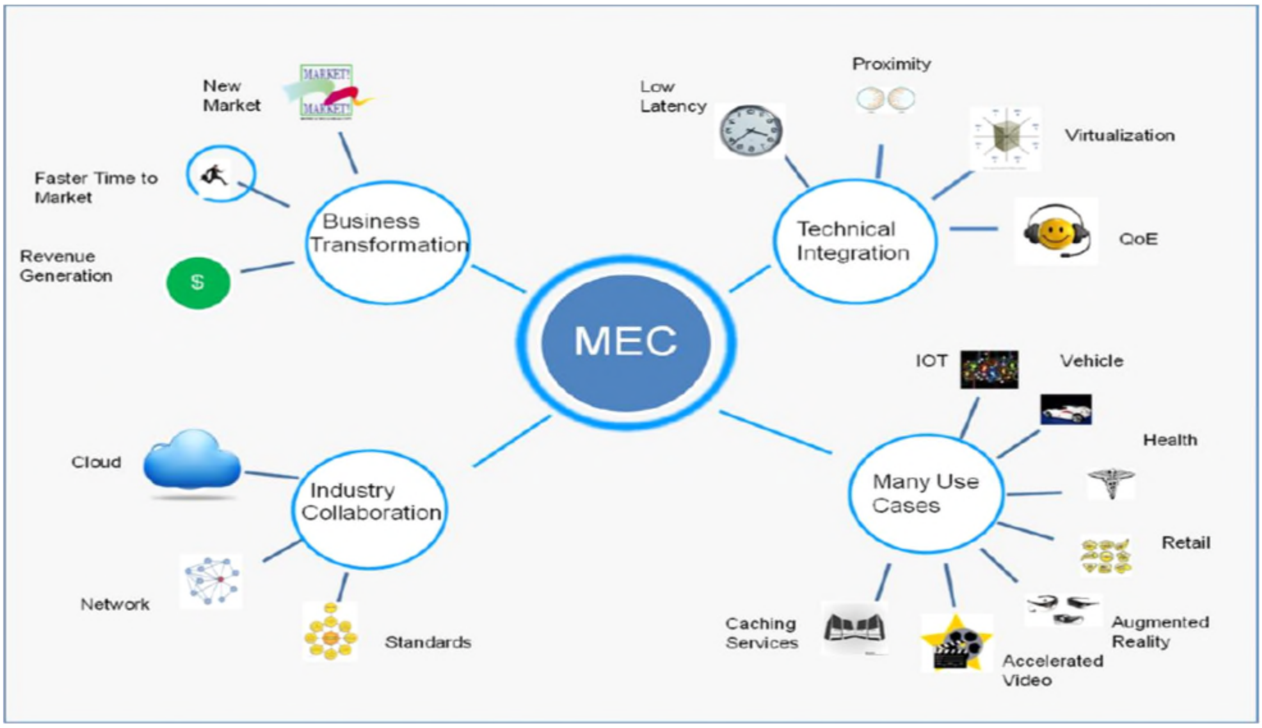

Figure 2-2 MEC Market Drivers. [5, p. 6]

2.3 Local Area Data Network

The MEC represents the distributed datacenter in the 5G core network so that the operator can easily and efficiently offload traffic to provide edge computing. The local Area Data network is an enabling technology of MEC. LADN provides data network connectivity services to the User Equipment (UE) by geographically isolating the operator's network resources [7, p. 141]. Therefore, the UE can only connect with the LADN session if the UE is located in a geographical area that supports LADN.

As soon as the UE is connected to the LADN session it gets allocated a new IP and Prefix but the existing PDU session is still maintained to support mobility [7, p. 141]. Since LADN is a relatively new concept the only details we were able to find on this topic were from [7] [6] .

Since LADN is the main topic we present below the principles of LADN in detail.

2.3.1 Concept

Figure 2-3 shows that A single LADN service area can cover multiple cells and can be overlapping with a neighboring LADN service area to satisfy the mobility requirements. Similarly, a single Registration Area may contain multiple LADN service areas, depending upon the application requirement and traffic density. If the UE is moving the LADN service Area 1 it can establish a Protocol Data Unit (PDU) session with LADN 1 via User Plan Function 1(UPF1). If the user is in geographical rea that is not covered by the LADN it cannot establish an LADN session but can still have a Data Network (DN) session.

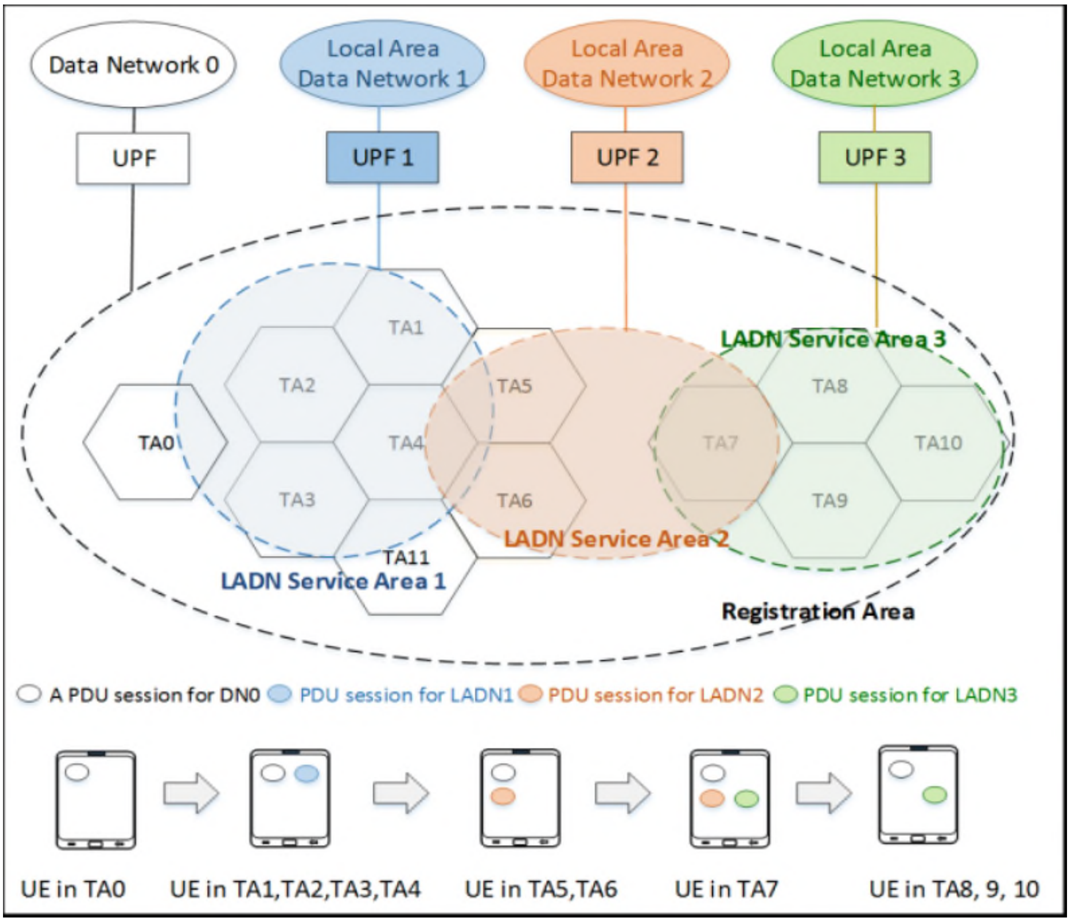

Figure 2-3 A Concept of LADN. [7, p. 141]

2.3.2 **Usage Scenarios**

There are four main usage scenarios listed below as described in [7] .

I. LADN realizes 5G application with Low latency and high data rate, since the operator can locate a dedicated UPF near RAN.
II. LADN supports the enterprise campus scenario. Restricts the IP connectivity of employees located in the Campus area, who are authorized access to local enterprise servers
III. LADN supports the shopping mall scenario. Provide customer sponsored IP connectivity to a customer located in the mall area.
IV. LADN supports the special event scenario. Offload the subscriber increasing data traffic that is coming from a localized area where the event is taking place

In this thesis document, we will consider only the first usage scenario and compare the latency or RTT among requests that can be processed by LADN and requests that need to be processed by the conventional data network.

2.3.3 **LADN Core Components**

The two main parts of LADN architecture that the operator need to configure while enabling LADN services are:

I. LADN Service Area

Whenever a UE needs to avail services from the service provider the UE needs to be register in the Access and Mobility Management (AMF) of the core network. The AMF then assigns a set of Tracking Areas (TA) in the (Tracking Area Identifier) TAI list [6, p. 51]. This list represents the registration area (RA). The entire registration area may not have LADN services. The part of the registration area that provides LADN services is known as the LADN service area. The LADN service area is further divided into tracking areas. The operator needs to add this service area information to the AMF in the core network.

II. Data Network Name (DNN)

Each LADN service area must also be given a data network name that will identify the LADN service area and its corresponding tracking areas. [7, p. 142]

2.3.4 **LADN Discovery**

In the 5G core Network, AMF notifies the UE if LADN services are available in its registration area. If the registration area contains LADN services, the AMF provides the UE with the DNN and set of TA corresponding to the LADN service area. [7]

There are some limitation or constraints such as:

I. LADN service applies only to 3GPP accesses and does not apply in Home Routed case. [6, p. 75]
II. The usage of LADN DNN requires an explicit subscription to this DNN or subscription to a wildcard DNN. [6]

2.3.5 **LADN Session Establishment**

After LADN discovery the UE may request a PDU session establishment with respective LADN service area. Based upon the UE application request if the LADN can process the request it will be processed. The UE will be allocated an UPtun IP Address which will be used to access LADN services among other things. The established session is then monitored by the Session Management Function (SMF).

2.3.6 **Session Termination Due To Mobility**

Since the UE is a mobile device and is in motion sometimes. if the UE moves out of the LADN service area it can no longer avail LADN services and the UPF will drop all the data packets sent to UE from LADN. but there is two way of doing this.

I. **The UE does not report its position when crossing the LADN boundary** [7, p. 143]
In this case, the network will perform the paging procedure and find out whether the UE is still in the LADN service area or not. If the UE is outside of the LADN service area the UPF will drop all downlink packets to the UE.

This will save power for the UE as it does not have to report its position while moving out of the LADN service area, however, it involves unnecessary paging to wake the UE up even if it is no longer in the LADN service area. [7]

II. **The UE reports its position when crossing the LADN boundary** [7]
The UE reports its position when moving into or out of the LADN service area. The position reporting is done by a mobility registration procedure. Although this solution will eliminate unnecessary paging but will enhance UE power consumption.
When the UE is out of a LADN service area, the UE:. [6, p. 77]
- shall not request to activate UP connection of a PDU Session for this LADN DNN
- shall not establish/modify a PDU Session for this LADN DNN;
- need not release any existing PDU Session for this LADN DNN unless UE receives explicit SM PDU Session Release Request message from the network.

When the UE is in a LADN service area, the UE: [6]
- may request a PDU Session Establishment/Modification for this LADN DNN;
- may request to activate the UP connection of the existing PDU Session for this LADN DNN.

2.4 Other Relevant Technologies

The list of other enabling technologies comprises 5GC, NAT, Routing protocols (EIGRP/OSPF) and LAMB stack. We will shortly describe these technologies while 5GC will be described in Chapter3.

2.4.1 **Network Address Translation (NAT)**

NAT stands for network Address translation and was created to reserve the IPv4 address but has many uses. There are two types of IP addresses Public and Private IP addresses. The Public IP address is a unique identifier and is routable on the internet and hence it needs to be purchased. The Private IP address is not unique and hence can’t be routed on the internet.

However, these addresses can be used as a local address for the internal network. Both 4G and 5GC uses these addresses. But since the client needs to access the global internet as well hence the Gateway router is configured to translate these Private addresses into public addresses when leaving the local domain. Similarly, the same procedure is adopted for the return traffic but now the public address is translated to private address this. This procedure is known as NAT.

Figure 2-4 [8] shows the basic operation of NAT. the inside local addresses are in private IP address range and the outside global address is in Public IP address range. The Table shows how the private IP address range can be translated as a single IP address in the public domain. The users are differentiated through ports that are used to initiate the session. This is known as NAT overload or Port Address Translation (PAT). The request-response when lands on Gateway or Edge router it gets translated to the user's private IP address based upon the NAT Table and port number.

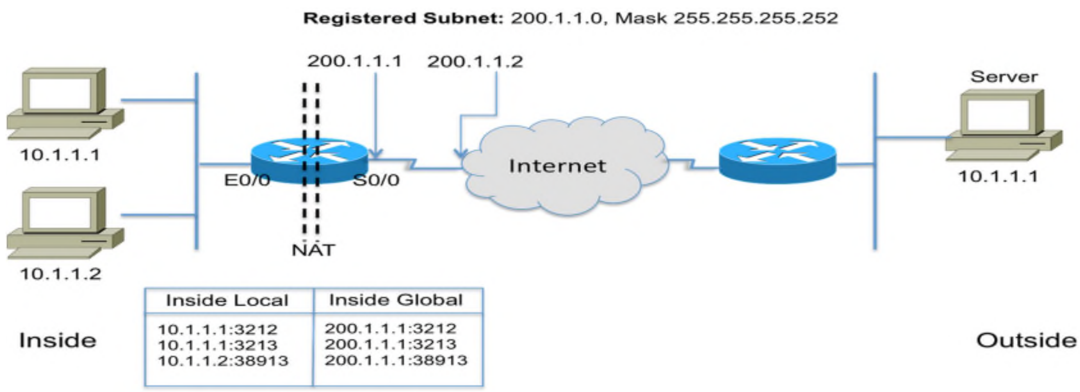

Figure 2-4 NAT. [8]

It was mainly developed to conserve rapidly depleting IPv4 addresses on the public domain, but it also adds to the security of the network as the attacker scanning the network will only see the public IP address and not the private IP address assigned to the users.

2.4.2 **Routing Protocols**

The routing protocols used to route traffic both internally and externally can be divided into two main types of protocols Link state and Distance vector. The main difference between them is how they select a route from the source to destination. We decided to use one from each type from Link state we used OSPF while from distance vector we used EIGRP. The main difference between distance vector and link-state is given in Table 2-1 [9, p. 102].

We used these protocols to configure our core networks in simulations to observe how they affect the RTT response. As per [9, p. 106] distance vector algorithm gave a better average delay then link-state algorithms. But link-state algorithms have other advantages as described in Table 2-1.

Different Aspects	Distance vector(DV)	Link state(LS)
Forwarding Table	A node sends to its neighbors the whole routing Table (its distance vector).	A node sends to each the other one the case of the link with the current neighbors by a dependable flooding.
Route Updates	Are sent periodically or when a topological variation is observed.	Are sent periodically or when a topological or when a topological variation is observed.
Path computation	It is established on a distributed version of the classical bellman ford algorithm (DBF)	A node can then make the chart of the network and can compute the path from itself to each other node independently.
Information generating	A node running a distance vector protocol does not know the entire network topology.	Because of flooding, all nodes eventually receive each the link cases from each the other nodes of the network
Topology Store	All node stores the neighbor's information at the end on the network topology.	All nodes have knowledge on the whole network with the state of each link between any two neighboring routers
Topology Change	Distance Vector (DV) protocols may poorly affect to a topology change ago, it endures from very low convergence (count to-infinity problem) and may make provisional loops.	Link States (LS) converges faster than DV but it needs a higher overhead.
Example	A well-known example of Distance Vector (DV) is RIP, EIGRP	A well-known example of Link States Advertisement (LS) is OSPF.

Table 2-1 Difference Between Distance Vector And Link State Routing Protocols. [9, p. 102]

2.4.3 **LAMP Stack**

LAMP stack is combination on LINUX+ Apache + MySQL+ PHP environments [10]. It is an open-source set of applications that once installed on ubuntu OS will allow it to host websites [10]. It is an Open source and widely used application that allows website hosting and database management. Its main advantage is the is highly flexible in supporting different database, web server, and scripting languages.

Since the LADN server located on the MEC requires a website to host web information on a website that can be accessed by the users traveling on the cruise ship hence we need to install some kind of web hosting platform and LAMP stack was suitable for this purpose in Ubuntu or Linux based environment.

3 Real-life Testbed-based Implementation and Experiments

This chapter describes the different components that came together to configure the LADN environment. How were they connected and configured? The configuration files for the LAB setup will also be shared in this chapter. Finally, we will illustrate some trouble-shooting tips and the test results that were gathered in this stage.

3.1 System Overview

This stage belongs to the installation/configuration of the real-life testbed and gathering the test result. Figure 3-1 shows the topology of the real-Life testbed. This testbed can be divided into two parts. Part 1 is the Lab which must be installed and configured. Everything below the UiA router comes under the access network. Part 2 is the actual core network that does not need installation and configuration. Part 2 includes the UIA router and everything above it. This stage is mostly concerned with the installation and configuration of Lab setup.

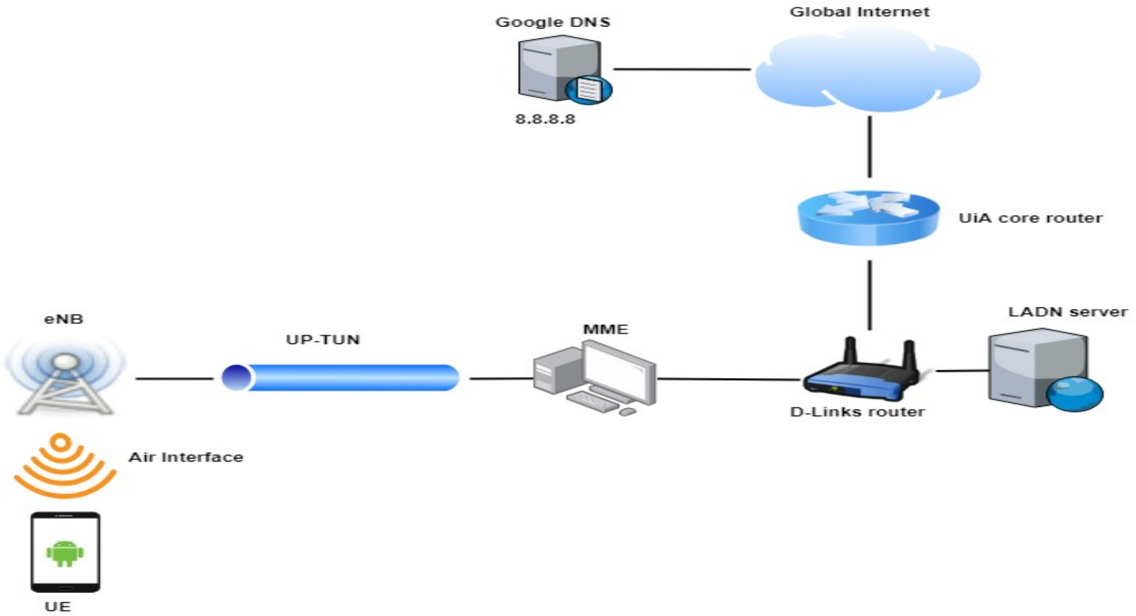

Figure 3-1 Real-life Testbed Topology.

3.1.1 Real-life Testbed Lab Setup

Figure 3-2 shows the actual lab setup. The major component required for lab setup is tagged in Figure 3-2 and are listed below:

I. One LTE small cell
II. One UE
III. MME
IV. LADN server
V. D-links router

We start with LTE small cell and to enable LTE signals we need to install and configure it as per our requirement. Once this is done, we will move to our next step which is the installation and configuration of Mobility Management Entity which is a desktop PC that holds the 5G application setup. Now we are ready to configure the UE so that it can be connected to the

MME via LTE small cell. Then the MME will be connected to the D-Link router which is connected to the internet. At this stage, we should be able to surf the internet from the UE. The last step is to configure the LADN server which will host the webpage with videos and connect it with the D-Link router. Now the lab setup is complete, and we can start the tests.

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Figure 3-2 Setup of Lab Equipment.

3.2 Hardware Installation

In this section, we will discuss in detail the different hardware components that we used and their configuration. the hardware component mainly consists of Small cells, MME, UE, LADN-Server and the D-Link router.

3.2.1 LTE Small Cell

This LTE small cell is based on the 3GPP standard R9 defined to implement all stack from L1-L3. The Figure. This small cell provides wireless signals, which allow the UE to be connected with the Small cell. Figure 3-3 illustrates different parts of LTE small cells.

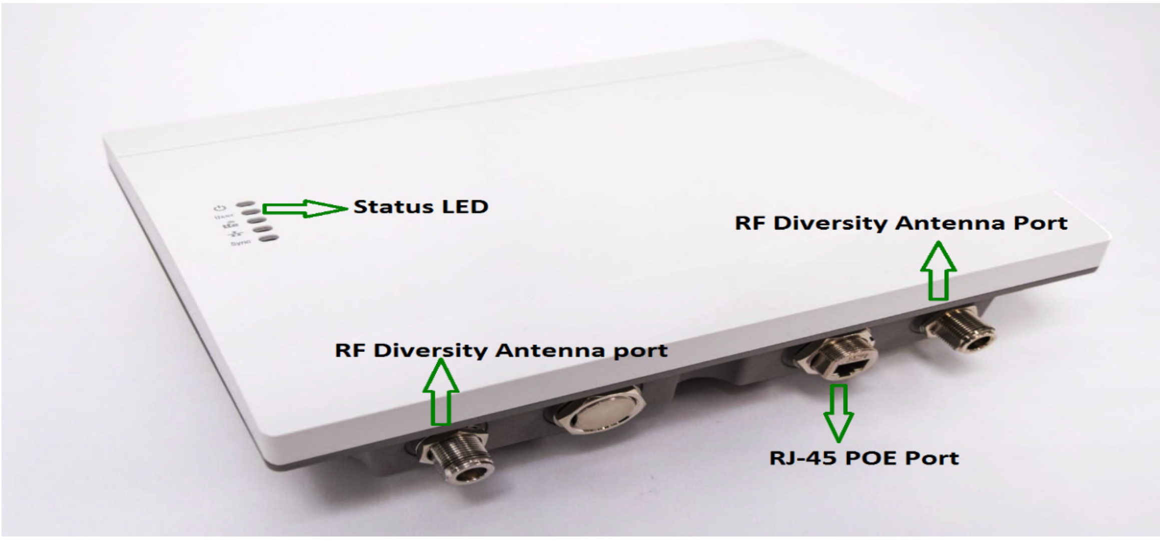


Figure 3-3 LTE Small Cell.

LTE eNB. It contains two RF antennas that support the frequency band B7 at 5/10/15/20 MHz Bandwidth. The signal strength of these antennas can be controlled by limiting the transmission power. This ensures that its signals don’t interfere with LTE signals of service providers. But we still took extra precaution and scan the bandwidth before starting the actual experiment. The LTE small cell powered by POE which makes it very efficient. The LEDs provide status info of the following POWER, LTE, Ethernet, GPS sync. All of these have three options which are illustrated in Table 3-1.

Sr.No	LED Display	Description
1	Power	**GREEN:** Power ready and system ready **RED:** Power ok during booting the device **RED:** System Error or Alarm
2	LTE	**ON:** UE is attached **BLINK:** UE's traffic TX and RX **OFF:** NO LTE server
3	Ethernet	**ON:** Ethernet connected **BLINK:** Under Ethernet traffic **OFF:** No Ethernet
4	GPS Sync	**ON:** GPS source is ready **BLINK:** Under synchronization **OFF:** No GPS can be detected

Table 3-1Status LED Of LTE Small Cell.

The main purpose of this device is to provide LTE coverage in areas where the available signal strength is very low. They can be basements, remote locations, villages, etc. but we are using this to create a home cell site to provide air interface for our UE connectivity.

3.2.2 **5GC and MME Server**

Since we were using an application based 5GC environment [11], we needed a server to host this application. We used an i7 HP desktop PC with 8GB RAM and install Ubuntu 18.04 OS on it before we started with actual application installation. 5GC or 5G core service-based architecture consists of the following components.

I. **AMF** is responsible for access control and Mobility management functions, an AMF server or a given network slice. network functions AMF within the Control Plane enables other authorized network functions to access their services. [6, pp. 15,19]
II. **HSS** is the common subscriber database in the case of EPC. It acts as a master database for a given user. [6, p. 150]
III. **SMF** is a session management function it establishes and manages a session. [6, p. 15]
IV. **PCRF** is policy control roaming function UEs that are not subject to 5GC and EPC interworking may be served by entities not dedicated for interworking PCRF. [6, p. 35]
V. **UPF** is used for traffic detection and routing, it uses the information identifying a domain for this purpose. [6, pp. 15,16]

All 5 Components make the 5G core service-based architecture. When a UE is trying to connect with a cell site its request is forwarded to AMF which first checks with HSS if the new UE is allowed. Once UE is allowed access it will create a tunnel between UE and UPF to establish a connection with UPF. After connection establishment and an IP allocation, the UPF starts to route the traffic to and from the internet based upon PCRF information. SMF keeps tracks of the established sessions and manage them till they are terminated.

As shown in Figure 3-4 the MME is located between two different networks. Therefore, MME needs to have two NIC cards since the Desktop had only one NIC card we have to find out a workaround to this problem. We used a Lenovo USB to ethernet converter in its place. Small cell is connected to NIC while the D-Link side is connected to the

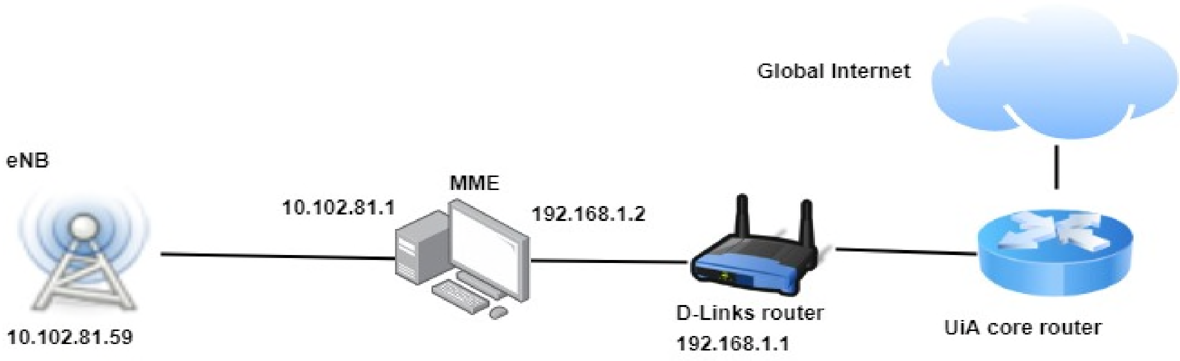


Figure 3-4 MME Connectivity.

USB to ethernet converter. The MME will work as the brain of the entire system and will be the designated gateway for all traffic that is originated from the UE. For installation, purposes follow the step by step approach in [11].

To run the application after complete installation and configuration give the following command

```
cd free5gc/install/bin/free5gc-ngcd
```

to stop the process

```
Ctrl+c
killall -9 testngc or killall -9 free5gc-ngcd
```

3.2.3 **UE**

We used a simple Samsung Android smartphone as UE. The sim card we got from the same supplier (Gemtek). Sim card's credential needs to be configured in the web-based interface. Once done successfully the UE can relate to the Small cell. The actual configuration steps are given section 3.3.3.

Multiple UEs can be attached to the same LTE small cell but for illustration clarity, we focused on one UE.

3.2.4 **D-Link Router**

We use the D-Link DIR-842 Wireless AC 1200 MU-MIMIO Dual-band router. This router has 4 Lan and 1 Wan port, which means both L2 and L3 traffic can be handled. it also has DHCP and NAT capability which made it perfect for our experiments. The router also has the Dual Ban wireless capability but since we already have the small cell we will not make use of these wireless bands. Figure 3-5 illustrates the router’s port description. Figure 3-6 depicts the specification of the router.

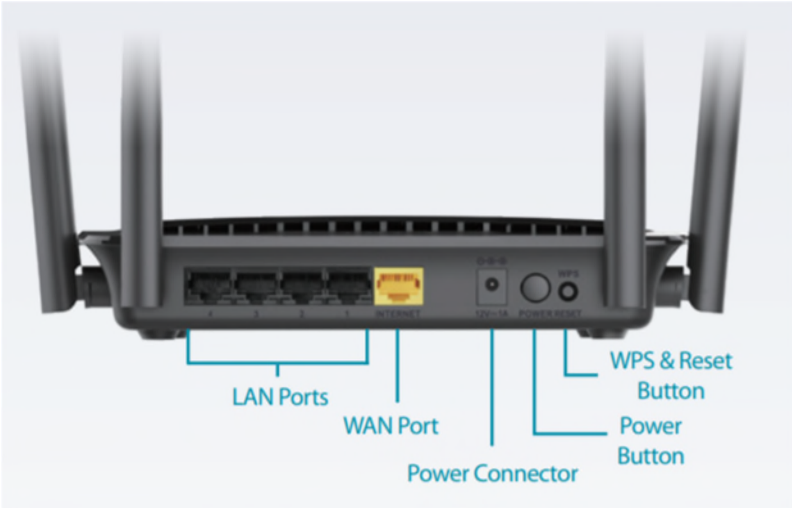


Figure 3-5 D-Links Router Port Description. [12]

Technical Specifications		
General		
Hardware Version	• C1	
Device Interfaces	• IEEE 802.11 ac/n/g/b/a wireless LAN • 10/100/1000 Gigabit Ethernet Internet WAN port	• Four 10/100/1000 Gigabit Ethernet LAN ports
LEDs	• Power • Internet • WLAN	• LAN (x4) • WPS
Antenna Type	• Four external antennas	
Operating Frequency	• 2.4 GHz band: 2400 - 2483.5 MHz	• 5 GHz band: 5150 - 5725 MHz
Standards	• IEEE 802.11ac • IEEE 802.11n • IEEE 802.11g • IEEE 802.3ab	• IEEE 802.11b • IEEE 802.11a • IEEE 802.3u
Minimum Requirements	• Internet Explorer 9, Firefox 20.0, Chrome 25.0, Safari 5.1, or other Java-enabled browser	• Cable/DSL modem or other Internet Service Provider equipment with Ethernet port
Functionality		
Security	• WPA & WPA2 (Wi-Fi Protected Access)	• WPS (Wi-Fi Protected Setup)
Advanced Features	• Web setup wizard • QoS (Quality of Service) • DMZ (Demilitarized Zone)	• Firewall - Network Address Translation (NAT) • Guest zone • IPv6 ready
Physical		
Dimensions	• 190 x 133 x 38 mm	
Weight	• 288 g	
Power Adaptor	• Input: 100 to 240 V AC, 50/60 Hz	• Output: 12 V, 1 A
Temperature	• Operating: 0 to 40 °C (32 to 104 °F)	• Storage: -20 to 65 °C (-4 to 149 °F)
Humidity	• Operating: 10% to 90% non-condensing	• Storage: 5% to 95% non-condensing
Certifications	• CE • RoHS	• FCC • D-Link Green

Figure 3-6 Router Specification. [12]

3.2.5 **LADN Server**

For LADN Server we used an i7 HP desktop PC with 8GB RAM and install Ubuntu 18.04 OS. Since this server needed to host some webpages that will host the video and audio content which will be accessed by the UE hence, we needed to install the LAMP stack. There are other uses of LAMP stack as well but since our main goal is website hosting, we will focus on that capability. Its detailed configuration will be illustrated in section 3.3.5.

3.3 System Configuration

After doing the hardware connection now we started with the actual software configuration of the equipment. The equipment was divided into 4 major phases and we will describe them one by one in detail.

3.3.1 Configuration of LTE Small Cell

This comes with a management web-based interface that can be used to configure are monitor it. The default IP to access the Web interface is 10.102.81.59/24. it needs to be connected to a desktop for this process. The desktop must have an IP address in the same range I used IP 10.102.81.1/24. Once I gave the IP address 10.102.81.59 the following Page open up as shown in Figure 3-7.

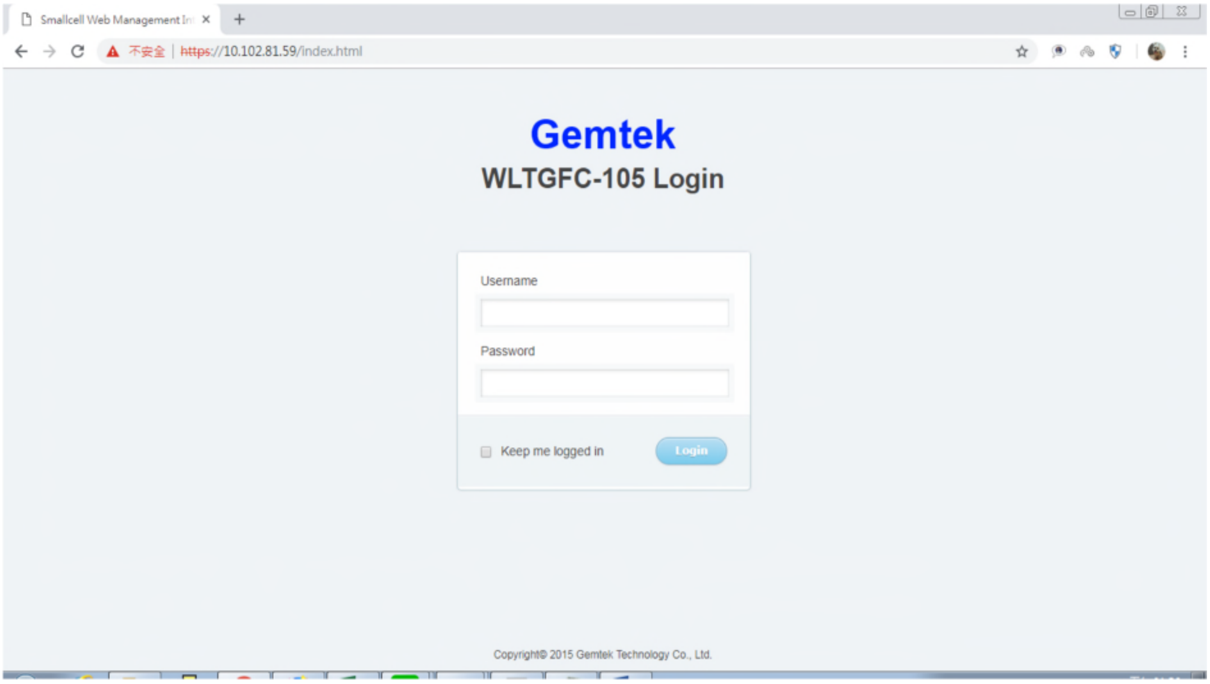


Figure 3-7 Small Cell Web Interface.

I. Login

To login provide the default username: admin password: admin. once you are logged in you will see the following status page will appear as shown in Figure 3-8.

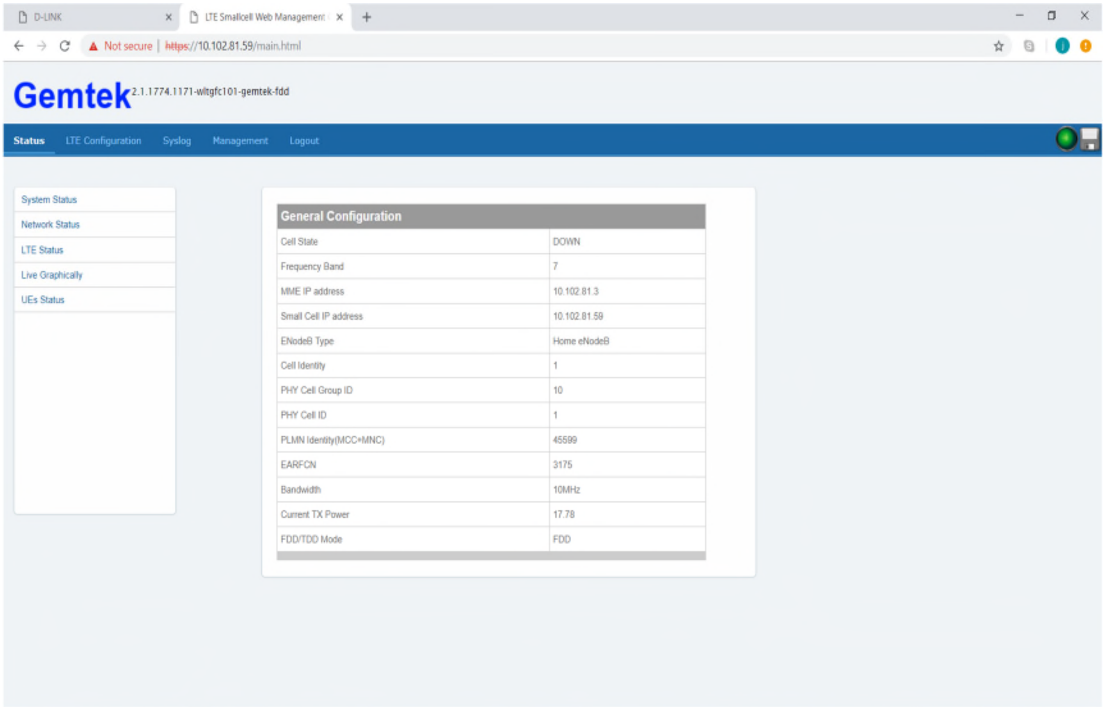


Figure 3-8 Small Cell Status Page.

II. LTE General Configuration

Now our next step is to click on the green light on the top right corner and then click on the tab LTE configuration. Now the page shown in Figure 3-9 will appear here we will change the values highlighted in red from points 4 to 7 should be changed according to the desired topology. In our case, we did the changes given below and click upload.

