# Performance Analysis of TCP over LTE

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***Abstract*— We have a lot of active research focused on developing improved protocols to support greater data throughput and better quality of service in the highly dynamic environment of an LTE network. In the face of the great success of cellular networking, especially with the advent of the high-speed LTE technology, the performance experienced by applications running over cellular networks is of prime importance. In this project our goal is to conduct assessment of TCP performance in an LTE network. We use a private locally managed LTE network installed at Clemson University with equipment using SDR (Software Defined Radio) technology from Airspan. SDR technology enables us to have more control over the experiments we plan to conduct. In this report we present the current architecture as well as the results of our analysis of the performance of a local and a simulated end-to-end LTE network.**

***Keywords— TCP, LTE, cellular networks, mobile, Internet, Software Defined Radio, architecture, EPC, eNodeB, MME, PGW, SGW, PCRF, EBS, QoS, bandwidth***

## I. Introduction

Mobile Internet usage has increased significantly over the last decade. The next few years are expected to be equally promising with upcoming 5G services and 4G traffic reaching quotas of more than three-quarters of the total mobile traffic by 2021. The growth expectation is not only related to the traffic volume itself but also to the average speed. To continue this growth and to meet user expectations, all the involved stakeholders have a common interest in faster downloads, quicker responses, higher utilization and fewer packet losses. Since a large part of mobile Internet comprises of TCP flows, the performance of TCP over cellular networks has become an important research topic [1]. Since TCP was developed originally for wired communication, its use in wireless communication network results in unforeseen problems due to uncertainty in wireless links at radio link level. High bit errors and frequent handoffs in the radio link are interpreted by TCP as congestion, and the actions taken to mitigate congestion result in poor or degraded performance. As a result. in the last three decades many different TCP implementations have been developed each of them targeting a different congestion control algorithm [2] [3].

The wireless media and wired media have very different characteristics. Wireless medium is generally affected by three major factors which are path loss, surrounding noise and the sharing of the radio spectrum. Path loss and ambient noise cause higher bit error rates (BER) in wireless link when compared to a wired link. For example, bit error rates are $10^{-6}$ or worse are common over wireless paths, whereas for wired path like fiber links error rates are typically in the range of $10^{-12}$ or better. In addition to this, mobility in wireless network results in further degradation due to fading as radio channel status changes intermittently thus increasing the bit error rate. In cellular network, coverage area is thus divided into smaller areas as per requirement and resources are shared between them. When a mobile user crosses the cell boundary, handoff from one cell to another cell is required as the mobile terminal must get synchronized with a new set of resources. These handoffs often cause additional delays and even data loss.

4G LTE is the latest deployed cellular network technology that provides high-speed data services for mobile devices with advertised bandwidths matching and even exceeding the home broadband network speeds. Compared to 3G, LTE provides the promise of higher energy efficiency as a result of a new resource management policy and higher achievable throughput. The reasons for the performance improvement in LTE are manifold. LTE provides a higher bit rate due to the OFDM transmission technology, higher coding and modulation schemes and multiple antenna configuration (MIMO), etc. It is important to evaluate the impact of increased bandwidth on essential network protocols such as TCP to identify their limitations for needed improvements. Intuitively, network protocol overheads can be significant enough to prevent efficient usage of available network resources.

The report is organized as follows. Section II talks about the background of LTE and its architecture. In Section III we discuss about our motivations and objectives. Section IV discusses a non-commercial LTE network installed at Clemson University for academic purposes. Section V talks about our methodology. In section VI we analyze and discuss our results. Section VII talks about the conclusion and future work.

## II. Background

LTE has been designed to support only Packet-Switched (PS) services, in contrast to the Circuit-Switched (CS) model of previous cellular systems. It aims to provide seamless Internet Protocol (IP) connectivity between User Equipment (UE) and the Packet Data Network (PDN), without any disruption to the end users' applications during mobility. While the term 'LTE' encompasses the evolution of the radio access through the Evolved-UTRAN (E-UTRAN), it is accompanied by an

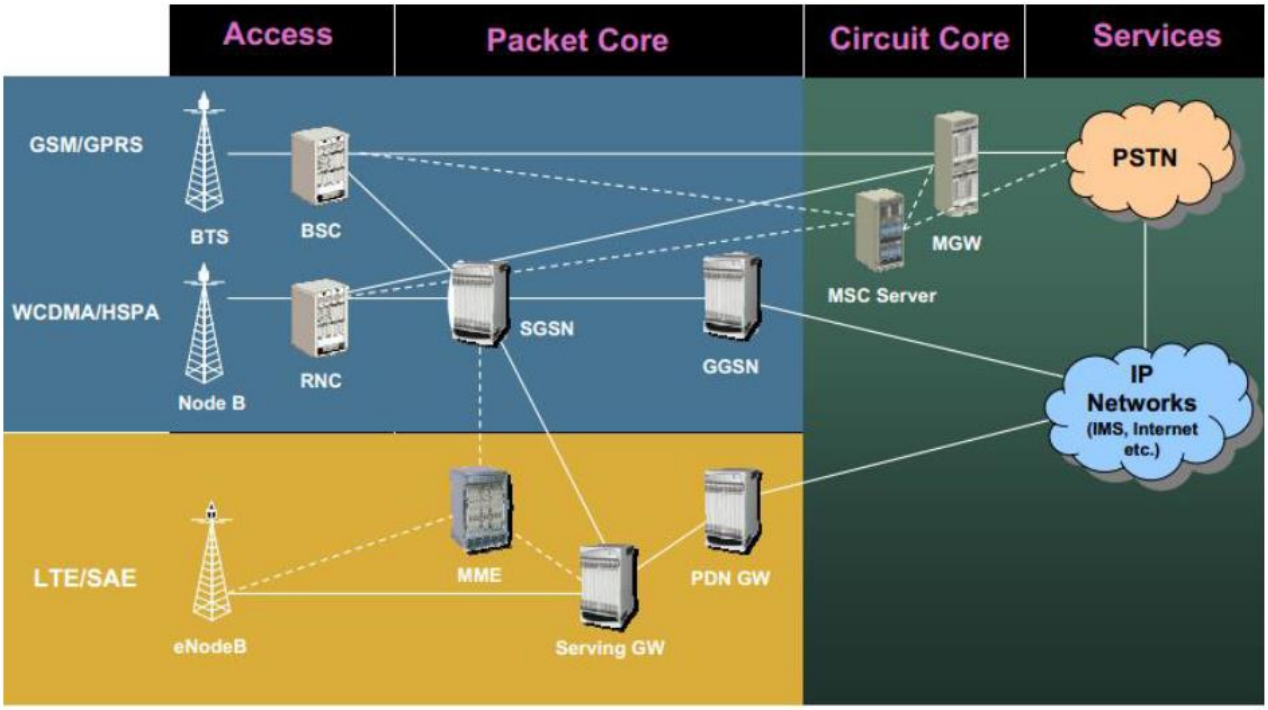



Fig. 1. 2G/3G to LTE

evolution of the non-radio aspects under the term 'System Architecture Evolution' (SAE) which includes the Evolved Packet Core (EPC) network. Together LTE and SAE comprise the Evolved Packet System (EPS) [4].

The EPS (Evolved Packet System), represents the EPC Core and the interworking with other domains. The basic network which implements the 3GPP Specification is shown below in Fig. 1.

EPS uses the concept of EPS bearers to route IP traffic from a gateway in the PDN to the UE. A bearer is an IP packet flow with a defined Quality of Service (QoS). The E-UTRAN and EPC together set up and release bearers as required by applications. EPS natively supports voice services over the IP Multimedia Subsystem (IMS) using Voice over IP (VoIP), but LTE also supports interworking with legacy systems for traditional CS voice support. EPS architecture defines the following domains and the interworking between them:

- GSM/GPRS represents 2G technology domain.
- WCDMA/HSPA represents 3G or 3.5G RAN (Radio Access Network).
- LTE represents the Long-Term Evolution domain.
- Non-3GPP domain consists of access networks, e.g. WiMAX and WLAN.

All the four domains are connected to Packet Core Domain (EPC). The EPC Architecture consists of packet core domain and user domain.

LTE features are supported by means of several EPS network elements with different roles. Fig. 2 shows the overall network architecture including the network elements and the standardized interfaces. At a high level, the network is comprised of the Core Network (CN) which is EPC and the access network (i.e. E-UTRAN). While the CN consists of many logical nodes, the access network is made up of essentially just one node, the evolved NodeB (eNodeB), which connects to the UEs. Each of these network elements is inter-connected by means of interfaces which are standardized in order to allow multivendor interoperability.

### *A. The Core Network*

The main logical nodes of the EPC are PDN Gateway (PGW), Serving Gateway (SGW) and the Mobility Management Entity (MME). In addition, EPC also includes other logical nodes and functions such as the Home Subscriber Server (HSS) and the Policy Control and Charging Rules Function (PCRF). Since the EPS only provides a bearer path of a certain QoS, control of multimedia applications such as VoIP is provided by the IMS which is outside the EPS itself.

*1) Mobility Management Entity (MME):* The MME is the control node which processes the signaling between the UE and the CN. The protocols running between the UE and the CN are known as the Non-Access Stratum (NAS) protocols. The main functions supported by the MME are classified as:

*a) Functions related to bearer management:* This includes the establishment, maintenance and release of the bearers, and is handled by the session management layer in the NAS protocol.

