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IMPLEMENTATION OF TACTICAL OPEN SOURCE 5G MOBILE NETWORKS

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THESIS

**IMPLEMENTATION OF TACTICAL OPEN SOURCE
5G MOBILE NETWORKS**

by

Justin T. Mitchell

September 2022

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Co-Advisor:	Darren J. Rogers

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**IMPLEMENTATION OF TACTICAL OPEN SOURCE
5G MOBILE NETWORKS**

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Submitted in partial fulfillment of the
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ABSTRACT

The implementation of fifth-generation (5G) communications technology is a global effort, with China leading the way. The Department of Defense has initiated efforts on 5G implementation from smart warehouses to virtual combat training; however, focus on the tactical communications level remains minimal. This thesis examines the feasibility of using OpenAirInterface Software Alliance (OSA) software to build a private mobile ad hoc 5G network for various military applications. First, we created a Fourth Generation/Long Term Evolution network utilizing commercial off-the-shelf equipment and software to operate the radio access network (RAN), software-defined radio, and an evolved packet core (EPC). Then we connected the EPC to an 802.11 network for internet access. We successfully configured a subscriber identification module and smartphone and attached it to the network for data services. Although the OSA software is robust and customizable, it is difficult to make changes, is restrictive in which user equipment (UE) can connect to the network, and does not reliably allow the UE to connect. The potential of OSA software for military applications is apparent but does not appear ready for field implementation. Going forward, we recommend researchers use this work to implement new software versions and test scalability to reassess the feasibility of OSA software.

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List of Acronyms and Abbreviations

3G   Third Generation

3GPP   Third Generation Partnership Project

4G   Fourth Generation

5G   Fifth Generation

AMQP   Advanced Message Queuing Protocol

API   application programming interface

APN   access point name

AWS   Amazon Web Services

C2   command and control

CT-API   chipcard terminal application programming interface (API)

CLI   command-line interface

CN   core network

COTS   commercial off-the-shelf

DARPA   Defense Advanced Research Projects Agency

dB   decibels

D/L   downlink

DNS   domain name service

DOD   Department of Defense

DUT   device under test

EIRP	Equivalent Isotropically Radiated Power
eNB	evolved NodeB
EPC	evolved packet core
EPS	evolved packet system
FSPL	Free Space Path Loss
GGSN	General Packet Radio Service (GPRS) Gateway Support Node
gNB	next-generation NodeB
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GTP	generic tunnel protocol
GUI	graphic user interface
HP	Hewlett-Packard
HTML	hypertext markup language
HTTP	hypertext transfer protocol
HSS	home subscriber server
IMAP	Internet Message Access Protocol
IMS	internet protocol (IP) multimedia core network subsystem
IMSI	international mobile subscriber identifier
IP	internet protocol
iOS	iPhone Operating System
I/Q	In-phase and Quadrature

jcli	Jasmin command-line interface (CLI)
LNA	low noise amplifier
LLR	log-likelihood ratio
LTE	long term evolution
MACO	Master of Science in Applied Cyber Operations
MAC	medium access control
MCC	Mobile Country Code
MCS	mobile cellular system
MF	modulated frequency
MME	mobile management entity
MMS	multimedia messaging service
mmW	millimeter-wave
MNC	Mobile Network Code
MNO	mobile network operator
MSC	multimedia service center
MS	Mobile Subscriber
MVNO	mobile virtual network operator
NPS	Naval Postgraduate School
NOA	Navy Operational Architecture
NR	New Radio
OAI	OpenAirInterface
OS	operating system

OSA	OpenAirInterface Software Alliance
O-Scope	oscilloscope
OTA	over the air
PC/SC	personal computer/smart card
PDCP	Packet Data Convergence Protocol
PGW	Packet Data Network Gateway
PHY	physical layer
PLMN	Public Land Mobile Network
POP3	post office protocol 3
PPG	push proxy gateway
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
RAN	radio access network
Rx	receiver
RF	radio frequency
RLC	radio link control
RRC	radio resource control
SDR	software-defined radio
SIM	subscriber identity module
SMA	SubMiniature version A
SMPP	short message peer-to-peer protocol
SMS	short message service