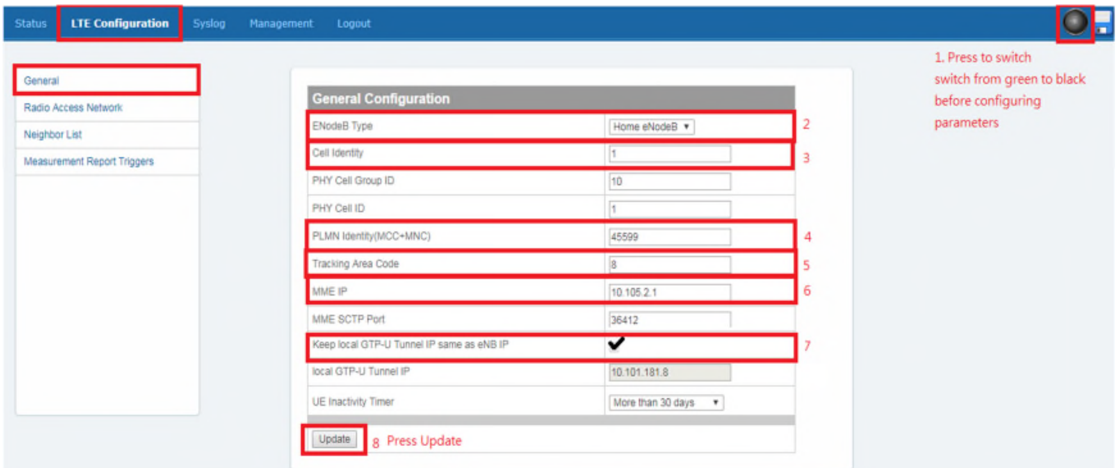


Figure 3-9 Small Cell LTE General Configuration.

- PLMN ID(MCC+MNC)= 20893
- Tracking area code = 1
- MME IP = 10.102.81.1

III. LTE Radio Access Network Configuration

This tab is used to change the bandwidth, transmission power and check the EARFCN value. If it is the same as shown in Figure 3-10 click update and go to the next step.

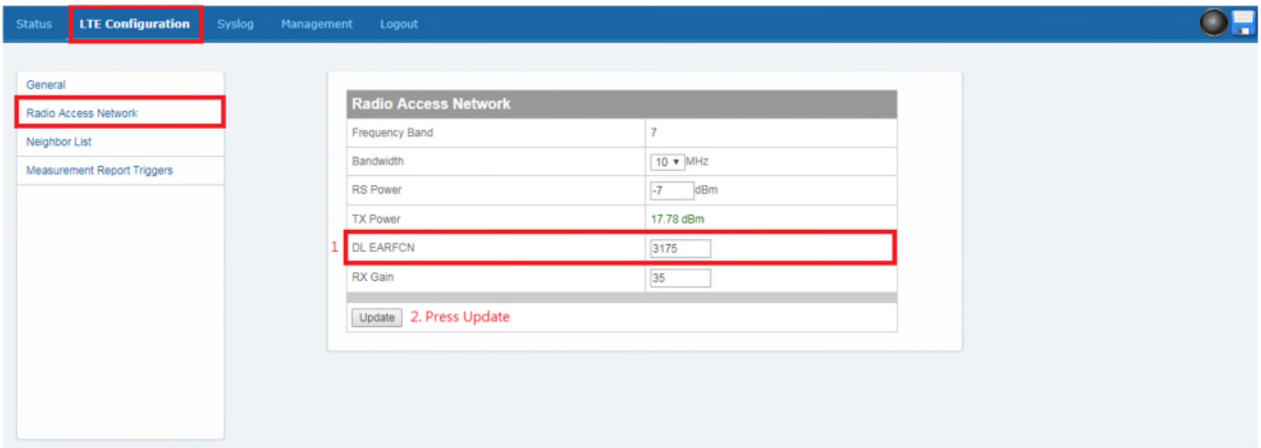


Figure 3-10 LTE Radio Access Network Configuration.

IV. Management Network Configuration

In this tab we will provide per our topology hence in Figure 3-8 1 and 2 will be changed while the value of 3 should be verified. The IP address as shown in Figure 3-11

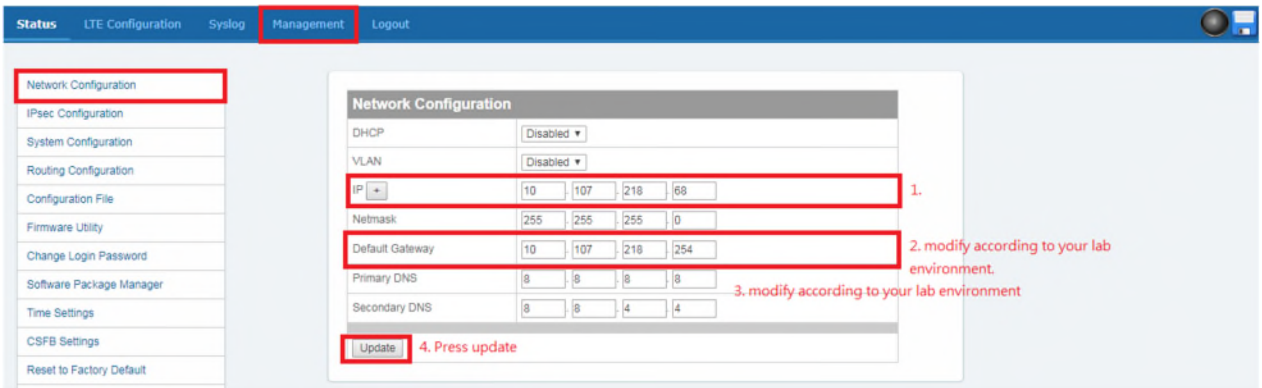


Figure 3-11 Network Configuration.

- IP=10.102.81.59
- Default gateway=10.102.81.1

After changing and verifying all these values the same and clicked on the black light on the top right corner and then clicked on reboot. Since all the parameter are in place we can now start with the next step of configuring MME.

3.3.2 MME Server Configuration

Once the installation is completed you will need to configure two things NAT rule and IP address as per the required topology.

I. NAT Configuration

The NAT configuration needs to be changed during the installation procedure. NAT is used to make the privet email address routable on the Public Internet. Since cellular network uses Private IP addresses which are not routable on the public domain NAT is required to translate these Private addresses to public address when the traffic leaves the Edge router. The MME will act as that edge router and will convert the UE address to 192.168.1.2. the D-Links router is the actual GW router and provides the actual NAT which will make this 192.168.1.2 address routable on the public domain. Here we are using NAT overload which provides many-to-one address translation.

The changed configuration is given below. Where enx3c18a00feb65 is the name of the interface facing the internet

[Option 1] Direct Configuration

```
sudo ifconfig eno1 10.102.81.1
sudo sh -c 'echo 1 > /proc/sys/net/ipv4/ip_forward'
sudo ipTables -t nat -A POSTROUTING -o enx3c18a00feb65 -j
MASQUERADE
sudo ipTables -I INPUT -i uptun -j ACCEPT
```

[Option 2] Configure as Auto Run On Boot

```
sudo sh -c "cat << EOF > /etc/init.d/ngc-network-setup
#!/bin/sh
### BEGIN INIT INFO
# Provides:          ngc-network-setup
# Required-Start:    networkd
# Required-Stop:     networkd
# Default-Start:     networkd
# Default-Stop:      networkd
# Short-Description:
# Description:
#
### END INIT INFO

ifconfig eno1 101.102.81.1
sh -c 'echo 1 > /proc/sys/net/ipv4/ip_forward'
ipTables -t nat -A POSTROUTING -o enx3c18a00feb65 -j
MASQUERADE
ipTables -I INPUT -i uptun -j ACCEPT
EOF"

sudo chmod 755 /etc/init.d/ngc-network-setup
sudo /etc/init.d/ngc-network-setup

sudo ln -s /etc/init.d/ngc-network-setup /etc/rc3.d/S99ngc-
network-setup
sudo ln -s /etc/init.d/ngc-network-setup /etc/rc4.d/S99ngc-
network-setup
```

II. Free5gc.config File Changes

Go to cd free5gc /install/etc/free5gc/free5gc.conf either open this file in text editor or give a nano command to edit the configuration. The edited configuration file is given below

```
db_uri: mongodb://localhost/free5gc

logger:
    file:
/home/ec5gc/free5gc/install/var/log/free5gc/free5gc.log
    trace:
        app: 1
        s1ap: 1
        nas: 1
        diameter: 1
        gtp: 1
        pfcp: 1
        sbi: 1

parameter:
    no_ipv6: true

amf:
    freeDiameter: amf.conf

    s1ap:
      addr: 10.102.81.1


    gummei:
      plmn_id:
        mcc: 460
        mnc: 88
      mme_gid: 1
      mme_code: 1

    tai:
      plmn_id:
        mcc: 460
        mnc: 88
      tac: 1

    security:
        integrity_order : [ EIA1, EIA2, EIA0 ]
        ciphering_order : [ EEA0, EEA1, EEA2 ]


    network_name:
        full: free5GC

hss:
    freeDiameter: hss.conf

pcrf:
```

```
    freeDiameter: pcrf.conf

smf:
    freeDiameter: smf.conf

    pfcp:
      - addr: 127.0.0.2
      - addr: ::1

    upf:
      - addr: 10.102.81.1

    http:
      addr: 127.0.0.1
      port: 8080

    ue_pool:
      - addr: 45.45.0.1/16
      - addr: cafe::1/64


    dns:
      - 8.8.8.8
      - 8.8.4.4
      - 2001:4860:4860::8888
      - 2001:4860:4860::8844

upf:
    pfcp:
      addr:
        - 10.102.81.1
        - ::1

    gtpu:
      - addr: 10.102.81.1j
      - addr: ::1

    ue_pool:
      - addr: 45.45.0.1/16
      - addr: cafe::1/64

    dns:
      - 8.8.8.8
      - 8.8.4.4
      - 2001:4860:4860::8888
      - 2001:4860:4860::8844
```

III. DNS Configuration

Since we need to access a local website on our LADN server we need to make a DNS binding on the MME as well for this purpose do the following configuration:

```
sudo nano /etc/hosts
192.168.1.3   jj.lan   // local website binding added
```

3.3.3 UE Configuration

Since the UE is using special Sim cards hence they need to be configured as well use the steps in [11] and first create a webserver.

I. Webserver

```
sudo apt-get -y install curl
curl -sL https://deb.nodesource.com/setup_8.x | sudo -E
bash -
sudo apt-get -y install nodejs
cd webui
npm install
cd webui
npm run dev
```

II. SIM Registration

Since the webserver is now created and working on link http://localhost:3000, we can now register our SIMs on the network. To register the SIMs, we need to add both SIMs one by one and give their IMSI number, key Value, and OPC. the exact values are given as under:

- **SIM 1**

IMSI= 460880000012345

Key = 0123456789abcdef0123456789abcdef

OPc=0123456789abcdef0123456789a46088

- **SIM 2**

IMSI= 460880000023456

Key = 0123456789abcdef0123456789abcdef

OPc=0123456789abcdef0123456789a46088

After that we inserted one of the sim card into our UE

III. UE APN Setup

- **Step1:** Settings →Connections →Mobile networks →Access Point Names →ADD
- **Step2:** Edit access point →Edit Name (input "internet" in the field) →Edit APN (input "internet" in the field) →Press the save button at the top right corner of screen.
- **Step3:** check if UE is connected to LTE Small cell and can surf the internet.

3.3.4 LADN Server Configuration

Since the LADN server need to host some website through which the videos will be accessed, hence we need to install LAMP (Linux + Apache + MySQL + PHP/Perl/Python) stack and configure some mock-up website.

I. LAMP stack

We used the configuration procedure provided in [13] and made the customizations where required. The complete configuration code is given below:

```
    1 sudo apt update && sudo apt install apache
    2 sudo service apache2 status
    3 sudo ufw allow OpenSSH
    4 apt-get install apache2 apache2-doc apache2-utils
    5 sudo apt-get install apache2 apache2-doc apache2-utils
    6 sudo service apache2 status
    7 sudo mkdir -p /var/www/html/jj.lan/public_html
    8 sudo chown -R $root:$root
/var/www/html/ostechnix1.lan/public_htm
    9 sudo chown -R $root:$root
/var/www/html/jj.lan/public_htm
   10 sudo mkdir -p /var/www/html/jj.lan
   11 sudo chown -R $root:$root /var/www/html/jj.lan
   12 sudo mkdir -p /var/www/jj.lan/public_html
   13 sudo chown -R $root:$root /var/www/jj.lan/public_html
   14 sudo chmod -R 755 /var/www
   15 sudo nano /var/www/jj.lan/public_html/index.html
       see html code for Website 1
   16 sudo nano /etc/apache2/sites-available/jj.lan.conf
       see html code for Website 2
      sudo a2ensite jj.lan.conf
      sudo systemctl restart apache2
   17 sudo mysql_secure_installation
   18 sudo apt update && sudo apt install mysql-server
   19 sudo service mysql status
   20 sudo mysql_secure_installation
   21 sudo mysqladmin -p -u root version
   22 sudo apt update && sudo apt install php libapache2-
mod-php   php-mysql
   23 php -version
   24 sudo nano /var/www/html/info.php
   25 sudo nano /etc/php/7.2/apache2/php.ini
   26 sudo systemctl restart apache2
   27 sudo apt update && sudo apt install phpmyadmin
       sudo mysql -p -u root
       CREATE USER 'pmauser'@'%' IDENTIFIED BY
'password_here';
       GRANT ALL PRIVILEGES ON *.* TO 'pmauser'@'%' WITH
GRANT    OPTION;
       exit
```

II. Website Configuration

We created two websites for video hosting. Can be accessed via the web browser of the UE if you type jj.lan, the HTML code given below needs to be copied in Step I 15 and 16 for these websites to be created.

- **Website 1**

```
sudo nano /var/www/example.com/public_html/index.html
<html>
  <head>
    <title>Welcome to jj.lan local entertainment
webside!</title>
  </head>
  <body>
    <h1>Success!  The jj.lan virtual host is working! </h1>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.flv" type="video/ogg">
Your browser does not support the video tag.
</video>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.ogg" type="video/ogg">
Your browser does not support the video tag.
</video>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.flv" type="video/ogg">
Your browser does not support the video tag.
</video>
  </body>
</html>
```

- **Website 2**

```
sudo nano /etc/apache2/sites-available/jj.lan.conf
<VirtualHost *:80>
    ServerAdmin admin@jj.lan
    ServerName jj.lan
    ServerAlias www.jj.lan
    DocumentRoot /var/www/jj.lan/public_html
    ErrorLog ${APACHE_LOG_DIR}/error.log
    CustomLog ${APACHE_LOG_DIR}/access.log combined
</VirtualHost>
```

Now open the UE browser and check if you give jj.lan as dress does these websites show up. If yes, then we can move to the testing stage.

3.3.5 Final Topology after Configuration

After completing 3.3.4 we will have the final topology as displayed in Figure 3-12. The topology drawings show the complete setup with configured IP address whereas Figure 3.1 shows only the concept. Therefor Figure 3-12 should be treated as the final topology drawing for the real-life based testbed implementation procedure. Everything below the UiA core router also known as an access network is configurable. Everything from the UiA core router and above also known as a core network is not under our control and hence can't be configured by us. The network address of all network segments is different from each other this is because a router can't have two interfaces with the same network address.

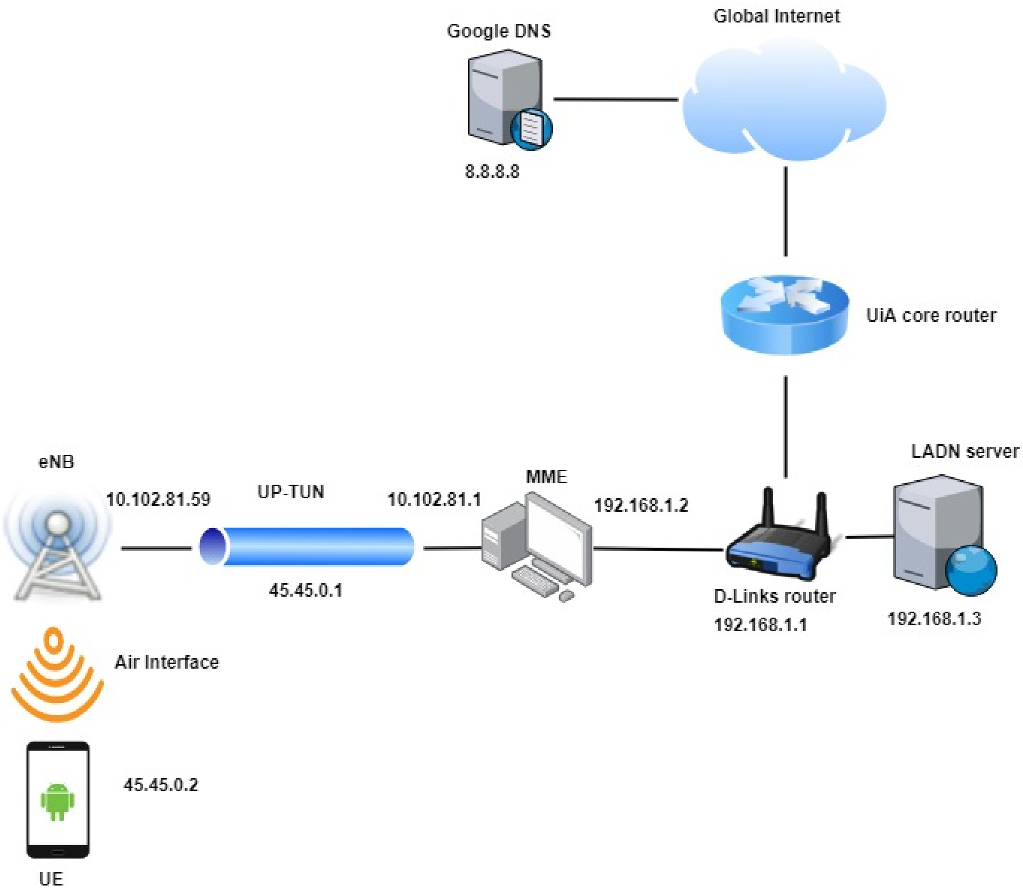


Figure 3-12 Final Topology Drawing.

Therefore, the 5G network is using 10.102.81.0/24, UE is using 45.45.0.0/16 network while the LDN is using 192.168.1.0/24 network. Since the MME is responsible for route between the 5G and LADN networks, therefore, it has an ON interface in each network segment. MME can also be known as a border router. The IP address from the eNB LTE small cell till the LADN is statically assigned. The only IP address on the internal network that is acquired by DHCP is the address of UE and interface of the D-Link router that connects with the UiA core router. the UE acquire IP address from the MME that is configured in UPTUN pool section of MME configuration while the D-Link acquired it automatically from the UiA core router

Figure 3-13 and 3-14 shows the actual operation of the testbed. The orange line indicates how the request sent by the UE is routed through the system and green lines show the response that the UE gets from its request. After connection with eNB small cell, the UE acquire an IP address from the MME. The MME provides the UE with a tunnel called UPTUN address so that the UE can establish a connection with MME Via this tunnel for LADN session. This tunnel encapsulates the actual packet that was supposed to be sent over 10.102.81.0/24 network into 45.45.0.0/16 network and the UE is now enabled to send a request to the MME. Once the MME receives the request it will check if the required data is available in LADN if it not then the MME will send the traffic through the D-Link router to the internet. The internet will send a response to the request. However, if the response to the request is available locally it will be sent to the LADN server.

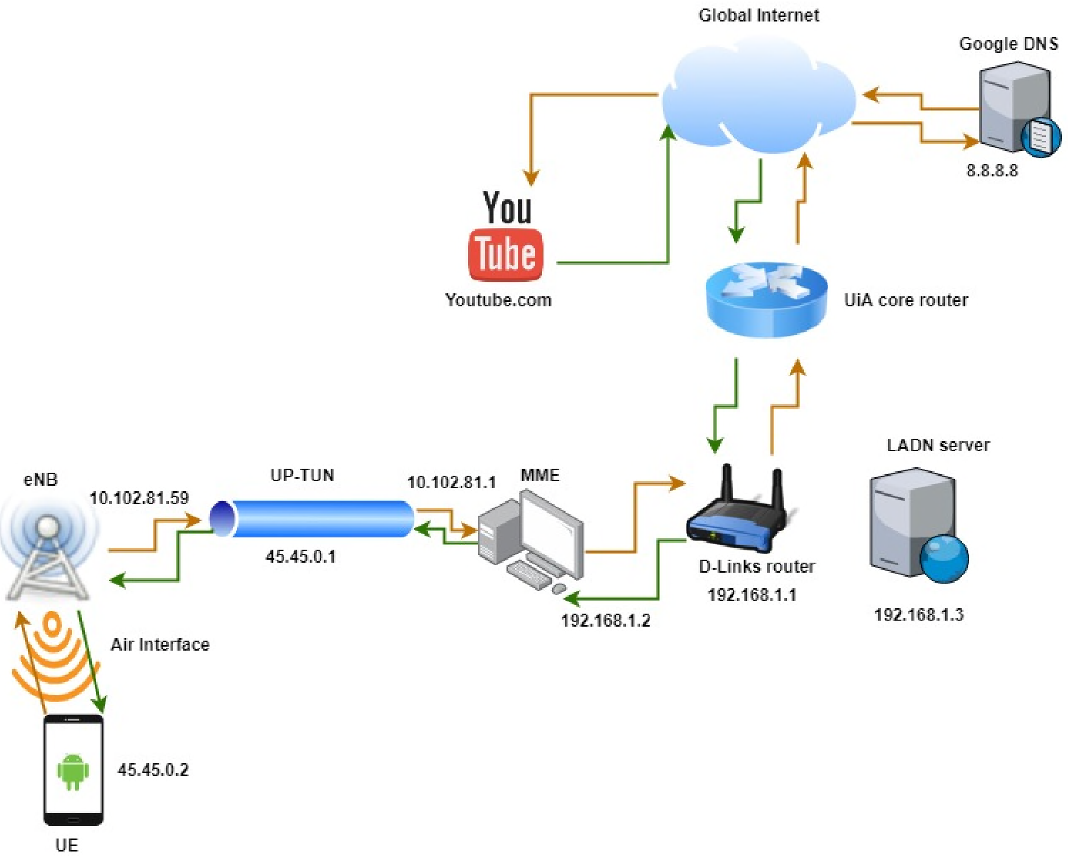


Figure 3-13 Operations of Request Sent To Internet.

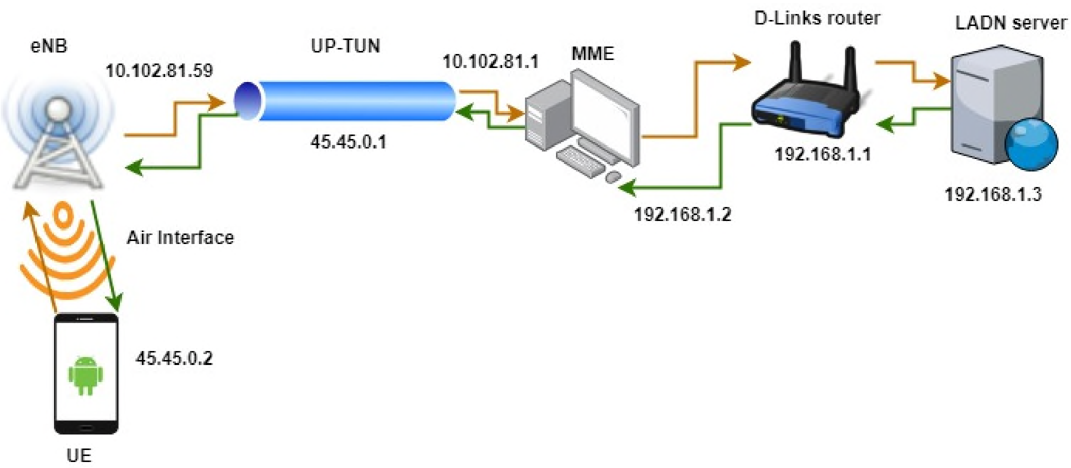


Figure 3-14 Operations of Request Sent To LADN.

3.4 System Operation

To run the system after configuration, power up all the devices and follow the steps given below:

a) Go to the terminal on MME and give command `cd free5gc/install/bin` to reach the required directory.
b) To start us the 5gc system application give command `./free5gc-ngcd`
c) the eNB LTE small cell light will start.

d) If the eNB small cell's LTE light does not start, follow the trouble shooting steps.
e) If the eNB small cell's LTE light is activated, then start your UE device.
f) The UE should have the pre-programmed SIM.
g) Once UE is active and 4G signal appears check if you can have internet.

3.5 Trouble-Shooting

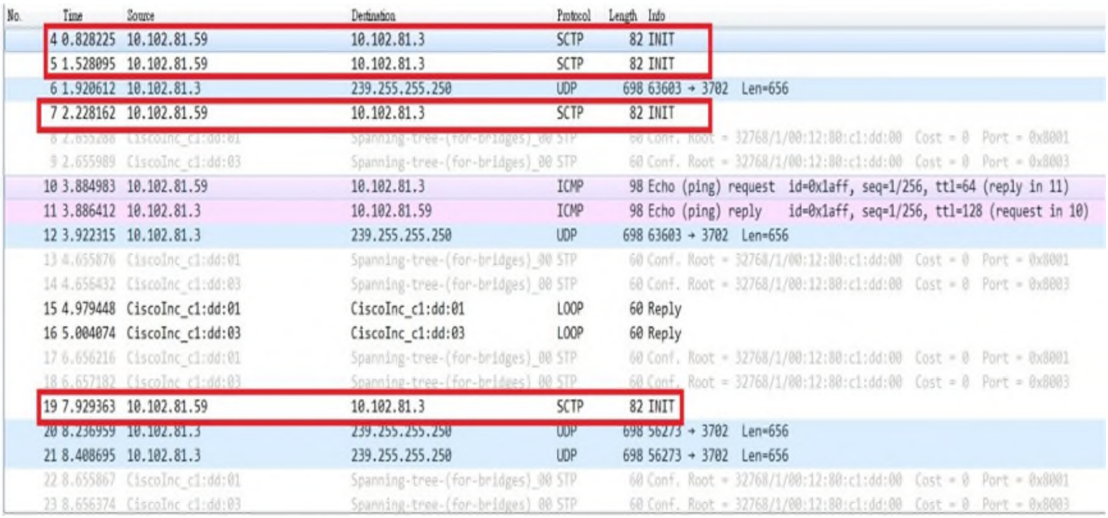
While deployment stage we faced two major issues which are listed below. in case the system is not functioning as it should be, go through the troubleshooting steps listed below:

I. If the MME is not connecting to eNB LTE small cell

a) Check if correct IP addresses and physical interface are connected with eachother
b) check if mmc and mnc valuesare the same on eNB LTE and MME
a) check if proper UP-tun address is assigned if not give the command `Ifconfig uptun 45.45.0.1 netmask 255.255.0.0`
b) check if the physical interface is properly assigned and working. Check via the GUI used to assign IP addresses.
c) Check NAT if it was configured properly, check the interface name on IPmasqurading (**enx3c18a00feb65**) if that was correct. If not change it to the correct value
d) Now check if the LTE LED is on at the LTE eNB small cell if yes

II. If the MME is unable to connect with eNB LTE small cell

- Open wire-shark and check if S1 init message is received from eNB and replied by MME.



No.	Time	Source	Destination	Protocol	Length	Info
4	0.828225	10.102.81.59	10.102.81.3	SCTP	82	INIT
5	1.528095	10.102.81.59	10.102.81.3	SCTP	82	INIT
6	1.920612	10.102.81.3	239.255.255.250	UDP	698	63603 → 3702 Len=656
7	2.228162	10.102.81.59	10.102.81.3	SCTP	82	INIT
8	[illegible]	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
9	2.655989	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
10	3.884983	10.102.81.59	10.102.81.3	ICMP	98	Echo (ping) request id=0x1aff, seq=1/256, ttl=64 (reply in 11)
11	3.886412	10.102.81.3	10.102.81.59	ICMP	98	Echo (ping) reply id=0x1aff, seq=1/256, ttl=128 (request in 10)
12	3.922315	10.102.81.3	239.255.255.250	UDP	698	63603 → 3702 Len=656
13	4.655876	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
14	4.656432	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
15	4.979448	CiscoInc_c1:dd:01	CiscoInc_c1:dd:01	LOOP	60	Reply
16	5.004074	CiscoInc_c1:dd:03	CiscoInc_c1:dd:03	LOOP	60	Reply
17	6.656216	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
18	6.657182	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
19	7.929363	10.102.81.59	10.102.81.3	SCTP	82	INIT
20	8.236959	10.102.81.3	239.255.255.250	UDP	698	56273 → 3702 Len=656
21	8.408695	10.102.81.3	239.255.255.250	UDP	698	56273 → 3702 Len=656
22	8.655867	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
23	8.656374	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003

Figure 3-15 Wireshark Traffic For INIT Procedure.

As can be seen in Figure 3-15 that the eNB LTE small cell is sending init messages but is not getting any reply from the MME. Figure 3-16 SCTP connection procedure between MME and eNB LTE small cell. SCTP [14] was designed as an alternative to TCP to efficiently support signaling protocols used in VOIP systems. The same protocol is required to establish a session between MME and LTE small cells. Figure 3-16 shows the exact procedure and as per wire shark logs we are at first message INIT, but since we don't receive an Ack from the MME we can't initiate the connection establishment procedure. In this case, follow the steps given below to troubleshoot this issue.

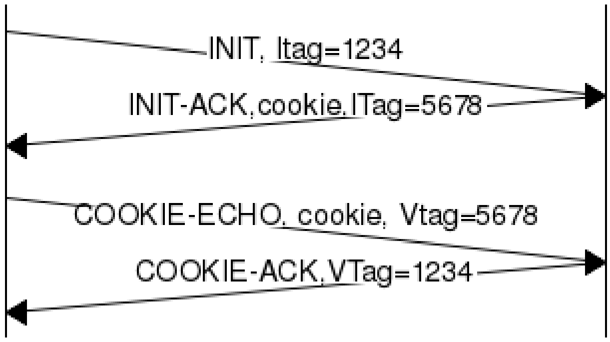


Figure 3-16 S1AP Connection Procedure. [15]

a) Check if appropriate interfaces are connected e.g. **eno1** at eNB side and `enx3c18a00feb65` at router side
b) Check other configuration if appropriate IP address is given in the configuration file located at `free5gc/install/etc/free5gc/ngcd.conf` file
c) Check if same mmc and mnc values are given at the eNB and config file mmc+mmc=86044

III. If the MME is connected with eNB LTE small cell and the LTE LED is on, but the UE can't access the internet.

a) Give command `ifconfig` if no IP address assigned then `Ifconfig uptun 45.45.0.1 netmask 255.255.0.0`
b) Check NAT if it was configured properly, check the interface name on IPmasqurading (**enx3c18a00feb65**) if that was correct. If not change it to the correct value
c) Now check if you have internet via UE

3.6 Real-Life Experiments and Empirical Results

Before we can start with testing phased we reconfirmed the following things

- 5gc application is running properly
- UE can surf the internet via LTE small cell
- UE can ping both the internet and the LADN server
- The websites configured on LADN server are accessible by the UE

Once all these steps were verified we can start with the test

3.6.1 Tests Scenarios

After verification of system operations, we will start the required test. The list of tests is given below our main evaluation criteria will find out and compare latency while accessing the LADN or internet for request-response.

I. Ping test to find end-to-end delay
II. traceroute to find the number of hops a packet travelled to reach the destination

III. i-Perf to calculate the data rate of the internal network Vs the data rate on public internet.

3.6.2 Test Scenario I: Ping Test

We used the ping test to find out about the RTT that each request will take from UE to the Google DNS server. We decided to run a ping test at least 36 times on each destination and then compare their results. We divided the test into two Steps in step 1 we calculated the Average RTT required by 5G air interface and in the second step, we calculated the difference between RTT of LADN VS RTT of internet requests.

I. RTT of Internet VS RTT of LADN

In this step, we sent 36 ping Iterations from UE to Google DNS and from UE to the LADN server. The results are shown in Figure 3-18. the orange line represents the Google DNS while the blue line represents the LADN server. It is quite evident from the graph that at any instance of the ping iteration LADN has lower RTT then Google DNS. The Table below the graph shows the RTT in msec for each ping iteration sent to LADN and Google DNS.

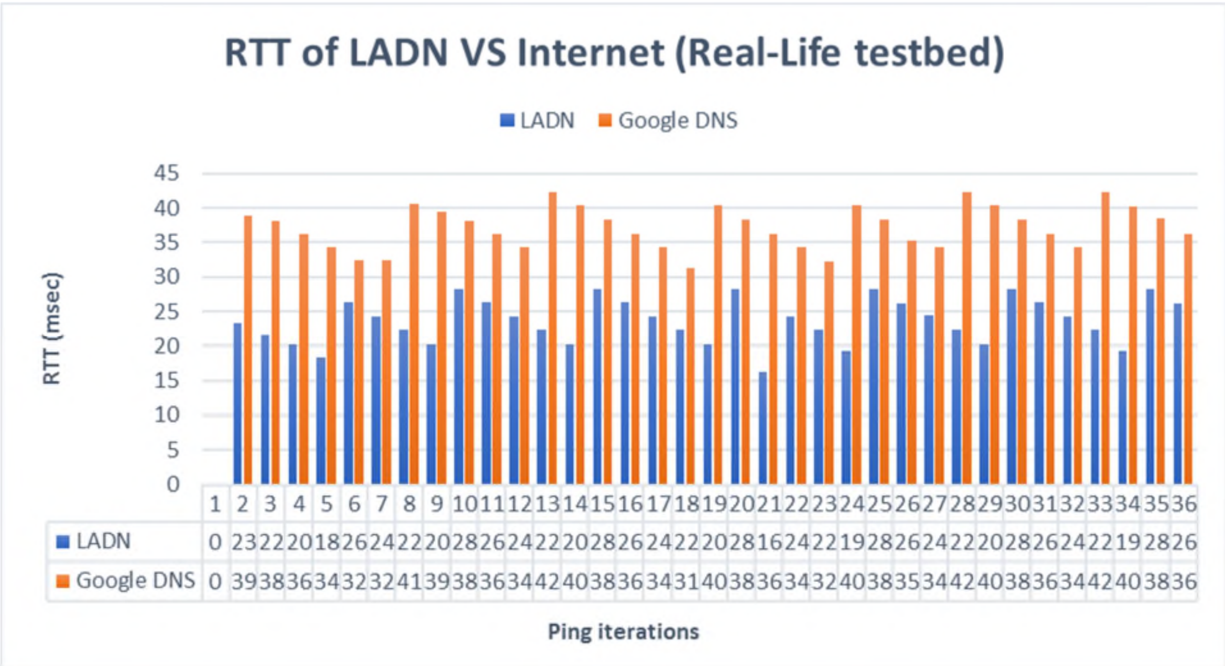


Figure 3-17 Ping Test Results LADN VS Internet.

If we take the average of both these values and subtract the RTT to Google DNS from RTT of LADN we the results as listed in Table 3-2. It is quite evident that on average we can save 13.21 msec per Request if we successfully deploy LADN in the 5G network.

	Ping to LADN	Ping to Google DNS
Ping iterations	**Time in msec**	**Time in msec**
1	0	0
2	23.2	38.9
3	21.6	38.1
4	20.3	36.3
5	18.3	34.4

6	26.4	32.4
7	24.3	32.4
8	22.4	40.6
9	20.3	39.4
10	28.3	38.2
11	26.3	36.2
12	24.3	34.3
13	22.3	42.3
14	20.3	40.3
15	28.3	38.3
16	26.3	36.3
17	24.3	34.3
18	22.3	31.3
19	20.3	40.3
20	28.3	38.3
21	16.3	36.3
22	24.3	34.3
23	22.3	32.3
24	19.3	40.3
25	28.3	38.3
26	26.2	35.3
27	24.4	34.3
28	22.3	42.3
29	20.3	40.3
30	28.3	38.3
31	26.3	36.3
32	24.3	34.3
33	22.3	42.3
34	19.3	40.2
35	28.3	38.4
36	26.2	36.3
Total RTT	**826.8 msec**	**1302.4 msec**
Average RTT	**22.97 msec**	**36.18 msec**
Average RTT saved LADN VS internet		**13.21 msec**

Table 3-2 RTT LADN VS Internet.

The video streaming over HTTP and HTTPS uses TCP, as per [16, p. 43] [17, p. 3]

$$TCP\ session\ throughput = \frac{Cwnd}{RTT} \qquad (3.1)$$

Equation (3-1) TCP Session Throughput calculation.

Where
Cwnd = congestion window size
RTT = round trip times

It is quite evident that TCP throughput is inversely proportional to RTT hence any decrease in RTT will increase the TCP throughput which will reduce buffer time. Therefore, any improvement in RTT will reflect in enhancing the user experience for video streaming over HTTP and HTTPS.

3.6.3 Test Scenario II: Traceroute Test

After the ping test, we needed to know that how many hops does a request has to travel if it requires a response from the internet VS the LADN server. For this purpose, we used the same IP address as in the ping test. With the traceroute test we will find out the no. of hops each request has to travel to reach its destination. Where 1 hop is when a packet is passed from one network segment to the next.

We used the traceroute command from UE and the results are shown in Figures 3-18 and 3-19.

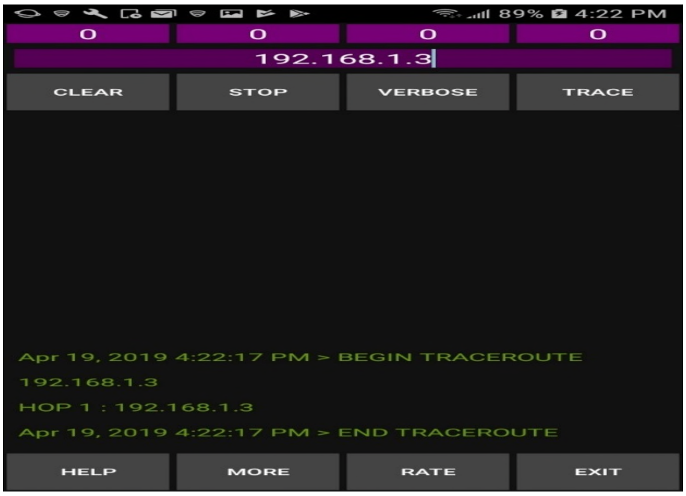


Figure 3-18 Traceroute to LADN.