*b) Functions related to connection management:* This includes the establishment of the connection and security

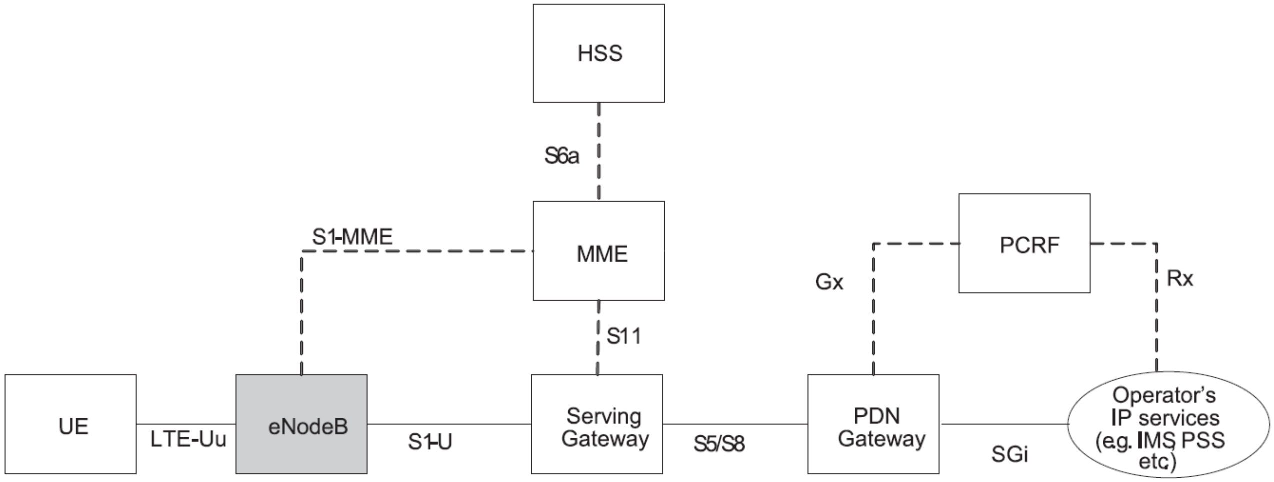



Fig. 2. The EPS network elements.

between the network and UE and is handled by the connection or mobility management layer in the NAS protocol layer.

*c) Functions related to inter-working with other networks:* This includes handing over of voice calls to legacy networks like GSM, UMTS and CDMA.

*d)* NAS Mobility management, tracking area management, idle mode management.

*e)* Handover support in cases where no X2 interface is available between two eNodeBs.

*2) Serving Gateway (S-GW):* All user IP packets are transferred through the S-GW, which serves as the local mobility anchor for the data bearers when the UE moves between eNodeBs. It also retains the information about the bearers when the UE is in idle state and temporarily buffers downlink data while the MME initiates paging of the UE to re-establish the bearers. In addition, the S-GW performs some administrative functions in the visited network, such as collecting information for charging (e.g. the volume of data sent to or received from the user) and legal interception. It also serves as the mobility anchor for inter-working with other 3GPP technologies such as GPRS and UMTS.

*3) Packet Data Gateway (P-GW):* The Packet Data Gateway is the gateway to the Internet. The P-GW is responsible for IP address allocation for the UE, as well as QoS enforcement and flow-based charging according to rules from the PCRF. The P-GW is responsible for the filtering of downlink user IP packets into the different QoS-based bearers. This is performed based on Traffic Flow Templates (TFTs). The P-GW performs QoS enforcement for Guaranteed Bit Rate (GBR) bearers. It also serves as the mobility anchor for inter-working with non-3GPP technologies such as CDMA2000 and WiMAX networks.

*4) Home Subscriber Server (HSS):* The Home Subscriber Server is a database that stores the information of every user in the network. HSS stores the user parameters like IMSI, authentication information to authenticate the subscriber and the services a user is allowed to use. It also contains the subscriber profile such as QoS profile, access restriction and roaming capabilities. It also holds information about the PDNs to which the user can connect. This could be in the form of an Access Point Name (APN) (which is a label according to DNS2 naming conventions describing the access point to the PDN), or a PDN Address (indicating subscribed IP address(es)). In addition, the HSS holds dynamic information such as the identity of the MME to which the user is currently attached or registered. The HSS may include an Authentication Center (AuC) which generates authentication vectors and security keys. The DIAMETER protocol is used to exchange the information between MME and HSS over the S6a interface.

*5) Policy Control and Charging Rules Function (PCRF):* The PCRF is responsible for policy control decision-making, as well as for controlling the flow-based charging functionalities in the Policy Control Enforcement Function (PCEF) which resides in the P-GW. The PCRF provides the QoS authorization (QoS class identifier and bit rates) that decides how a certain data flow will be treated in the PCEF and ensures that this is in accordance with the user's subscription profile.

## *B. The Access Network*

The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs, as illustrated in Fig. 3. For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be flat. The eNodeBs are normally inter-connected with each other by means of an interface known as X2, and to the EPC by means of the S1 interface – more specifically, to the MME by means of the S1-MME interface and to the S-GW by means of the S1-U interface. The protocols which run between the eNodeBs and the UE are known as the Access Stratum (AS) protocols.

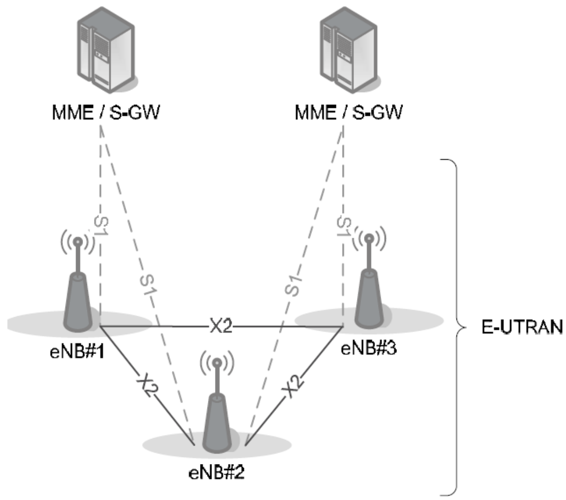



Fig. 3. Overall E-UTRAN architecture.

The E-UTRAN is responsible for all radio-related functions, which can be summarized briefly as:

*1) Radio Resource Management*: This covers all functions related to the radio bearers, such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources to UEs in both uplink and downlink.

*2) Header Compression*: This helps to ensure efficient use of the radio interface by compressing the IP packet headers which could otherwise represent a significant overhead, especially for small packets such as VoIP.

*3) Security*: All data sent over the radio interface is encrypted.

*4) Positioning*: The E-UTRAN provides the necessary measurements and other data to the Evolved Serving Mobile Location Centre (E-SMLC) and assists the E-SMLC in finding the UE position.

*5) Connectivity to the EPC*: This consists of the signaling towards the MME and the bearer path towards the S-GW.

On the network side, all these functions reside in the eNodeBs, each of which can be responsible for managing multiple cells. Unlike some of the previous second and third generation technologies, LTE integrates the radio controller function into the eNodeB. This allows tight interaction between the different protocol layers of the radio access network, thus reducing latency and improving efficiency. Such distributed control eliminates the need for a high-availability, processing-intensive controller, which in turn has the potential to reduce costs and avoid 'single points of failure'. Furthermore, as LTE does not support soft handover there is no need for a centralized data-combining function in the network.

One consequence of the lack of a centralized controller node is that, as the UE moves, the network must transfer all information related to a UE, i.e. the UE context, together with any buffered data, from one eNodeB to another. Thus, in LTE networks mechanisms are therefore in place to avoid data loss during handover.

### C. *Protocol Architecture*

*1) User Plane:* An IP packet for a UE is encapsulated in an EPC-specific protocol and tunneled between the P-GW and the eNodeB for transmission to the UE. Different tunneling protocols are used across different interfaces. A 3GPP-specific tunneling protocol called the GPRS Tunneling Protocol (GTP) is used over the core network interfaces, S1 and S5/S8. The E-UTRAN user plane protocol stack, shown greyed in Fig. 4, consists of the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC)

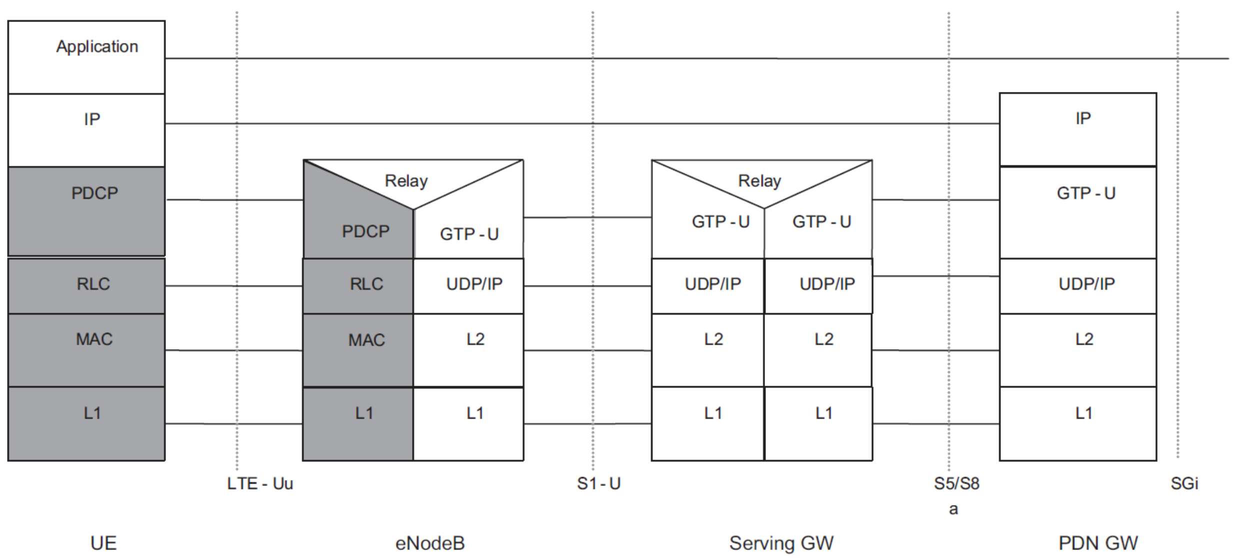



Fig. 4. The E-UTRAN user plane protocol stack.

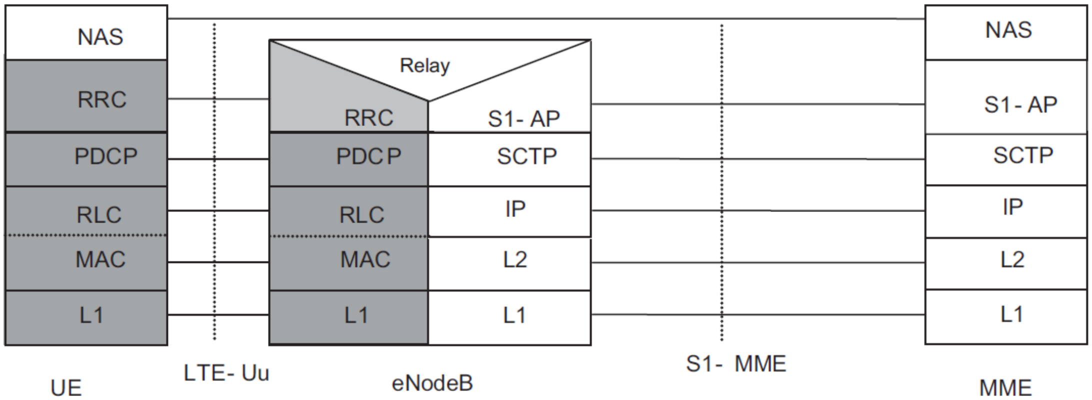



Fig. 5. Control plane protocol stack.

sublayers which are terminated in the eNodeB on the network side.