SMSC	short message service center
SMPP	short message peer-to-peer
SMTP	simple mail transfer protocol
SNR	Signal to Noise Ratio
SPGW-C	serving packet data network gateway – control plane
SPGW-U	serving packet data network gateway – user plane
SSH	secure shell protocol
SSHv2	secure shell protocol (SSH) version 2
SS7	Signaling System No. 7
SYSMOCOM	Systems for Mobile Communications
Tx	transmitter
TS	technical specifications
telecom	telecommunication
telecoms	telecommunications
TOA	time-of-arrival
UCI	uplink control information
UE	user equipment
UHD	Universal Software Radio Peripheral (USRP) hardware driver
U/L	uplink
URL	Uniform Resource Locator
USRP	Universal Software Radio Peripheral
VM	virtual machine

VoLTE	voice over LTE
WAP	wireless application protocol
WML	wireless markup language
WWW	world wide web

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CHAPTER 1:
Introduction

The work in this thesis focuses on furthering opportunities in the Fifth Generation (5G) New Radio (NR) field of study. This introduction provides an overarching view of our problem statement, background information, equipment and network setup, results, and conclusions and research contributions.

1.1   Problem Statement

Discussion about 5G cellular technology for military applications continues at the highest leadership levels. In October 2020, the Acting Under Secretary of Defense for Research and Engineering announced $600 million in awards to 15 prime contractors to test and evaluate 5G technology across five military installations [1]. The Department of Defense (DOD) effort is the most extensive full-scale 5G test for dual-use applications worldwide [1].

DOD efforts, however, continue to focus on the large-scale use of 5G technology. Released in December 2020, the DOD 5G Strategy Implementation Plan highlights focus areas, including smart warehouses, dynamic spectrum utilization, virtual reality for distributed ground combat training, and robust distributed command and control (C2) [2]. This list is not a complete capture of valuable 5G applications for military purposes, but our use case for a tactical "fly-away" 5G communications network is not addressed. The lack of focus on a tactical use case in the current DOD strategy led us to derive our research questions.

- Is it feasible to use open-source software and commercial off-the-shelf (COTS) equipment to create a 5G mobile ad cellular network to support tactical operations?

- Would a private open-source 5G mobile ad hoc network be reliable and secure for tactical operations?
    - Will the signal strength be adequate?
    - Will data throughput support use requirements?
    - Can the connection be maintained reliably?
    - What is the user capacity for the network?
    - How easy is it for an adversary to monitor or disable the network?

The benefits that 5G cellular technology promises, such as higher bandwidth, low latency, higher user capacity than Fourth Generation (4G), and enhanced security, are essential to highlight. Low latency is vital for applications such as self-driving vehicle communications, as any lag could create catastrophic accidents. A clear advantage of 5G over 4G is that download speeds are approximately ten times faster [3]. Network security through slicing is also a significant advance with 5G. According to [4], network slicing allows for physical network separation into logical segments. Slicing typically isolates the threat to the affected logical segment if an unauthorized intrusion or security threat occurs. However, the most significant advantage is that open-source software and hardware 5G solutions are available, which can remove reliance on larger telecommunications (telecoms) for private network services.

Open-source software and hardware provide a unique opportunity to create private networks at a reduced cost. The ability to manipulate software without a third-party contractor or software engineer enables complete control for the owner, and modifying the underlying code provides greater latitude to tailor capabilities. For example, if a network does not require a legacy short message service (SMS) capability, the owners and maintainers can remove that code and implement a data-only network. Removing unneeded code is a best practice and improves the network security posture.

1.2   Background

This thesis inherited a partial physical testbed open-source network from research by a prior student. Chapter II provides a baseline of the network at the beginning of our research, the current state of our testbed network, alternate Third Generation Partnership Project (3GPP) compliant open stack projects, and other work ongoing in the 5G NR field.