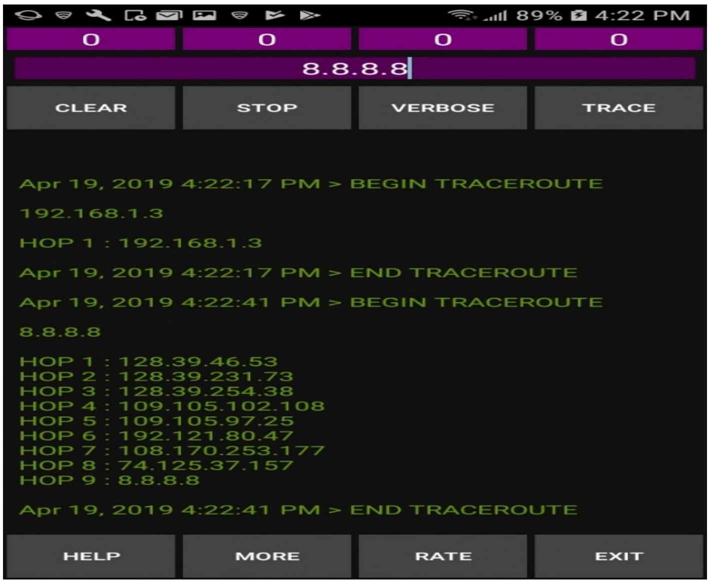


Figure 3-19 Traceroute to Google DNS.

Figure 3-13 shows that to get a response from the LADN server the request must travel 1 hop. Similarly, to get request services by the internet the request will have to travel at least 9 hops before it gets a response. Hence in the later cases the request will have to travel pass 8 router to reach Google DNS, there for the implementation of LADN will save 8 hops in terms of the distance the request has to travel.

But what if Google DNS is not the destination but merely a means to reach the destination what if someone wants to use YouTube how many hops does that request need to travel. Figure 3-20 shows the result of a traceroute command sent from UE to youtube.com. this test was run on a different date then the first test hence the IP address may vary and since the first app was not able to ping with DNS we shifted to another App called the ping tools. The Figure 3-20clearly shows that the number of hops goes to 11 which means that LADN will save 10 hops.

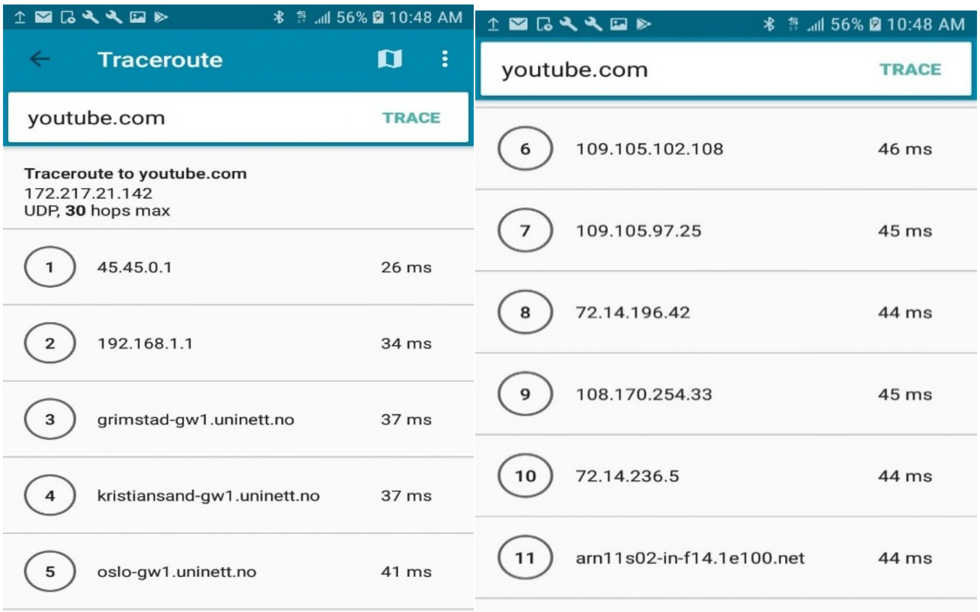


Figure 3-20 Traceroute to youtube.com.

Table 3-4 clearly shows the comparison between LADN VS Google DNS and LADN VS youtube.com. it is quite evident that in both these cases 8-14 hops can be saved and therefor is implemented the LADN will result in significant traffic reduction on the internet.

Description	Hops
Traceroute Google DNS	9
Traceroute youtube.com	11
Traceroute LADN	1
Hops saved LADN VS Google DNS	**8**
Hops saved LADN VS YouTube	**10**

Table 3-3 Test Scenario III: i-Perf Test.

3.6.4 Test scenario III: i-Perf Local Network vs Public Network

The i-perf is a tool that is used to find out maximum available bandwidth on a IP network [4]. i-perf supports two major protocols TCP and UDP, the main difference when running these two protocols are the values in results and in UDP test a bandwidth in bits/sec has to be provided. During TCP testing mode the client generate as much traffic as it can and send it to server. But since we are more interested in the download speed we will conduct the test in both directions. The bandwidth results are dependent on the following factors

- The Connection speed of the client and server network Interfaces
- Bandwidth available between client and server

There are multiple Variations in the i-perf test the one that were utilized during this test are given below. Since the UE only supports i-perf V2 there for some of these variations may not be available for the test conducted from the UE

Command	Description	Command	Description
-s	Run in server mode	-b	Specify bandwidth in bits/sec for UDP traffic
-c	Run in Clinet mode	-d	Run the test in both directions simultaneously
-t	Total duration of test in sec	-r	Run the test in Both directions alternatively
-i	Interval time in sec to display results		

Table 3-4 i-Perf Commands and Their Meaning

We have decided to run the i-perf test both internally on LADN server and externally on a public i-perf server and then compare their results with each other. Since our primary focus is on TCP we will run more detailed test there. We will also conduct UDP test but since they are not used for the required application we will not discuss them in detail.

I. **i-perf tests TCP**

The List of the test we conducted for TCP are given below:

- `iperf -c 192.168.1.3 -r -t 300 -i 10 //MME→LADN`
- `iperf -c speedtest.serverius.net -r -t 300 -i 10//MME→Public`
- `iperf -c 192.168.1.3 -d -t 300 -i 10 //UE→LADN`
- `iperf -c speedtest.serverius.net -r -t 300 -i 10 //UE→Public`

each variation of the test uses TCP as protocol and then continues for 300 sec. An output will be provided on the terminal screen after every 10 sec. Since the bandwidth option is only used for UDP therefor it was not mentioned here. we made the LADN server as i-Perf server and UE as an i-Perf client. Then we used UE to download TCP data from the LADN server and recorded the amount of data transfer and acquired bandwidth for this connection. Then the same test was repeated with a public i-perf server located in Netherlands (speedtest.serverius.net) [4]. Table 3-5 and Figure 3-21,Figure3-22 shows the results of the above-mentioned TCP test .

TCP Results								
	UE-->LADN		UE-->Public Server		MME-->LADN		MME-->Public Server	
Interval	Data Volume	Throughput	Data Volume	Throughput	Data Volume	Throughput	Data Volume	Throughput
0.0-10.0 sec	26.0 Mb	21.8 Mbps	9.88 MB	8.28 Mbps	422 MB	354 Mbps	117 MB	97.9 Mbps
10.0-20.0 sec	24.8MB	20.8 Mbps	5.38 MB	4.51 Mbps	422 MB	354 Mbps	363 MB	305 Mbps
20.0-30.0 sec	25.6 MB	21.5 Mbps	13.6 MB	11.4 Mbps	422 MB	354 Mbps	404 MB	339 Mbps
30.0-40.0 sec	25.8 MB	21.6 Mbps	9.38 MB	7.86 Mbps	422 MB	354 Mbps	397 MB	333 Mbps
40.0-50.0 sec	26.0 MB	21.8 Mbps	2.12 MB	1.78 Mbps	422 MB	354 Mbps	381 MB	319 Mbps
50.0-60.0 sec	25.8 MB	21.6 Mbps	0.38 MB	0.315 Mbps	422 MB	354 Mbps	380 MB	319 Mbps
60.0-70.0 sec	23.9 MB	20.0 Mbps	6.12 MB	5.14 Mbps	420 MB	352 Mbps	379 MB	318 Mbps
70.0-80.0 sec	4.2 MB	20.3 Mbps	21.9 MB	18.4 Mbps	421 MB	353 Mbps	378 MB	317 Mbps
80.0-90.0 sec	24.0 MB	20.1 Mbps	9.00 MB	7.55 Mbps	419 MB	352 Mbps	405 MB	340 Mbps
90.0-100.0 sec	4.0 MB	20.1 Mbps	7.50 MB	6.29 Mbps	420 MB	352 Mbps	410 MB	344 Mbps
100.0-110.0 sec	24.2 MB	20.3 Mbps	7.75 MB	6.50 Mbps	418 MB	350 Mbps	408 MB	342 Mbps
110.0-120.0 sec	24.2 MB	20.3 Mbps	6.62 MB	5.56 Mbps	420 MB	352 Mbps	410 MB	344 Mbps
120.0-130.0 sec	10.2 MB	8.60 Mbps	5.75 MB	4.82 Mbps	420 MB	352 Mbps	409 MB	343 Mbps
130.0-140.0 sec	6.12 MB	5.14 Mbps	3.62 MB	3.04 Mbps	421 MB	353 Mbps	410 MB	344 Mbps
140.0-150.0 sec	15.6 MB	13.1 Mbps	5.88 MB	4.93 Mbps	421 MB	353 Mbps	409 MB	343 Mbps
150.0-160.0 sec	1.38 MB	1.15 Mbps	3.50 MB	2.94 Mbps	421 MB	353 Mbps	409 MB	343 Mbps
160.0-170.0 sec	5.62 MB	4.72 Mbps	11.5 MB	9.65 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
170.0-180.0 sec	3.25 MB	2.73 Mbps	7.50 MB	6.29 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
180.0-190.0 sec	16.0MB	13.4 Mbps	19.2 MB	16.1 Mbps	421 MB	353 Mbps	410 MB	344 Mbps
190.0-200.0 sec	2.00 MB	1.68 Mbps	4.50 MB	3.77 Mbps	422 MB	354 Mbps	409 MB	343 Mbps
200.0-210.0 sec	13.5 MB	11.3 Mbps	18.6 MB	15.6 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
210.0-220.0 sec	24.0MB	20.1 Mbps	6.25 MB	5.24 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
220.0-230.0 sec	24.1MB	20.2 Mbps	7.00 MB	5.87 Mbps	422 MB	354 Mbps	408 MB	342 Mbps
230.0-240.0 sec	24.1MB	20.2 Mbps	2.75 MB	2.31 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
240.0-250.0 sec	2.38MB	1.99 Mbps	15.2 MB	12.8 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
250.0-260.0 sec	14.0MB	11.7 Mbps	21.1 MB	17.7 Mbps	422 MB	354 Mbps	409 MB	343 Mbps
260.0-270.0 sec	25.5MB	21.4 Mbps	1.50 MB	1.26 Mbps	422 MB	354 Mbps	409 MB	343 Mbps
270.0-280.0 sec	25.8MB	21.6 Mbps	4.12 MB	3.46 Mbps	422 MB	354 Mbps	410 MB	344 Mbps
280.0-290.0 sec	25.9MB	21.7 Mbps	6.50 MB	5.45 Mbps	422 MB	354 Mbps	409 MB	343 Mbps
290.0-300.0 sec	25.6MB	21.5 Mbps	1.38 MB	1.15 Mbps	422 MB	354 Mbps	409 MB	343 Mbps
0.0-300.0 sec	**564 MB**	**15.8 Mbps**	**246 MB**	**6.87 Mbps**	**12.8 GB**	**365Mbps**	**11.5GB**	**330Mbps**

Table 3-5 i-Perf TCP Test Results.

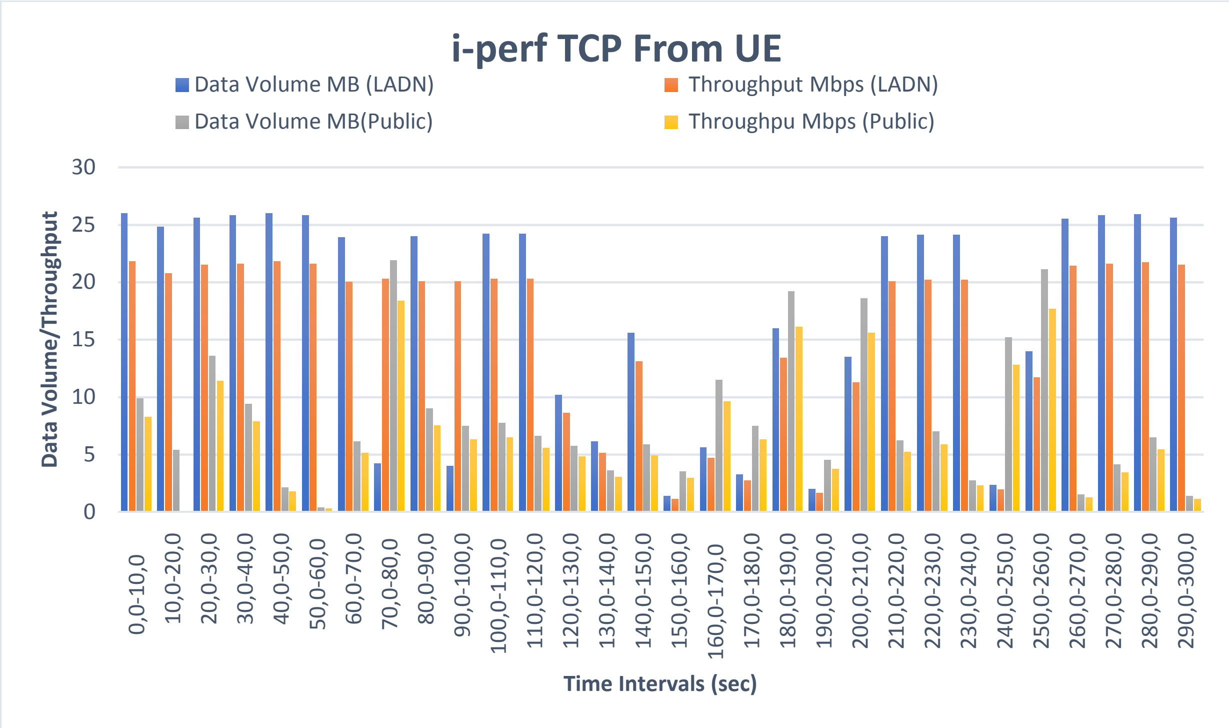


Figure 3-21 UE i-Perf Test Results.

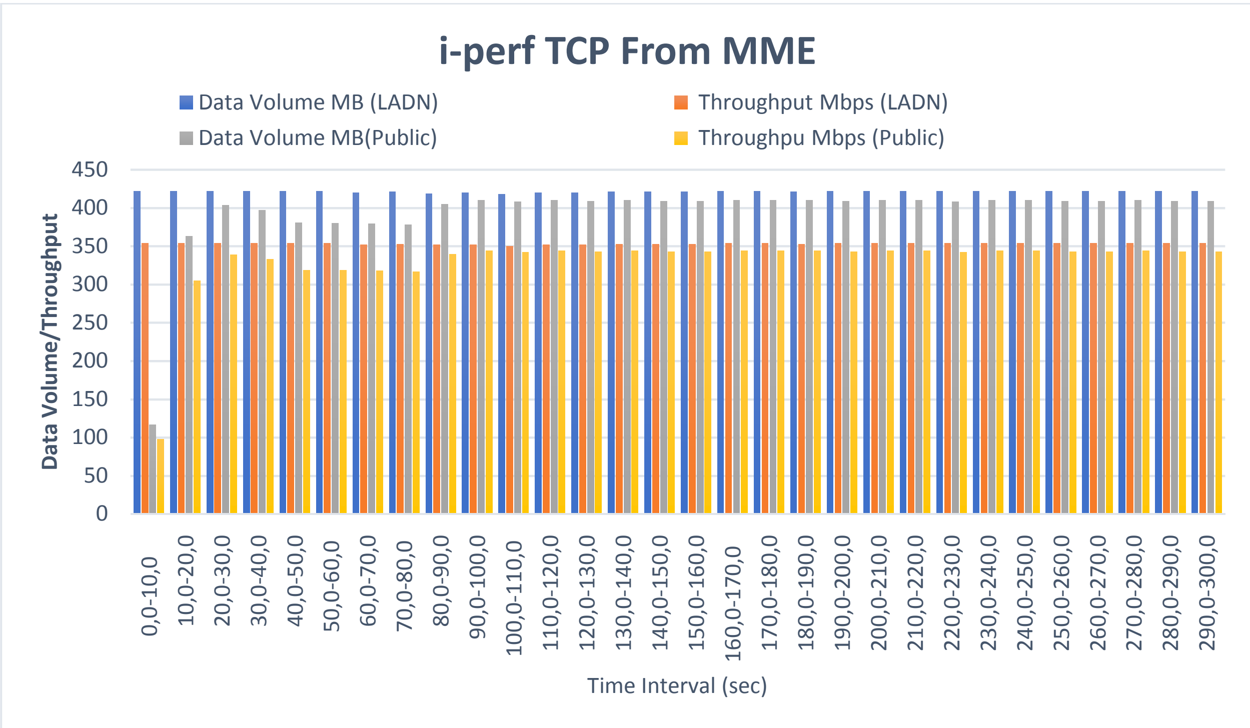


Figure 3-22 MME TCP i-Perf Results.

As it is quite evident from Figure 3-21, Figure 3-22 that the data volume is represented in blue and the throughput is represented in orange for the LADN network, is always higher than the data volume represented in grey and the throughput is represented in yellow for the Public network in Figure 3-21and Figure 3-22.The table 3-6 Summarizes the results of i-perf TCP test. From the table it can be seen that LADN provide 8.98 Mbps higher throughput when tested from UE and 35 Mbps higher when tested from MME. Which means that the throughput in terms of TCP is quite higher when using LADN solution. Especially in case of UE where LADN provide more than twice the throughput achieved over the Public network.

Description	Interval	Data Volume	Throughput
UE over LADN	0-300 sec	564 MB	15.8 Mbps
UE over Public Network	0-300 sec	246 MB	6.87 Mbps
MME Over LADN	0-300 sec	12.8 GB	365 Mbps
MME Over Public Network	0-300 sec	11.5 GB	330 Mbps

Table 3-6 i-Perf TCP Test Summary.

The Table 3-6 also shows a huge difference between the throughput of UE and MME tests. This is because the MME is using LAN based connection and the UE is operating of an LTE wireless interface. Therefore, the UE has one bottleneck with LTE Bandwidth limit and second with the nature of Wireless medium which is always more hostile than the wired medium. Both of these factors paly in their roles, as in Figure 3-22 the MME graph results are pretty much consistent whereas the UE graph results are very unpredictable and far from consistent. We can at least overcome the data rate bottleneck of UE connection if we use 5G air interface, but the nature of Wireless medium will still play its part. The screen shots taken in these tests are displayed in Appendix B.

II. **i-perf Tests UDP**

We ran the same test with UDP as well. The only difference with UDP is that we have to specify the bandwidth in bits per second (bps). And since we wanted to know the maximum achievable bandwidth we set 1GB or 10000000000 bps as the allocated bandwidth. The list of tests that were conducted are given below:

- `iperf -c 192.168.1.3 -u -r -b 10000000000 -t 300 -i 10 //MME→LADN`
- `iperf -c speedtest.serverius.net -u -d -b 10000000000 -t 300 -i 10   //MME→Public`
- `iperf -c 192.168.1.3 -u -r -b 10000000000 -t 300 -i 10 //UE→LADN`
- `iperf -c 178.21.16.76 -u -r -b 10000000000 -t 300 -i 10 //UE→Public`

each variation of the test uses TCP as protocol and then continues for 300 sec. An output will be provided on the terminal screen after every 10 sec. we made the LADN server as i-Perf server and UE as an i-Perf client. Then we used UE to download UDP data from the LADN server and recorded the amount of data transfer and acquired bandwidth for this connection. Then the same test was repeated with a public i-perf server located in Netherlands (`speedtest.serverius.net`) [4].

Table 3-7 and Figure 3-23,Figure 3-24 shows the results of the above-mentioned UDP test .

UDP Results								
	UE-->LADN		UE-->Public Server		MME-->LADN		MME-->Public Server	
Interval	Data Volume	Throughput	Data Volume	Throughput	Data Volume	Throughput	Data Volume	Throughput
0.0-10.0 sec	11.0 MB	9.27 Mbps	8.43 MB	7.07 Mbps	430 MB	361 Mbps	404 MB	339 Mbps
10.0-20.0 sec	16.0 MB	13.4 Mbps	18.2 MB	15.3 Mbps	430 MB	361 Mbps	402 MB	337 Mbps
20.0-30.0 sec	11.8 MB	9.89 Mbps	26.1 MB	21.9 Mbps	430 MB	361 Mbps	403 MB	338 Mbps
30.0-40.0 sec	5.65 MB	4.74 Mbps	11.8 MB	9.89 Mbps	430 MB	361 Mbps	403 MB	338 Mbps
40.0-50.0 sec	6.05 MB	5.07 Mbps	13.7 MB	11.5 Mbps	428 MB	359 Mbps	403 MB	338 Mbps
50.0-60.0 sec	10.2 MB	8.60 Mbps	6.49 MB	5.45 Mbps	429 MB	360 Mbps	404 MB	339 Mbps
60.0-70.0 sec	23.7 MB	19.9 Mbps	16.0 MB	13.4 Mbps	430 MB	361 Mbps	398 MB	334 Mbps
70.0-80.0 sec	18.2 MB	15.3 Mbps	8.19 MB	6.87 Mbps	430 MB	361 Mbps	393 MB	330 Mbps
80.0-90.0 sec	10.4 MB	8.72 Mbps	20.7 MB	17.4 Mbps	430 MB	361 Mbps	381 MB	320 Mbps
90.0-100.0 sec	25.0 MB	21.0 Mbps	10.2 MB	8.57 Mbps	430 MB	361 Mbps	379 MB	318 Mbps
100.0-110.0 sec	21.3 MB	17.9 Mbps	9.67 MB	8.11 Mbps	430 MB	360 Mbps	395 MB	331 Mbps
110.0-120.0 sec	8.88 MB	7.45 Mbps	9.15 MB	7.67 Mbps	430 MB	360 Mbps	390 MB	327 Mbps
120.0-130.0 sec	22.6 MB	19.0 Mbps	13.4 MB	11.2 Mbps	430 MB	360 Mbps	396 MB	332 Mbps
130.0-140.0 sec	25.6 MB	21.5 Mbps	10.0 MB	8.40 Mbps	430 MB	361 Mbps	386 MB	323 Mbps
140.0-150.0 sec	6.30 MB	5.28 Mbps	23.3 MB	19.6 Mbps	429 MB	360 Mbps	388 MB	325 Mbps
150.0-160.0 sec	11.2 MB	9.41 Mbps	12.4 MB	10.4 Mbps	430 MB	361 Mbps	393 MB	330 Mbps
160.0-170.0 sec	9.78 MB	8.20 Mbps	14.9 MB	12.5 Mbps	430 MB	361 Mbps	396 MB	332 Mbps
170.0-180.0 sec	22.1 MB	18.6 Mbps	25.7 MB	21.6 Mbps	430 MB	361 Mbps	403 MB	338 Mbps
180.0-190.0 sec	6.35 MB	5.33 Mbps	24.5 MB	20.6 Mbps	430 MB	361 Mbps	397 MB	333 Mbps
190.0-200.0 sec	12.4 MB	10.4 Mbps	24.5 MB	20.6 Mbps	430 MB	361 Mbps	388 MB	326 Mbps
200.0-210.0 sec	8.01 MB	6.72 Mbps	24.5 MB	20.6 Mbps	430 MB	361 Mbps	393 MB	329 Mbps
210.0-220.0 sec	12.5 MB	10.5 Mbps	24.5 MB	20.6 Mbps	430 MB	361 Mbps	400 MB	335 Mbps
220.0-230.0 sec	6.35 MB	5.33 Mbps	6.30 MB	5.28 Mbps	430 MB	361 Mbps	396 MB	332 Mbps
230.0-240.0 sec	7.65 MB	6.42 Mbps	18.2 MB	15.3 Mbps	430 MB	361 Mbps	395 MB	332 Mbps
240.0-250.0 sec	7.24 MB	6.07 Mbps	24.9 MB	20.9 Mbps	430 MB	361 Mbps	380 MB	319 Mbps
250.0-260.0 sec	20.0 MB	16.8 Mbps	26.5 MB	22.2 Mbps	430 MB	361 Mbps	386 MB	323 Mbps
260.0-270.0 sec	5.46 MB	4.58 Mbps	23.4 MB	19.6 Mbps	430 MB	361 Mbps	394 MB	331 Mbps
270.0-280.0 sec	7.32 MB	6.14 Mbps	24.9 MB	20.9 Mbps	430 MB	361 Mbps	379 MB	318 Mbps
280.0-290.0 sec	21.5 MB	18.0 Mbps	24.5 MB	20.6 Mbps	430 MB	361 Mbps	381 MB	319 Mbps
290.0-300.0 sec	9.05 MB	7.59 Mbps	24.6 MB	20.6 Mbps	430 MB	361 Mbps	397 MB	333 Mbps
0.0-300.0 sec	**390 MB**	**10.9 Mbps**	**530 MB**	**14.8 Mbps**	**13.0 GB**	**373 Mbps**	**11.5 GB**	**330 Mbps**

Table 3-7 i-Perf UDP Test Results.

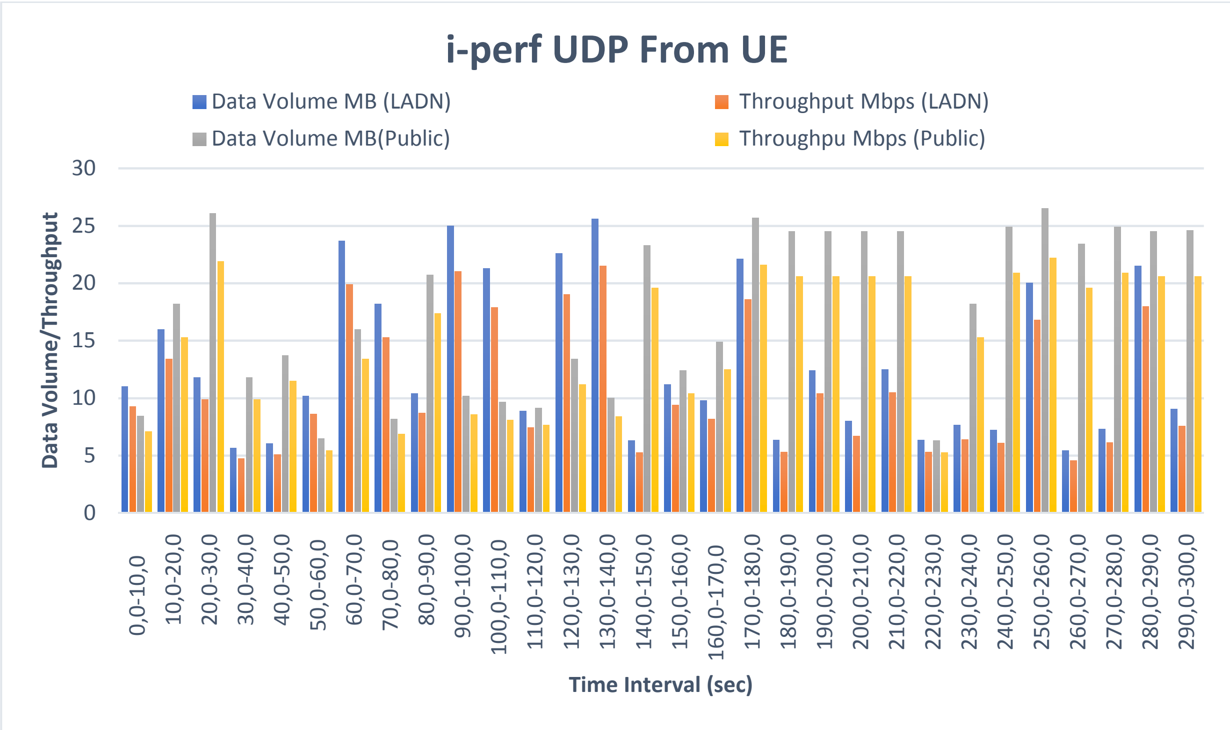


Figure 3-23 UE UDP i-Perf Results.

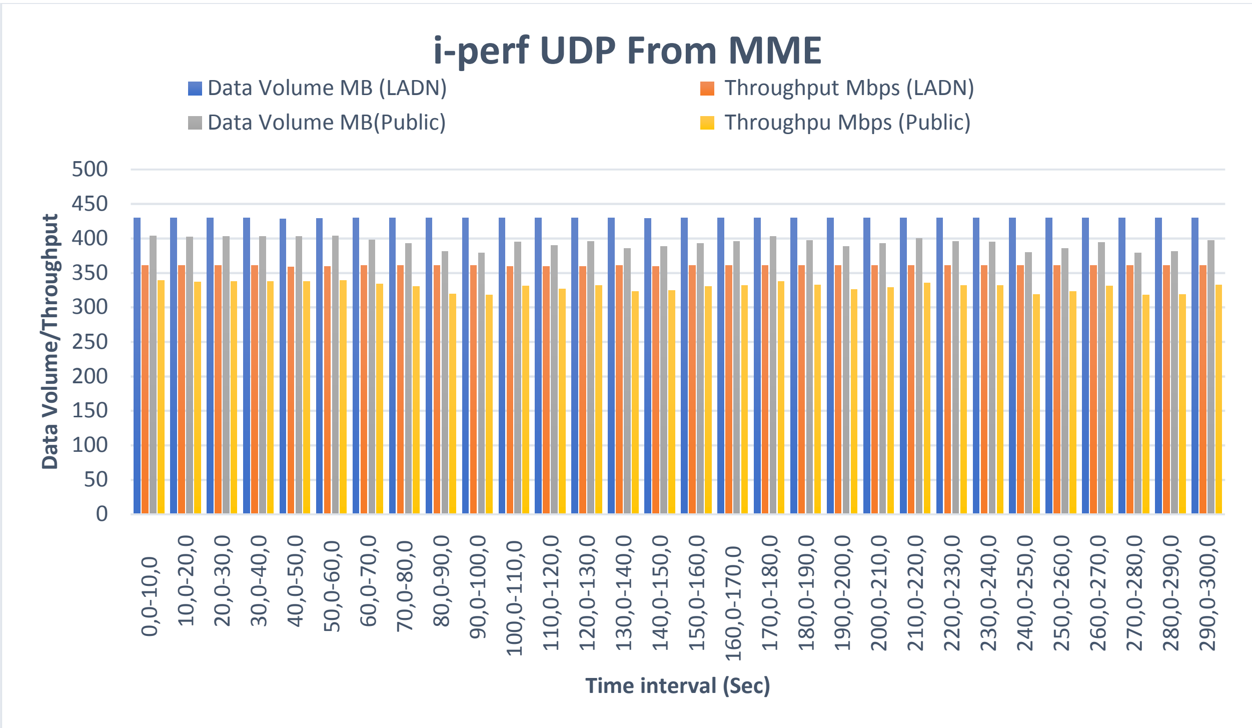


Figure 3-24 MME UDP i-Perf Results.

As it is quite evident from Figure 3-24 that the data volume is represented in blue and the throughput is represented in orange for the LADN network, it is always higher than the data volume abd the throughput represented in grey and yellow respectively for the Public Network. However, in Figure 3-23 the results show opposite trend as the Public Network results are better than then LADN results.

Description	Interval	Data Volume	Throughput
UE over LADN	0-300 sec	390 MB	10.9 Mbps
UE over Public Network	0-300 sec	530 MB	14.8 Mbps
MME Over LADN	0-300 sec	13 GB	373 Mbps
MME Over Public Network	0-300 sec	11.5 GB	330 Mbps

Table 3-8 UDP i-Perf Results Summary.

The table 3-8 Summarizes the results of i-perf UDP test. From the table it can be seen that LADN provide 3.9 Mbps lower throughput when tested from UE and 43 Mbps higher when tested from MME. Since the UDP achieved bandwidth was not the focus of this thesis we did not examine the reason for these results or tried to find out how to improve this.

3.7 Summary

The entire chapter can be summarized as the installation and configuration procedure for the real-life base testbed for LADN implementation and its test results. It also illustrates the steps to initialize the 5GC environment and how to troubleshoot the known issues. Finally, we ran some tests and illustrated their results. It was observed that by properly implanting LADN we can reduce the average RTT to 13.21 msec, while the hop-count can be reduced from 8-10 hops on per request basis. This reduction in latency will result in enhancement of user experience among other benefits. We also found out that the achievable bandwidth provided by the LADN solution is quite higher than the achievable bandwidth provided by the Public Network. For TCP Traffic the achievable throughput of LADN solution is more than twice (56.5%) as compared to Public Network when testing from UE and 9.5% when testing from MME. Similarly, the with UDP the test from MME displays 11.5% higher throughput can be achieved from LADN solution, however the test from UE displays that the Public Network provides 26% higher throughput as compared to LADN.

Hence it can be derived from these results that for the required application that uses TCP LADN provide Better Bandwidth, lower end-to-end latency and fewer hop counts to furnish a request sent from user.

4 Further Studies Based on Simulations

In this chapter, we will create a simulation-based upon the traceroute test results in 3.6.3. Simulation is necessary since the traffic does not always take the same route and there can be more UEs connected to the same LTE small Cell. Since we have only a limited number of SIM cards, we decided to create a simulation. Another added advantage of simulation is that we can change the configuration of the core network and see how that will affect the results. For this part, we decided to use two different routing protocols OSPF and EIGRP in the core network. We sent parallel pings from all 5 UEs and then consolidated the results.

4.1 Simulator Selection

Since the results need to be as close to reality as possible hence, we could not use any simulator tools and need to have a well-established simulator. For this reason, we used Cisco's packet tracer which is an open-source and widely used simulator among the computer network student. It is very flexible, and you can create any network-related topology that is needed. Packet tracer is a power simulator platform that supplements physical equipment and allows the user to create a network with unlimited devices. It is also used for testing and troubleshooting of network topologies.

It has end devices like PC, UE, VOIP, etc while the networking part contains the actual Cisco's IOS for all the router, switches and firewalls. Therefore, the results acquired are very accurate. For configuration purposes, the simulator provides actual GUI or CLI based interface for end devices and network devices respectively. It supports a vast variety of protocols which makes it ideal to simulate what-if scenarios and gather results from them. All these factors were needed to create and study the network behavior hence we used packet tracer as a simulator.

4.2 Topology

The actual topology used in this stage II is shown in Figure 4-1. From 3.6.3 we found out to reach the Google DNS a request must travel 9 hops. The traceroute test also displayed the IP address of each hop in Figure 3-19. We copied the data from there and then created our Topology as displayed in Figure4-1. We added 5 UEs and 1 4G cell site which connect with MME which is displayed as central office server and then to UiA router. The UiA router represents the D-Link router in the actual testbed scenario. From UE till the UiA router we have our access network whereas from UiA core router onwards we have our core network. Since it is a simulation, therefore, we can configure both the core and the access network as per required scenarios. But the Only way the UE can reach the LADN or Google DNS is via the Wireless 4G link provided by the cell-Tower representing LTE small cell.

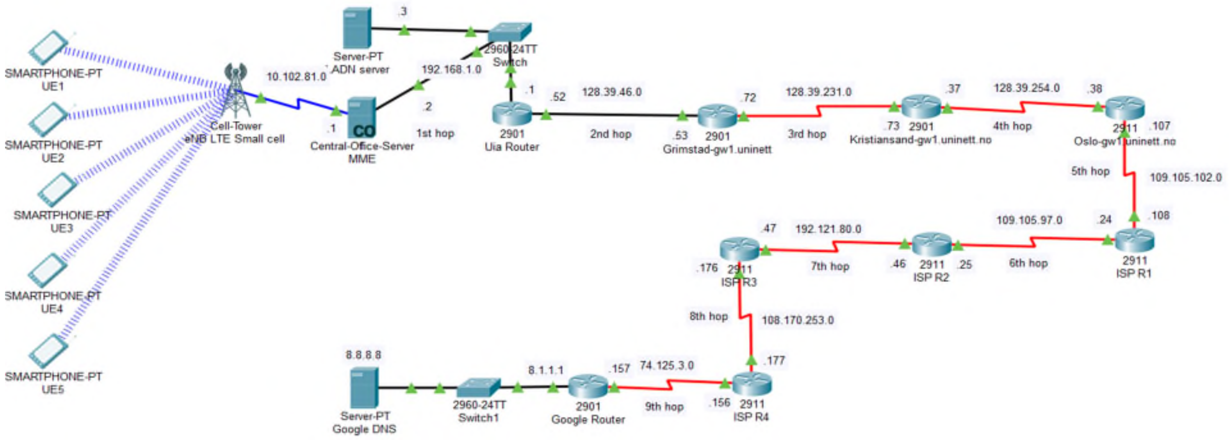


Figure 4-1 Simulaton .

4.2.1 **Topology Setup**

Figure 4-2 shows the main menu option of the simulator. Since it is a GUI based simulator, you need to first select the device that you want to install in the topology. For this first, you click on the correct device type on the main menu and then drag the required device from the sub-option menu.