In the absence of any centralized controller node, data buffering during handover due to user mobility in the E-UTRAN must be performed in the eNodeB itself. Data protection during handover is a responsibility of the PDCP layer. The RLC and MAC layers both start afresh in a new cell after handover is completed.

*2) Control Plane:* The protocol stack for the control plane between the UE and MME is shown in Fig. 5. The greyed region of the stack indicates the AS protocols. The lower layers perform the same functions as for the user plane with the exception that there is no header compression function for control plane. The Radio Resource Control (RRC) protocol is known as 'Layer 3' in the AS protocol stack. It is the main controlling function in the AS, being responsible for establishing the radio bearers and configuring all the lower layers using RRC signalling between the eNodeB and the UE.

## III. Motivations And Objectives

We are motivated by the fact that LTE uses unique backhaul and radio network technologies, and has unique features distinguishing it from other access technologies, thus requiring the performance of some existing network protocols like TCP to

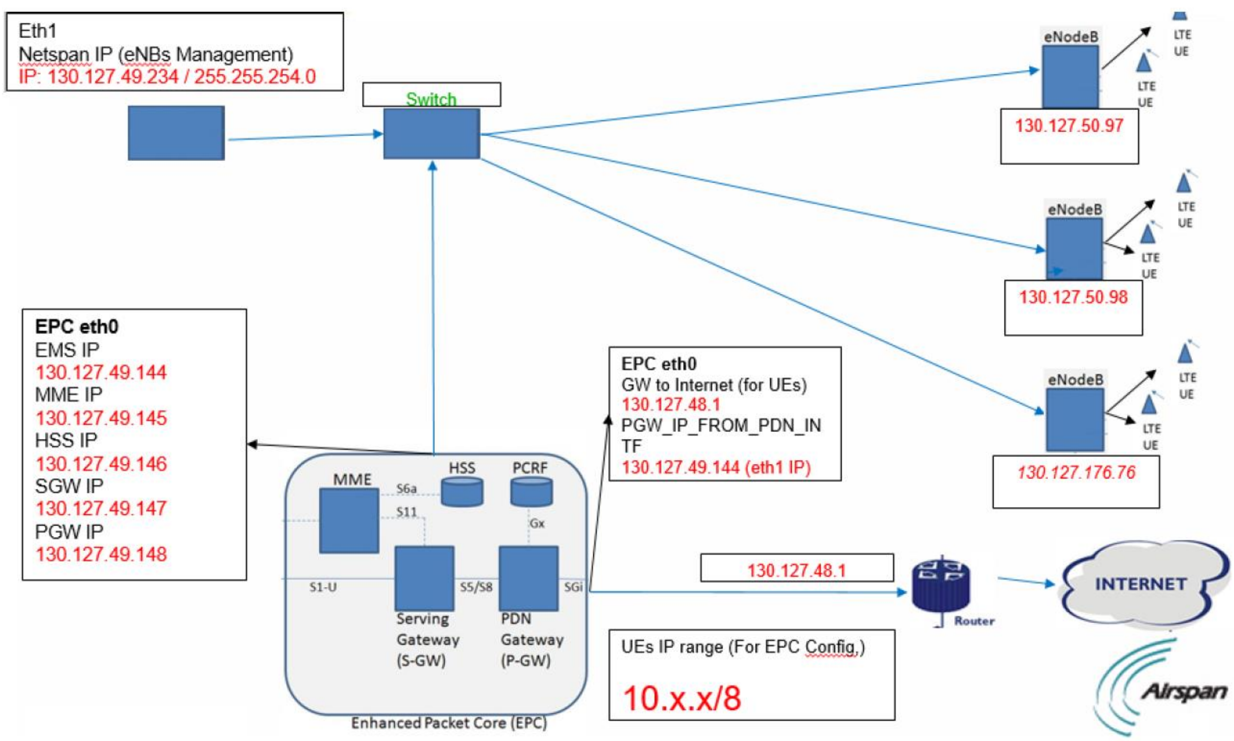



Fig. 6. Clemson University LTE Network Architecture.

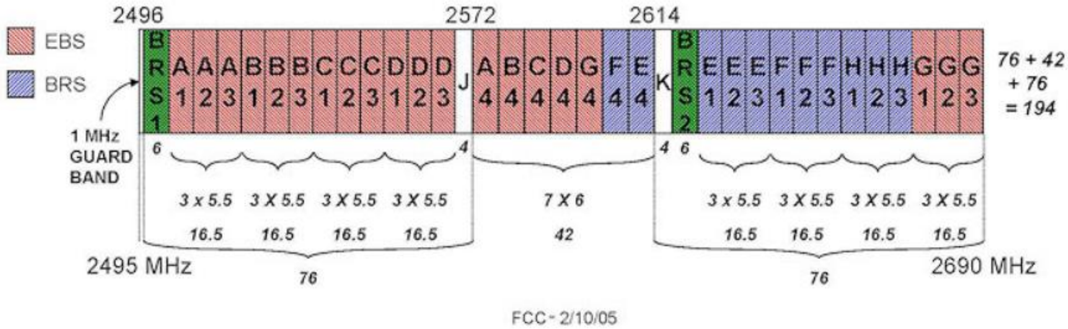



Fig. 7. BRS-EBS Band Plans (Post-Transition at 2496-2690 MHz).

be re-evaluated. However, there is significant lack of control while conducting experiments in a commercial LTE network which is why in this work, we evaluate the usage of LTE network resources of a locally managed LTE network at Clemson University.

## IV. Non-Commercial LTE Network at Clemson University

The LTE network built locally at Clemson University for academic purposes is shown in Fig. 6.

This LTE network operates in the licensed EBS Spectrum in bands A1-A3 and B1-B3. EBS stations are licensed in the 2.5 GHz band, which extends from 2496 MHz to 2690 MHz and is shown in Fig. 7 [5]. In the 2.5 GHz band, there are 20 EBS channels and 13 commercial Broadband Radio Service (BRS) channels, in addition to several small "guard-band" channels associated with certain EBS and BRS channels.

### A. *The Core Network*

The EPC core components for the LTE network are deployed using Airspan's aCore system [6]. aCore EPC entities support all the standard interfaces as defined in 3GPP thus allowing it to be deployed as "Network in a box". The core network is responsible for the overall control of the UE and establishment of the bearers. The main logical nodes of the EPC are PDN Gateway (PGW), Serving Gateway (SGW), Mobility Management Entity (MME) and the Home Subscriber Server (HSS).

*1) aCore Interfaces:* The interfaces of aCore entities are shown in Fig. 8. Some of the critical interfaces exposed by aCore are detailed as follows:

- *S5/S8*: This is the interface from PGW towards SGW. This interface uses 3GPP defined GTP version 2.
- *Gx/Gy/Gz*: These are the interfaces from PGW towards PCRF/OCS/CDF respectively. They are diameter-based protocol for retrieving policy for QoS from PCRF, online charging and for supporting offline charging for the data sessions and bearers.
- *SGi (transparent)*: This is the interface for connection to external PDN. The IP allocation as well as IP connection is established through this interface. DHCP based interface is exposed here.

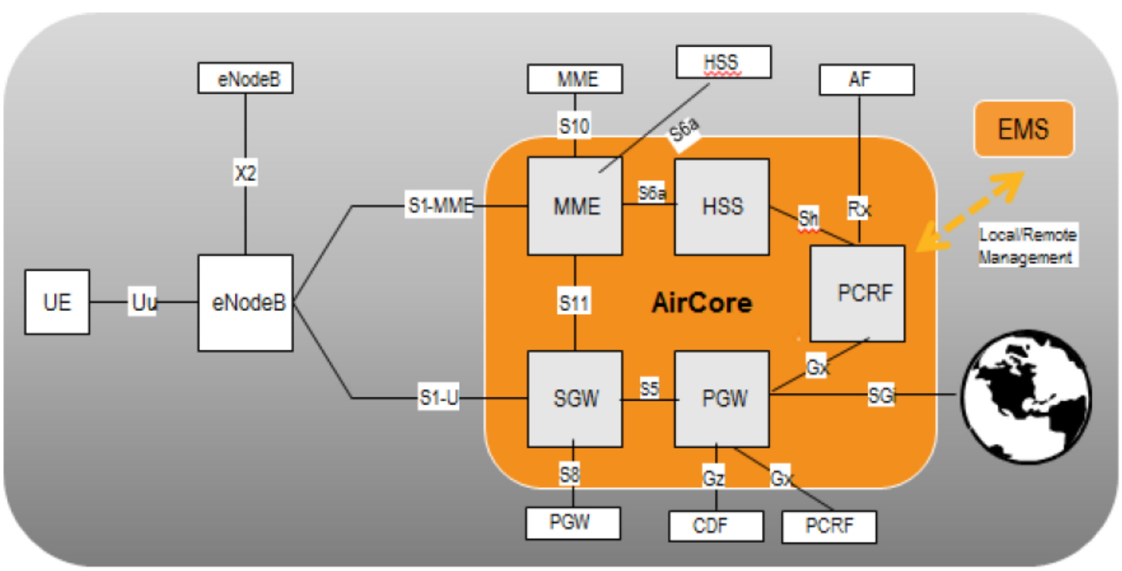



Fig. 8. aCore Interfaces.