Open5GS and srsRAN are open-source software options available for use on COTS equipment [5], [6]. Other options, such as Amarisoft and yateBTS, are full-build, in-a-box cellular networks available at much higher costs [7], [8]. The benefit that Amarisoft and yateBTS bring is that both are plug-and-play, with little user configuration required. All four of these implementations claim to be 3GPP compliant.

Compliance with the 3GPP standards is critical because of the influence that China continues to have on 5G technology and the 3GPP standards development process. Chinese efforts in the 5G race served as a solid justification to pursue our research for compliant, but alternative, software implementations. China dramatically impacts the supply chain due to its dominance of radio frequency (RF) component manufacturing and standards development. Their manufacturing dominance includes subcomponents of semiconductors, switches, and amplifiers [9]. As a result, the integrated chipsets, combined with multiple subcomponents and subsystems that interface with system components on the motherboard, likely will be built to Chinese 5G network specifications.

Chinese influence underscores the importance of utilizing 3GPP compliant systems built to the accepted standards to ensure the secure communications required for tactical military operations. Equally important is that with the use of COTS equipment, we can potentially verify the components and subcomponents of our network and avoid Chinese-manufactured technology.

1.3 Equipment and Network Setup

Chapter III discusses how our testbed network operates on open-source software from the OpenAirInterface Software Alliance (OSA) and describes a few virtual tools useful for network diagnostics and troubleshooting. We provide insight into the physical network changes made during our thesis work and the integration of a short message service center (SMSC) into the network. The OSA software does not include a text messaging capability, and although current messaging services run over applications such as Whatsapp and Signal, traditional SMS could be a valuable capability. We also discuss access point name (APN) settings on the user equipment (UE), which enabled us to achieve a fully wireless network architecture.

1.4 Overview of Results

We sought to explore network capabilities and limitations to provide answers to our problem statement and research questions. This section provides an overview of the experiments conducted during our research. We discuss the detailed results of our experiments in Chapter IV.

1.4.1 Testbed Speed Tests

We conducted various speed tests to assess the testbed network speed compared to commercial service providers. Specifically, we tested our radio access network (RAN), evolved packet core (EPC), and our UE (the Nokia 1A), using the Measurement Lab speed test website [10]. We also tested the throughput speed of our UE while connected to our testbed and three other devices on commercial networks to compare our results. Our testbed network outperformed the other service providers' download rates by about 5 MB/s except for the Google Fi network, which had a download speed of approximately 17 MB/s greater than the other three UEs. We also conducted tests with the same UE devices on the campus wireless to compare to our testbed network. Overall, the network speeds were comparable to the commercial service providers; however, our testbed network was faster.

1.4.2 Testbed Data Reliability Test

Another aspect of our testbed that needed consideration was data throughput reliability. We conducted a test in our office lab to determine reliable data throughput at various distances. We determined that the network could reliably send and receive data to and from the UE at 12 m. After reaching 12 m, the data reliability took a significant dip. Considering the various physical barriers the signal had to traverse, the network performance was consistent and reliable.

1.4.3 Link Budget Analysis on Our Testbed Network

We utilized our network parameters to conduct a link budget analysis on our network. Ultimately, we did not use the MathWorks Link Budget Analyzer application because it could not provide calculations for distances under 20 m. The Rohde and Schwarz link budget analysis tool offered similar results to what we saw in our live network tests.

1.5 Conclusions and Contributions

This section provides an overview of the conclusions we derived based on our tests and our research contributions. We provide further detail in Chapter V.

1.5.1 Our Conclusions

Our tests found that the OpenAirInterface (OAI) open stack software has vast potential. However, the software is difficult to modify and manipulate. Once a connection is established the data is reliable, but the connectivity is too volatile to utilize functionally. Continued research and stability enhancement of the OAI implementation is required to provide safe, reliable, and secure communications in military operations.