We used three types of devices which are network devices, end devices, and cable connectors. Network devices consist of router switches and cell towers. Since the internet uses multiple types of routers we used two different types of router devices which are cisco's 2901 and 2911 series. End devices consist of UEs, LADN servers, Google DNS and MME server. Finally, we used appropriate cables to connect devices the list of connection is given below:

- UE to Cell- tower = Wireless 4G
- Cell-Tower to MME = coaxial cable
- MME to Switch = Fast Ethernet with bandwidth of 100 MB (LAN-link)
- LADN to Switch = Fast Ethernet with bandwidth of 100 MB (LAN-link)
- Switch to UiA Router = Gigabit Ethernet with bandwidth of 1000 MB (LAN-link)
- UiA Router to Grimstad-gw1.uninett = Gigabit Ethernet with bandwidth of 1000 MB
- Grimstad-gw1 to Kristiansand-gw1 to Oslo-gw1 = Serial with bandwidth of 1.544 MB (WAN-link)
- ISP routers to ISP routers= Serial with bandwidth of 1.544 MB (WAN-link)
- ISP router to google router= Serial with bandwidth of 1.544 MB (WAN-link)

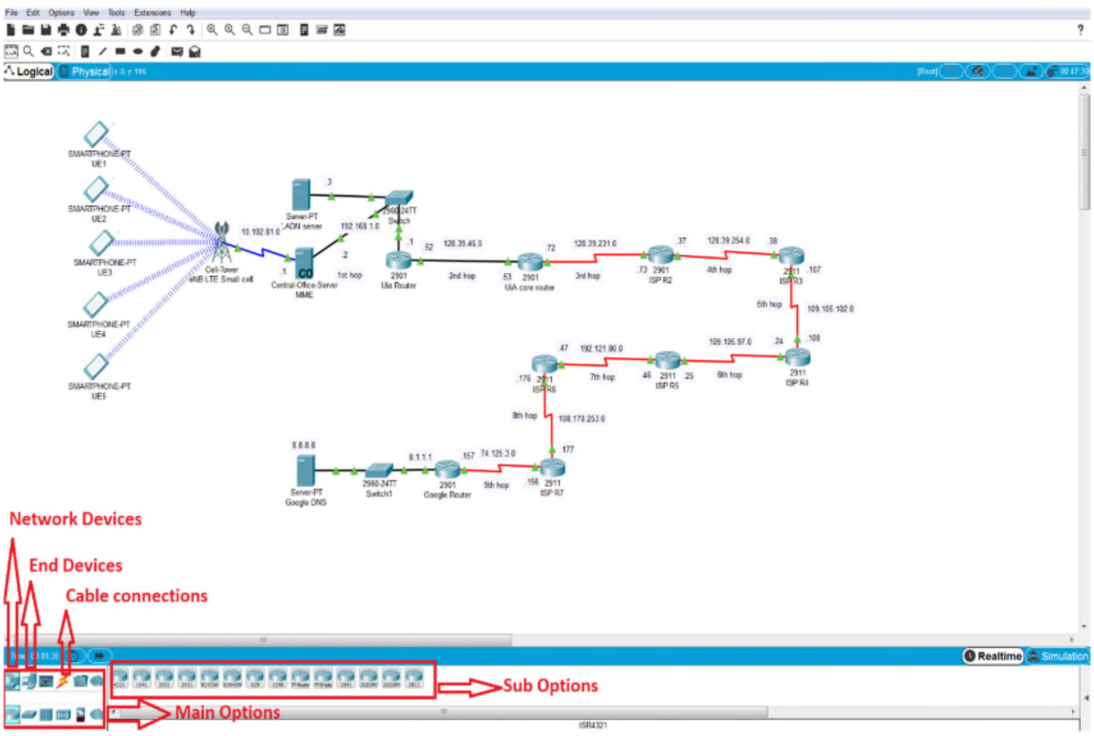


Figure 4-2 Simulator Topology Setup.

After setting up the links we edited the name of the devices and labeled the IP address so that during configuration we don't have to refer to 3.6.3 every time. The topology for both protocols are represented in Appendix C

4.3 Topology Configuration

Once the Topology was setup we proceeded with the configuration steps. We started from the end devices and worked our way to the network devices. Now we will go through them one by one.

4.3.1 LADN and Google DNS

For the LADN and Google DNS server, all we needed to do was to set up the IP address and default gateways which were done through a GUI interface. Once you click on the device there will be a prompt window that opens up. On this prompt window, you click on config and then click on fast ethernet 0. Now under the IP configuration click on static and provide you the desired IP address. Figure 4-3 shows the result of this configuration.

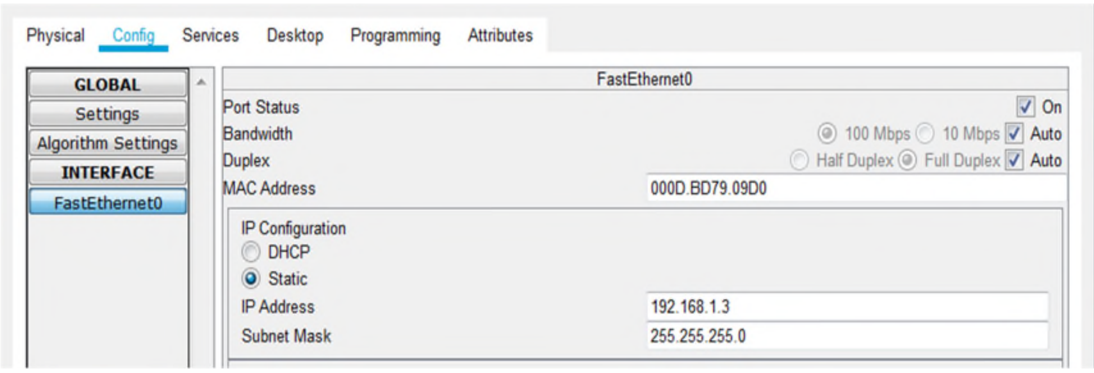


Figure 4-3 IP Address Configuration LADN And Google DNS.

4.3.2 UE Configuration

For the UE configuration we need to check if it is set to acquire its IP address via DHCP or not. For that

- Click on UE
- Click on Config
- Click on 3G/4G cell 1and then click on DHCP refresh.

Figure 4-4 shows the result of the steps given above.

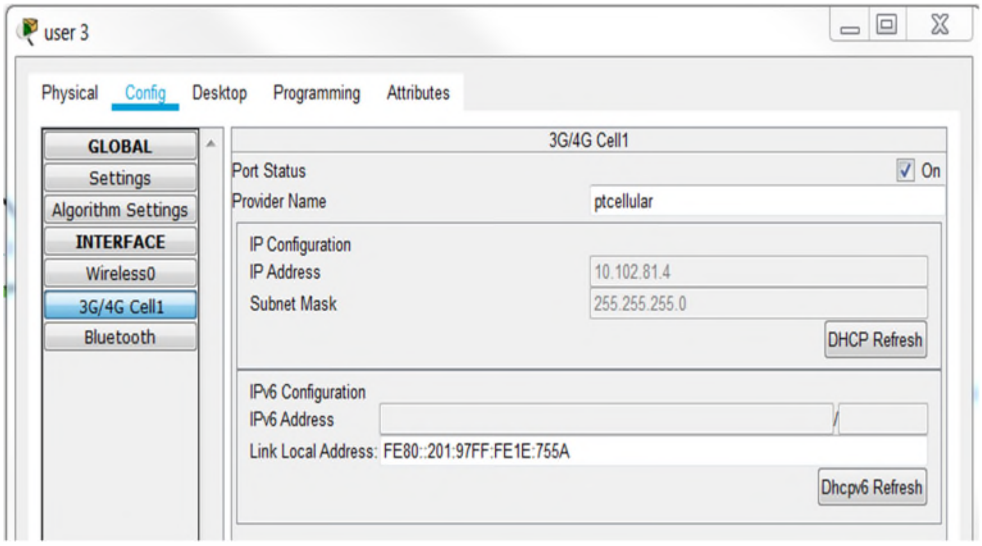


Figure 4-4 UE Configuration.

4.3.3 **CO Server/MME Configuration**

The CO server which is acting as MME here need to allocate IP address to UEs via cell tower. It also needs to have an IP address with which it will be connected to the switch and then to the UiA router

I. IP Configuration

For IP configuration flows the steps given below:

- Click on CO server
- Click on Config
- Click Backbone under Interface menu
- Under IP configuration click on static and provide IP address and default gateway. This is for connection between CO-server and UiA router
- Click on Cell Tower under interface menu¨
- Provide IP address with which the CO server will be connected to the Cell-Tower

The resulting configuration is shown in Figure 4-5.

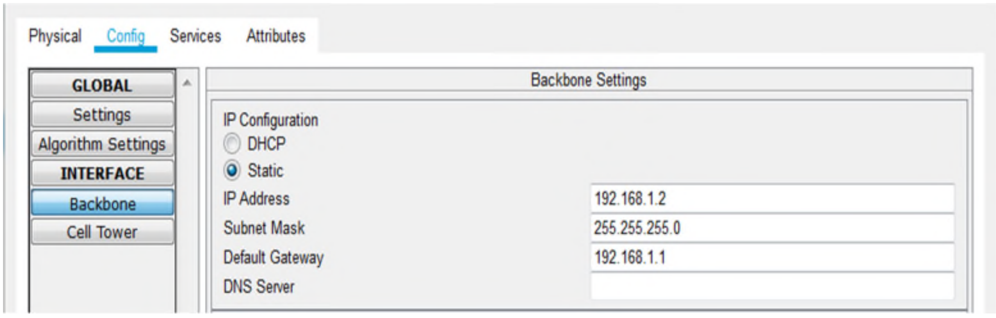


Figure 4-5 CO Server Configuration.

II. Services Config

DHCP will be configured under the service tab. The steps for configuration are given below:

- Click on CO server
- Click on Services
- Click on DHCP and edit the Ip address range that will be provided to UE connected to Cell-Tower.
- Click on Save.
- Go to Cell-Tower and UE and click on refresh DHCP button

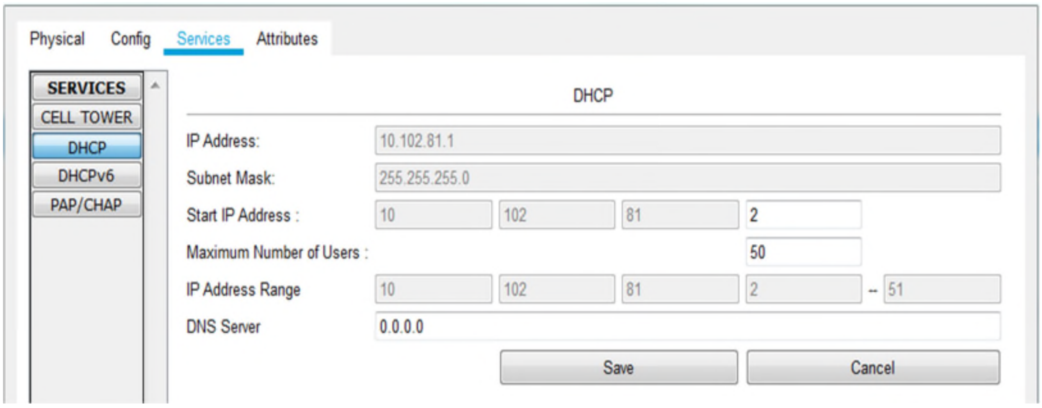


Figure 4-6 CO Server Services Configuration.

4.3.1 Routers Configuration

After we were done with the configuration of end devices we started with the configuration or network devices which were mostly routers as we were not using any segregation at layer 2. Every router had a CLI interface that comes under the CLI tab once you click on the router that you want to configure. All the routers were configured with OSPF and EIGRP while NAT was only configured on UiA router. The detailed configuration is given below.

UiA Router with OSPF	UiA Router with EIGRP
enable ! config t ! interface GigabitEthernet0/0 ip address 128.39.46.52 255.255.255.0 ip nat inside duplex auto speed auto ! interface GigabitEthernet0/1 ip address 192.168.1.1 255.255.255.0 ip nat outside duplex auto speed auto !	enable ! config t ! ! interface GigabitEthernet0/0 ip address 128.39.46.52 255.255.255.0 ip nat inside duplex auto speed auto ! interface GigabitEthernet0/1 ip address 192.168.1.1 255.255.255.0 ip nat outside duplex auto speed auto

router ospf 1 log-adjacency-changes network 192.168.1.0 0.0.0.255 area 1 network 128.39.46.0 0.0.0.255 area 1 ! ip nat inside source list 1 interface GigabitEthernet0/1 overload ip classless ip route 0.0.0.0 0.0.0.0 GigabitEthernet0/1 ! ip flow-export version 9 ! access-list 1 permit 192.168.1.0 0.0.0.255 ! end ! Copy run start	! router eigrp 1 network 192.168.1.0 network 128.39.46.0 0.0.0.255 ! ip nat inside source list 1 interface GigabitEthernet0/1 overload ip classless ip route 0.0.0.0 0.0.0.0 GigabitEthernet0/1 ! ip flow-export version 9 ! end ! Copy run start

Table 4-1 Configuration Of UiA Router.

Grimstad-gw1.uninett with OSPF	Grimstad-gw1.uninett with EIGRP
enable ! config t ! interface GigabitEthernet0/0 ip address 128.39.46.53 255.255.255.0 no shut duplex auto speed auto ! interface GigabitEthernet0/1 no ip address duplex auto speed auto ! interface GigabitEthernet0/0/0 no ip address shutdown ! interface Serial0/1/0 ip address 128.39.231.72 255.255.255.0 ! interface Serial0/1/1 no ip address clock rate 2000000 shutdown !	enable ! config t ! interface GigabitEthernet0/0 ip address 128.39.46.53 255.255.255.0 no shut duplex auto speed auto ! interface GigabitEthernet0/1 no ip address duplex auto speed auto ! interface GigabitEthernet0/0/0 no ip address shutdown ! interface Serial0/1/0 ip address 128.39.231.72 255.255.255.0 ! interface Serial0/1/1 no ip address clock rate 2000000 shutdown !

router ospf 1 log-adjacency-changes network 128.39.46.0 0.0.0.255 area 1 network 128.39.231.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end ! Copy run start	router eigrp 1 redistribute bgp 2 network 128.39.231.0 0.0.0.255 network 128.39.46.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-2 Configuration Of Grimstad-gw1.uninett.no Router.

Kristiansand-gw1.uninett.no with OSPF	Kristiansand-gw1.uninett.no with EIGRP
enable ! config t ! interface Serial0/1/0 ip address 128.39.231.73 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 128.39.254.37 255.255.255.0 no shut ! router ospf 1 router-id 2.2.2.2 log-adjacency-changes network 128.39.231.0 0.0.0.255 area 1 network 128.39.254.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9end ! Copy run start	enable ! config t ! interface Serial0/1/0 ip address 128.39.231.73 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 128.39.254.37 255.255.255.0 no shut ! router eigrp 1 network 128.39.231.0 0.0.0.255 network 128.39.254.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-3 Configuration Of Kristiansand-gw1.uninett.no Router.

Oslo-gw1.uninett.no with OSPF	Oslo-gw1.uninett.no with EIGRP
enable ! config t ! interface Serial0/1/0	enable ! config t ! interface Serial0/1/0

ip address 109.105.102.107 255.255.255.0 no shut ! interface Serial0/1/1 ip address 128.39.254.38 255.255.255.0 clock rate 2000000 no shut ! router ospf 1 router-id 3.3.3.3 log-adjacency-changes network 109.105.102.0 0.0.0.255 area 1 network 128.39.254.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end ! Copy run start	ip address 109.105.102.107 255.255.255.0 no shut ! interface Serial0/1/1 ip address 128.39.254.38 255.255.255.0 clock rate 2000000 no shut ! router eigrp 1 network 128.39.254.0 0.0.0.255 network 109.105.102.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-4 Configuration Of Oslo-gw1.uninett.no Router.

ISP R1 with OSPF	ISP R1 with EIGRP
enable ! config t ! interface Serial0/1/0 ip address 109.105.102.108 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 109.105.97.24 255.255.255.0 no shut ! router ospf 1 router-id 4.4.4.4 log-adjacency-changes network 109.105.102.0 0.0.0.255 area 1 network 109.105.97.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end	enable ! config t ! interface Serial0/1/0 ip address 109.105.102.108 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 109.105.97.24 255.255.255.0 no shut ! router eigrp 1 network 109.105.102.0 0.0.0.255 network 109.105.97.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

! Copy run start	

Table 4-5 Configuration Of ISP R1 Router.

ISP R2 with OSPF	ISP R2 with EIGRP
enable ! config t ! interface Serial0/1/0 ip address 192.121.80.46 255.255.255.0 no shut ! interface Serial0/1/1 ip address 109.105.97.25 255.255.255.0 clock rate 2000000 no shut ! router ospf 1 router-id 5.5.5.5 log-adjacency-changes network 192.121.80.0 0.0.0.255 area 1 network 109.105.97.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end ! Copy run start	enable ! config t ! interface Serial0/1/0 ip address 192.121.80.46 255.255.255.0 no shut ! interface Serial0/1/1 ip address 109.105.97.25 255.255.255.0 clock rate 2000000 no shut ! router eigrp 1 network 192.121.80.0 network 109.105.97.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-6 Configuration Of ISP R2 Router.

ISP R3 with OSPF	ISP R3 with EIGRP
enable ! config t ! interface Serial0/1/0 ip address 192.121.80.47 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 108.170.253.176 255.255.255.0 no shut ! router ospf 1 router-id 6.6.6.6 log-adjacency-changes	enable ! config t ! interface Serial0/1/0 ip address 192.121.80.47 255.255.255.0 clock rate 2000000 no shut ! interface Serial0/1/1 ip address 108.170.253.176 255.255.255.0 no shut ! router eigrp 1 network 192.121.80.0 network 108.170.253.0 0.0.0.255

network 192.121.80.0 0.0.0.255 area 1 network 108.170.253.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end ! Copy run start	! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-7 Configuration Of ISP R3 Router.

ISP R4 with OSPF	ISP R4 with EIGRP
enable ! config t ! interface Serial0/1/0 ip address 74.125.37.156 255.255.255.0 no shut ! interface Serial0/1/1 ip address 108.170.253.177 255.255.255.0 clock rate 2000000 no shut ! router ospf 1 router-id 7.7.7.7 log-adjacency-changes network 74.125.37.0 0.0.0.255 area 1 network 108.170.253.0 0.0.0.255 area 1 ! ip classless ! ip flow-export version 9 ! end ! Copy run start	enable ! config t ! interface Serial0/1/0 ip address 74.125.37.156 255.255.255.0 no shut ! interface Serial0/1/1 ip address 108.170.253.177 255.255.255.0 clock rate 2000000 no shut ! router eigrp 1 redistribute bgp 3 network 108.170.253.0 0.0.0.255 network 74.125.37.0 0.0.0.255 ! ip classless ! ip flow-export version 9 ! end ! Copy run start

Table 4-8 Configuration Of ISP R4 Router.

Google router with OSPF	Google router with EIGRP
enable ! config t ! interface GigabitEthernet0/1 ip address 8.1.1.1 255.0.0.0 no shut	enable ! config t ! interface GigabitEthernet0/1 ip address 8.1.1.1 255.0.0.0 no shut

duplex auto speed auto ! interface Serial0/1/0 ip address 74.125.37.157 255.255.255.0 no shut clock rate 2000000 ! interface Serial0/1/1 no ip address clock rate 2000000 ! router ospf 1 router-id 8.8.8.8 log-adjacency-changes network 74.125.37.0 0.0.0.255 area 1 network 8.0.0.0 0.255.255.255 area 1 ! ip classless ip route 0.0.0.0 0.0.0.0 Serial0/1/0 ! end ! Copy run start	duplex auto speed auto ! interface Serial0/1/0 ip address 74.125.37.157 255.255.255.0 no shut clock rate 2000000 ! interface Serial0/1/1 no ip address clock rate 2000000 ! router eigrp 1 network 8.0.0.0 network 74.125.37.0 0.0.0.255 ! ip classless ip route 0.0.0.0 0.0.0.0 Serial0/1/0 ! end ! Copy run start

Table 4-9 Configuration Of Google Router.

4.4 Testing Scenarios

Since we have already performed the traceroute and the i-Perf test on the real-life based testbed solution there is no need to replicate these tests here. The only test which is relevant at this stage is the Ping test. In this way, we can observe how the values of RTT will be affected under ideal conditions and different routing protocols. Will the LADN solution still be beneficial under these conditions.

Before we can start with the test we first need to check if the topology is working properly for that, we send a ping from UE to LADN and Google DNS. The ping result came positive and now we can start our test.

4.4.1 Test Scenario I - 32-byte Ping VS 64-byte Ping

The UE that we used in our real-life testbed solution used a 64-bytes ping packet while the UE on the Simulator sends a 32-byte ping packet. The extended ping command was not available on the UE in simulation, so we tested on a simple PC to the observer if we send ping t 8.8.8.8 with both 64 and 32-bytes what will be their result. We sued the following ping commands:

I. # ping -n 36 8.8.8.8 // for 32-byte to be repeated 36 times
II. #ping -l 64 -n 36 8.8.8.8 // for 64-byte to be repeated 36 times

The results from these commands are shown in Figures 4-7 and 4-8 respectively. It is Highlighted in red that the min and average RTT for both 32 and 64-byte ping is the same while the max RTT is different. Since we are more concerned with average RTT, its value is

12 milliseconds in both cases. Therefore, we can now proceed with the ping test of our simulation.

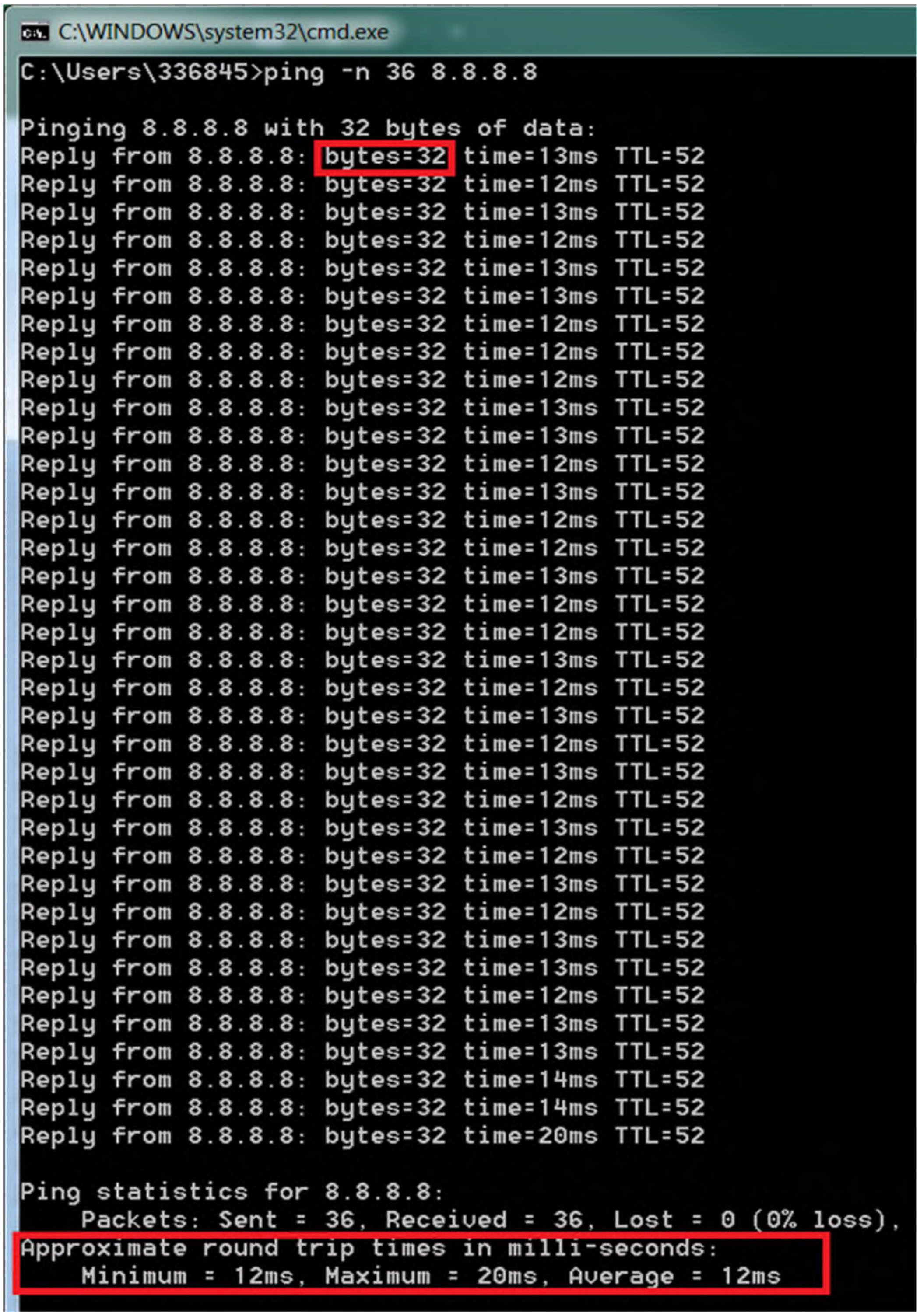
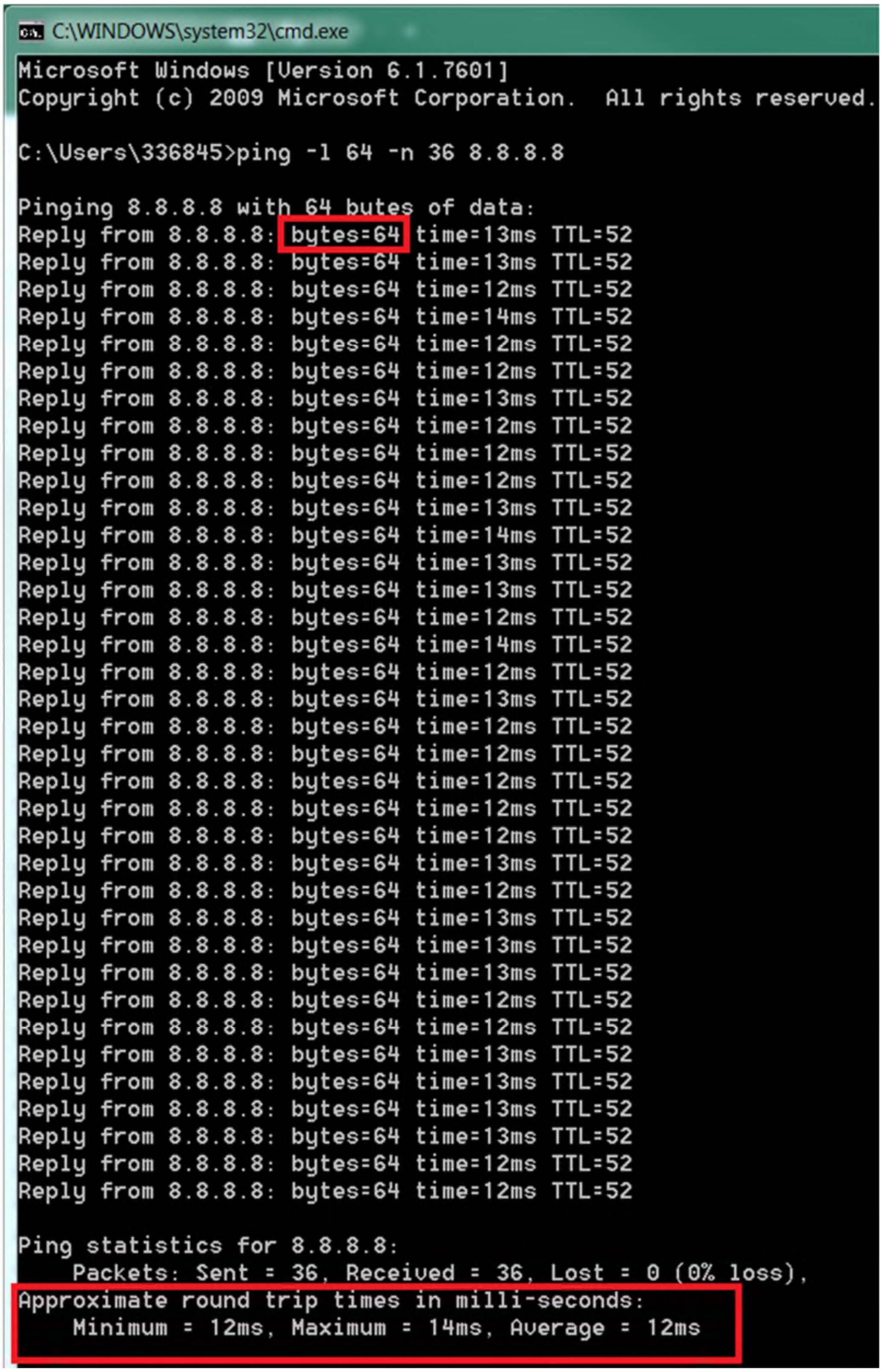


Figure 4-7 RTT Of 32-Byte Ping Test.



```
C:\WINDOWS\system32\cmd.exe
Microsoft Windows [Version 6.1.7601]
Copyright (c) 2009 Microsoft Corporation.  All rights reserved.

C:\Users\336845>ping -l 64 -n 36 8.8.8.8

Pinging 8.8.8.8 with 64 bytes of data:
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=14ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=14ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=14ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=13ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52
Reply from 8.8.8.8: bytes=64 time=12ms TTL=52

Ping statistics for 8.8.8.8:
    Packets: Sent = 36, Received = 36, Lost = 0 (0% loss),
Approximate round trip times in milli-seconds:
    Minimum = 12ms, Maximum = 14ms, Average = 12ms
```

Figure 4-8 RTT Of 64-Byte Ping Test.

4.4.1 **Test Scenario II - Ping Test with OSPF in Core Network**

In the simulation where we configured OSPF as routing protocol, we opened the terminal of all 5 UEs and gave the command # ping -n 36 192.168.1.3. all 5 UE started to send ping simultaneously to the LADN server and we gathered the data in Table 4-10. The repeated the test but changed the destination to Google DNS. The command we used was # ping -n 36 8.8.8.8, similarly all the results were gathered and displayed in Table 4-11.

Ping Iterations	RTT UE1 (msec)	RTT UE2 (msec)	RTT UE3 (msec)	RTT UE4 (msec)	RTT UE5 (msec)	Average RTT (msec)
1	14	17	32	41	14	23.6
2	10	9	9	9	18	11
3	5	8	14	15	13	11
4	12	20	10	12	24	15.6
5	12	13	7	10	27	13.8
6	7	16	31	14	15	16.6
7	17	16	14	31	10	17.6
8	19	19	13	9	7	13.4
9	10	13	12	9	14	11.6
10	13	21	8	8	7	11.4
11	24	12	13	19	10	15.6
12	15	21	9	20	12	15.4
13	30	7	5	37	10	17.8
14	16	17	16	16	10	15
15	13	17	19	27	6	16.4
16	18	12	14	14	10	13.6
17	45	27	18	11	14	23
18	41	27	30	18	6	24.4
19	27	27	8	35	14	22.2
20	29	37	9	17	9	20.2
21	21	38	12	31	13	23
22	17	27	15	6	6	14.2
23	9	30	9	12	10	14
24	8	13	15	22	15	14.6
25	11	27	5	18	7	13.6
26	15	9	16	6	6	10.4
27	23	14	17	63	11	25.6
28	15	18	14	34	9	18
29	15	11	12	9	8	11
30	6	23	14	20	9	14.4
31	14	17	11	17	14	14.6
32	22	11	10	8	17	13.6
33	14	9	7	15	10	11
34	8	4	13	5	11	8.2

35	16	12	11	18	7	12.8
36	12	6	6	12	16	10.4
Total RTT	**603 msec**	**625 msec**	**478 msec**	**668 msec**	**419 msec**	**558.6 msec**
Average RTT	**16.75 msec**	**17.36 msec**	**13.28 msec**	**18.56 msec**	**11.64 msec**	**15.52 msec**

Table 4-10 RTT Results For OSPF Based Ping Test To LADN Server.

Ping Iterations	RTT UE1 (msec)	RTT UE2 (msec)	RTT UE3 (msec)	RTT UE4 (msec)	RTT UE5 (msec)	Average RTT (msec)
1	22	23	41	26	28	28
2	17	55	27	21	35	31
3	24	28	18	28	19	23.4
4	24	27	17	20	16	20.8
5	35	25	18	35	31	28.8
6	28	25	41	33	19	29.2
7	32	20	26	43	30	30.2
8	22	22	31	18	55	29.6
9	33	13	28	22	13	21.8
10	47	27	44	18	25	32.2
11	15	27	23	16	18	19.8
12	38	38	25	18	19	27.6
13	42	31	33	17	19	28.4
14	16	25	19	22	20	20.4
15	16	33	44	14	15	24.4
16	19	19	31	15	28	22.4
17	14	22	31	26	28	24.2
18	29	24	25	22	19	23.8
19	22	21	19	50	37	29.8
20	33	30	20	20	43	29.2
21	18	30	13	22	27	22
22	37	21	20	15	14	21.4
23	43	22	28	20	25	27.6
24	16	22	23	25	18	20.8
25	26	22	20	15	25	21.6
26	45	23	34	16	34	30.4
27	51	30	22	37	29	33.8
28	41	39	31	40	21	34.4
29	24	39	12	17	38	26
30	26	28	40	28	47	33.8
31	39	30	29	42	23	32.6
32	15	14	18	39	32	23.6
33	22	21	29	39	40	30.2
34	28	19	29	33	39	29.6
35	18	13	26	25	39	24.2
36	15	23	21	28	32	23.8
Total RTT	**992 msec**	**931 msec**	**956 msec**	**925 msec**	**1000 msec**	**960.8 msec**

Average RTT	**27.56 msec**	**25.86 msec**	**26.56 msec**	**25.69 msec**	**27.78 msec**	**26.69 msec**

Table 4-11 RTT Results For OSPF Based Ping Test To Google DNS.

4.4.2 RTT Improvement with LADN and OSPF

From Table 4-10 and Table 4-11 we compared the results and found out that the average time that can be saved is 11.17 msec on per request basis as displayed in Table 4-12.

Sr.no	Description	UE1	UE2	UE3	UE4	UE5
1	Average RTT(msec) Internet	27.56 msec	25.86 msec	26.56 msec	25.69 msec	27.78 msec
2	Average RTT(msec) LADN	16.75 msec	17.36 msec	13.28 msec	18.56 msec	11.64 msec
3	**RTT (msec) saved with LADN**	**10.81 msec**	**8.50 msec**	**13.28 msec**	**7.14 msec**	**16.14 msec**
4	**Average RTT (msec) saved with LADN**	**11.17 msec**				

Table 4-12 Summary Of Ping Test RTT LADN VS Internet (OSPF).

We then Plotted the graph for the average RTT for both the LADN and Google DNS ping tests of all 5 UEs and the results are shown in Figure 4-9. The blue line displays the RTT of LADN while the orange line displays RTT of the Google DNS server. It is quite evident that most of the time the RTT of LADN is below the RTT of Google DNS. There are two instances (18 and 21) where the RTT of LADN touches that of RTT of the Internet, but that can be nominated as exceptional cases.

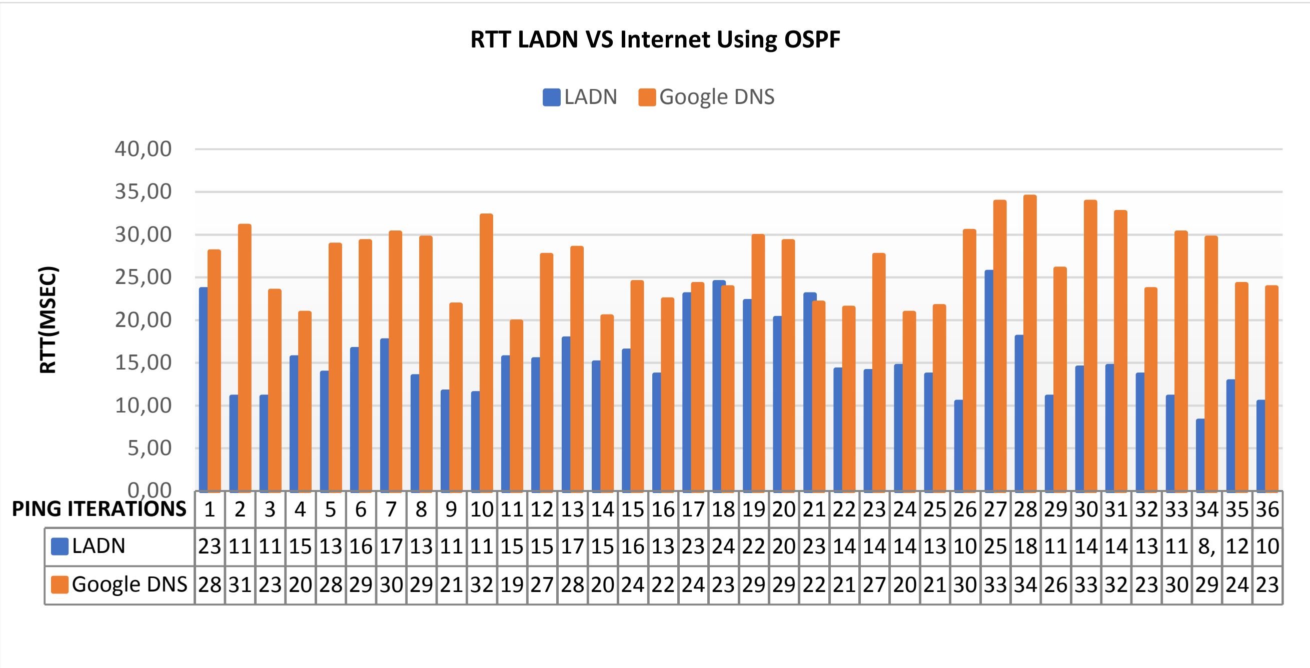


Figure 4-9 RTT LADN VS Internet (OSPF)

4.4.3 Ping Test with EIGRP in Core Network

We repeated the same test 4.4.2 but this time we used the simulation that was configured with EIGRP as the routing protocol in the core network. The results for pings to LADN and Google DNS are displayed in Tables 4-13 and 4-14 respectively.