- *S11*: This is the interface between SGW and MME. This is a GTPv2 based protocol for bearer session control.
- *S1-C*: This is the control interface from MME towards eNodeB. This is a S1AP and NAS based interface for IMSI and bearer session control.
- *S10*: This is the interface from MME towards peer MME. This is a GTPv2 based interface.
- *S6a*: This is the interface between MME and HSS. This is a diameter-based interface.
- *Sh*: This is the interface from HSS towards PCRF for delivering subscriber profile information towards PCRF for policy control. This is diameter-based interface. This is added for supporting the Sp interface from PCRF towards SPR.
- *Rx*: This is interface from PCRF towards AF (Application Function) for getting information about services dynamically. This is diameter-based interface.

*2) aCore Software:* aCore's EPC software is built from modules allowing each node to carry out its functions separately and independently even when running on the same hardware. Further, each EPC component is assigned its own interface with different IP address that would allow us to monitor them individually even when they exist in the same hardware. The nodes communicate between them using standard TCP/IP or SCTP (Stream Control Transmission Protocol) interfaces for Diameter (authentication, authorization, and accounting protocol), UDP for GTP (GPRS Tunneling Protocol) and SCTP for S1-C interface (interface from MME towards eNodeB).

## B. *The Access Network*

The Radio Access Network (RAN) of the private LTE network built at Clemson University shown in Fig. 9 has three outdoor eNodeBs and one indoor LTE small cell. These consist of two AirHarmony-1000 which are compact microcells and one AirSynergy-2000 which is an all-in-one compact pico base station supporting a wide range of radio interfaces including 4G LTE and WiMAX technologies. The AirHarmony-1000s are deployed near Jarvey Gym on Clemson campus with one base station having omni-directional antenna and the second with a directional antenna. The AirSynergy-2000 is located on roof top at Byrnes Hall on campus. Also, deployed in the lab in McAdams Hall is an AirVelocity-1000 which is an LTE small cell that is designed to bring LTE networks to indoor spaces thus creating a greater indoor coverage for the end user. All the eNodeBs operate on LTE Band 41 which is a relatively high-frequency radio band that spans from 2,502 MHz to 2,690 MHz.

*AirHarmony-1000* is part of Airspan's carrier-class 4G Micro eNodeB family that supports 3GPP's Long Term Evolution (LTE) eNodeB specifications, providing high-speed

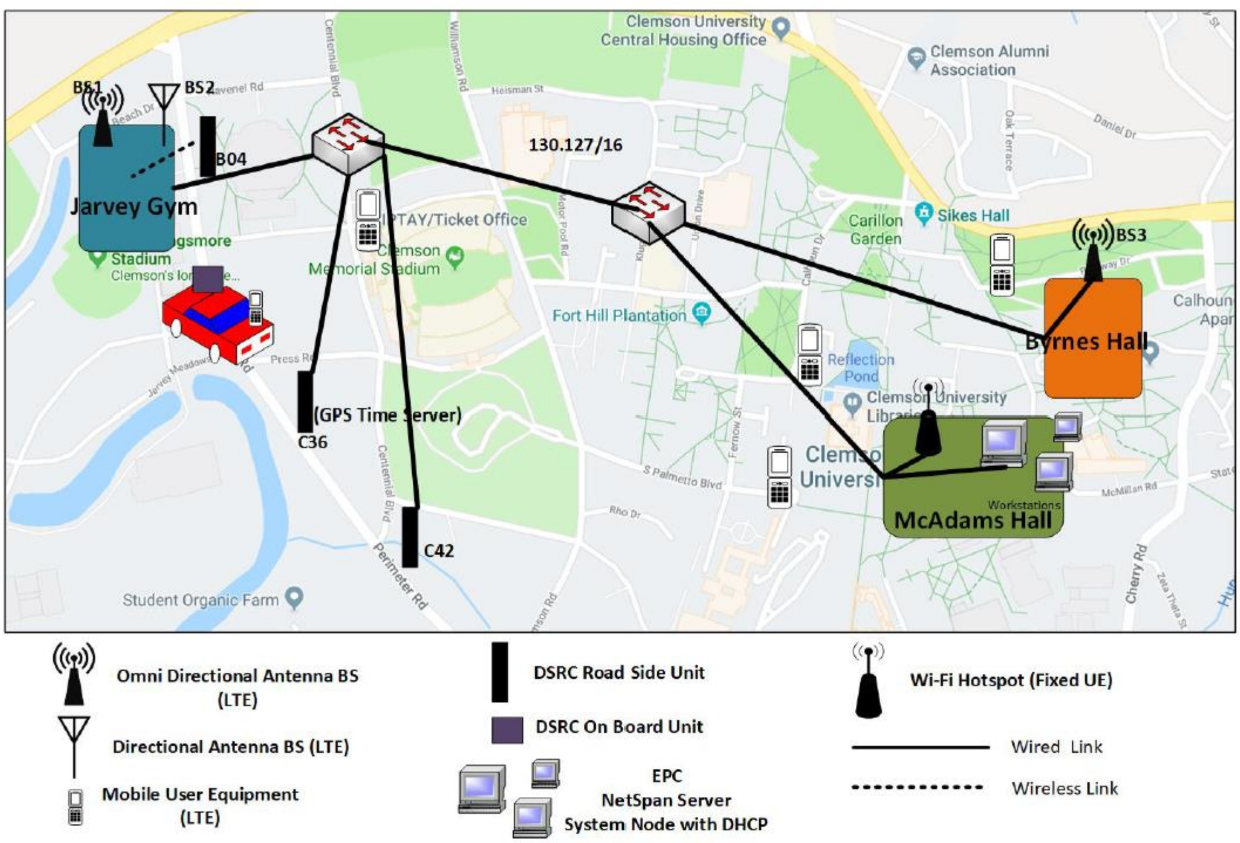



Fig. 9. Radio Access Network of Clemson University LTE Network.

data and mobility. It is a compact, easy to install micro-cell, which allows an operator to deploy LTE broadband services using existing infrastructure. It employs Software Defined Radio (SDR) technology, together with two transmit and receive paths, antennas and a GPS receiver. It fully supports the standard LTE (Uu/S1/X2) interfaces. AirHarmony-1000 supports the following channel bandwidths: 5MHz, 10MHz, 15MHz and 20MHz per carrier and the center frequency is tunable with a 100 KHz resolution. It can support both IPv4 and IPv6 and complies with 3GPP for the MAC, RLC, PDCP and RRC sub-layers. The radio resource management (RRM) ensures efficient use of the available radio resources. AirHarmony-1000 supports unique and sophisticated RRM algorithms to ensure an efficient use of the radio resources. The RRM includes, among other things, a control of the radio bearers, admission control and connection mobility control, dynamic resource allocation and Inter Cell Interference Coordination (ICIC). It can support Intra and Inter frequency handovers. In order to protect the S1 and X2 control plane, AirHarmony-1000 supports IPSec ESP according to RFC 4303. For both S1-MME and X2-C, IKEv2 certificates-based authentication are implemented and for S1-MME and X2-C, tunnel mode IPSec is supported.

*AirSynergy-2000* is Airspan's Pico base station using Software Defined Radio (SDR) technology, providing both data access and wireless backhaul from the same unit. It also supports a wide range of radio interfaces supporting both 4G LTE and WiMAX technologies. It supports multiple system features including Inter-RAT Mobility, RAN Sharing, eICIC, LTE and WiFi link aggregation etc.

*AirVelocity-1000* uses Airspan's LTE-Advanced Software Defined Radio (SDR) and is implemented within a state-of-the-art System on a Chip technology providing both data access and backhaul from the same architecture. AirVelocity is a indoor, high performance, high power, LTE-Advanced small cell, designed to bring Public Access LTE networks to indoor spaces like enterprises, large public spaces and stadiums. It is designed to solve the issue of hotspots where large numbers of users make demands for mobile data that macro cell only networks fail to provide. AirVelocity supports standardized 3GPP LTE access technologies and has interoperable S1 and X2 interfaces.

### C. *Netspan Server*

To manage and maintain Airspan's LTE eNodeBs and backhaul network elements, a client-server application is available called Netspan. Netspan is a client-server application, with 'always-on' server components implemented as element management services, and a front-end web application. Netspan uses SNMP to communicate with Network Elements (NE), and can be adjusted to meet customer requirements through its flexible configuration options. The key features associated with Netspan are as follows:

- Single management system for all Airspan products.
- Topology and map-based management of nodes.
- Support of virtualization and high availability of Netspan application.
- Database master for provisioning data.
- Separate database for storage of statistics.
- Web based client that is easy to use and configurable to user requirements.
- Comprehensive Northbound interface using SNMP, SOAP and FTP protocols.
- Management using SNMP v2c and SNMP v3 protocols.
- Ease of provisioning using profile based provisioning.
- Integrate with external LDAP.

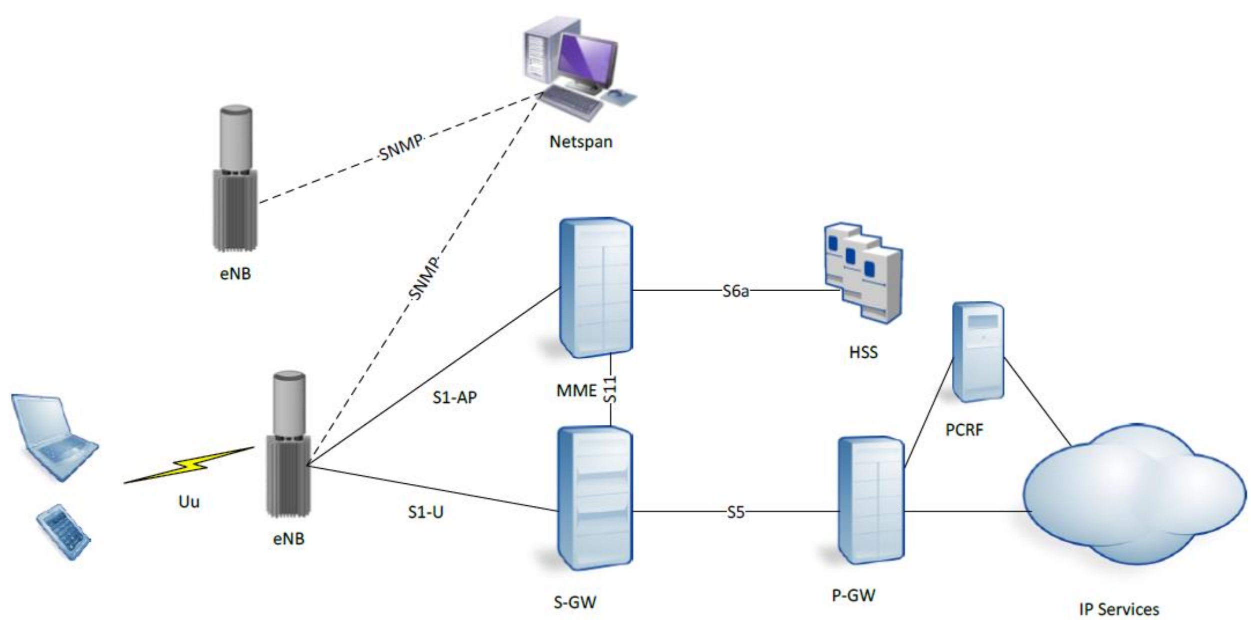



Fig. 10. Netspan Management of LTE eNodeBs.