1.5.2 Contributions

Our main contributions include creating the first fully functional 4G/long term evolution (LTE) open-source network with COTS equipment as a testbed and mechanism for 5G research at the Naval Postgraduate School (NPS). We tested the capabilities and limitations of the OAI open-source software and explored additional network integration options to implement features found in commercial networks. While the focus on modern wireless technologies has shifted to data, the expectation is that systems will support foundational services using earlier protocols such as call routing using Signaling System No. 7 (SS7) and SMS using an integrated SMSC.

As discussed above, the remainder of this thesis consists of four additional chapters: background; equipment and network setup; results; and conclusions, contributions, and recommendations for follow-on research.

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CHAPTER 2:
Background

This chapter discusses our research network origins, the open-source network implementation, alternate open-stack network projects, and other work ongoing in the 5G field of study. We also investigated additional network capabilities, namely integrating an SMSC into the OSA open-stack software. The background information helps establish the importance of creating our network as a testbed platform for future research.

2.1   Origin of Research Network

A previous NPS thesis student built the first iteration of the test network used in this research to investigate a security vulnerability in the Global Navigation Satellite System (GNSS) protocol used in 4G and 5G mobile network chipsets [11]. Because of the difficulty of gaining access to a commercial mobile network for research and testing the vulnerability, the student decided to build a non-proprietary network from open-source software, creating a 3GPP compliant network from OSA technology. Research has subsequently led us to expand the original build towards a "proper" wireless cellular network. The simulated UE used in the prior work was a Hewlett-Packard (HP) laptop emulating a cell phone. Previous research and experimentation led to establishing a wireless connection for mobile data services to the UE and experimenting with other network capabilities.

The work in this thesis attempted to connect multiple devices, which is vital to fully test and expand the functional capacity of the network. Table 2.1 outlines the network components used in our testbed implementation. Components can vary depending on network requirements and unique to operational use cases.

Table 2.1. Network Testbed Components and Roles

Equipment	Function
HP Laptop "A"	EPC
	HSS
	MME
	SPGW-C
	SPGW-U
HP Laptop "B"	eNB
Ettus B200	Base Station RF Interface
Netgear Switch	Physical Connection (eNB - EPC)
Nokia 1A Smartphone	UE

The following list provides more information and explains the function of each component listed in Table 2.1 [12], [13]:

- The EPC is the core of the LTE network and manages the overall network, including routing and authentication
- The home subscriber server (HSS) database handles information related to the network subscribers and performs functions for managing mobile users, initiating sessions, and authentication
- The mobile management entity (MME) handles the control plane, dealing with signaling and security; the MME also tracks and pages the UE
- The serving packet data network gateway – control plane (SPGW-C) handles the control requests from the MME and communication with the serving packet data network gateway – user plane (SPGW-U)
- The SPGW-U is the gateway that connects UEs to external networks and acts as the link that connects the RF network to the EPC. It is responsible for routing IP traffic
- The evolved NodeB (eNB) is a complex base station that handles radio communications for the network through the Ettus B200 software-defined radio (SDR), radio resource management, and handover decisions

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- The Netgear switch acts as the physical medium that the data traverses from the eNB to the EPC, comparable to the fiber connection from a cell tower to the mobile switching station in a large-scale cellular network