Ping to LADN from UE						
Ping Iterations	RTT UE1 (msec)	RTT UE2 (msec)	RTT UE3 (msec)	RTT UE4 (msec)	RTT UE5 (msec)	Average RTT (msec)
1	15	31	35	18	25	24,8
2	21	6	18	15	11	14,2
3	5	13	8	8	10	8,8
4	11	14	14	27	11	15,4
5	23	7	19	13	37	19,8
6	9	10	5	9	12	9
7	14	7	14	13	11	11,8
8	14	10	17	22	9	14,4
9	18	10	27	14	7	15,2
10	8	8	9	18	11	10,8
11	10	18	36	15	13	18,4
12	15	13	23	24	14	17,8
13	6	8	20	21	7	12,4
14	10	10	12	40	17	17,8
15	8	11	10	21	8	11,6
16	15	15	12	12	8	12,4
17	6	37	19	9	8	15,8
18	11	8	8	22	10	11,8
19	8	14	7	8	27	12,8
20	12	7	9	30	8	13,2
21	16	8	7	7	17	11
22	13	22	21	9	8	14,6
23	31	8	9	12	11	14,2
24	6	13	17	13	8	11,4
25	15	3	29	13	10	14
26	10	9	25	18	7	13,8
27	9	18	40	12	9	17,6
28	21	22	10	18	10	16,2
29	12	19	28	26	17	20,4
30	12	9	17	34	12	16,8
31	7	32	28	12	9	17,6
32	9	17	42	19	8	19
33	15	12	14	27	10	15,6
34	8	9	6	24	11	11,6
35	15	6	16	33	8	15,6
36	7	9	15	19	9	11,8
Total RTT (msec)	**445**	**473**	**646**	**655**	**428**	**529,4**
Average RTT(msec)	**12,36**	**13,14**	**17,94**	**18,19**	**11,89**	**14,71**

Table 4-13 RTT Results For EIGRP Based Ping Test To LADN Server.

Ping to Google DNS from UE						
Ping Iterations	RTT UE1 (msec)	RTT UE2 (msec)	RTT UE3 (msec)	RTT UE4 (msec)	RTT UE5 (msec)	Average RTT (msec)
1	19	37	29	39	46	34
2	21	16	36	27	18	23.6
3	22	18	20	15	19	18.8
4	18	23	25	33	26	25
5	17	24	25	33	21	24
6	16	18	11	16	78	27.8
7	22	21	14	17	32	21.2
8	20	16	19	23	13	18.2
9	24	16	19	19	24	20.4
10	16	19	37	16	24	22.4
11	25	17	17	24	29	22.4
12	15	24	27	17	23	21.2
13	15	32	12	12	15	17.2
14	22	21	12	21	19	19
15	19	28	25	16	17	21
16	12	23	28	12	19	18.8
17	13	20	21	12	16	16.4
18	23	20	25	15	17	20
19	15	14	17	16	17	15.8
20	15	24	14	14	21	17.6
21	15	20	12	19	15	16.2
22	18	26	19	18	22	20.6
23	27	26	17	15	15	20
24	24	15	12	15	20	17.2
25	32	31	17	11	19	22
26	27	40	19	18	14	23.6
27	20	39	25	15	13	22.4
28	24	51	30	14	18	27.4
29	30	48	49	19	16	32.4
30	28	35	36	20	15	26.8
31	28	40	39	28	12	29.4
32	24	43	36	39	20	32.4
33	23	35	45	27	24	30.8
34	23	29	52	29	27	32
35	27	24	34	19	12	23.2
36	27	23	25	52	22	29.8
Total RTT (msec)	766	956	900	755	778	831
Average RTT(msec)	21.28	26.56	25.00	20.97	21.61	23.08

Table 4-14 RTT Results For EIGRP Based Ping To Google DNS.

4.4.4 **RTT Improvement with LADN and EIGRP**

From Table 4-13 and Table 4-14, we compared the results and found out that the average time that can be saved is 8.38 msec on per request basis as displayed in Table 4-15.

Sr.no	Description	UE1	UE2	UE3	UE4	UE5
1	Average RTT(msec) Google DNS	21.28	26.56	25.00	20.97	21.61
2	Average RTT(msec) LADN	12.36	13.14	17.94	18.19	11.89
3	**RTT (msec) saved with LADN**	**8.92**	**13.42**	**7.06**	**2.78**	**9.72**
4	**Average RTT (msec) saved with LADN**	**8.38**				

Table 4-15 Summary Of Ping Test RTT LADN VS Internet (EIGRP).

We then Plotted the graph for the average RTT for both the LADN and Google DNS ping tests of all 5 UEs and the results are shown in Figure 4-10. The blue line displays the RTT of LADN while the orange line displays RTT of the Google DNS server. It is quite evident that most of the time the RTT of LADN is below the RTT of Google DNS. Then there is no instance of the ping at which the Blue line is higher than the orange one. Hence it is established that by using LADN solution the RTT can be improved.

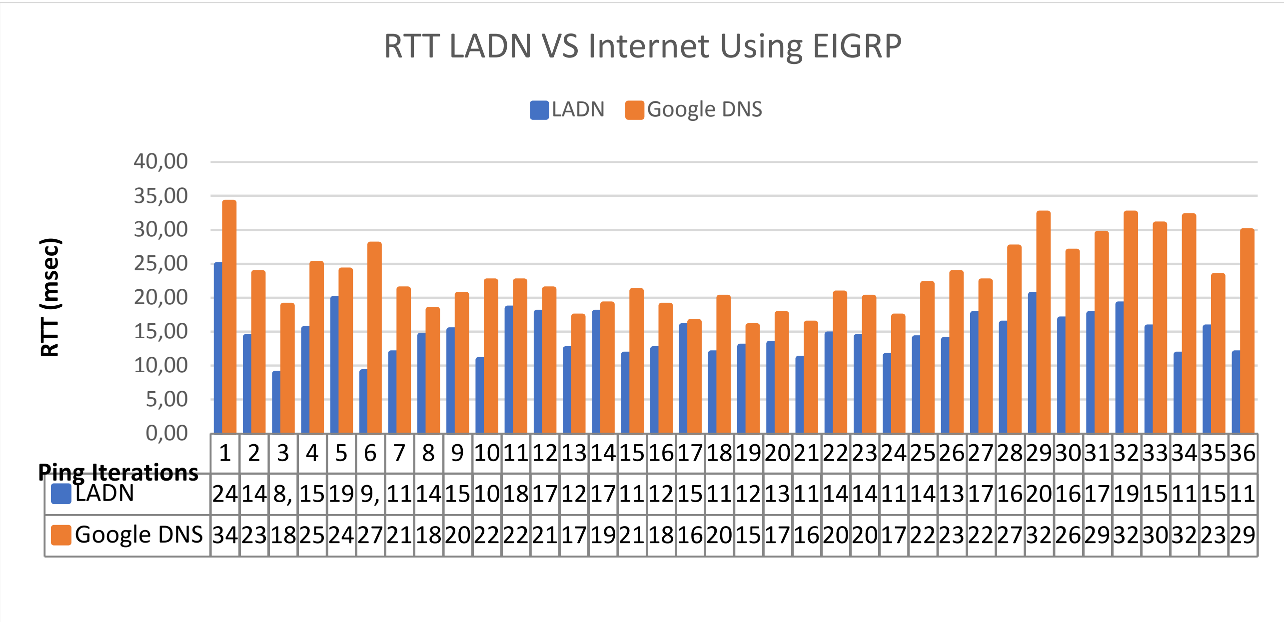


Figure 4-10 RTT LADN VS Internet (EIGRP).

4.5 Summary

In this chapter we created a simulation to replicate the real-life testbed-based topology because we wanted to add more UEs, change the core network configuration and simulate the UEs sending a request to the internet with no external traffic. We needed to gather data and analyses will the LADN still be beneficial under these conditions and if yes how much RTT can be improved by it. Hence, we created two simulations with 5 UEs and used the core network with two routing protocols OSPF and EIGRP. After the ping test of both simulations, we found out that the OSPF will improve RTT by 11.17 msec while EIGRP will improve by 8.38 msec. Although with EIGRP the RTT of the core network also improve slightly by 2.79 msec but still the use of LADN saves approximately three times this value. Therefore, LADN implementation will save RTT regardless of which protocol is being used on the core network. Applying LADN to satellite communication and results in comparison.

5 Applying LADN to Satellite Link: A Comparison Study

In this chapter, we will discuss the types of delays and the minimum delay that is added to RTT when using satellite communication. Then we add this delay to our already available results and compare all the results from Chapters 3,4 and 5 with each other.

5.1 Satellite Communication

In areas where it is either physical or economically not possible to provide connectivity by conventional wireless networks and mobile systems are covered by satellite communication. Since satellite needs nominal equipment to provide coverage around the globe hence satellite communication is more feasible in low populated areas, difficult terrain and over the sea. There are three main types of Satellite, Low Earth Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Equatorial Orbit (GEO). The main difference is their altitude or distance from the ground base station. Their main characteristics are share in Table 5-1.

LEO	MEO	GEO
Altitude/range 150-1,000 Km	Altitude/range 5,000-10,000 Km	Altitude/range up to 36,000
Reduced Latency and favored for voice communication	Provide compromise between LEO and GEO and has reduced latency as Compared to GEO	Easy and cost effective to deploy and operate, however latency is an issue for some applications.
Large constellation and pairings are needed.	Small constellation or paring is required.	Single satellite is sufficient.
Limited coverage Favors Cross-links	Each satellite covers a large area, landmass or ocean, cross-links of limited value	Each satellite covers a hemisphere, very little or no use of cross-links.
Nearly three-quarters of satellites over ocean at a given time.	Satellite coverage extends across oceans.	Satellite coverage extends across oceans and continents.

Table 5-1 Types Of Satellite And Their Comparison. [18, pp. 405,407]

It is clear from the Table that for long coverage area MEO and GEO satellites are used, and Telenor is using Thor7 which is a GEO satellite with an altitude of 35.786 km to provide coverage to cruise ships.

5.2 Scenarios: Internet Services on Cruise Ships

While you are traveling by ship and want to access the internet to watch videos or read e-mails then we need to use the satellite link. This is because conventional connectivity can be provided to a cruise ship moving on the open seas. Hence the ship will have VSAT transverse-mounted on it which will route the user request via the satellite (GEO, MEO) to the service providers Network Operation Center. The NOC will have conventional connectivity with the internet and from there onwards the request will travel on the wired conventional internet. Since the ship will always be moving on the sea hence its distance will keep on changing, since we are only focusing on 1 hop Satellite link communication, we can have two scenarios:

I. **Scenario 1:** Ship is right below the satellite with minimum distance between the satellite and ship

II. **Scenario 2:** Ship is at the edge of the coverage area. This is the maximum distance from the satellite.

Since we don't have a satellite link to run this test upon, we decided to calculate the total end-to-end delays and then add them to find RTT for 1 ping and then add them to our results obtained in real-life testbed-based solution and simulation solutions.

5.3 End-to-end Delays

In computer network communication End-to-end delays can be divided into 4 basic types which are listed below.

I. **Processing Delay D_{pros}:** Process delay is denoted as the time required to process a packet at each node and prepare it for transmission or re-transmarine. Its variation depends upon available computational power, the complexity of the protocol stack and interface card that receives the request. This is not a constant delay and can't be calculated in a deterministic way as it has a stochastic process. To calculate we need to determine what the router is doing when it receives the request. [19, p. 1]

II. **Transmission Delays D_{trans}:** It is the time needed to transmit an entire packet over a communication link. The transmission delay can be controlled by the link speed and capacity. [19, p. 1]

$$D_{trans} = \frac{Number\ of\ bits\ to\ send}{Link\ data\ rate} \qquad (5.1)$$

Equation (5-1) Transmission Delay. [19, p. 1]

III. **Propagation Delay D_{prop}:** It is the time required to propagate a bit over the link [19, p. 1]. It is the travel time that a bit takes to move from location A to Location B and hence is dependent upon the distance between the two entities and the speed at which the bit moves. This delay can be calculated accurately if these two variables are known. Since in communication the maximum speed of transmission can't exceed the speed of light, therefore we can use that to calculate this delay.

$$D_{prop} = \frac{d}{s} = \frac{Link\ distance\ (mtr)}{Speed\ of\ signal\ propagation\ (mtr/sec)} \qquad (5.2)$$

Equation (5-2) Propagation Delay.

IV. **Queuing Delays D_{que}:** It is the waiting time of a packet in the buffer before transmission [19, p. 1]**.** This delay can be reduced by adopting various queuing techniques.

So, the **end-to-end delay** can be calculated as

$$END - to - End\ delay\ = D_{pros} + D_{que} + D_{prop} + D_{trans} \qquad (5.3)$$

Equation (5-3) End-To-End Delay.

5.4 Delay Calculations on Satellite Link

Since we did not have a satellite link to run the ping test, we decided to calculate the minimum delay that a packet must suffer on a satellite link and then add that delay to our real-life testbed-based and simulation results. In the ideal condition, we can assume that there is no Processing or queuing delay. This will leave only the Propagation delay and transmission delays . Hence, we decided to calculate the Propagation delay and transmission delay for GEO and MEO satellite which is normally used to provide internet services. But we should keep in mind that this is a hypothetical scenario and will result in a minimum delay that can be added by adding one hop of satellite communication. Figure 5-1 shows 1 hop of satellite communication with RTT of each segment. [17, p. 2]. Where the orange line shows request and green line shows request-response. The Figure 5-1 shows the end-to-end communication after adding 1 hop of GEO satellite communication.

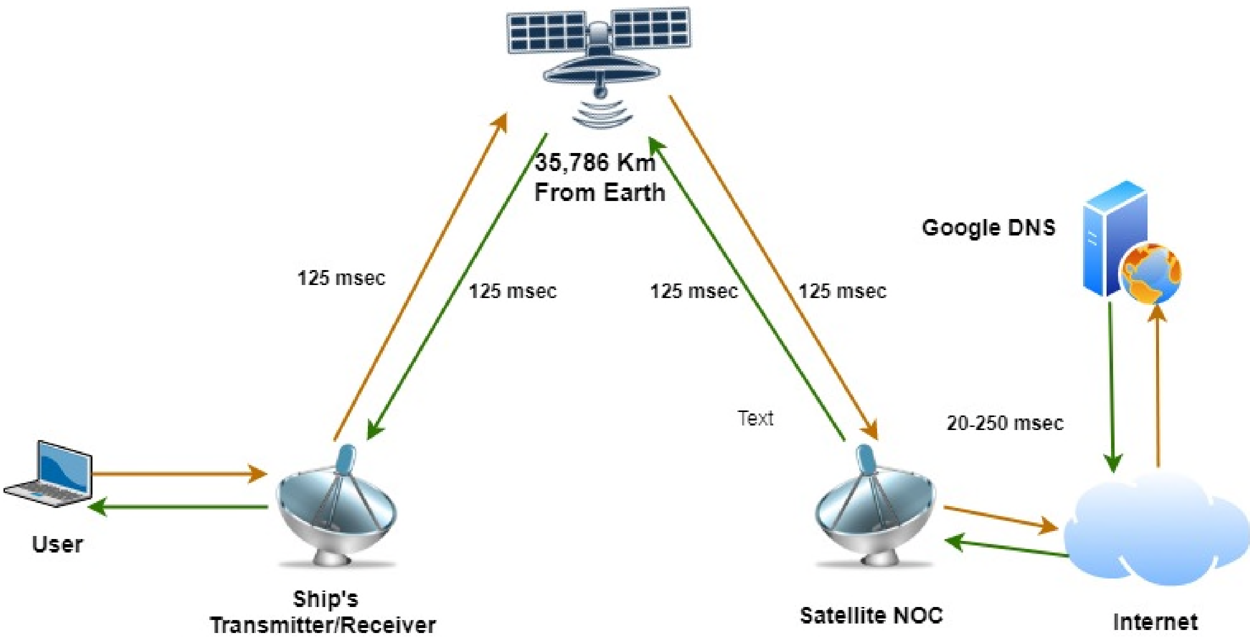


Figure 5-1 RTT Of GEO Satellite Link. [17, p. 2]

5.4.1 **Propagation Delay**

Distance between the remote site and satellite is the same as the distance between the Satellite and Satellite NOC. Hence the link distance will be 2x 22,240 mile or 2x 35, 791.81 km. since the speed of RF communication is equal to the speed of Light 299,792,458 m/secs. Putting both values in Equation 5-2

$$\mathbf{Dprop} = \frac{\mathbf{2 * 35,786}\ \boldsymbol{mtr}}{\mathbf{299,792,458}\ \boldsymbol{mtr/sec}}$$

$$\mathbf{Dprop} = \mathbf{238.74}\ \boldsymbol{msec}$$

Similarly, if the Remote site is moved to the edge of the satellite coverage area the propagation delay will be

$$\mathbf{Dprop} = \frac{\mathbf{2*41,756,000}\ \boldsymbol{mtr}}{\mathbf{299,792,458}\ \boldsymbol{mtr/sec}}$$ [20, p. 1]

$$\mathbf{Dprop} = \mathbf{278,56}\ \boldsymbol{msec}$$

Similarly, if we consider RTT then the total propagation delay will be twice as much as shown in Equation 5-5 and will be 557 msec [20, p. 1]] in case of edge scenario and the RTT in case of Equation 5-4 and [17, p. 2] is 500 msec. Table 5-2 shows the propagation delays for Scenario 1 and Scenario 2. Similarly, the Orbital distance of the MEO satellite is between 9000-11000 Km [21, p. 5] by placing these values in Equation 5-2 we can calculate the Propagation delays of the MEO satellite as well. The result for MEO is below 75 msec [18, p. 407]

Scenario. No	Description	GEO Link delay	MEO link delay
1	**Scenario 1**	238.78 msec	60.04 msec
2	**Scenario 2**	278.56 msec	73.38 msec
	Average delay	**258.6 msec**	**66.71 msec**

Table 5-2 Average Delay Using 1 Hop Satellite Link.

5.4.2 **Transmission Delays**

Normally the available bandwidth of 50-100 Mbps is shared among 3500 people on a mid-sized cruise ship. This means if everyone is using the internet and available bandwidth is divided equally among all users they will have 14.28-28.57 Kbps data rate. Now if we are sending a ping of 64 bytes and we place the maximum available data rate in e Equation 5-1 we get a delay of 4,48 msec. since this delay is not dependent on the distance it will be the same for Scenario 1 and Scenario 2, both for GEO and MEO satellite links. The Table 5-3 shows the calculations for transmission delays that can be experienced while surfing the internet on a cruise ship.

Transmission delays					
Data (bytes)	Users	Shared Data Rate	Average Data rate/user	Delay	Delay (msec)
64	3500	50Mbps	14285.714 bytes/sec	0.00896 sec	8.96 msec
64	3500	100Mbps	28571.42 bytes/sec	0.00448 sec	4.48 msec

Table 5-3 Transmission Delay Calculation.

5.4.1 **RTT for Satellite Link**

Since we have calculated both the Propagation and transmission delays we can now calculate RTT for 64bytes ping packet. From Table 5-2 and Table 5-3 we extracted the data and Placed that in Equation 5-4. Since Table 5-2 and 5-3 represents the delays for 1-way traffic we needed to add the delays for the return traffic as well to calculate actual RTT. Hence, we multiplied the results by two and the RTT results are displayed in Table 5-3

Sr.No	Description	Propagation delay	Transmission delay	GEO RTT
1	Scenario 1 (GEO)	238.74 msec	4.48 msec	486.44 msec
2	Scenario 2 (GEO)	278.57 msec	4.48 msec	557.13 msec
Average delay/RTT		**258.65 msec**	**4.48 msec**	**521.78 msec**

Sr.No	Description	Propagation delay	Transmission delay	MEO RTT
1	Scenario 1 (MEO)	60.04 msec	4.48 msec	129.04 msec
2	Scenario 2 (MEO)	73.38 msec	4.48 msec	155.73 msec
Average delay/RTT		**66.71 msec**	**4.48 msec**	**142.39 msec**

Table 5-4 RTT Calculation For Satellite Communication.

It can now be deduced that the bottleneck is the propagation delay since it represents the lion's share of the total delay in terms of Satellite communication. The acceptable Latency range for VSAT communication for the GEO satellite is between 550-650 msec [22]. Table 5-4 shows the RTT for one hop satellite communication, with zero queuing and processing delays. In ideal conditions, this can be treated as RTT for 1 hop satellite communication.

We added these RTT values to our real-life testbed based RTT values and illustrated the RTT values of MEO and GEO satellites in Figure 5-2. The blue lines represent RTT of the GEO satellite while the orange line shows RTT of the MEO satellite. The RTT of the MEO satellite is more than 3 times the RTT of the MEO Satellite. But since Telenor is using the GEO satellite we will focus more on the results calculated for the GEO satellite communications.

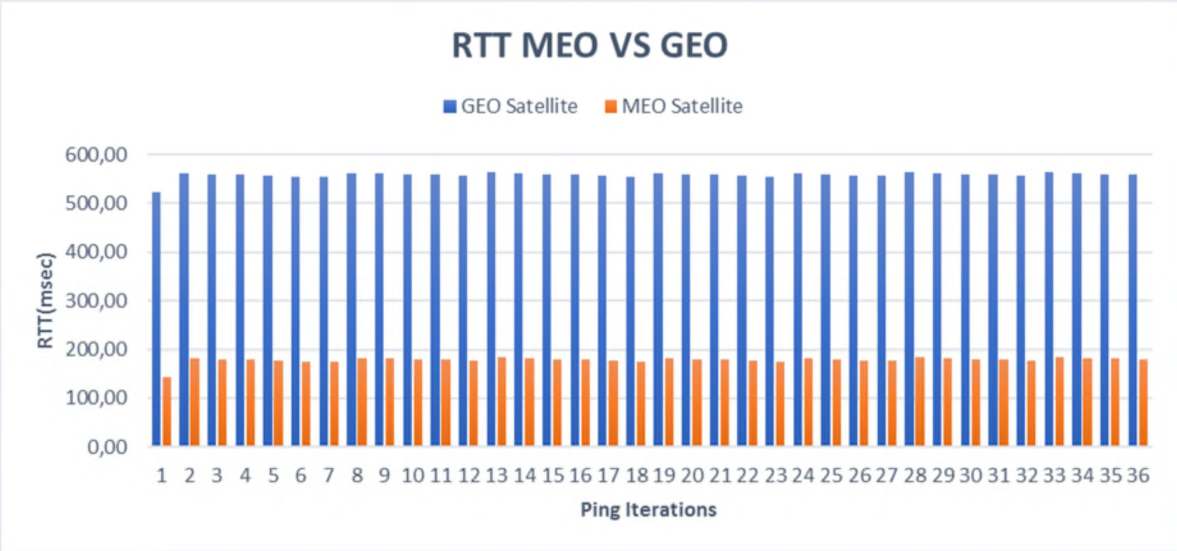
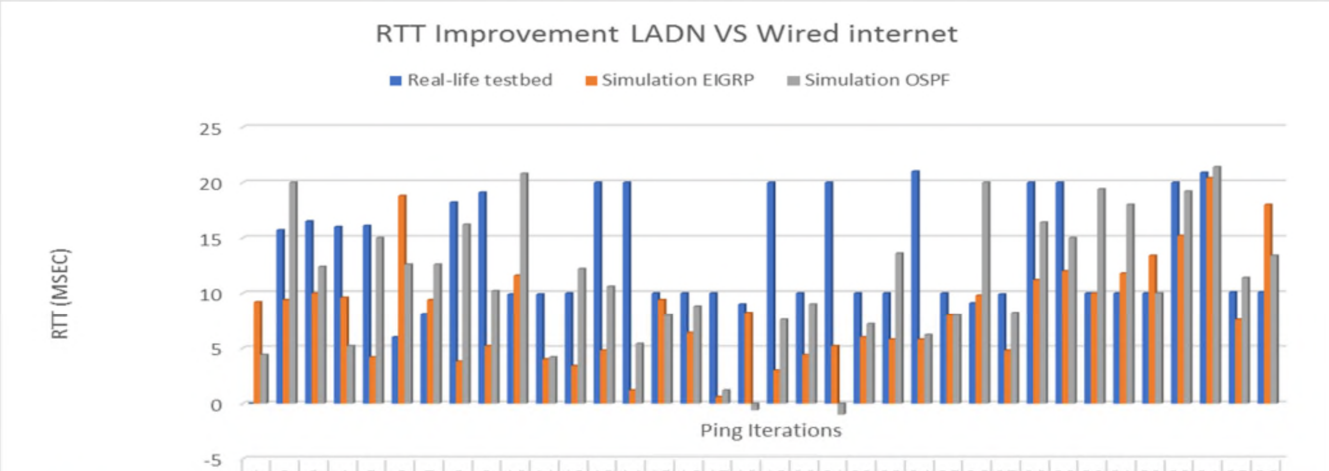


Figure 5-2 RTT GEO VS MEO.

5.5 Results and Comparison

The 517.2 msec value from Table 5-2 will be added to the RTT of Table 3-2, 4-11 and 4-14 in the column of ping to google DNS and average RTT respectively. This way a new column will be created that will show the RTT in case of routing traffic via the 1 hop of satellite communication. This will be done to calculate the RTT of a person trying to reach the internet while traveling on by sea. Then we will compare the RTT reduction between LADN VS Real-life testbed based and LADN VS satellite internet. As shown in Figures 5-3 and 5-4 respectively. The blue line represents the RTT reduction in the real-life testbed, the orange line represents the RTT reduction in EIGRP simulation and the grey line represents the RTT in OSPF simulation. These values are attained by subtracting the RTT of wired, GEO satellite and MEO satellite internet scenario from the RTT of the LADN scenario for each instance of ping results. It is quite evident that the maximum RTT improvements were achieved from the real-life testbed and the OSPF simulation results.

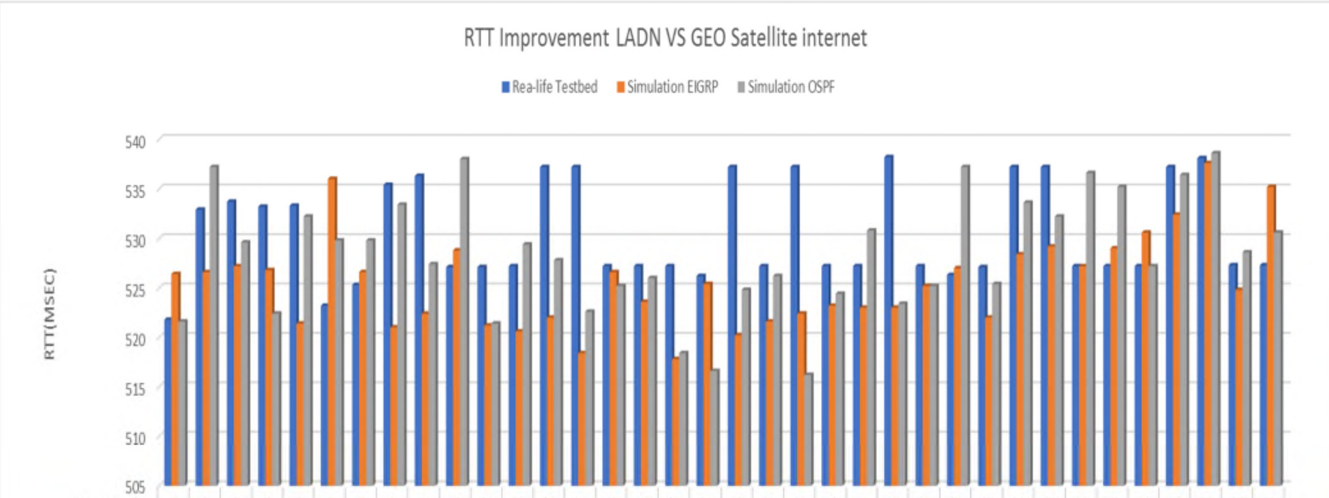


	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Real-life testbed	0	16	17	16	16	6	8	18	19	10	10	10	20	20	10	10	10	9
Simulation EIGRP	9	9	10	10	4	19	9	4	5	12	4	3	5	1	9	6	1	8
Simulation OSPF	4	20	12	5	15	13	13	16	10	21	4	12	11	5	8	9	1	-1

	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Real-life testbed	20	10	20	10	10	21	10	9	10	20	20	10	10	10	20	21	10	10
Simulation EIGRP	3	4	5	6	6	6	8	10	5	11	12	10	12	13	15	20	8	18
Simulation OSPF	8	9	-1	7	14	6	8	20	8	16	15	19	18	10	19	21	11	13

Figure 5-3 RTT Improvement LADN VS Wired Internet.

The blue line represents the RTT reduction in the real-life testbed, the orange line represents the RTT reduction in EIGRP simulation and the grey line represents the RTT in OSPF simulation. These values are attained by subtracting the RTT of the satellite internet scenario from the RTT of the LADN scenario for each instance of ping results. From Figure 5-3,5-4 and 5-5, it is quite evident that the maximum RTT improvements were achieved from the real-life testbed and the OSPF simulation results regardless of which technology was used. All the values are represented in milliseconds.



Ping Iterations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Rea-life Testbed	522	533	534	533	533	523	525	535	536	527	527	527	537	537	527	527	527	526
Simulation EIGRP	526	527	527	527	521	536	527	521	522	529	521	521	522	518	527	524	518	525
Simulation OSPF	522	537	530	522	532	530	530	533	527	538	521	529	528	523	525	526	518	517

Ping Iterations	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
Rea-life Testbed	537	527	537	527	527	538	527	526	527	537	537	527	527	527	537	538	527	527
Simulation EIGRP	520	522	522	523	523	523	525	527	522	528	529	527	529	531	532	538	525	535
Simulation OSPF	525	526	516	524	531	523	525	537	525	534	532	537	535	527	536	539	529	531

Figure 5-4 RTT Improvement LADN VS GEO Satellite Internet.

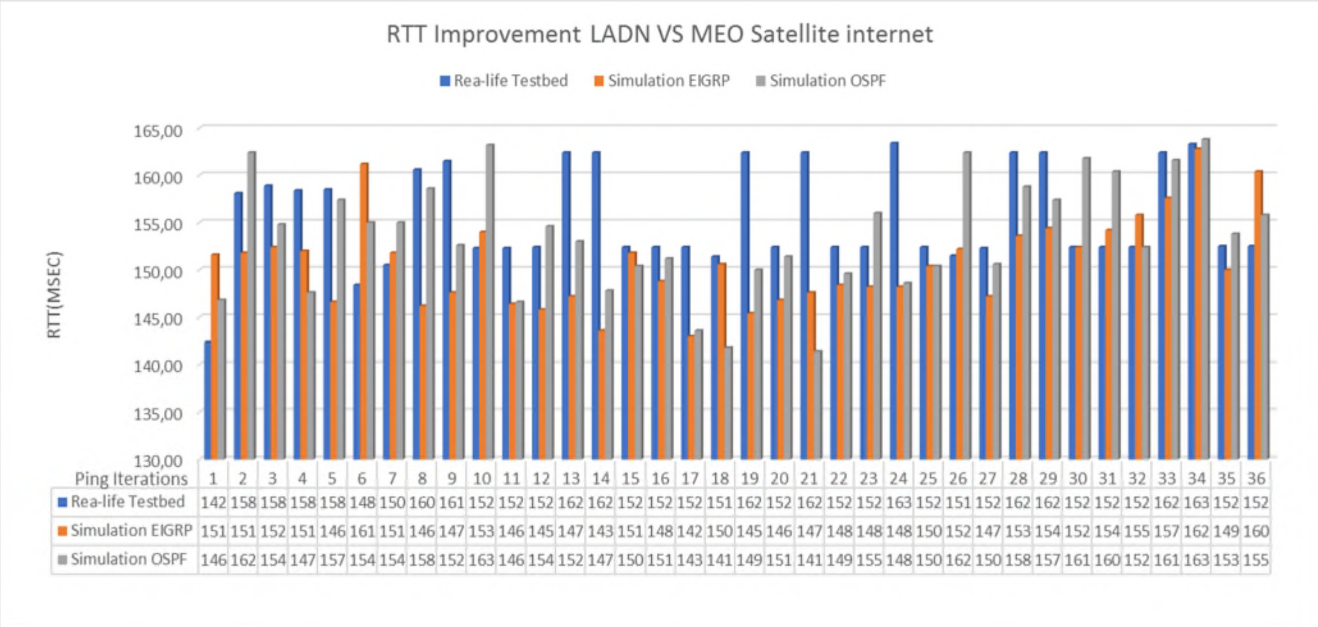


Figure 5-5 RTT Improvement LADN VS MEO Satellite Internet.

To summarize the results of Figure 5-3,5-4 and 5-5 we took average values of all three RTT improvement scenarios and represented them in Table 5-5. The result clearly shows that he maximum RTT improvement (13.21 msec, 530.41 msec,155.60 msec) is attending in the real-life testbed solution while the minimum RTT improvement (8.38 msec, 525.58 msec,150.76 msec) is attended by the Simulation where EIGRP was used as routing protocol in the core network with no external traffic influencing the topology. Although the EIGRP simulation improves internet performance by 4.83 msec in both cases but in real-world Core network uses a combination of different protocols, links and routers and queuing techniques which will add to the RTT values. As can be seen when OSPF was used the RTT difference between the real-life testbed and OSPF was reduced to 2.04 msec. This is more than Half (2.79 msec) the value saved by using EIGRP.

Description	LADN	Wired Internet	Internet satellite GEO	Internet satellite MEO
Average RTT real-life testbed	22.97	36.18	557.96	178.56
Average RTT simulation EIGRP	14.71	23.08	544.87	165.47
Average RTT Simulation OSPF	15.52	26.69	548.47	169.07
Improvement in RTT LADN VS Real-life test bed		**13.21**	**535.00**	**155.60**
Improvement in RTT LADN VS Simulation EIGRP		**8.38**	**530.16**	**150.76**
Improvement in RTT LADN VS Simulation OSPF		**11.17**	**532.96**	**153.56**

Table 5-5 Average RTT Improvement In All Three Scenarios.

5.6 Summary

If we translate these results in light of Equation 3-1 then the use of LADN will be most effective when used in real-life testbed scenarios and least useful in simulation using EIGRP. This is because RTT is inversely proportional to TCP session throughput and since YouTube and other website uses TCP for video streaming hence the higher the TCP throughput the lower are the delays and therefore user experience is enhanced. Similarly, even inside the real-life testbed the RTT of Wired internet << RTT of Satellite internet and RTT MEO of satellite<< RTT of GEO satellite. Hence as per Equation 3-1, the TCP throughput reduced drastically with increasing RTT values, therefore LADN will be most beneficial when we can substitute it with GEO and MEO satellite internet connections. Then LADN can be used in small rural areas with limited access to the outside world, sea travel or remote cabins where it is not possible or not feasible to provide internet via wired infrastructure.

Although the MEO satellite link reduces RTT improvement of LADN implementation still the RTT of MEO 150.76-155.60 is very high as compared to 8.38-13.21 in case of wired internet. Therefore, the LADN will be beneficial regardless of which type of satellite (MEO/GEO) is being used to provide connectivity.

6 Conclusions and Future work

In this chapter, we will provide a conclusion based on the work and experiments completed. We will also list contributions to this thesis and lastly, we will highlight a few research directions relevant to the work carried out in this thesis.

6.1 Conclusions

The LADN solution is very beneficial if implemented properly. Although satellite communication is a solid way of communicating over the great seas since normal radio communication cannot reach far enough. Comparing satellite and radio communications, satellite links are slower and more expensive which leads to higher delays. This means that users experience excessive lags while using satellite communication. To reduce these delays and the amount of traffic that needs to traverse on these links LADN was introduced in 5G communication.

We implement a small-scale real-life testbed-based LADN solution and observe how beneficial it will be to improve the lags experienced by users and reduce traffic load on both wired and satellite internet access scenarios. We decided to run the ping test to measure the end to end delays on per request basis and traceroute to check how many hops the request has to travel to get a response. Then we also introduced the i-perf test to see what kind of data rate the user will be able to enjoy if LADN is implemented for TCP and UDP communications.

Since in the real-life testbed-based solution did not allow us to change the parameters of the core network and see how they will affect the RTT, therefore we made a simulation where we could change the parameter of the core network and ensures that no external traffic will affect the results of the ping test. We used two different types of routers and routing protocols and ran the test.

After completing several tests, we compare all the results and from Figure 5-2, 5-3, Table 5-2 the amount of time that can be saved per request basis is quite high. The minimum value is 525.58 msec and 8.38 msec. which in the case of satellite communication is very large and hence if we can reduce this amount of time on every request the delays while streaming videos will be reduced significantly.

6.2 Contributions

In this project, we constructed the entire topology of the real-life testbed-based solution and establish connectivity between them before we can start with the actual testing procedure. The main contributions of this thesis are as follows:

I. Implementation of a real-life testbed-based LADN solution. The solution was based on a newly developed free5GC platform but support for LADN was not included in the Platform.

II. Created test scenarios to find to find out the benefits of LADN over the public internet and satellite Link.

- 5GC was a recently developed platform, therefore we needed to perform some troubleshooting before we can establish the 5GC environment.
- To find out the response time we conducted a ping test which provided us RTT of LADN as well as RTT of public internet. Then we created a comparison between them.
- We conducted the Traceroute test which gave us insight on how many hops the request needs to traverse before getting a response from both LADN and public internet.