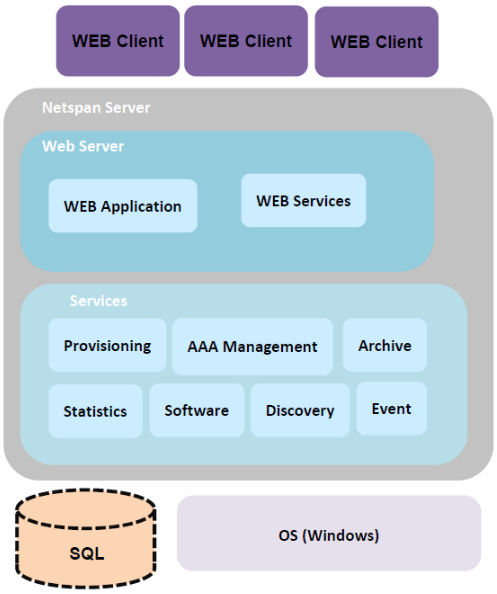


Fig. 11. Netspan components architecture.

- Synchronization between equipment and EMS to keep up to date status and information of the nodes.

The Netspan server is accessed using an Internet browser with all functionality and element management provided via web pages. The Netspan client's browsers operate remotely from the Netspan server, through configurable secure connections. Netspan has been designed to support efficient operation and maintenance of LTE and backhaul networks. A Microsoft SQL database is used to store all the provisioning information, configuration, events and history, with a separate database provided for the storage of statistical information.

*1) Netspan Architecture:* Netspan server consists of an SQL database server, web server, and a set of always-on Windows services. The Netspan client is a web browser application and northbound interface is mainly based on SOAP/HTTP. Netspan manages the Airspan eNB products as part of the LTE network architecture as shown in Fig. 10.

Netspan architecture is shown in Fig. 11 and consists of the following components:

- *SQL Server*: Provides the storage for all management data.
- *Web Application*: Implements management webpages for the Netspan clients.
- *Web Services*: Implements Netspan northbound interface methods.
- *IIS Server*: Hosts Netspan's ASP.NET web application and web services.
- *Provisioning Service and SNMP Jobs Engine*: Responsible for all the configuration performance on the SNMP managed equipment.
- *Alarm Service and Event Service*: Responsible for all the fault management functions: traps reception, events logging, and alarm generation.
- *Discovery Service*: Implements automatic SNMP discovery, equipment status polling, keep-alive functions, and automatic provisioning.
- *Software Service*: Responsible for upgrading the equipment software and scheduling the software upgrade tasks.
- *Statistics Service*: Responsible for statistics collection, storage, and buffer management.
- *Archive Service*: Responsible for archiving the activity logs in the files.

## V. Methodology

### A. Clemson LTE Network

We use the Local Area Radio Interface provided by AirVelocity cell in the lab to connect to the LTE network. The LTE to WiFi router (IPs: 192.168.0.1 and 192.168.8.32) creates a private WiFi network with prefix 192.168.0.0/24 and is also connected to the private LTE network with prefix 192.168.8.0/24. It also offers services like DHCP to allow our laptops to acquire an IP address on the 192.168.0.0/24 network as soon as we connect to the WiFi access point and also has NAT enabled on it which allows our laptops to talk to hosts outside the private network. The EPC core (IP: 192.168.8.3) is connected to an Intel NUC (IP: 192.168.8.1) which is also on the 192.168.8.0/24 network.

In order to be able to measure the TCP throughput over any network we need some tools that can generate traffic at various rates and measuring throughput, loss, latency, etc. For testing TCP throughput, we planned to start an iPerf client on our laptop that was connected to the WiFi router from the LTE network and ping a remote iPerf server on the internet. However, running a ping from our laptop to any remote host on the internet revealed that the EPC core and hence the LTE network had no internet connectivity. On further investigations of the EPC core, we observed that we could ping from our laptops to the Intel NUC but a ping in the reverse direction did not go through. Also, further testing showed that ping was working between the EPC core and the Intel NUC on both directions. This leads us to think that some firewall rule on the EPC core allows incoming packets to go through to the NUC but doesn't forward packets coming from the NUC.

To test this theory we ran iPerf server on the Intel NUC that was connected to the EPC core and ran the iPerf client on our laptop. Our laptop was connected to Wifi network created by the LTE to Wifi converter router located in the lab. The test was run initially with default TCP options, for a duration of 60 seconds with an interval of 1 second. Further iPerf tests were conducted by changing various iPerf parameters like client bandwidth, TCP window size, buffer size, etc. Next, we tried running the client in the bidirectional mode which would open a client and server at both ends and show the bandwidth results for the link on both

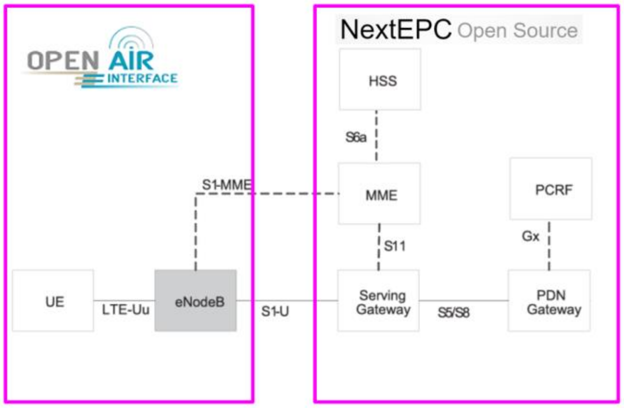



Fig. 12. Simulated end-to-end LTE network.

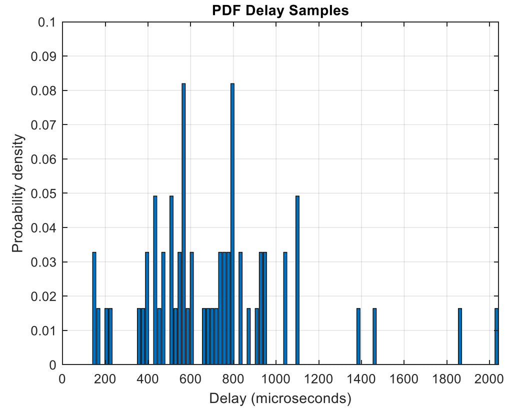



Fig. 13. PDF of RTT Results from laptop to Intel NUC.

directions. We used the watch command in Linux to monitor the data flow through the interfaces of the EPC core over time.

### B. *Simulated end-to-end LTE network*

As the testing on the Clemson University LTE network did not provide expected testing environment, we planned to use an open source implementation of the Evolved Packet Core of LTE networks supporting 3GPP provided by NextEPC as shown in Fig. 12. We ran this experiment on the POWDER platform which is a facility for conducting research on wireless networks. In this experiment we created an end-to-end LTE network with the following components:

- An *epc* node with HSS, MME, PGW, and SGW functions provided by NextEPC.
- A *sim-enb* node with eNodeB and UE functionality over a simulated RAN provided by Open Air Interface.
- A network link connecting the *epc* and *sim-enb* nodes.

We configure these services, start them up, and observe the communication between the eNodeB and MME/SGW services over the network link. For the EPC services, we start with a compute node running a stock Ubuntu 18.04 image with essential POWDER platform client-side scripts. The following is a brief overview of the steps that were followed to setup the end-to-end test LTE network:

*1) Instantiate the base experiment with two nodes*. Once the nodes are up, using ssh client open shells on each of the *epc* and *sim-enb* nodes on the POWDER platform.

*2) Download and compile the OAI RAN software*.

*3) Install NextEPC prerequisites*. NextEPC has some prerequisites for building and running successfully like MongoDB, nodeJS, other library packages etc. It uses MongoDB as its database backend for the HSS and nodeJS as HSS database interface. We also install wireshark on the *epc* node to monitor packets flowing in and out of the node.

*4) Download and compile the NextEPC software*.

*5) Configure networking* on the *epc host node*. NextEPC requires a tunnel device to be setup, as well as IP masquerading or NAT for UE internet connectivity.

*6) Configure NextEPC's services*. Configuration files for HSS, MME, SGW, and PGW components of NextEPC must be edited to point to correct interfaces in the experiment.

*7) Add the simulated UE's subscriber information to the HSS database.* We use NextEPC provided UI written in nodeJS for interacting with the HSS database.

*8) Start NextEPC services*.

*9) Start Wireshark*. We use it to watch the network interface we identified earlier when editing the NextEPC configuration file.

*10) Start the simulated eNodeB and UE services on the sim-enb node*.

*11) Verify UE attachment and connectivity*. Also, observe S1-AP and GTP-U (S1-U) activity.

*12) Test internet connectivity*. We run *ping* and *iperf* tests to study the performance of the end-to-end LTE network.

## VI. Analysis And Results

### A. *Testing on the Clemson LTE Network*

Our initial study of the Clemson University LTE network using the available documentation and examining the setup in the lab helped us understand the expected behavior of the network. We were successful in logging in to the Netspan server and were able to find out the status and the operating frequency of the base stations. The base station at Jarvey Athletic center with omni directional antenna showed an online status whereas the base station with directional antenna was offline and showed communication failure. The online eNodeB was operating at a bandwidth of 20 MHz and a downlink and uplink center frequency of 2.61 GHz. The Tx power for this eNodeB was found to be 37 dBm. The third base station on top of Byrnes hall was also operating at a bandwidth of 20 MHz but at a center frequency of 2.57 GHz. As mentioned earlier, this test network is expected to operate in the A1-A3 or B1-B3 bands of the EBS spectrum which would mean the current operating frequency range is higher than expected. As a result, we identified the options available in the Netspan server that would allow us to re-provision the eNodeBs to the allotted frequency channels.