Figure 2.1 provides a schematic to illustrate the components within the research network.
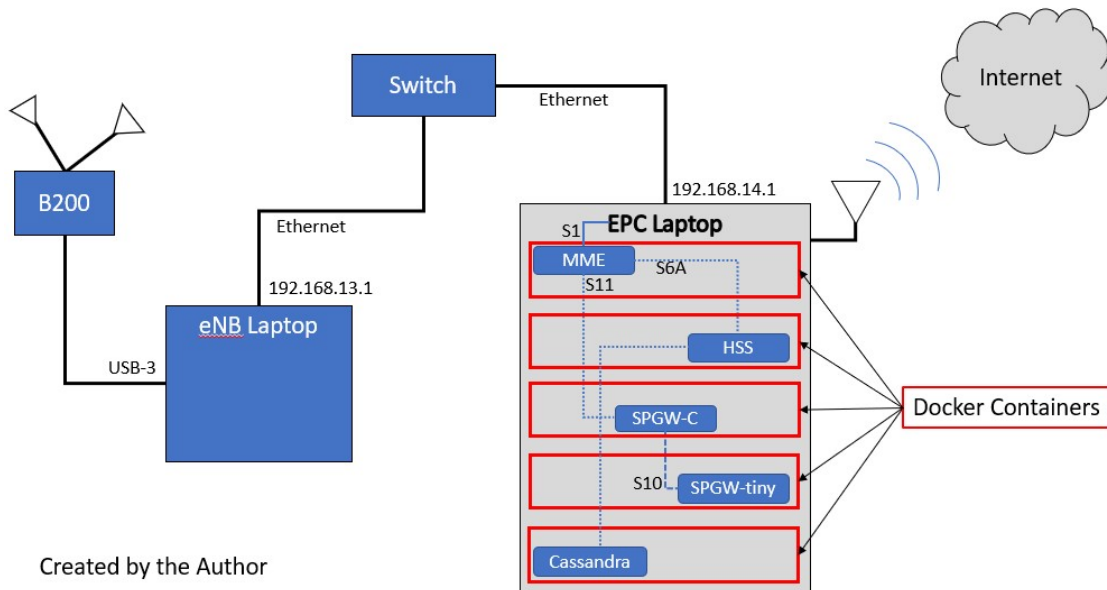
Figure 2.1. Network Diagram for Our Research Network with Components

2.2 Open-Source Network Implementation

Our testbed network is wholly composed of open-source software, which makes the network a compelling option for developing a scalable private 5G network with potential military applications. This section discusses OSA software, additional network capabilities, and other work in the 5G field.

2.2.1 OSA for 4G/5G Network

OSA, a French non-profit organization, was established in 2014 and is the home of OAI. OAI is an open software group that has created a community of developers worldwide,

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collaborating to build wireless cellular RAN and core network (CN) technologies [14]. Our research network utilizes OAI software because it is 3GPP compliant, ensuring that the network follows the industry standard guiding 5G implementation.

The 3GPP is the governing standards body for cellular technology. The organization's name originates from Third Generation (3G) technology. 3GPP is responsible for and produces technical specifications (TS) and reports for 3G Mobile Systems. The group also supports evolved Global System for Mobile Communications (GSM) core network and radio access technology [15].

2.2.2 Alternate Open Stack Network Projects

There is a myriad of alternate Open Stack networks. Open5GS is used to configure an NR/LTE network with the 5G Core and EPC in the C programming language [5]. Another option is the srsRAN suite, which currently includes software for a UE, eNB, and EPC and runs on Linux [6]. Open5GS and srsRAN are software implementations built utilizing COTS equipment, but other options are available already in a box, ready for use. YateBTS and Amarisoft have 5G-in-a-box implementations for thousands of dollars [8], [7]. Our research focused on the open-source software options to avoid the higher-cost implementations.

Magma is another open-source software platform that provides a flexible, extendable mobile core network. Magma is comprised of three major components, the Access Gateway, Orchestrator, and Federation Gateway. The Access Gateway is what provides network services and policy enforcement. The Orchestrator is a cloud service providing wireless access to configure and monitor the network [16]. The Federation Gateway is how the Mobile Network Operators integrate with Magma. Magma is a powerful option and is currently involved in a Defense Advanced Research Projects Agency (DARPA) project [17].