- Finally, we conducted i-Perf tests in which we downloaded TCP and UDP data from the LADN server to find out the throughputs of LADN and then repeated the same test over the public internet.

III. Created a simulation to make changes in the core network and observer behavior of LADN solution under these changes. We used two types of routing protocol (EIGRP/OSPF) and did the ping test as described in II.

IV. Provide feasibility of the LADN VS satellite (MEO/GEO) link. Since we did not have a satellite link to run these tests as described in II. We decided to calculate the end-to-end delay for 1 hop of both MEO/GEO satellite links and then multiply them by two which gave us the RTT of both links in ideal scenarios. These RTT were added in the RTT obtained from II and III and then RTT improvement while using LADN against the Satellite link was shown in Chapter 5

6.3 Future Work

These results are based upon the theoretical calculation of RTT and propagation delay on the satellite link. If in the future, we can get access to a satellite link it will give more concrete results. In future following tasks can be done

I. Edit the free5GC application code to enable a database match clause so that the user doesn't have to give the IP address or a certain Website name to access Data hosted on the LADN server. This will provide seamless access to the user.

II. Get access to real-life satellite links or acquire a simulator that can imitate a satellite link to get more precise results in case of a satellite communication scenario.

III. Make an emulator that can calculate the lags when streaming videos on the internet and on the LADN server to compare their results. To make a benchmark.

IV. Run these Tests over a 5G New Radio Air interface to see if the Eliminates the LTE air interface bandwidth bottleneck.

A. Appendix A (User Manual)

The desired operation of the LADN solution is shown in Figure 0-1. The figure shows the assigned IP address. The subnet mask for all IP address is 255.255.255.0, except UP-tun IP subnet mask is 255.255.0.0. make sure that correct IP address are assigned. The Upper part shows quires being responded by LADN server while the lower part shows quires being responded by Internet. The orange arrows are the quires while the green arrows represents query responses.

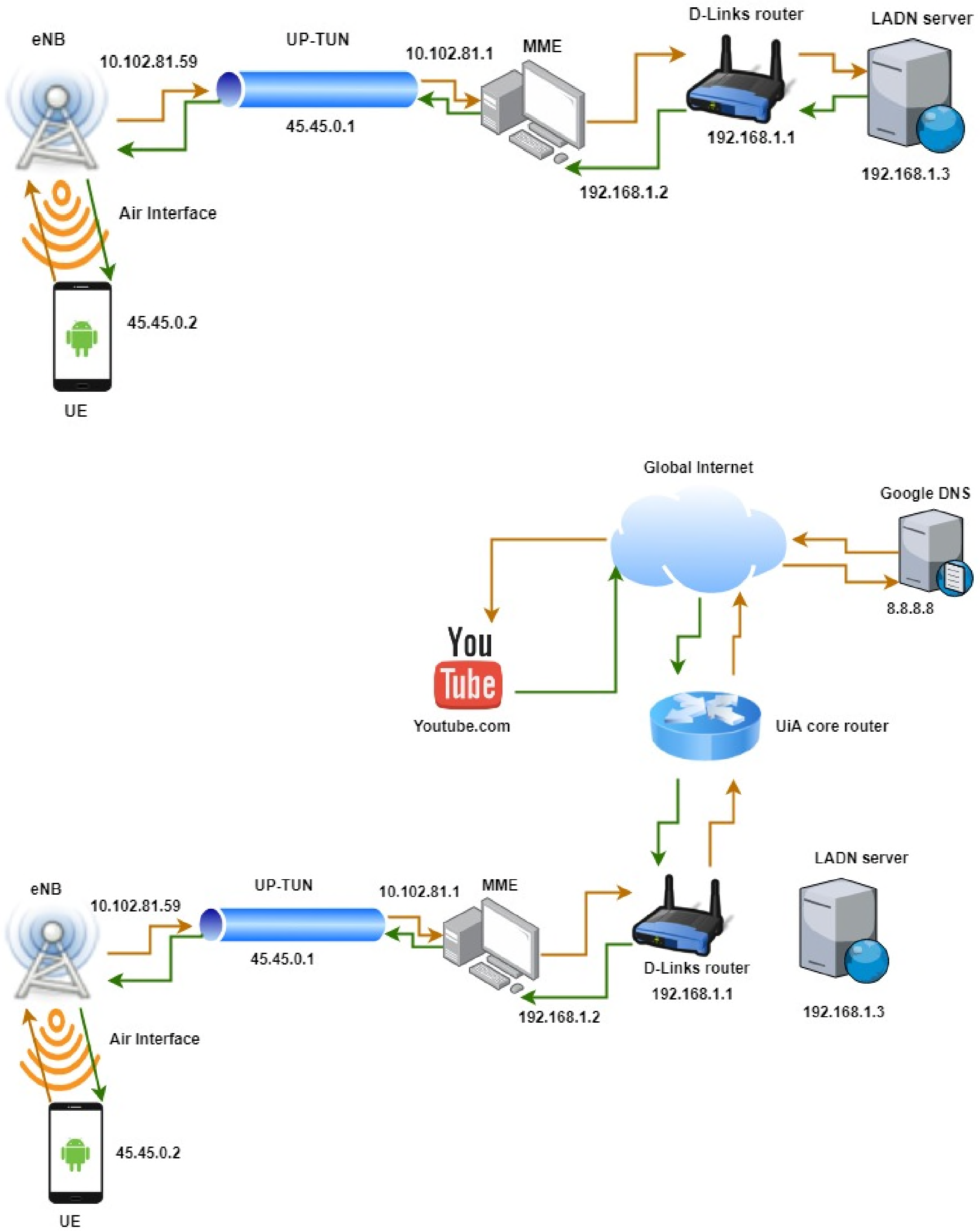


Figure A- 1 LADN Operation.

A.1 System Setup

We should start with setting up the system Figure 0-2 shows all the different components of the system.

Figure A- 2 Systems Setup.

The connection details is shown below:

- UE to LTE small Cell → LTE Air interface.
- LTE small Cell to MME → Cat6 Cable
- MME to D-links Router → Cat6 Cable (LAN port)
- LADN to D-links Router → Cat6 Cable (LAN port)
- D-links Router to internet → Cat6 Cable (Internet/WAN port)

The main point to note over here is that the MME need two NIC ports. Since the standalone PC has only one we used a USB to ethernet converter to overcome this issue.

A.2 IP Address Allocation (MME/LADN Server /D-Links)

We start with Ubuntu based MME and LADN server. Ip allocation can be done based on terminal and based upon GUI. We used the GUI based for normal NIC port and command based for the UP-tun interface. as shown in Figure 0-3 click on the Lan interface

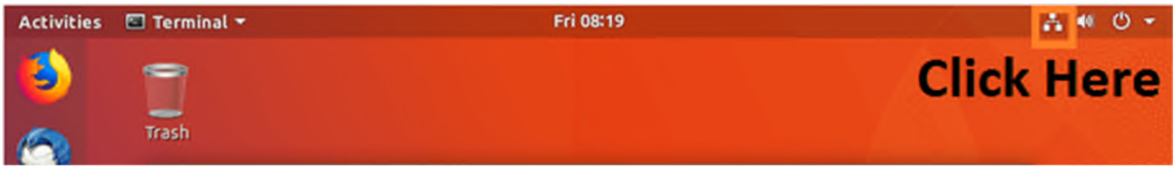


Figure A- 3 LAN Interface on Ubuntu.

- Click on LAN tab on the upper Left corner of the screen.
- Click on the available NIC port 1 at a time
- On the new pop up page Click on settings

Figure A- 4 Wired Interfaces IP Setup 1.

- Click on IPV4

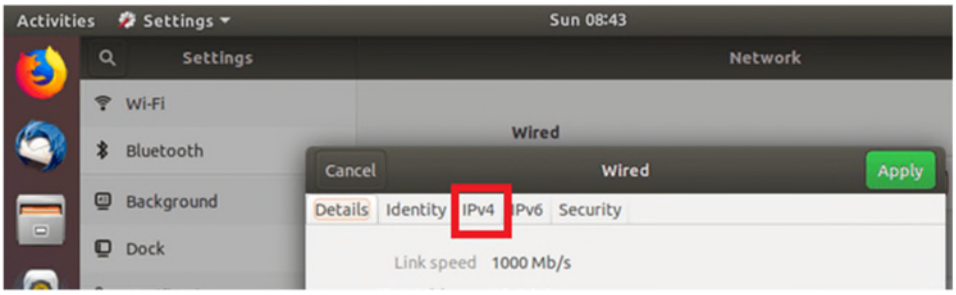


Figure A- 5 Wired Interfaces IP Setup 2.

- Provide Correct IP address/Subnet mask and Default Gateway Address
- Click on apply to finalize the setup

Figure A- 6 Wired Interfaces IP Setup 3.

- Default Gateway address not needed on the interface between MME and LTE small cell

For the D-links Router go to its default webpages and do the steps given below

- Click settings on the menu
- Click Network settings for the setting menu
- Disable DHCP
- Allocate proper IP address and subnet mask.
- IP address and subnet mask of this interface mush be same as IP address and subnet mask which we allocated to MME and LADN server for default Gateway.

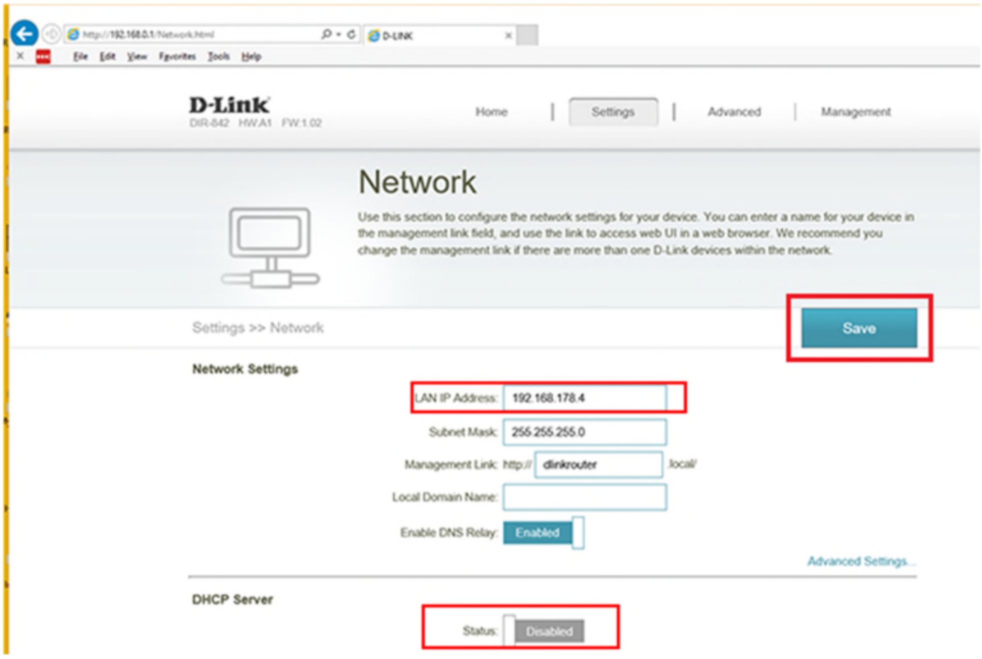


Figure A- 7 D-links Router IP Allocation.

A.3 Gemtek LTE Small Cell

The next stage will be to start configuring the LTE small Cell. Follow the steps given below for this

I. Login

To login provide the default username: admin password: admin. once you are logged in you will see the following status page will appear as shown in Figure 0-8.

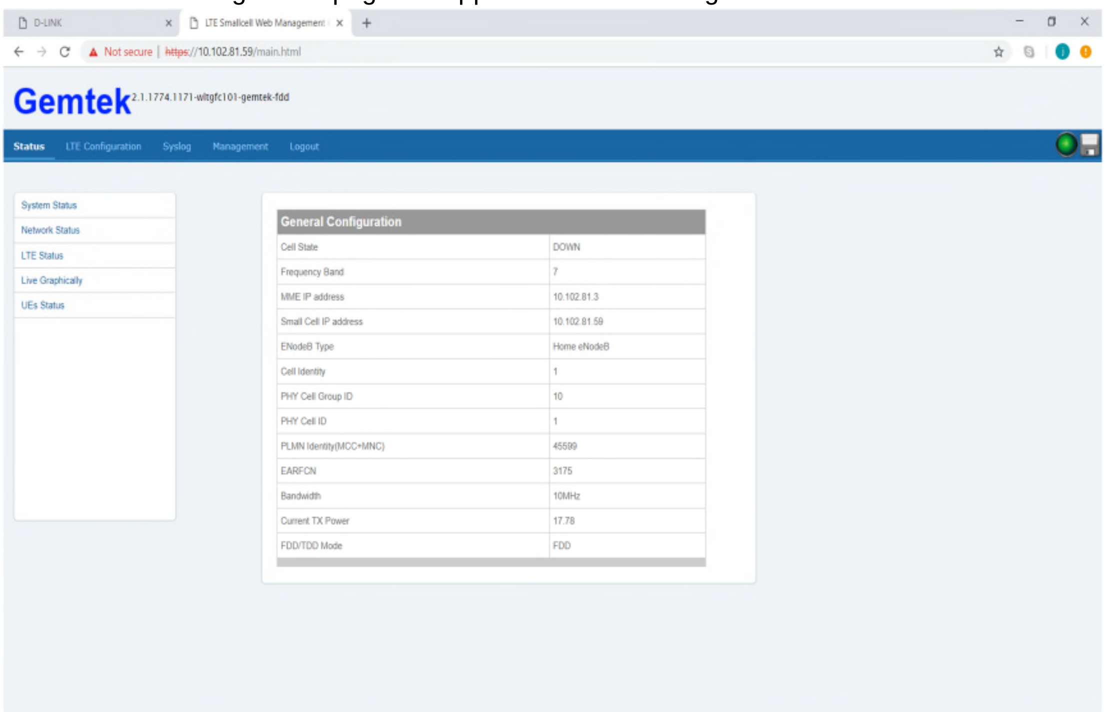


Figure A- 8 Small Cell Status Page.

II. LTE General Configuration

Now our next step is to click on the green light on the top right corner and then click on the tab LTE configuration. Now the page shown in Figure 0-9 will appear here we will change the values highlighted in red from points 4 to 7 should be changed according to the desired topology. In our case, we did the changes given below and click upload.

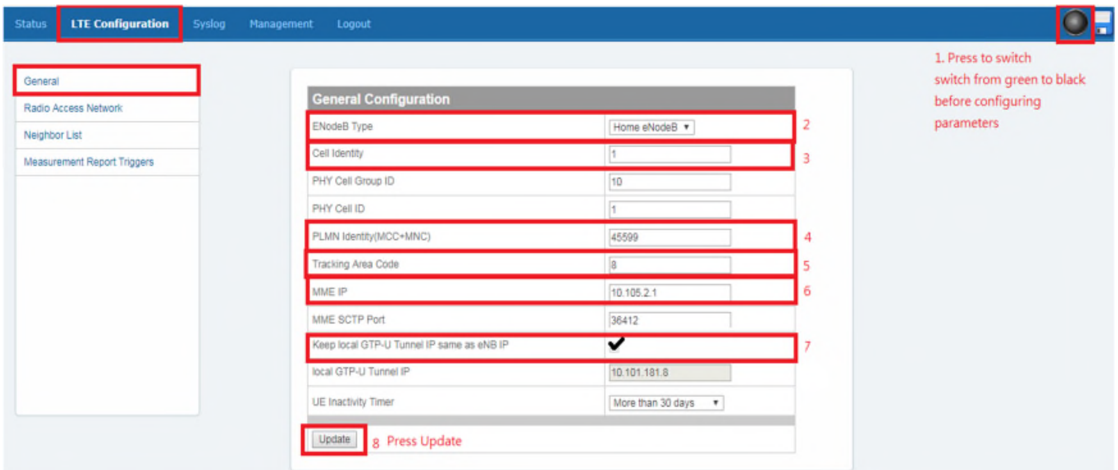


Figure A- 9 Small Cell LTE General Configuration.

- PLMN ID(MCC+MNC)= 20893
- Tracking area code = 1
- MME IP = 10.102.81.1

III. LTE Radio Access Network Configuration

This tab is used to change the bandwidth, transmission power and check the EARFCN value. If it is the same as shown in Figure 0-10 click update and go to the next step.

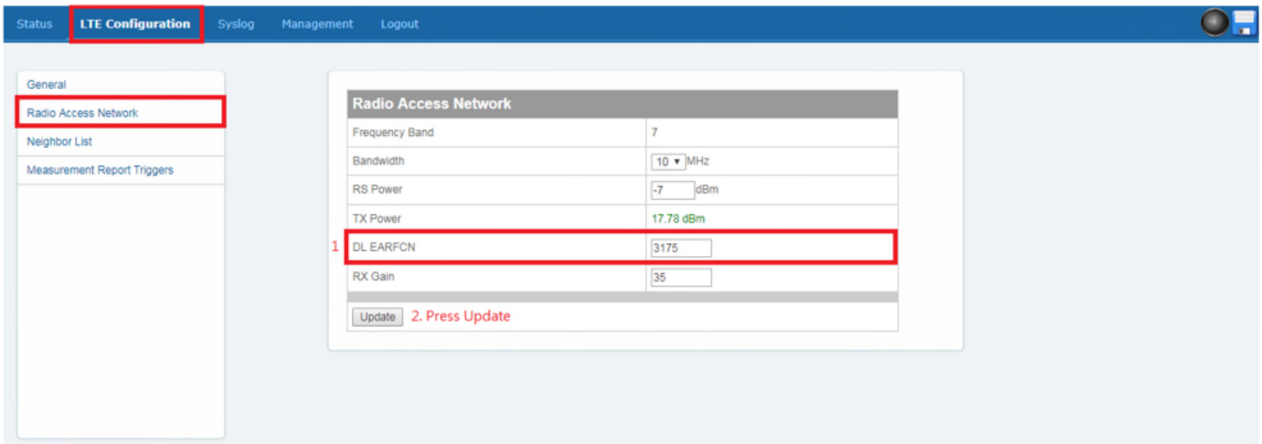


Figure A- 10 LTE Radio Access Network Configuration.

IV. Management Network Configuration

In this tab we will provide per our topology hence, the IP address as shown in Figure 0-11.

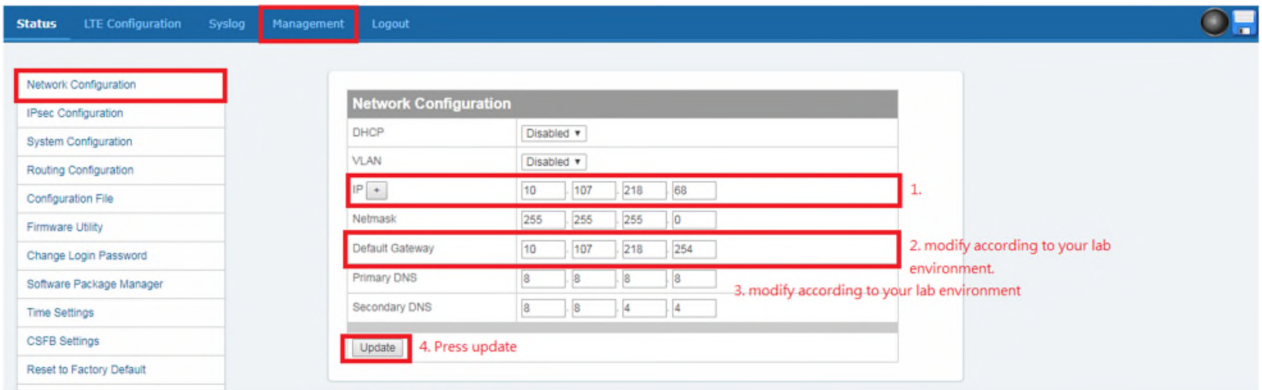


Figure A- 11 Network Configuration.

- IP=10.102.81.59
- Default gateway=10.102.81.1

After changing and verifying all these values the same and clicked on the black light on the top right corner and then clicked on reboot. Since all the parameter are in place we can now start with the next step of configuring MME.

At this stage the LAN and Power LEDs will in on stage(green) while the LTE and GPS LEDs will be in off stage(no color). The Figure 0-12 Provide details components of this LTE small cell

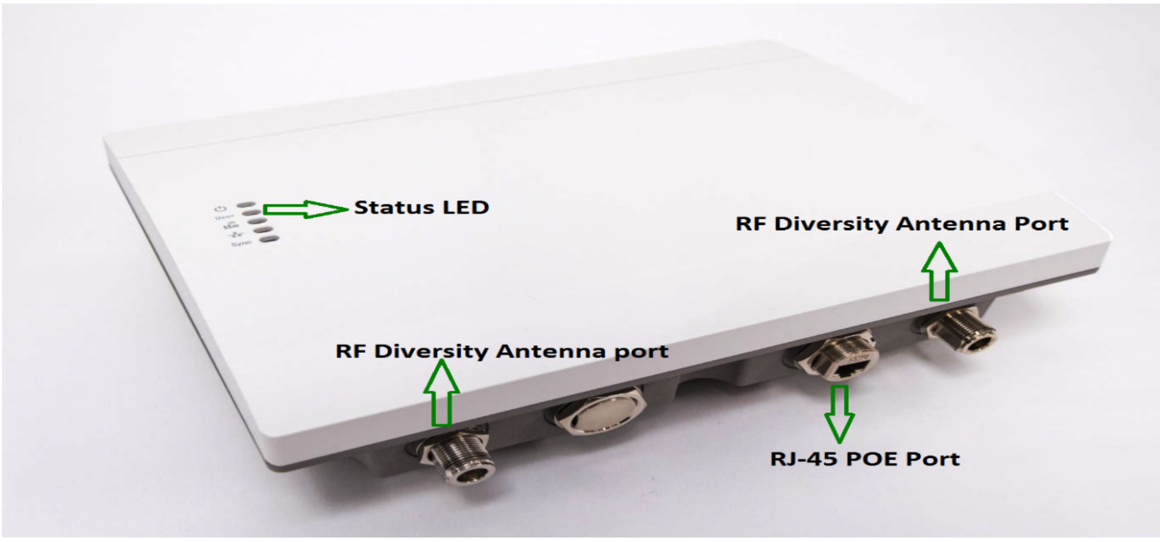


Figure A- 12 LTE Small Cell

A.4 MME Server Configuration

Once the LTE small cell is configured we move to MME configuration. The MME configuration will need some supporting programs as well. The best way will be to:

- click on https://www.free5gc.org/installation,
- under installations tab on the top right corner select stage 1 All-in-one
- follow all the steps as it is before Part B. after that make changes e.g. interface name IP address etc as required.
- Some of these changes are highlighted in yellow.

Once the installation is completed you will need to configure two things NAT rule and IP address as per the required topology.

I. NAT Configuration

The NAT configuration needs to be changed during the installation procedure. NAT is used to make the privet email address routable on the Public Internet. Since cellular network uses Private IP addresses which are not routable on the public domain NAT is required to translate these Private addresses to public address when the traffic leaves the Edge router. The MME will act as that edge router and will convert the UE address to 192.168.1.2. the D-Links router is the actual GW router and provides the actual NAT which will make this 192.168.1.2 address routable on the public domain. Here we are using NAT overload which provides many-to-one address translation.

The changed configuration is given below. Where enx3c18a00feb65 is the name of the interface facing the internet

[Option 1] Direct Configuration

```
sudo ifconfig eno1 10.102.81.1
sudo sh -c 'echo 1 > /proc/sys/net/ipv4/ip_forward'
sudo ipTables -t nat -A POSTROUTING -o enx3c18a00feb65 -j
MASQUERADE
sudo ipTables -I INPUT -i uptun -j ACCEPT
```

[Option 2] Configure as Auto Run On Boot

```
sudo sh -c "cat << EOF > /etc/init.d/ngc-network-setup
#!/bin/sh
### BEGIN INIT INFO
# Provides:          ngc-network-setup
# Required-Start:    networkd
# Required-Stop:     networkd
# Default-Start:     networkd
# Default-Stop:      networkd
# Short-Description:
# Description:
#
### END INIT INFO

ifconfig eno1 101.102.81.1
sh -c 'echo 1 > /proc/sys/net/ipv4/ip_forward'
ipTables -t nat -A POSTROUTING -o enx3c18a00feb65 -j
MASQUERADE
ipTables -I INPUT -i uptun -j ACCEPT
EOF"

sudo chmod 755 /etc/init.d/ngc-network-setup
sudo /etc/init.d/ngc-network-setup
```

```
sudo ln -s /etc/init.d/ngc-network-setup /etc/rc3.d/S99ngc-
network-setup
sudo ln -s /etc/init.d/ngc-network-setup /etc/rc4.d/S99ngc-
network-setup
```

II. Free5gc.config File Changes

Go to cd free5gc /install/etc/free5gc/free5gc.conf either open this file in text editor or give a nano command to edit the configuration. The edited configuration file is given below

```
db_uri: mongodb://localhost/free5gc

logger:
    file:
/home/ec5gc/free5gc/install/var/log/free5gc/free5gc.log
    trace:
        app: 1
        s1ap: 1
        nas: 1
        diameter: 1
        gtp: 1
        pfcp: 1
        sbi: 1

parameter:
    no_ipv6: true

amf:
    freeDiameter: amf.conf

    s1ap:
      addr: 10.102.81.1


    gummei:
      plmn_id:
        mcc: 460
        mnc: 88
      mme_gid: 1
      mme_code: 1

    tai:
      plmn_id:
        mcc: 460
        mnc: 88
      tac: 1

    security:
        integrity_order : [ EIA1, EIA2, EIA0 ]
        ciphering_order : [ EEA0, EEA1, EEA2 ]
```

```
    network_name:
        full: free5GC

hss:
    freeDiameter: hss.conf

pcrf:
    freeDiameter: pcrf.conf

smf:
    freeDiameter: smf.conf

    pfcp:
      - addr: 127.0.0.2
      - addr: ::1

    upf:
      - addr: 10.102.81.1

    http:
      addr: 127.0.0.1
      port: 8080

    ue_pool:
      - addr: 45.45.0.2/16
      - addr: cafe::1/64


    dns:
      - 8.8.8.8
      - 8.8.4.4
      - 2001:4860:4860::8888
      - 2001:4860:4860::8844

upf:
    pfcp:
      addr:
        - 10.102.81.1
        - ::1

    gtpu:
      - addr: 10.102.81.1j
      - addr: ::1

    ue_pool:
      - addr: 45.45.0.2/16
      - addr: cafe::1/64

    dns:
      - 8.8.8.8
      - 8.8.4.4
      - 2001:4860:4860::8888
      - 2001:4860:4860::8844
```


Save the File before exiting

III. DNS Configuration

Since we need to access a local website on our LADN server we need to make a DNS binding on the MME as well for this purpose do the following configuration:

```
sudo nano /etc/hosts
192.168.1.3   jj.lan   // local website binding added
```

Save the File before exiting

A.5 UE Configuration

Since the UE is using special Sim cards hence they need to be configured as well use the steps inhttps://www.free5gc.org/installation and first is to create a webserver. These steps should be implemented upon MME.

I. Webserver

```
sudo apt-get -y install curl
curl -sL https://deb.nodesource.com/setup_8.x | sudo -E bash -
sudo apt-get -y install nodejs
cd webui
npm install
cd webui
npm run dev
```

II. SIM Registration

Since the webserver is now created and working on link http://localhost:3000, we can now register our SIMs on the network. To register the SIMs, we need to add both SIMs one by one and give their IMSI number, key Value, and OPC. the exact values are given as under:

- **SIM 1**

IMSI= 460880000012345

Key = 0123456789abcdef0123456789abcdef

OPc=0123456789abcdef0123456789a46088

- **SIM 2**

IMSI= 460880000023456

Key = 0123456789abcdef0123456789abcdef

OPc=0123456789abcdef0123456789a46088

After that we inserted one of the sim card into our UE

III. UE APN Setup

- **Step1:** Settings →Connections →Mobile networks →Access Point Names →ADD
- **Step2:** Edit access point →Edit Name (input "internet" in the field) →Edit APN (input "internet" in the field) →Press the save button at the top right corner of screen.
- **Step3:** check if UE is connected to LTE Small cell and can surf the internet.

A.6 LADN Server Configuration

Since the LADN server need to host some website through which the videos will be accessed, hence we need to install LAMP (Linux + Apache + MySQL + PHP/Perl/Python) stack and configure some mock-up website.

I. LAMP stack

We used the configuration procedure provided in [13] and made the customizations where required. The complete configuration code is given below:

```
    1 sudo apt update && sudo apt install apache
    2 sudo service apache2 status
    3 sudo ufw allow OpenSSH
    4 apt-get install apache2 apache2-doc apache2-utils
    5 sudo apt-get install apache2 apache2-doc apache2-utils
    6 sudo service apache2 status
    7 sudo mkdir -p /var/www/html/jj.lan/public_html
    8 sudo chown -R $root:$root
/var/www/html/ostechnix1.lan/public_htm
    9 sudo chown -R $root:$root
/var/www/html/jj.lan/public_htm
   10 sudo mkdir -p /var/www/html/jj.lan
   11 sudo chown -R $root:$root /var/www/html/jj.lan
   12 sudo mkdir -p /var/www/jj.lan/public_html
   13 sudo chown -R $root:$root /var/www/jj.lan/public_html
   14 sudo chmod -R 755 /var/www
   15 sudo nano /var/www/jj.lan/public_html/index.html
       see html code for Website 1
   16 sudo nano /etc/apache2/sites-available/jj.lan.conf
       see html code for Website 2
      sudo a2ensite jj.lan.conf
      sudo systemctl restart apache2
   17 sudo mysql_secure_installation
   18 sudo apt update && sudo apt install mysql-server
   19 sudo service mysql status
   20 sudo mysql_secure_installation
   21 sudo mysqladmin -p -u root version
   22 sudo apt update && sudo apt install php libapache2-
mod-php   php-mysql
   23 php -version
   24 sudo nano /var/www/html/info.php
   25 sudo nano /etc/php/7.2/apache2/php.ini
   26 sudo systemctl restart apache2
   27 sudo apt update && sudo apt install phpmyadmin
       sudo mysql -p -u root
       CREATE USER 'pmauser'@'%' IDENTIFIED BY
'password_here';
```

```
       GRANT ALL PRIVILEGES ON *.* TO 'pmauser'@'%' WITH
GRANT    OPTION;
       exit
```

II. Website Configuration

We created two websites for video hosting. Can be accessed via the web browser of the UE if you type jj.lan, the HTML code given below needs to be copied in Step I 15 and 16 for these websites to be created.

- **Website 1**

```
sudo nano /var/www/example.com/public_html/index.html
<html>
  <head>
    <title>Welcome to jj.lan local entertainment
webside!</title>
  </head>
  <body>
    <h1>Success!  The jj.lan virtual host is working! </h1>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.flv" type="video/ogg">
Your browser does not support the video tag.
</video>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.ogg" type="video/ogg">
Your browser does not support the video tag.
</video>
 <video width="320" height="240" controls>
  <source src="movie.mp4" type="video/mp4">
  <source src="movie.flv" type="video/ogg">
Your browser does not support the video tag.
</video>
  </body>
</html>
```

- **Website 2**

```
sudo nano /etc/apache2/sites-available/jj.lan.conf
<VirtualHost *:80>
    ServerAdmin admin@jj.lan
    ServerName jj.lan
    ServerAlias www.jj.lan
    DocumentRoot /var/www/jj.lan/public_html
    ErrorLog ${APACHE_LOG_DIR}/error.log
    CustomLog ${APACHE_LOG_DIR}/access.log combined
</VirtualHost>
```

Now open the UE browser and check if you give jj.lan as dress does these websites show up. If yes, then we can move to the testing stage.

Now Since All the equipment has been configured properly lets start the MME process.

A.7 System Operation

Now Since All the equipment has been configured properly lets start the MME process. To run the system after configuration, power up all the devices and follow the steps given below:

a) Go to the terminal on MME and give command `cd free5gc/install/bin` to reach the required directory.
b) To start us the 5gc system application give command `./free5gc-ngcd`
c) the eNB LTE small cell light will start.
d) If the eNB small cell's LTE light does not start, follow the trouble-shooting steps.
e) If the eNB small cell's LTE light is activated, then start your UE device.
f) The UE should have the pre-programmed SIM.
g) Once UE is active and 4G signal appears check if you can have internet.
h) If internet and online applications are working this means the system is working.

A.8 Trouble-Shooting

While deployment stage we faced two major issues which are listed below. in case the system is not functioning as it should be, go through the troubleshooting steps listed below:

IV. If the MME is unable to connect with eNB LTE small cell

Open wire-shark and check if S1 init message is received from eNB and replied by MME.

No.	Time	Source	Destination	Protocol	Length	Info
4	0.828225	10.102.81.59	10.102.81.3	SCTP	82	INIT
5	1.528095	10.102.81.59	10.102.81.3	SCTP	82	INIT
6	1.920612	10.102.81.3	239.255.255.250	UDP	698	63603 → 3702 Len=656
7	2.228162	10.102.81.59	10.102.81.3	SCTP	82	INIT
8	2.655288	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
9	2.655989	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
10	3.884983	10.102.81.59	10.102.81.3	ICMP	98	Echo (ping) request id=0x1aff, seq=1/256, ttl=64 (reply in 11)
11	3.886412	10.102.81.3	10.102.81.59	ICMP	98	Echo (ping) reply id=0x1aff, seq=1/256, ttl=128 (request in 10)
12	3.922315	10.102.81.3	239.255.255.250	UDP	698	63603 → 3702 Len=656
13	4.655876	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
14	4.656432	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
15	4.979448	CiscoInc_c1:dd:01	CiscoInc_c1:dd:01	LOOP	60	Reply
16	5.004074	CiscoInc_c1:dd:03	CiscoInc_c1:dd:03	LOOP	60	Reply
17	6.656216	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
18	6.657182	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003
19	7.929363	10.102.81.59	10.102.81.3	SCTP	82	INIT
20	8.236959	10.102.81.3	239.255.255.250	UDP	698	56273 → 3702 Len=656
21	8.408695	10.102.81.3	239.255.255.250	UDP	698	56273 → 3702 Len=656
22	8.655867	CiscoInc_c1:dd:01	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8001
23	8.656374	CiscoInc_c1:dd:03	Spanning-tree-(for-bridges)_00	STP	60	Conf. Root = 32768/1/00:12:80:c1:dd:00 Cost = 0 Port = 0x8003

Figure A- 13 Wireshark Traffic For INIT Procedure.

a) Check if appropriate interfaces are connected e.g. **eno1** at eNB side and `enx3c18a00feb65` at router side
b) Check other configuration if appropriate IP address is given in the configuration file located at `free5gc/install/etc/free5gc/ngcd.conf` file
c) Check if same mmc and mnc values are given at the eNB and config file mmc+mmc=86044

V. If the MME is not connecting to eNB LTE small cell

e) Check if correct IP addresses and physical interface are connected with eachother
f) check if mmc and mnc valuesare the same on eNB LTE and MME
c) check if proper UP-tun address is assigned if not give the command `Ifconfig uptun 45.45.0.1 netmask 255.255.0.0`
d) check if the physical interface is properly assigned and working. Check via the GUI used to assign IP addresses.
g) Check NAT if it was configured properly, check the interface name on IPmasqurading (**enx3c18a00feb65**) if that was correct. If not change it to the correct value
h) Now check if the LTE LED is on at the LTE eNB small cell if yes

VI. If the MME is connected with eNB LTE small cell and the LTE LED is on, but the UE can't access the internet.

a) Give command `ifconfig` if no IP address assigned then `Ifconfig uptun 45.45.0.1 netmask 255.255.0.0`
b) Check NAT if it was configured properly, check the interface name on IPmasqurading (**enx3c18a00feb65**) if that was correct. If not change it to the correct value
c) Now check if you have internet via UE

B Appendix B (i-Perf Test results)

This Appendix displays the screen shorts of the i-perf test conducted from UE and MME to LADN and Public network.