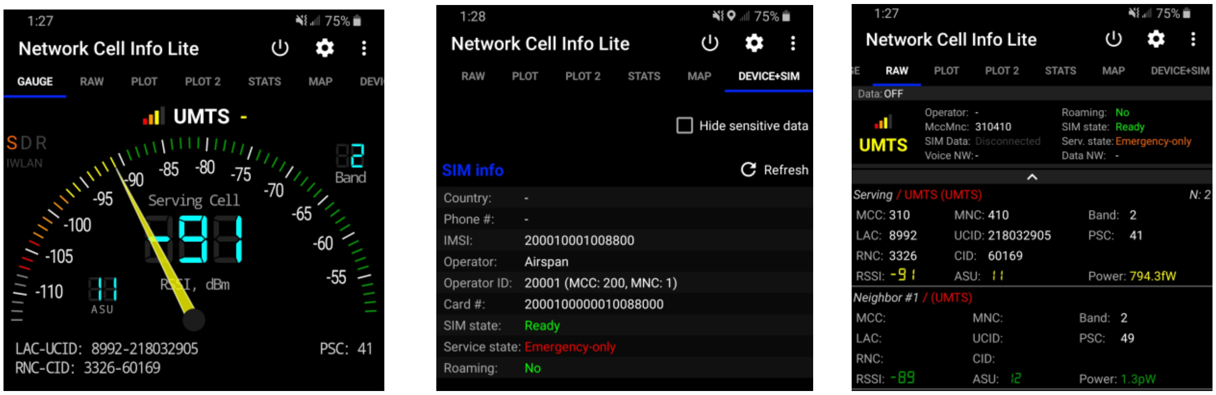



Fig. 14. Results of outdoor field testing of the Clemson LTE network.

In the lab we tested the network by running an iPerf server on the Intel NUC and iPerf client on our laptop. The test was run with default TCP options, for a duration of 60 seconds with an interval of 1 second. As expected, this connection was successful and showed a bandwidth of 972 Kbps. The PDF of the RTT results for the test are shown in Fig. 13. We also ran tests by increasing the client bandwidth to 2 Mbps, changing the TCP window size from default of 85 KB to 170 KB as well as changing the write buffer size from the default of 128 KB to 256 KB. The results for the overall bandwidth were found to be 991 Kbps, 984 Kbps and 992 Kbps respectively. We also ran a test with no delay between sent packets which also showed the resulting bandwidth as 1 Mbps. We also found a similar bandwidth of 1.03 Mbps for an UDP connection with default options.

Next, we tried running the client in the bidirectional mode which would open a client and server at both ends and show the bandwidth results. Upon testing we found that the results in this case matched the result from earlier cases when data flows from the laptop to the NUC but there was no data transferred from the Intel NUC to our laptops. By using the watch command, we also monitored the interfaces of the EPC core. We could see packets arriving at one interface and going out of the interface connected to the Intel NUC. But no data flow was seen in the other direction on the EPC core interfaces. Thus, confirming our concern regarding the issue with the firewall settings of the core. We also recognized that there could potentially be some issue with the settings of the tunnel that exists at the EPC core which is responsible for transferring data from the UE to the P-GW and then to the internet.

We also tried doing some outdoor field tests to check the connectivity of the LTE network and see if UEs can latch on to the Clemson LTE network. We used a Samsung Galaxy S9 Plus phone running on Android 9 Pie OS having LTE Band 41 (TD 2500) support. We used the phone with two different Airspan provided SIM cards but were not able to connect to the LTE network on campus. We used an application called Network Cell Info Lite available on the Google Play store to monitor cellular network status. In both cases we were only able to connect to the UMTS channel for Emergency services and the SIM data status showed disconnected as can be seen in Fig. 14. These outdoor testing results point to issue with either the Subscriber Identity Module not being registered on the HSS database or an issue with the network itself. This will be further debugged and investigated in detail.

## B. *Testing on the Simulated end-to-end LTE network*

After successfully installing OAI RAN software on the *sim-enb* node and the NextEPC components on the *epc* node we must edit the configuration files of the EPC components for them to be able to communicate with each other and the eNodeB correctly. The config files are written in *YAML* format and we must edit the network as well as the LTE settings of the EPC core depending on our experimental setup. For IP connectivity we modify the configuration files of MME and SGW. The S1AP address for MME is assigned the private IP address of 10.10.1.2 that belongs to *epc* node interface in our experiment. As we deploy all the EPC components on the same node, we allocate the GTPC interface of the MME a localhost address of 127.0.0.1. On the SGW side we also assign the GTPU interface

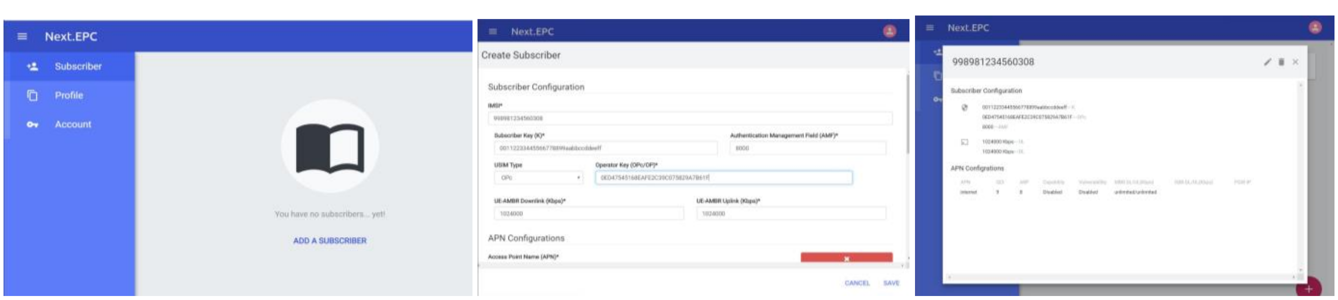



Fig. 15. Web UI to add subscriber to the HSS database.

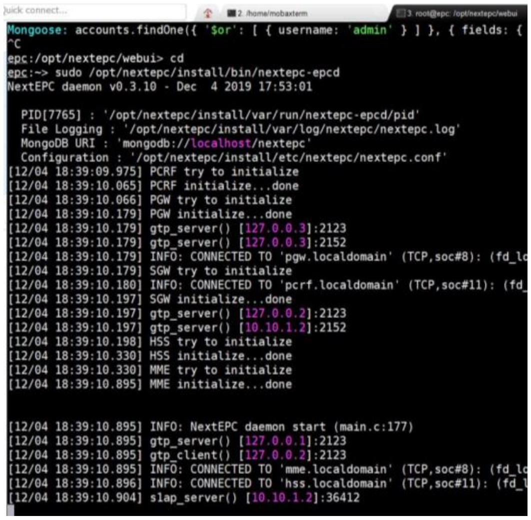



Fig. 16. EPC Core Initialization.

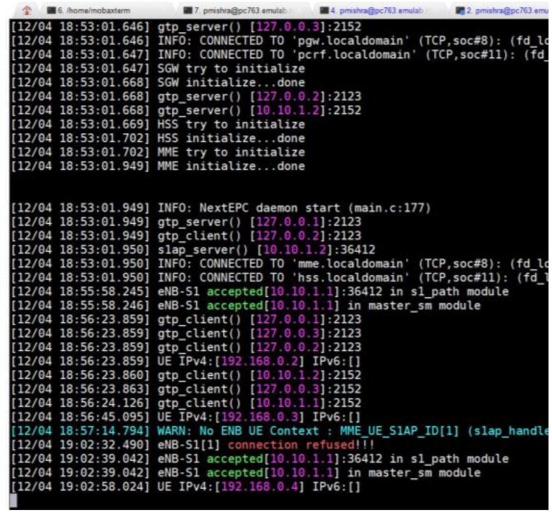



Fig. 17. EPC core messages when eNobeB and UE connect.

with the IP address 10.10.1.2 of the *epc* node. As part of the LTE settings we edit the MCC and MNC entries that define the PLMN ID on the MME along with the TAC ID.

Next, we must update the *ue_pool* section of the PGW entries on the config file. The PGW is responsible for assigning UEs with an IP address when they connect to the network. The *ue_pool* section defines the addresses that will be used for this purpose. We allocate IP addresses from network with ID 192.168.0.1/24 for this purpose.

After updating the config file, we must update the HSS database to make sure the UE is able to register itself on our simulated network. For this purpose, we use the Web UI provided by NextEPC as shown in Fig. 15. Using the hostname of the *epc* node from our experiment we open the UI on port 3000 using our browser and add a subscriber to the database as per specification of the OAI UE module we would simulate. We then start the NextEPC services on the *epc* node. The messages from the initialization sequence of the EPC core is shown in Fig. 16. We also open a Wireshark application on this node to monitor the network interface connected to the eNodeB.

Next, we open shells on the *sim-enb* node to start the simulated eNodeB and the UE. We can see from the messages printed on the *epc* node side in Fig 17 when the eNodeB is accepted by the MME after initialization. We also see messages in the figure showing the IP addresses assigned to the UE when it attaches itself successfully to the network.