2.2.3 Additional Network Capabilities

The use of open-source software allows for complete control of the code that makes up the network. The network owner/operator can maintain capabilities that the user might need, with the flexibility to add or remove features on demand. The current OSA software release allows the UE to connect to a data network. However, the software is not equipped with an SMSC to handle text messaging or internet protocol (IP) multimedia core network subsystem

(IMS) for voice over LTE (VoLTE) handling. These capabilities could be advantageous and potentially integrated into the OAI software stack. Our research investigated open-source SMS options to determine compatibility and ease of integration into the research network.

2.3   Open Source SMSC Options

The OAI software allows customization of the code to enhance the capability of the network. In attempting to include an SMS function in the network stack, we investigated four open-source SMS programs to determine the best fit based on features, compatibility, and scalability. The following section provides a brief explanation of each software suite.

2.3.1   JasminSMS

This open-source SMS Gateway has many enterprise-class features [18]. The software is customizable to the specific needs of a network. The Jasmin message routing algorithms allow the administrator to use rule-based routing defined by parameters such as sender information, the source, and the destination [18]. Written in Python and Twisted frameworks, the software allows SMS delivery through hypertext transfer protocol (HTTP) and short message peer-to-peer (SMPP). Intelligent routing is configurable in real-time through an application programming interface (API), command-line interface (CLI), or web-enabled back-end access [18]. The current JasminSMS software supports Ubuntu 20.04 and is not compatible with the version of Ubuntu that the research network uses (Ubuntu 18.04) [18]. We discuss the process of building a work-around for the JasminSMS software to enable integration in our network in Chapter III.

Figure 2.2 represents the JasminSMS data flow across the network. As depicted, JasminSMS utilizes Advanced Message Queuing Protocol (AMQP) for message handling [18]. A central exchange controls the messaging across the network. The client resides at the bottom of the diagram. A client message flows into the exchange, where the exchange will send the message to the "DLRLookup" and the "RoutePB" to determine where the message needs to go. Once the look-up and route query finish, the message moves back to the exchange, where the exchange will route the message to the consumer through the "DLRThrower" and the "deliverSMThrower."
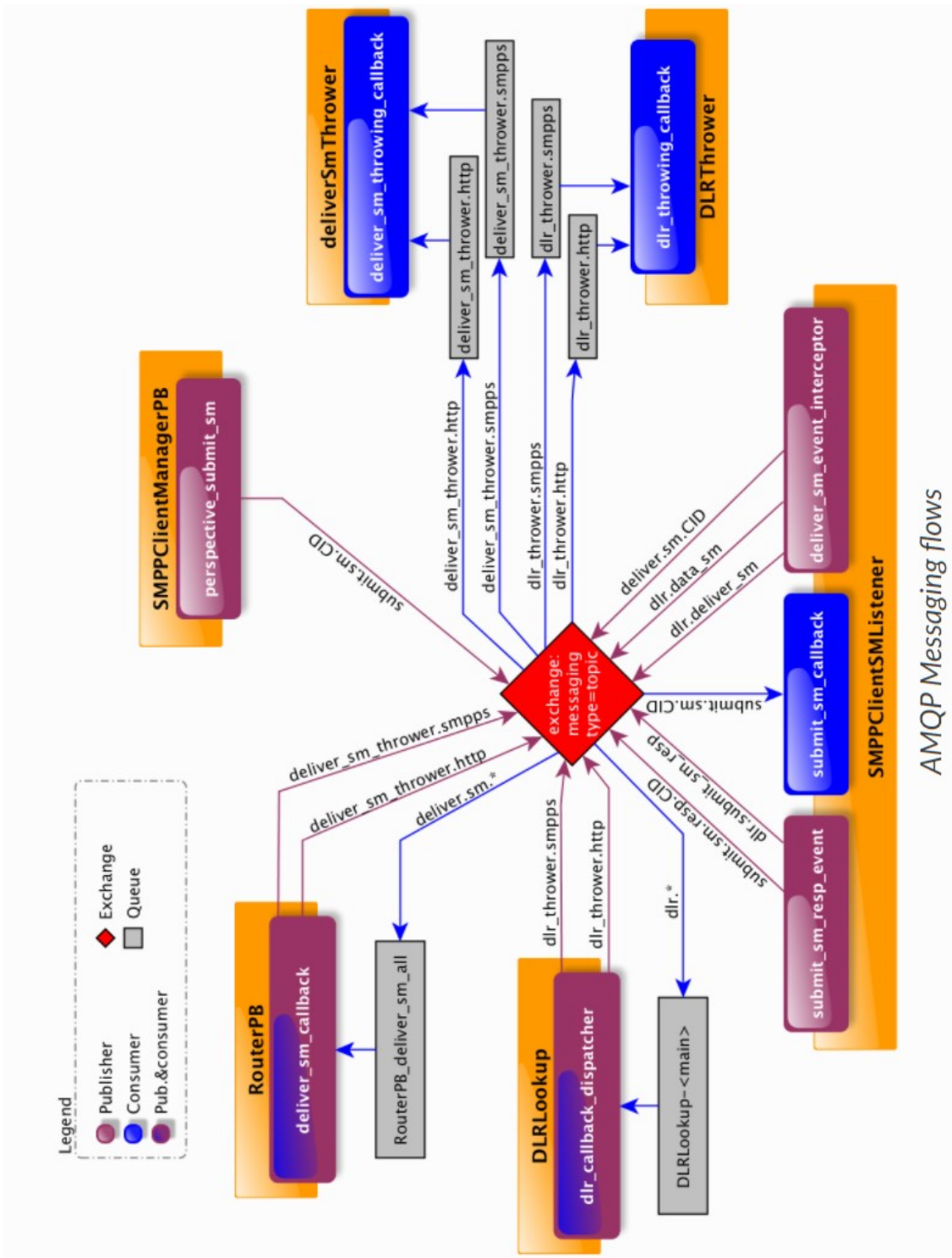
Figure 2.2. JasminSMS AMQP SMS Flow. Source: [18].