B.1 i-perf Test Results TCP

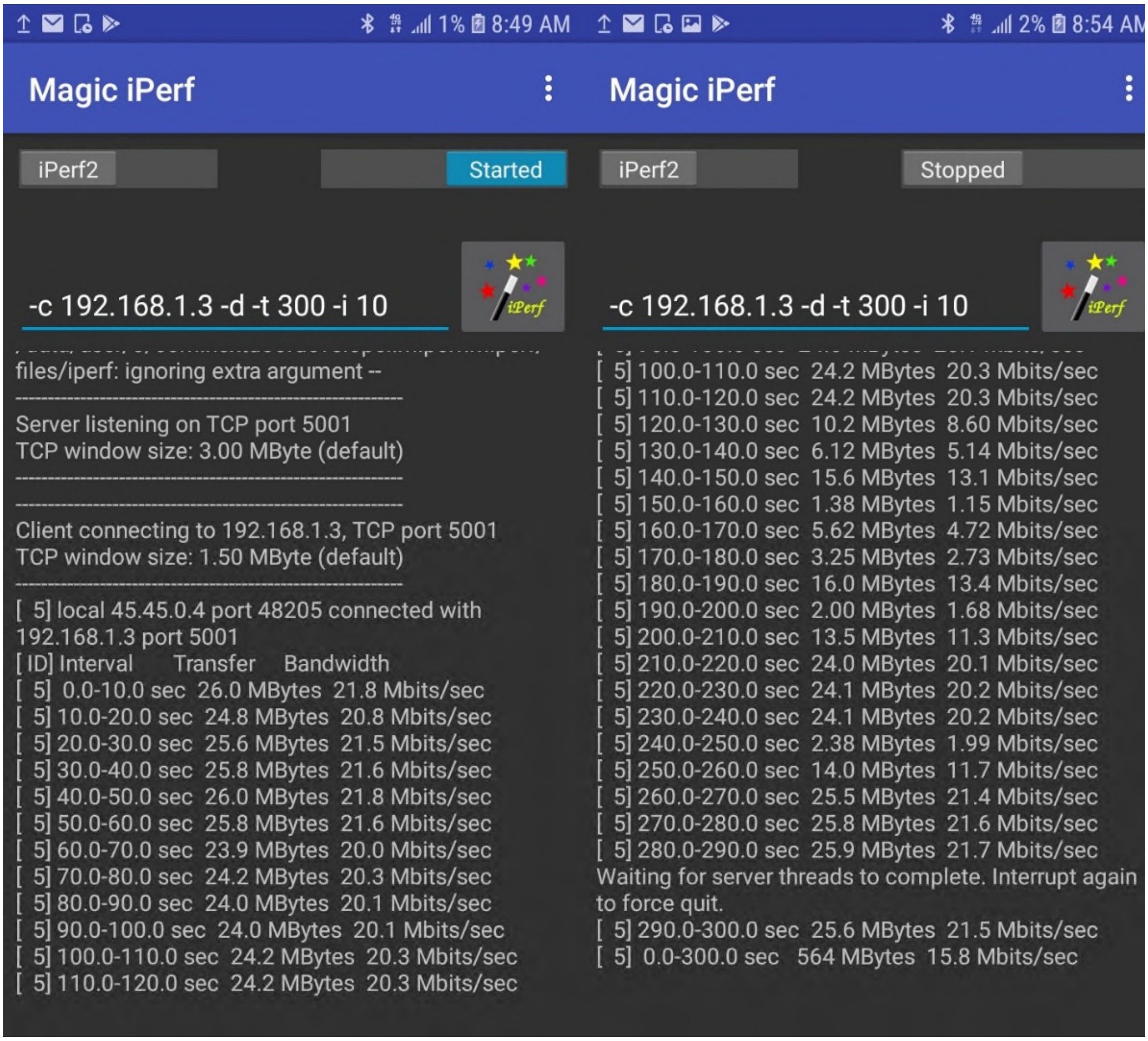


Figure B- 1 UE To LADN i-Perf TCP Test.

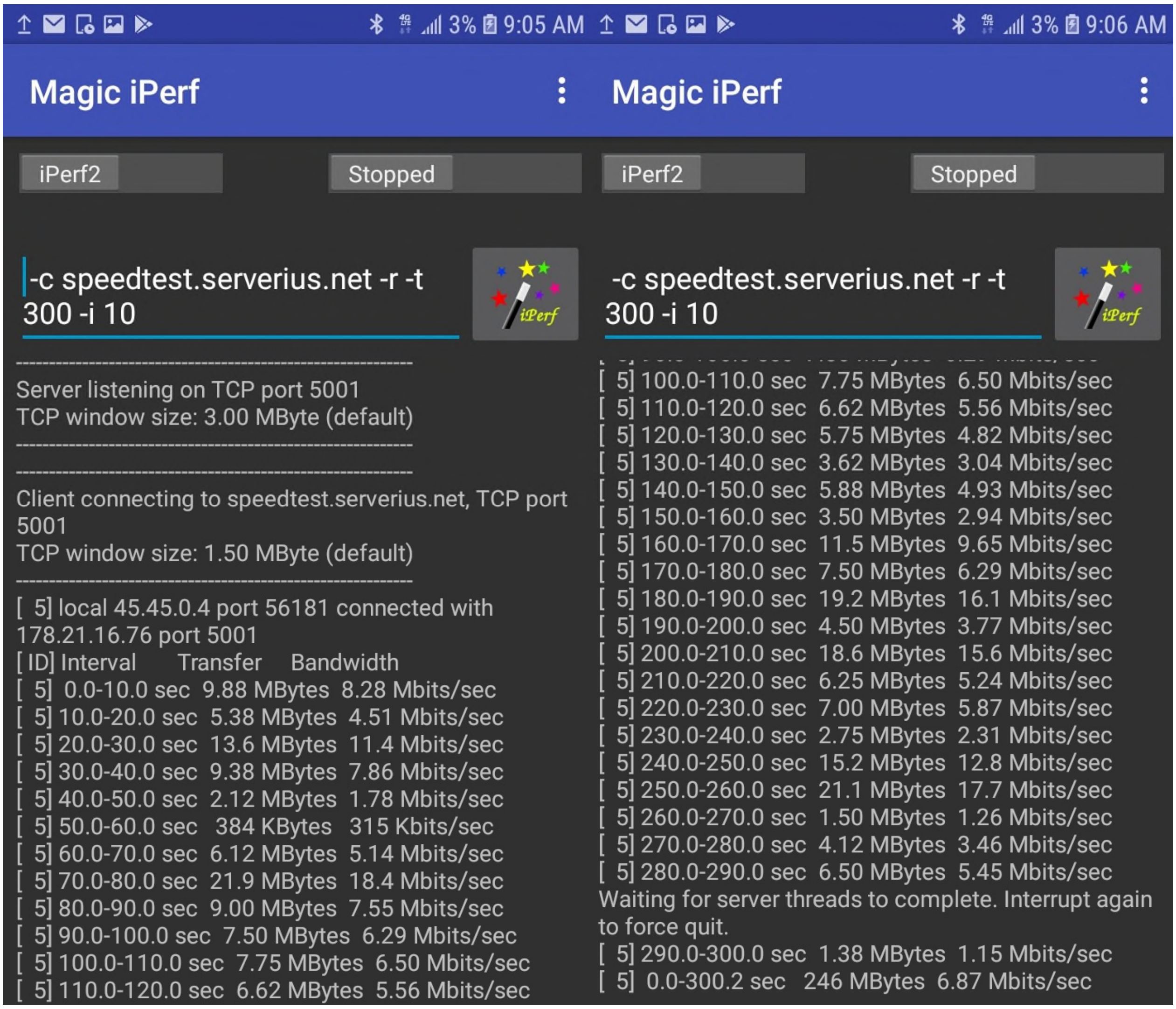


Figure B- 2 UE To Public Network i-Perf TCP Test.

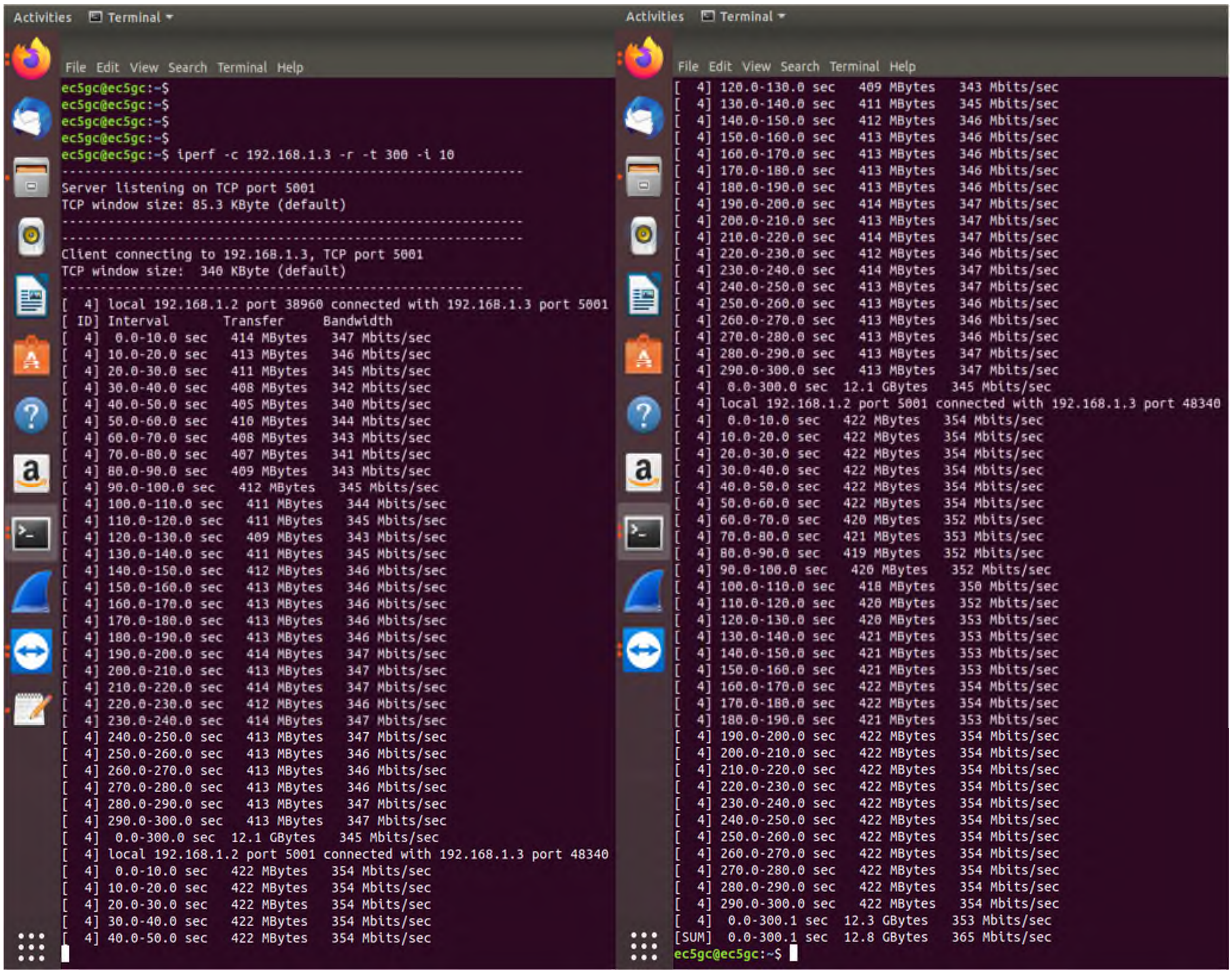


Figure B- 3 MME To LADN i-Perf TCP Test.

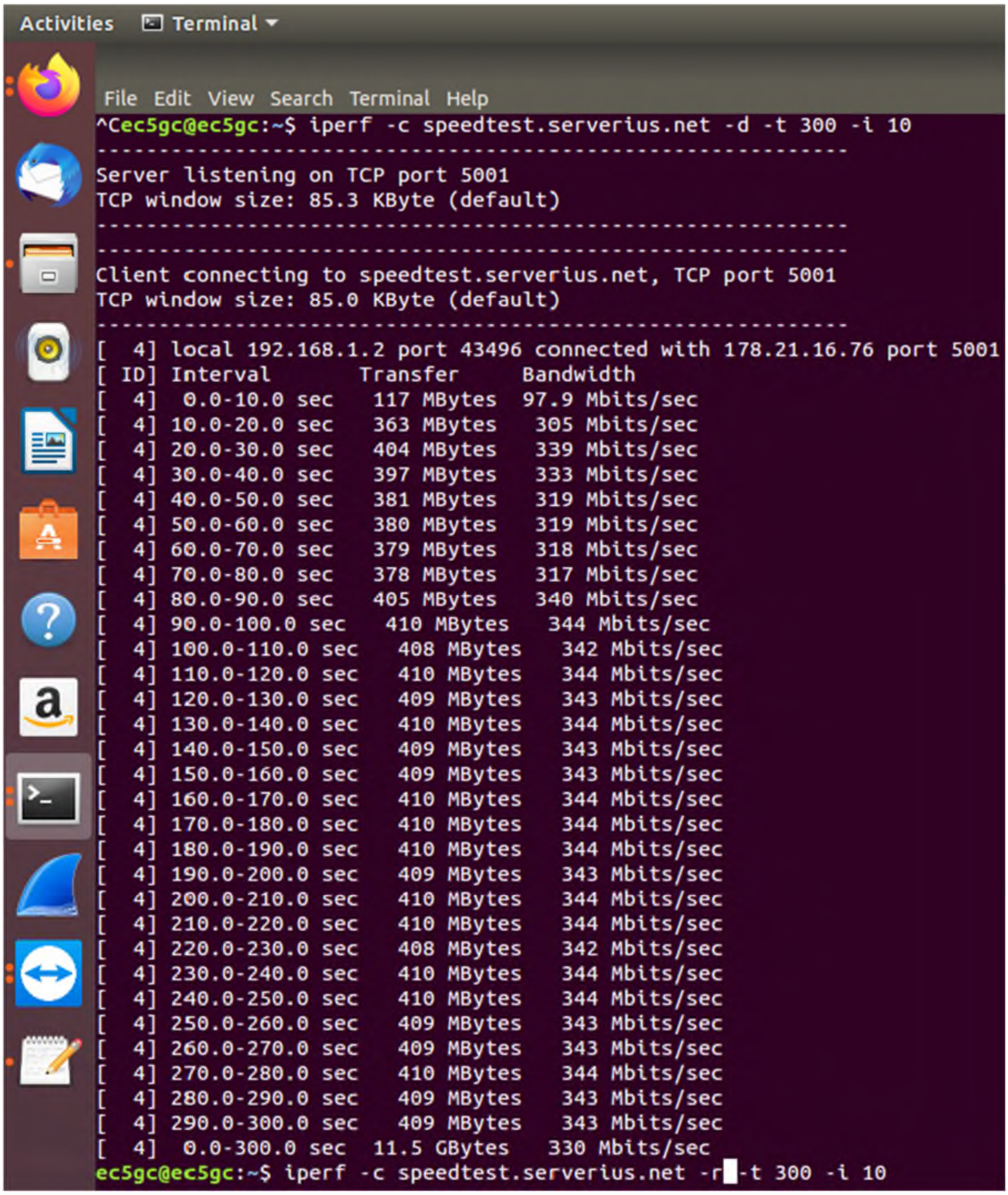


Figure B- 4 MME To Public Network i-Perf TCP Test.

B.2 i-Perf Test Results UDP

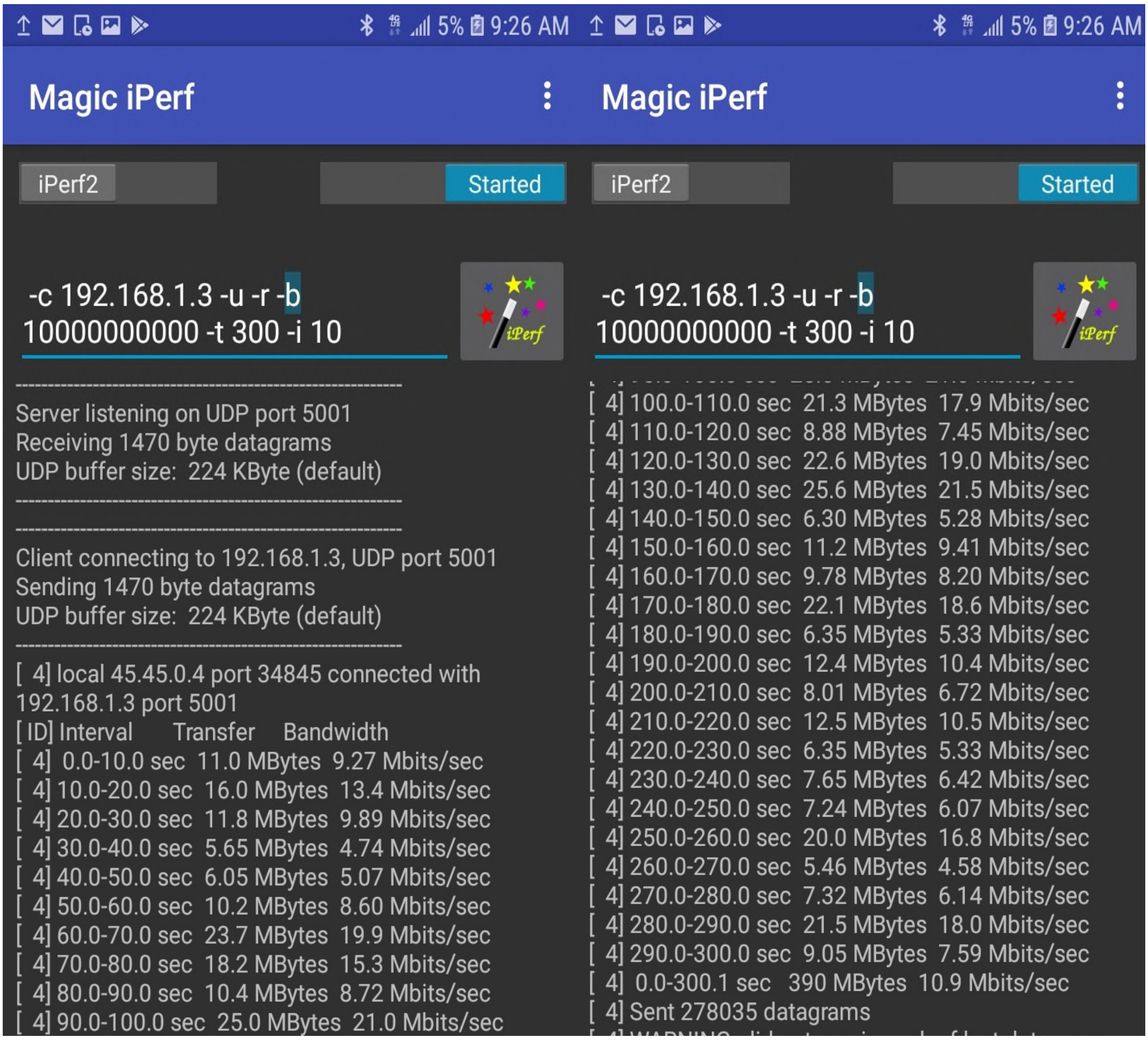


Figure B- 5 E to LADN i-Perf Test UDP.

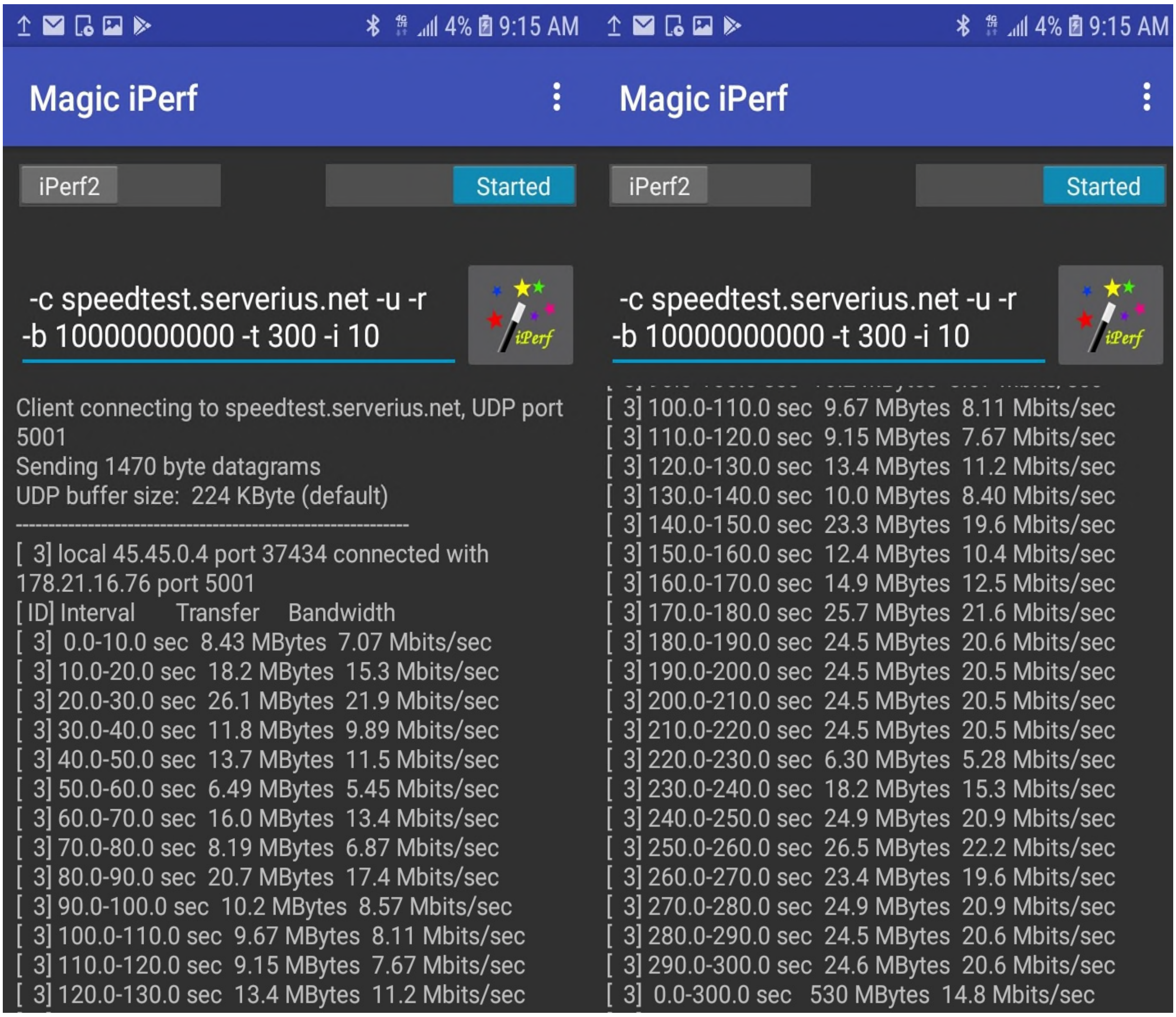


Figure B- 6 UE to Public Network i-Perf Test UDP.

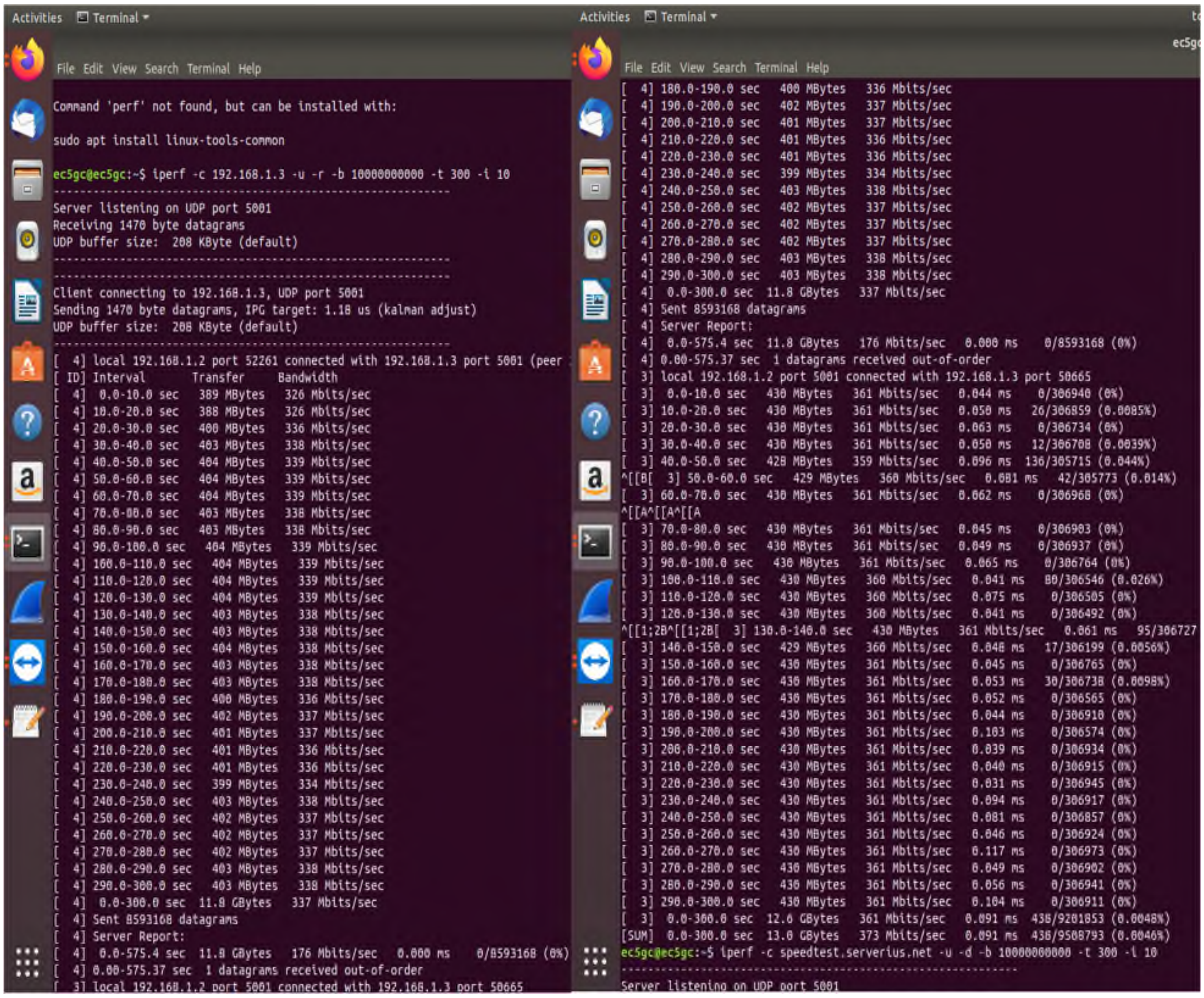


Figure B- 7 MME To LADN i-Perf Test UDP.

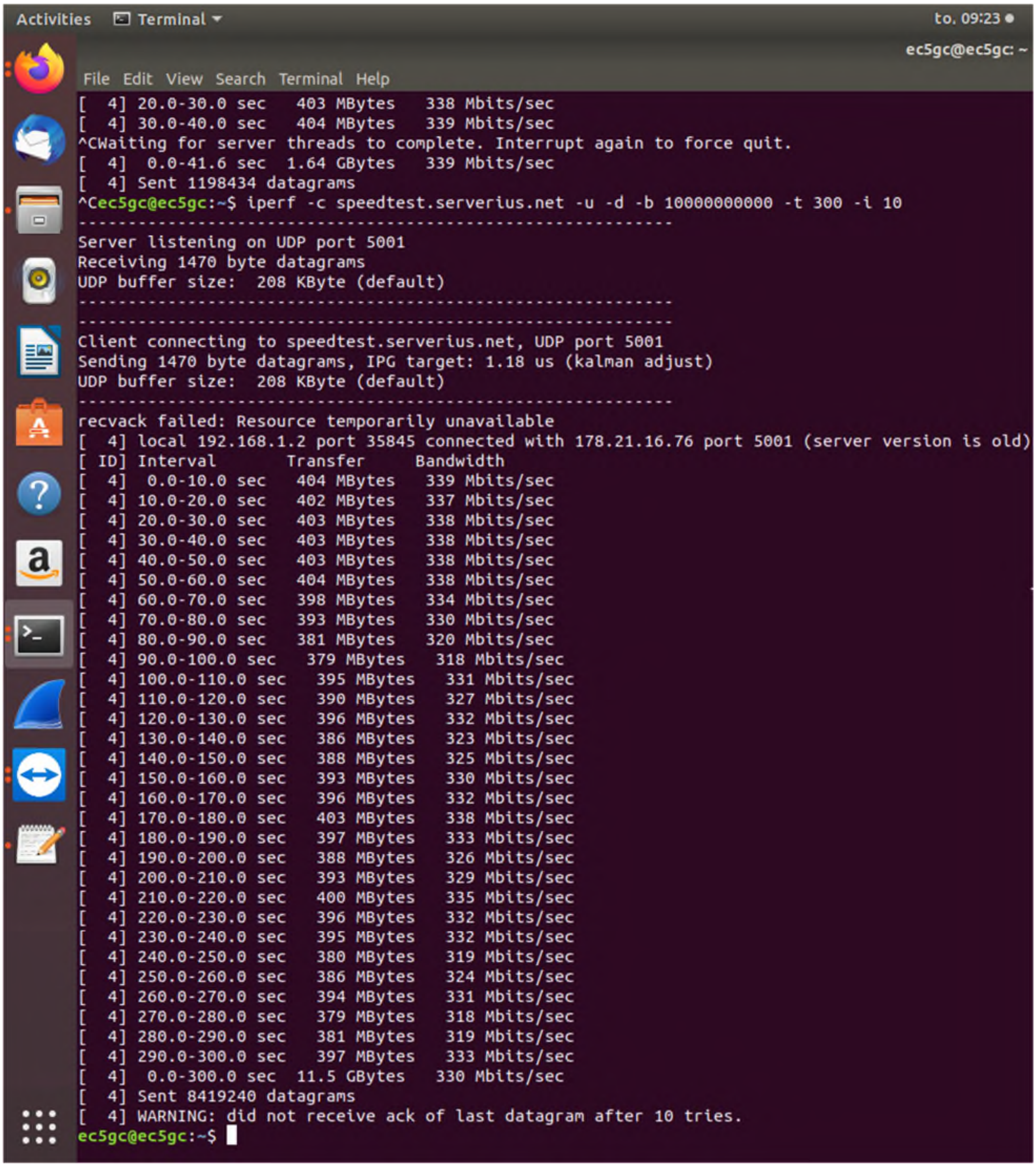


Figure B- 8 MME to Public Network i-Perf Test UDP.

C Appendix C (Simulation Results)

The screen shots of the simulator's topology and results screen shots

C.1 OSPF Simulation

The screen shots of simulation topology and ping test results are given below

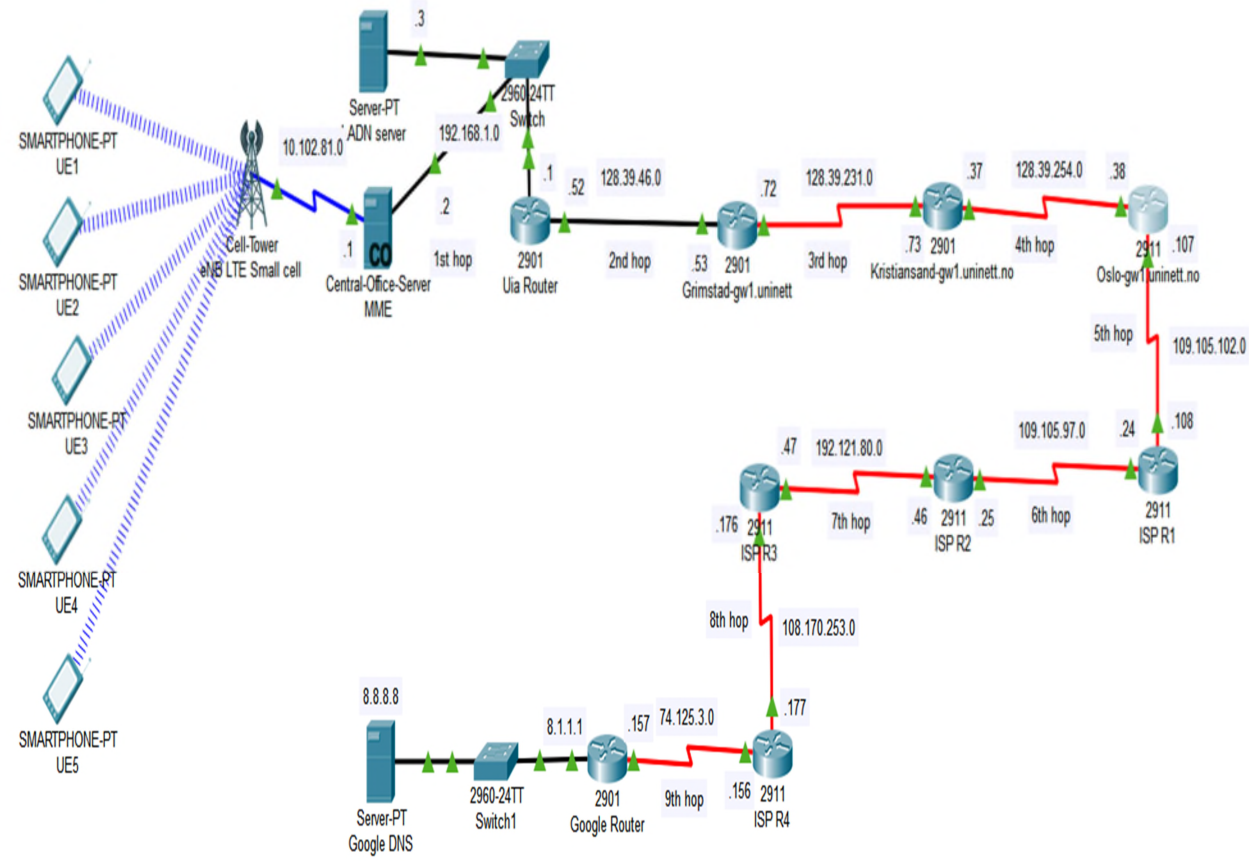


Figure C- 1 Packet Tracer OSPF Simulation.

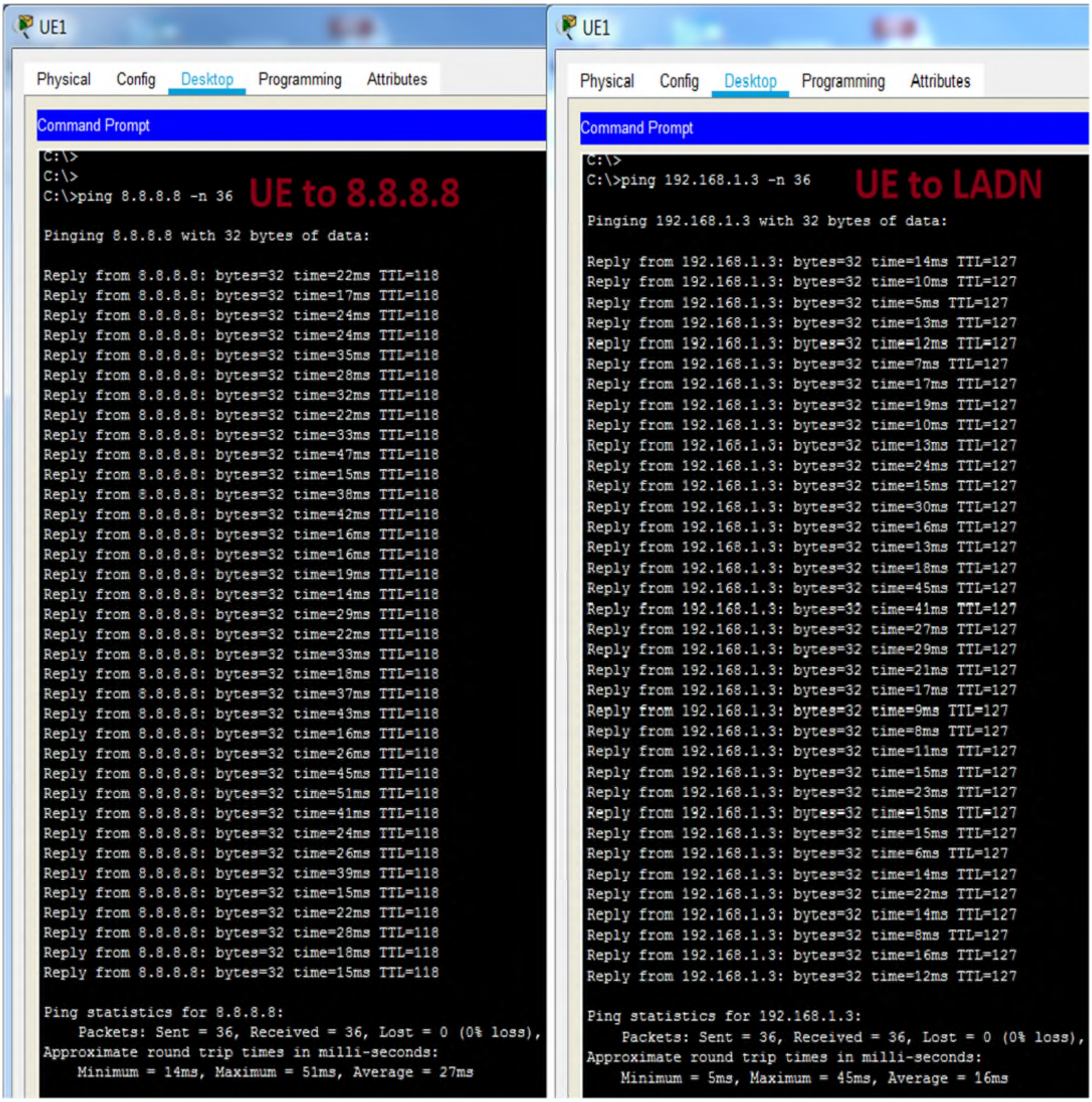


Figure C- 2 OSPF Simulation UE1 Ping Results Google DNS (8.8.8.8) VS LADN.