We can also observe this procedure on the Wireshark trace that we started and the same has been shown on a screenshot in Fig. 18. This figure shows *InitialUEMessage* or the Attach request that was sent from the eNodeB with IP 10.10.1.1 to the

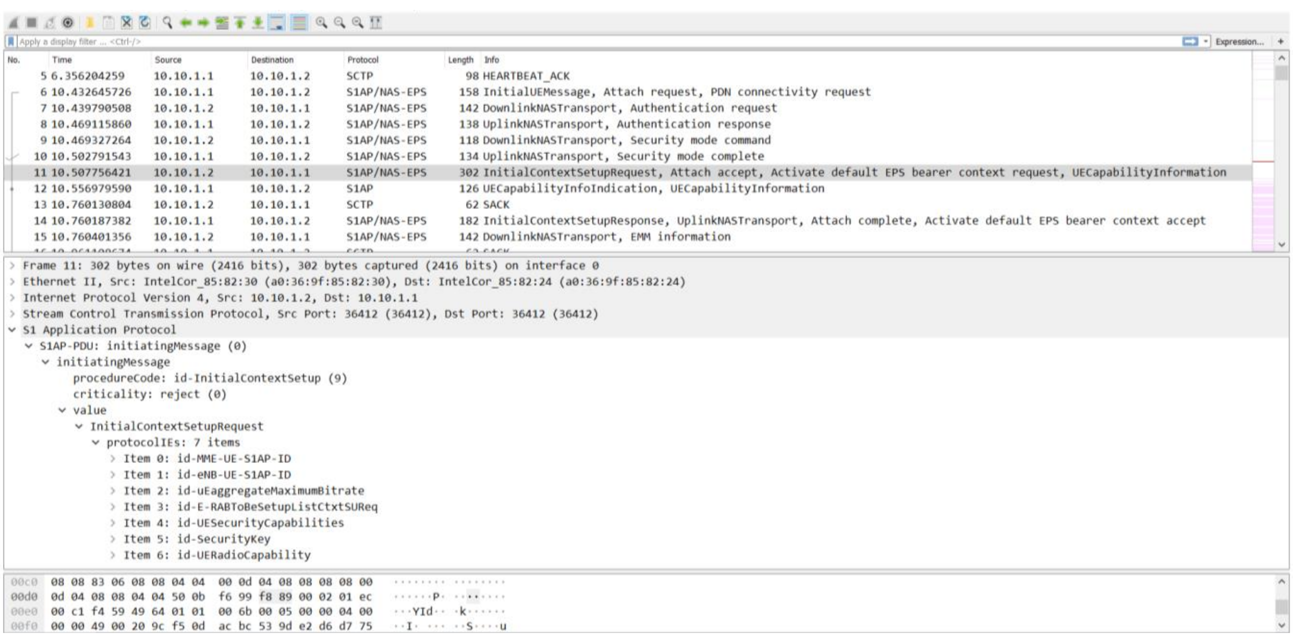



Fig. 18. Configuring 4G core using NextEPC.

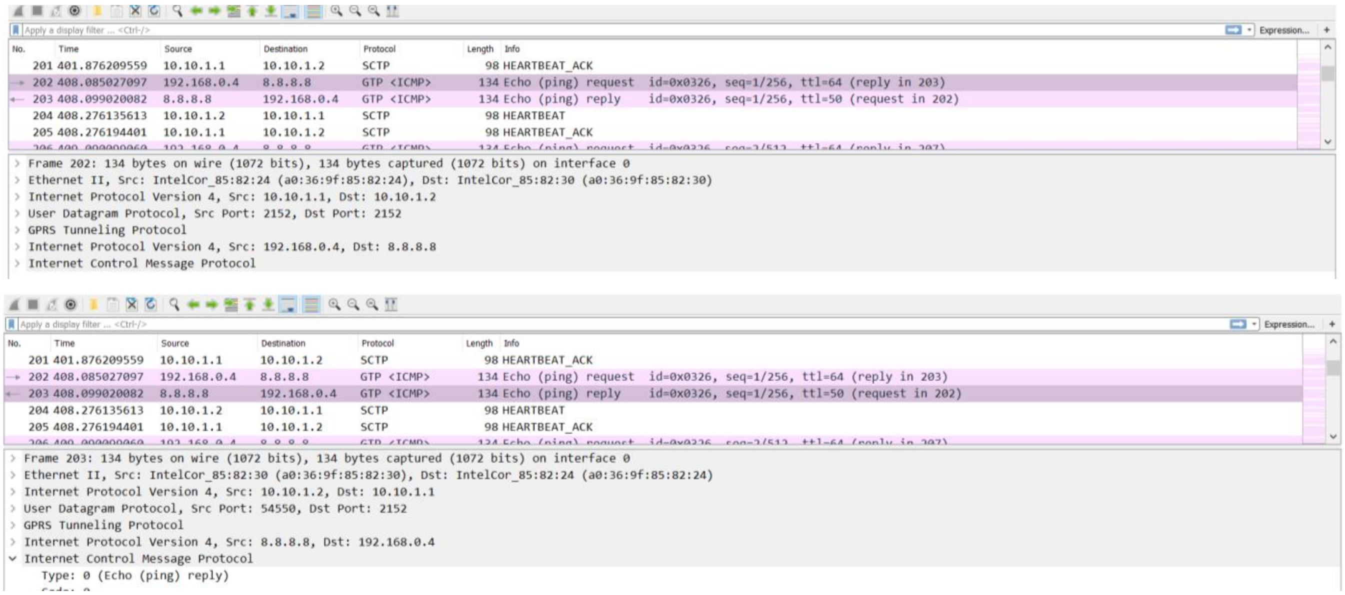



Fig. 19. Wireshark trace for A) Ping request. B) Ping reply.

EPC node with IP 10.10.1.2. This request results in exchange of authentication and security messages between the eNodeB and the MME on the EPC side. After this we also see on the trace an *Attach Accept* message which confirms that the MME was able to verify the UE and that it has accepted the UE's request to attach itself on to the network. Also, seen in the figure are the contents of this Attach Accept message which shows details like the security key, radio capability, etc. that were passed on to the UE by the MME upon connection.

Next, we confirmed the internet connectivity on the UE by successfully pinging the Google DNS server on IP 8.8.8.8 as well as the *ada8* machine with IP 130.127.48.229 in the School of Computing at Clemson University. A part of the Wireshark trace from the ping is shown in Fig. 19. In this figure we can see ping requests going from the UE with IP 192.168.0.4 to the Google DNS server at IP 8.8.8.8 and the replies coming in the other direction. Also, seen in the trace is how LTE core implements the GTP tunneling. For the ping requests we could see the ICMP requests encapsulated in an IP packet with source as the UEs IP and destination as Google DNS server's IP.

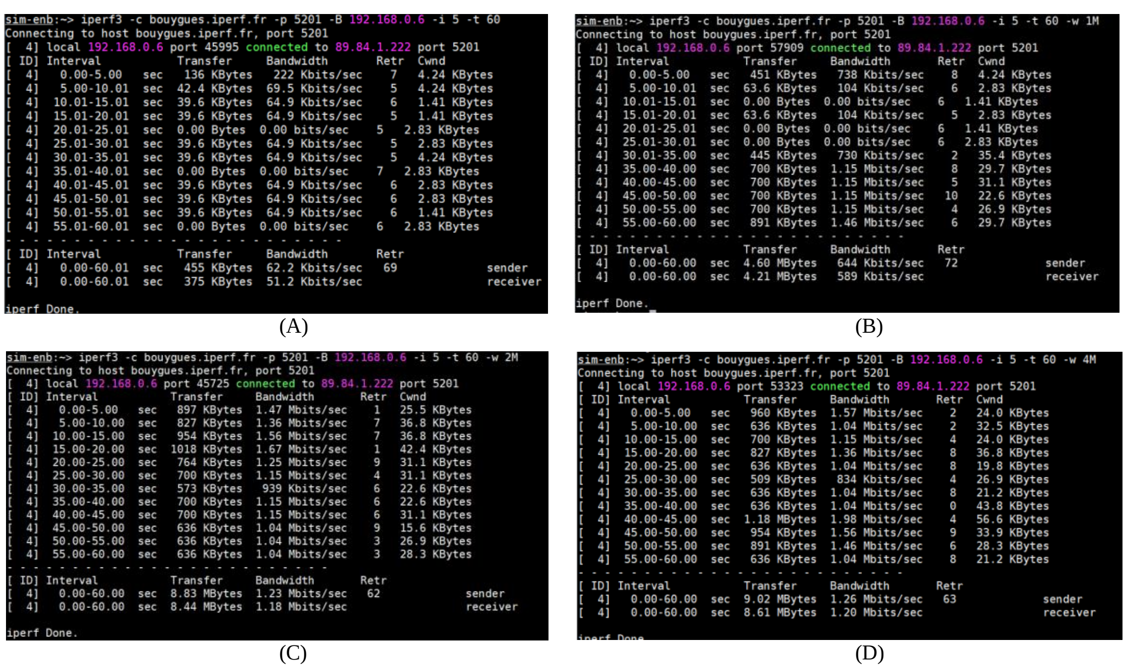



Fig. 20. Comparison of LTE Uplink speed with changing window size A) Default (64 KB) B)1MB C)2MB D)4MB

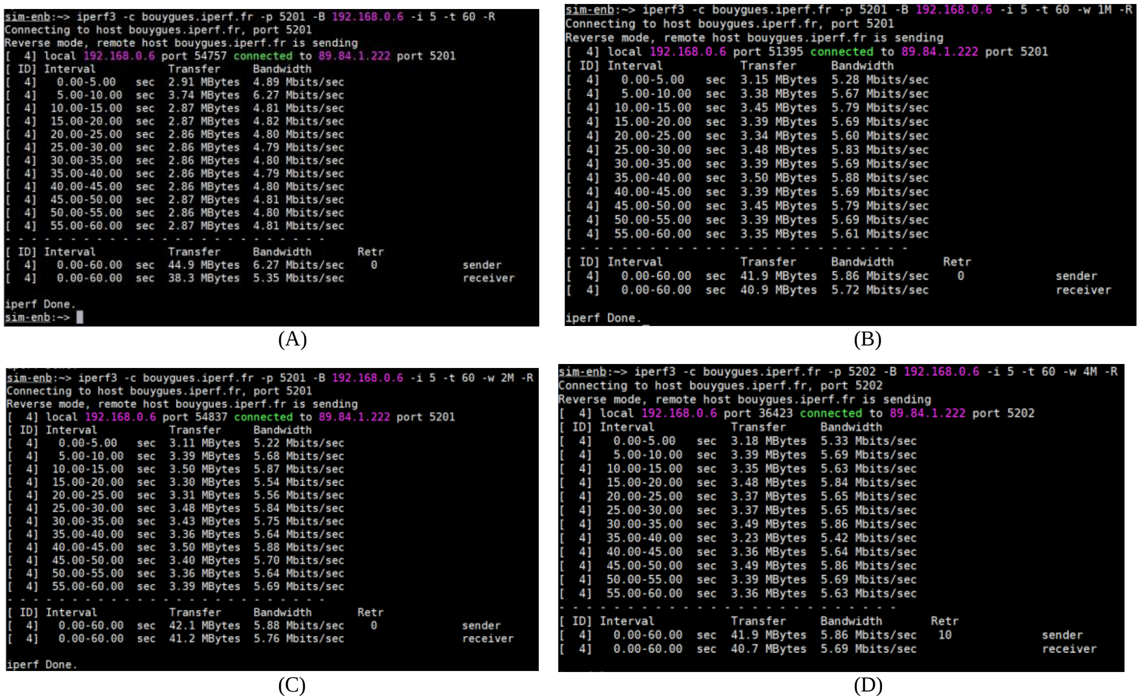



Fig. 21. Comparison of LTE Downlink speed with changing window size A) Default (64 KB) B)1MB C)2MB D)4MB

However, upon receiving this IP packet from the UE, the eNodeB adds a GTP tunnel header, consisting of three individual headers - a GTP header, UDP header, and IP header for GTP tunneling - in front of the IP packet. Thus, the routing network performs routing based on the destination IP address of the packet i.e. the IP address of the P-GW, and then delivers the IP packet to the P-GW accordingly. The P-GW then removes all three headers (Outer IP header/UDP header/GTP header) from the packet and delivers the original packet sent by the UE to the Internet. Similar phenomenon happens in the reverse direction when the UE receives ping replies from the DNS server.