Twisted is an event-driven networking engine written in Python that supports the CPython 3.6+ and PyPy3 language sets [19]. Twisted has a variety of custom network applications, including echo servers, web servers, publish/subscribe, mail clients, and secure shell protocol (SSH) clients. The Twisted software also supports many standard network protocols, including simple mail transfer protocol (SMTP), post office protocol 3 (POP3), Internet Message Access Protocol (IMAP), SSH version 2 (SSHv2), and domain name service (DNS) [19].

2.3.2 Kannel SMS

Kannel is another open-source SMS gateway that uses wireless application protocol (WAP), which is a protocol that provides a stripped-down browser for use by the UE [20]. WAP wirelessly optimizes its markup, scripting language, and a transmission protocol [20]. The Kannel WAP gateway then translates the protocols into HTTP. WAP is a collection of various languages and tools, and infrastructure for implementing services for mobile phones [20]. Traditionally the services rolled into WAP had to operate via regular phone calls and text messages, but neither are as efficient or user friendly. WAP similarly provides these services to the world wide web (WWW). The Kannel WAP gateway acts as a translation tool between the internet and mobile device. Kannel uses wireless markup language (WML), a language specific to its software and similar to hypertext markup language (HTML); however it is more straightforward and defined with more structure [20].

Kannel is also an SMS gateway that serves GSM networks [20]. All mobile devices send and receive SMS messages, making Kannel an option to serve clients that use GSM and WAP-capable mobile devices. Another helpful feature is the push proxy gateway (PPG) which allows content servers to send data to mobile devices.

2.3.3 PlaySMS

Unlike JasminSMS and Kannel, PlaySMS is an open-source SMS management software and web interface for SMS gateways and bulk SMS services; PlaySMS is not an SMS gateway [21]. PlaySMS cannot be utilized independently and needs an SMS gateway to function correctly, and the PlaySMS website suggests using the Kannel SMS software as its gateway. First, the user must install PlaySMS and verify the software functions properly

before installing and configuring the Kannel SMS gateway [22]. PlaySMS offers many services through its graphic user interface (GUI), including user management, credits, features, routes, and gateways to send and receive SMS messages [21].