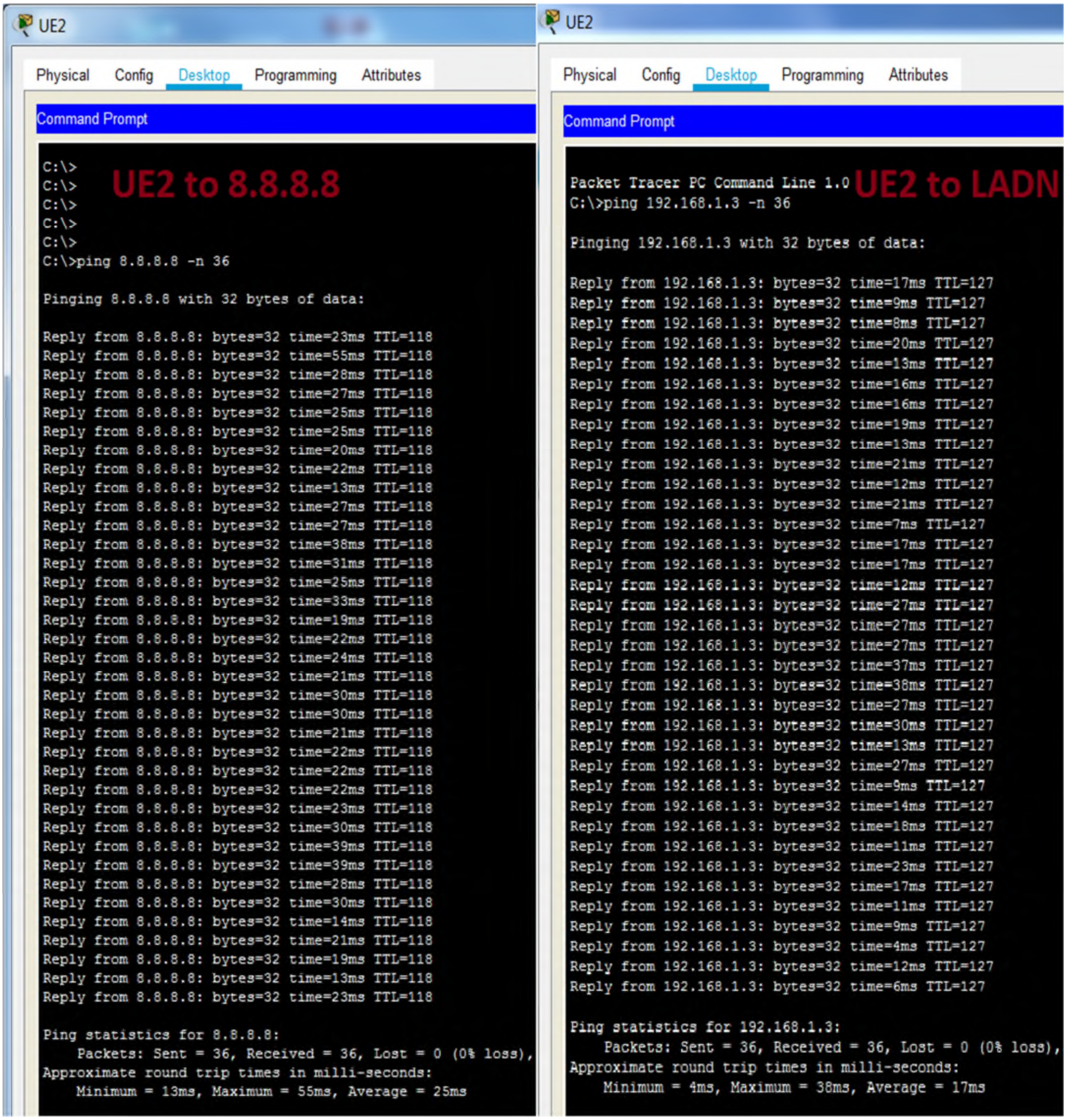


Figure C- 3 OSPF Simulation UE2 Ping Results Google DNS (8.8.8.8) VS LADN.

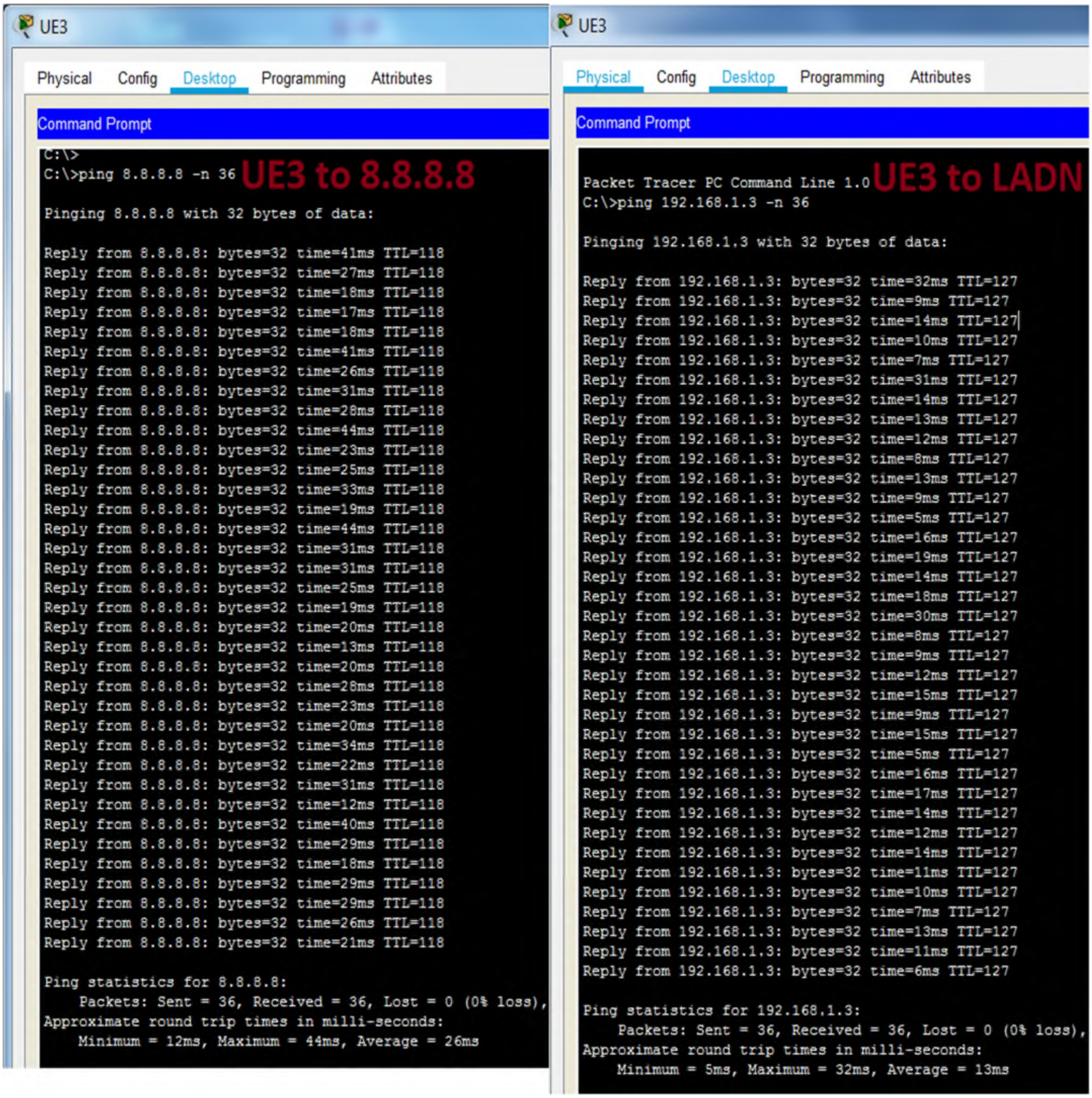


Figure C- 4 OSPF Simulation UE3 Ping Results Google DNS (8.8.8.8) VS LADN.

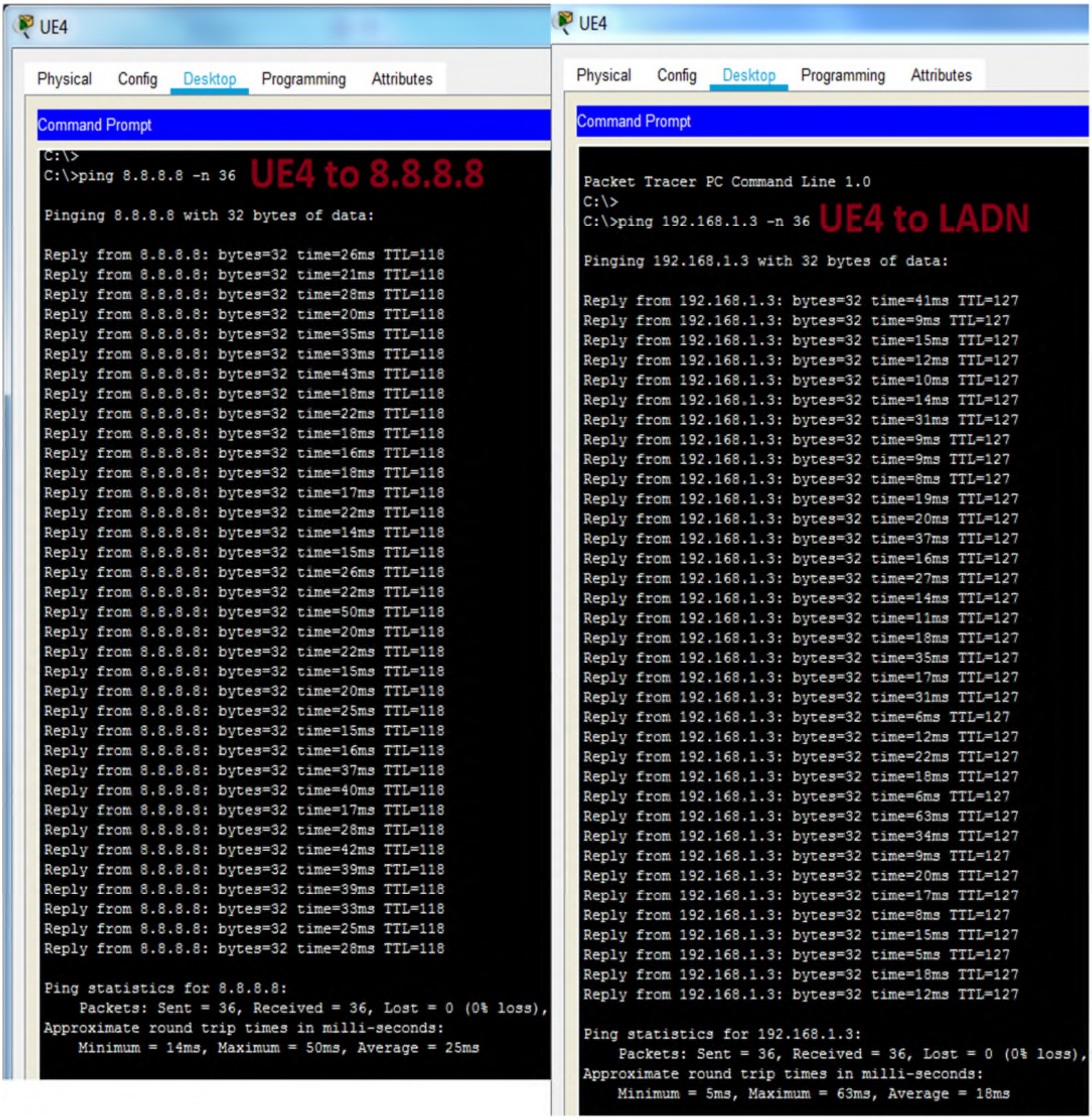
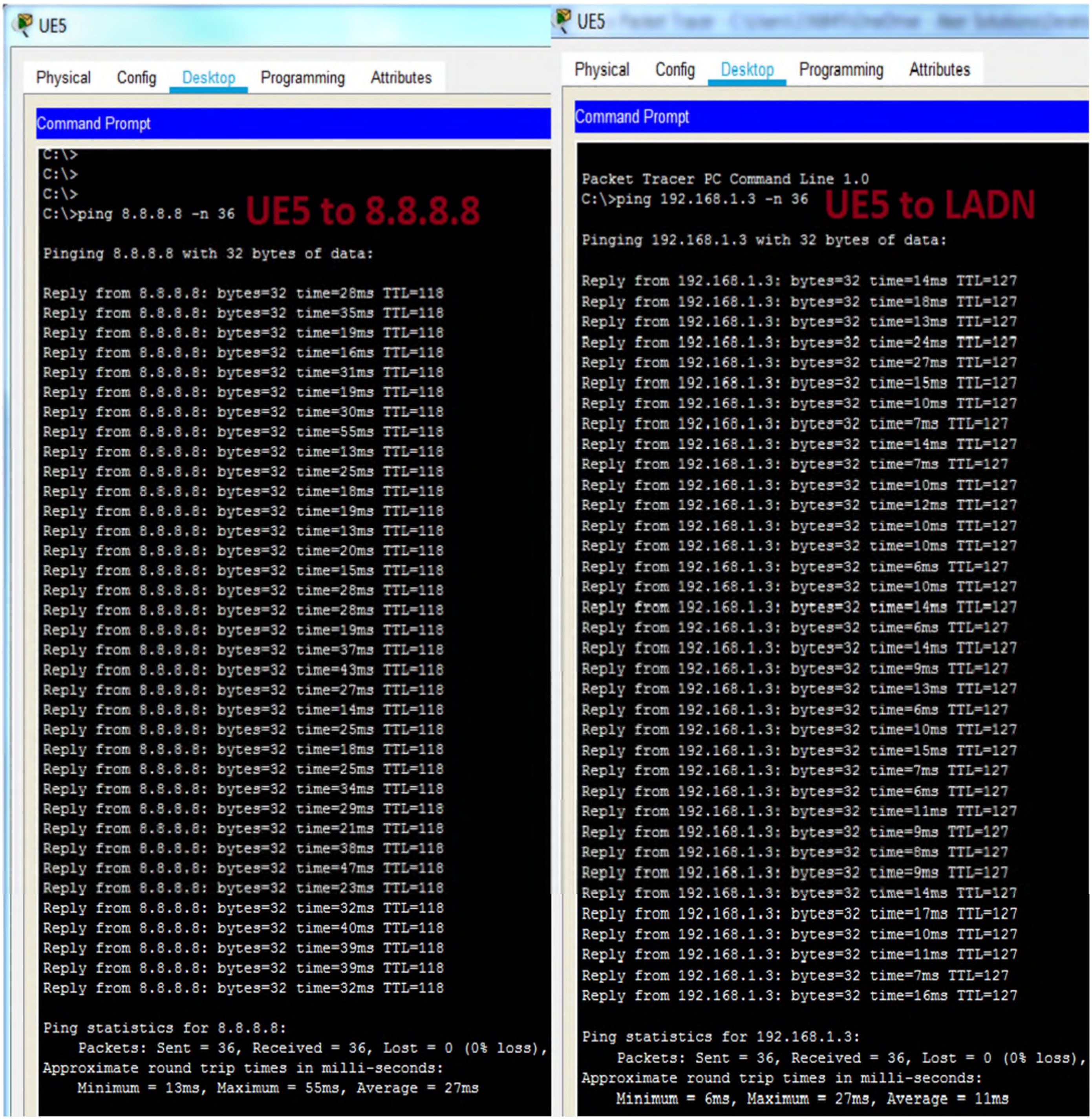


Figure C- 5 OSPF Simulation UE4 Ping Results Google DNS (8.8.8.8) VS LADN.



F Figure C- 6 OSPF Simulation UE5 Ping Results Google DNS (8.8.8.8) VS LADN.

C.2 EIGRP Simulation

The screen shots of simulation topology and ping test results are given below

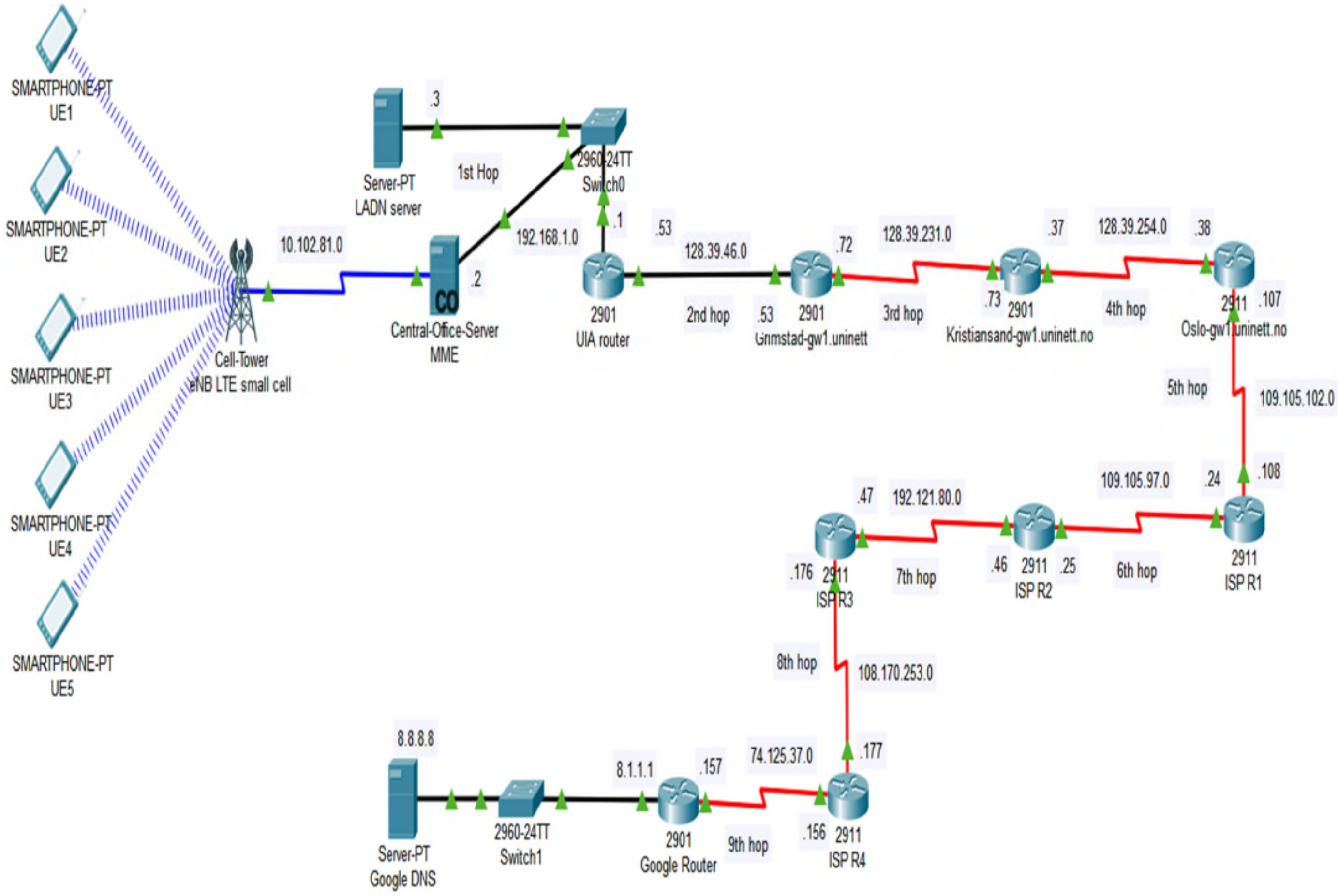


Figure C- 7 Packet Tracer EIGRP Simulation.

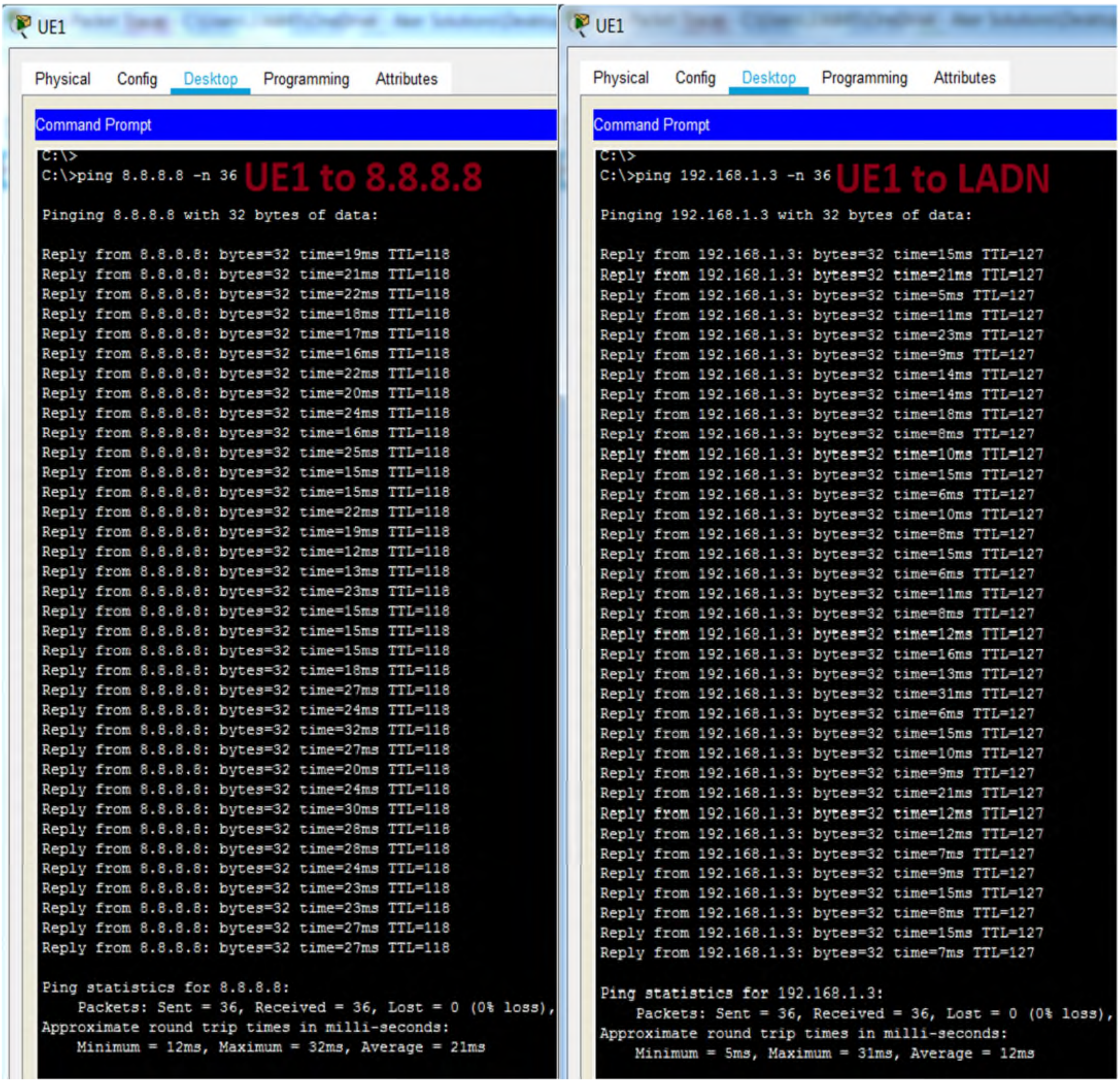


Figure C- 8 EIGRP Simulation UE1 Ping Results Google DNS (8.8.8.8) VS LADN.

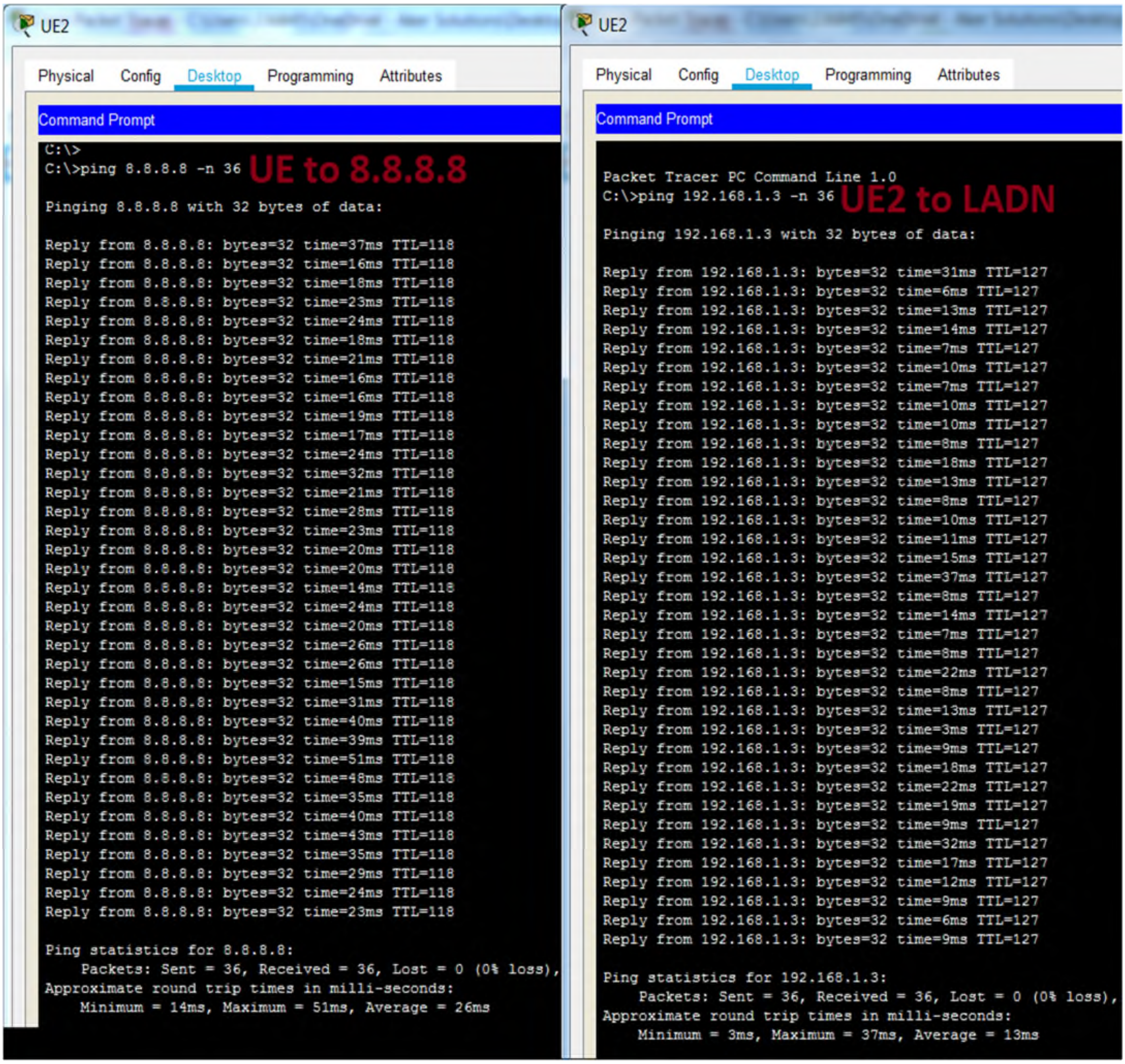


Figure C- 9 EIGRP Simulation UE2 Ping Results Google DNS (8.8.8.8) VS LADN.

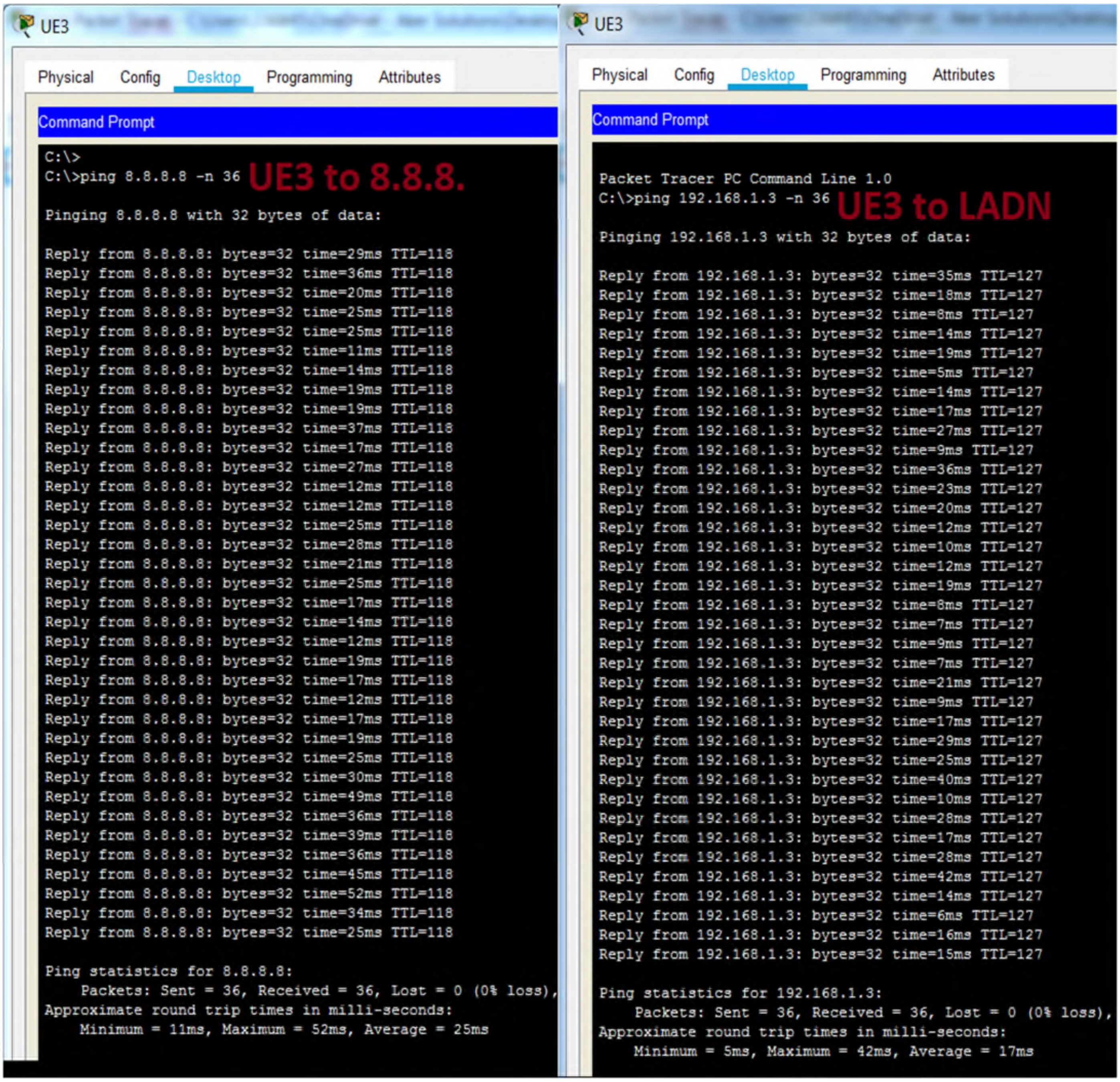


Figure C- 10 EIGRP Simulation UE3 Ping Results Google DNS (8.8.8.8) VS LADN.

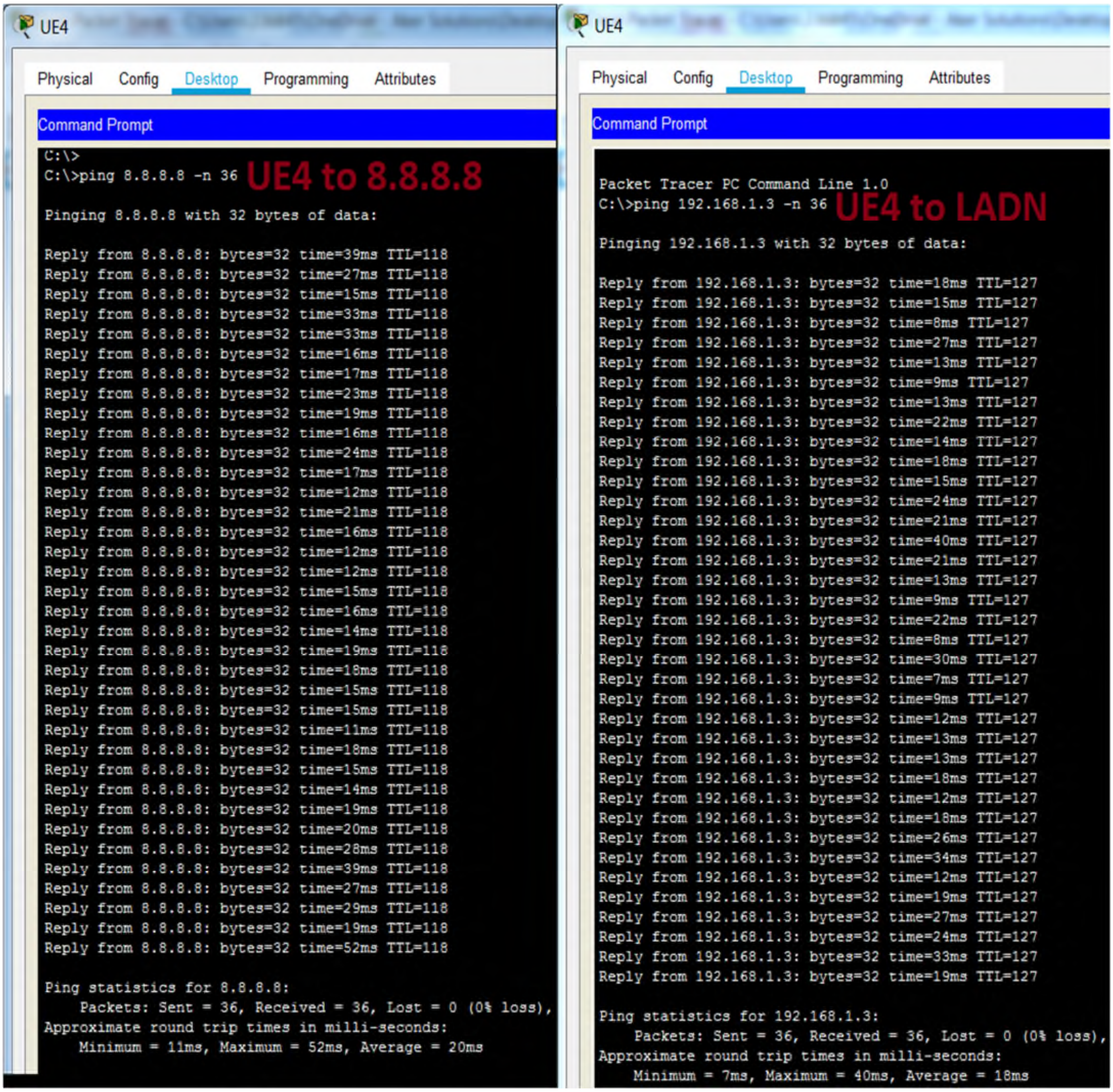


Figure C- 11 EIGRP Simulation UE4 Ping Results Google DNS (8.8.8.8) VS LADN.

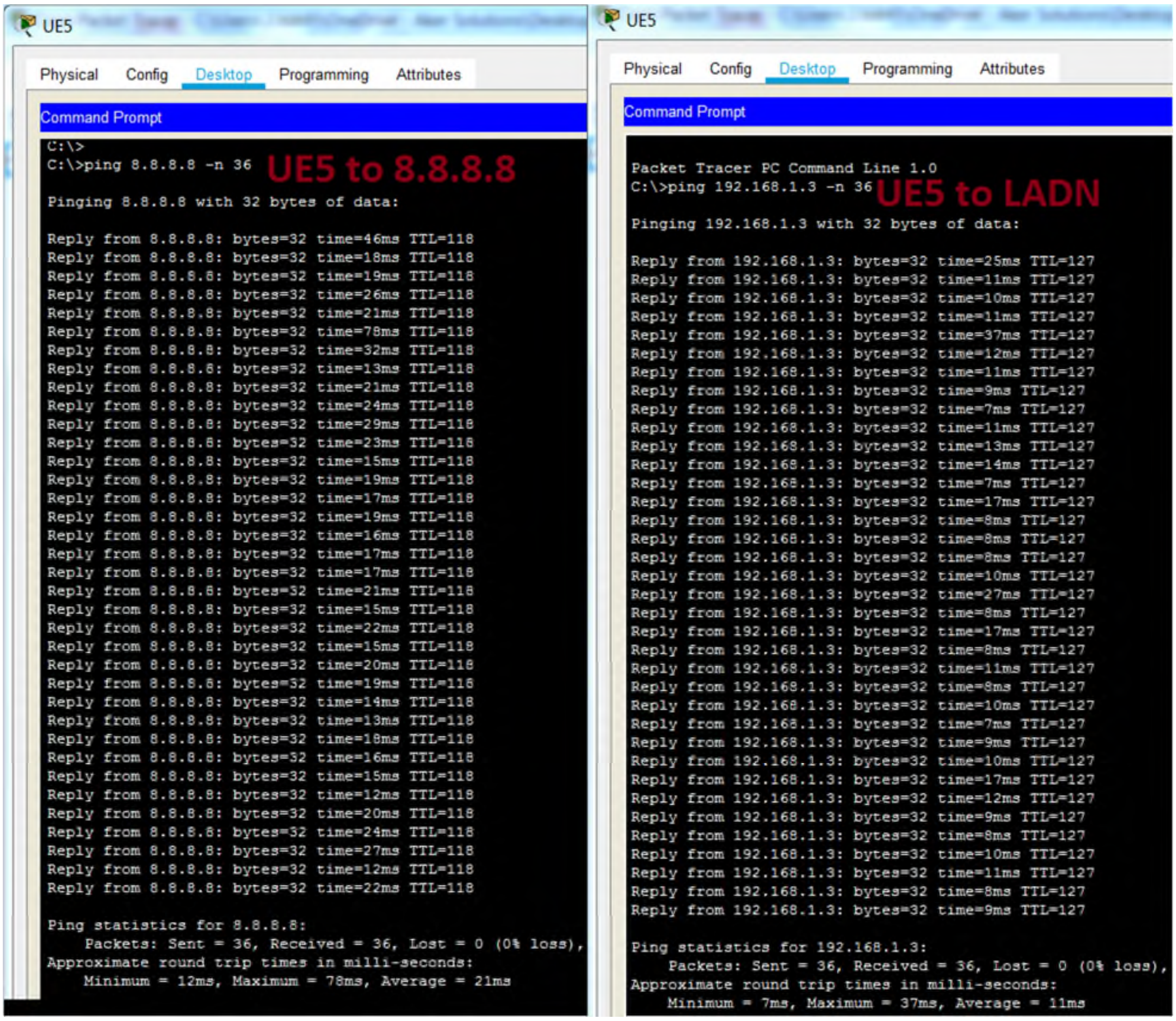


Figure C- 12 EIGRP Simulation UE5 Ping Results Google DNS (8.8.8.8) VS LADN.

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