We also test the LTE performance by running iPerf3 between the UE and a public iPerf3 server. The results of the iPerf tests have been shown in Fig. 20 and Fig. 21. We test the bandwidth in both the uplink as well as the downlink by using the reverse option on iPerf which basically sends data from the server to the UE. One of the first observation we make is that the LTE uplink speed of 62.2 Kbps is significantly lesser than that of the downlink speed of 6.27 Mbps. We also ran tests by varying iPerf parameters like TCP window size, etc. In case of uplink tests, we notice that the bandwidth sees an increase of up to 1.23 Mbps by increasing the window size from the default of 64 KB to 2 MB. After 2MB any further increase in the window size does not result in increase in the bandwidth. Running a

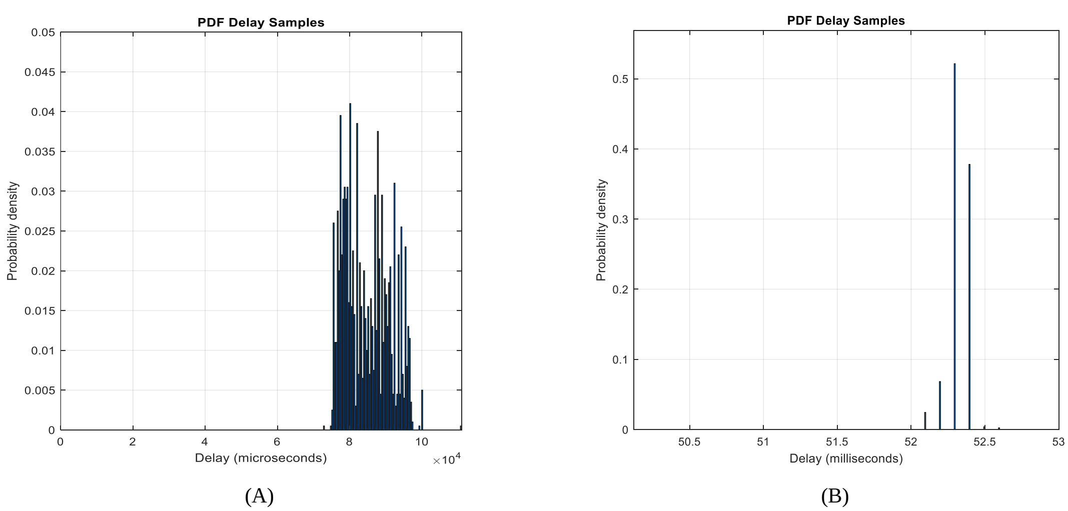
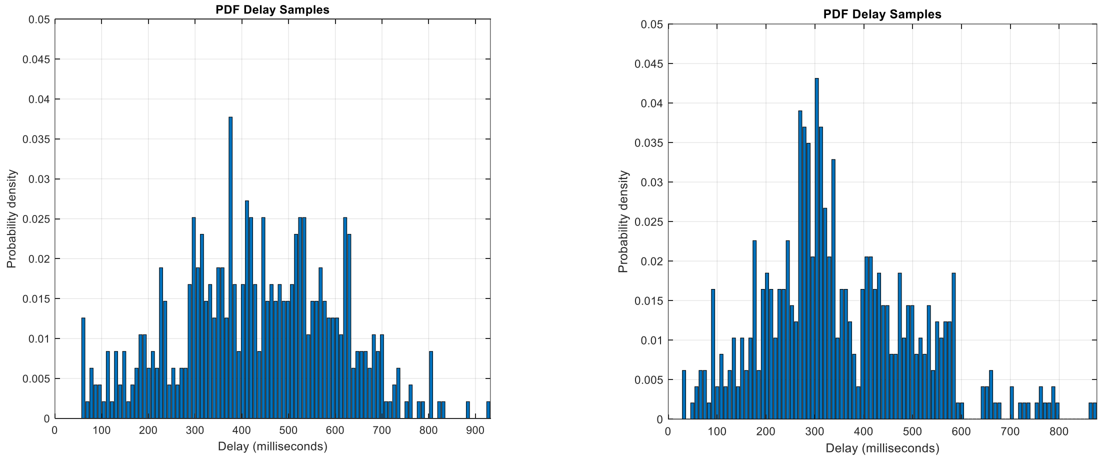



Fig. 22. Comparison of RTT: A) LTE vs B) Wired




(A) (B)

Fig. 23. Comparison of RTT: A) Commercial LTE vs B) WiFi

similar test on the downlink does not show any increase in the bandwidth.

We ran some other tests to test how different TCP congestion control algorithms perform on LTE. Mainly we tested the currently default algorithm TCP CUBIC against the TCP Reno and found that TCP CUBIC performs better on LTE. We also did RTT measurements on the LTE network and compared it with the results from a wired connection between the same hosts. This result is shown in Fig. 22. This figure shows that in case of LTE network we see a lot variation in the RTT samples as compared to the case with a wired connection. Such a variation is expected from a wireless network with many variables in the link as compared to a more stable environment of a wired connection. We also show a comparison between the RTT results we obtained by comparing the performance of a commercial LTE network against a commercial WiFi network as shown in Fig. 23. These results show similar values for the LTE network and the WiFi network. But, the average RTT for the Wifi network was slightly smaller than that of the commercial LTE network. However, this statistic may not hold true everywhere as commercial LTE connections are highly variable and the speeds we observe would depend on the carrier, geographic location, time of the day, type of subscription, etc.

## VII. Conclusion And Future Work

The performance of TCP over cellular networks has become an important research topic due to an increasingly growing number of users for mobile devices. Communication channels in cellular networks are complex and highly dynamic. In this project, we have analyzed the performance of TCP over different types of LTE networks. We have also developed an end-to-end simulated LTE network on the POWDER platform and studied the working of an LTE network. We have also performed a comparison of the performance of LTE networks with wired and WiFi networks. We plan to further look into the performance of these networks in our future work. Performance evaluation of TCP protocol will pave the way for developing improved protocols for current cellular networks as well as next generation networks like 5G.

## Acknowledgment

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## References

[1] Junxian Huang, Feng Qian, Yihua Guo, Yuanyuan Zhou, Qiang Xu, Z. Morley Mao, Subhabrata Sen, and Oliver Spatscheck. 2013. An in-depth study of LTE: effect of network protocol and application behavior on performance. In Proceedings of the ACM SIGCOMM 2013 conference on SIGCOMM (SIGCOMM '13). ACM, New York, NY, USA, 363-374.

[2] N. Becker, A. Rizk and M. Fidler, "A measurement study on the application-level performance of LTE," 2014 IFIP Networking Conference, Trondheim, 2014, pp. 1-9.

[3] Binh Nguyen, Arijit Banerjee, Vijay Gopalakrishnan, Sneha Kasera, Seungjoon Lee, Aman Shaikh, and Jacobus Van der Merwe. 2014. Towards understanding TCP performance on LTE/EPC mobile networks. In Proceedings of the 4th workshop on All things cellular: operations, applications, & challenges (AllThingsCellular '14). ACM, New York, NY, USA, 41-46.

[4] Sesia, Stefania, et al. "LTE - The UMTS Long Term Evolution : From Theory to Practice", John Wiley & Sons, Incorporated, 2011. ProQuest.

[5] https://www.phonescoop.com/glossary/term.php?gid=557

[6] https://www.airspan.com/products/#4g-outdoor

[7] POWDER (Platform for Open Wireless Data-driven Experimental Research). https://powderwireless.net

[8] Navid Nikaein, Mahesh K. Marina, Saravana Manickam, Alex Dawson, Raymond Knopp, and Christian Bonnet. 2014. OpenAirInterface: A Flexible Platform for 5G Research. SIGCOMM Comput. Commun.

[9] NextEPC Open Source: https://nextepc.org/

[10] H. Park, J. Lee and B. Kim, "TCP performance issues in LTE networks," ICTC 2011, Seoul, 2011, pp. 493-496.

[11] D. Zhou, W. Song, N. Baldo and M. Miozzo, "Evaluation of TCP performance with LTE downlink schedulers in a vehicular environment," 2013 9th International Wireless Communications and Mobile Computing Conference (IWCMC), Sardinia, 2013, pp. 1064-1069.

[12] Yung-Chih Chen, Yeon-sup Lim, Richard J. Gibbens, Erich M. Nahum, Ramin Khalili, and Don Towsley. 2013. A measurement-based study of MultiPath TCP performance over wireless networks. In Proceedings of the 2013 conference on Internet measurement conference (IMC '13). ACM, New York, NY, USA, 455-468.

[13] L. Zhang, T. Okamawari and T. Fujii, "Performance Evaluation of End-to-End Communication Quality of LTE," 2012 IEEE 75th Vehicular Technology Conference (VTC Spring), Yokohama, 2012, pp. 1-5

[14] iPerf Application: https://iperf.fr