2.3.4 Kalkun

Like PlaySMS, Kalkun is a management service that relies on a separate open-source software-set to serve as the gateway, specifying the Gammu-SMSD as the gateway software Kalkun depends on [23]. Gammu-SMSD periodically scans a GSM modem (or UE) for received messages, stores messages, and sends queued messages in this storage [24]. Figure 2.3 provides a network flow for the Kalkun SMS software.
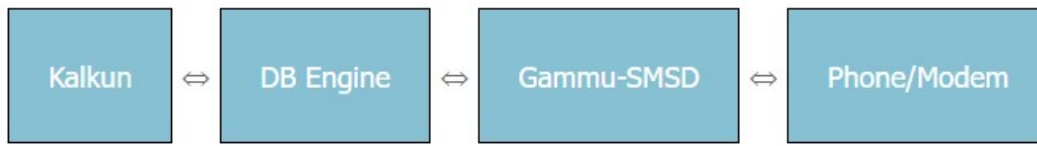

Figure 2.3. Simple Illustration of Kalkun Architecture. Source: [23].

Now that we have discussed OAI and open-source alternatives, we turn to our methodology and network description. Chapter III discusses the specific network configuration and settings required to connect the UE to the RAN, and EPC, the benefits of built-in software utilities, and the justification for SMS software selection.

CHAPTER 3:
Equipment and Network Setup

This chapter details the network configuration for our work, open stack network hardware and software selection rationale, various software utility tools, and software configuration. This chapter also outlines a detailed description of the steps to establish full wireless connectivity with a smartphone. Finally, this chapter discusses the selected open-source SMSC software, UE configuration, including APN settings, and customized subscriber identity module (SIM) cards for the research network.

3.1 Open Stack Network

As discussed in Chapter II, open stack networks permit leveraging affordable hardware and open-source software to build a cellular network typically only available through large telecommunication (telecom) providers. The customizability of open stack software makes it desirable for private network use, ranging from small personal networks to corporate enterprises.

3.1.1 Hardware Selection Rationale

As shown in Table 2.1, modestly priced hardware is all that is needed to build an open-source private cellular network. The two laptops used for the network are identical. The significant difference between the network in [11] and our current network is that we use two laptops, vice three, due to the transition to a fully wireless connection between the UE and the eNB. Each computer is an HP ProBook 640 G1 with Intel Core i7 processors and 16GB of random-access memory, and both are running the Ubuntu 18.04 operating system (OS).

The eNB needs a radio to provide connectivity, and the network utilizes the Universal Software Radio Peripheral (USRP) B200 device from Ettus Research. The SDR is configurable to transmit from 70MHz to 6GHz, allowing for 5G network compatibility in future iterations of the research network. The USRP utilizes USB3 connectivity for power and high-rate data transfer. This use of laptops and common connection protocols allow the mobile network to be powered through high-capacity batteries, creating a minimal overall size and weight and

providing potential for a backpack-sized network for use in the field. Appendix A provides complete technical specifications for the USRP B200.

3.1.2 Testbed Network Antenna Parameters

In conducting network testing, our research considered two different antennae options. The following sections outline the antenna parameters of each antenna used.

Ettus VERT900 Antenna

The first antenna utilized on the network was the VERT900 antenna from Ettus Research LLC [25]. The VERT900 is the default antenna for the Ettus B200 USRP. Table 3.1 provides the parameters.

Table 3.1. VERT900 Antenna Parameters. Source: [25].

Specification	Value
Model	WSS016
Antenna Profile	236.5 mm
Operating Frequencies	824-960 MHz
	1710 - 1990 MHz
Polarization	Omni-directional vertical
Radiation Type	Toroidal
Impedance	50 ohms
Gain	3 dBi
Diameter	2.53 mm +/- 0.10
Band Type	Quad-band cellular/PCS and ISM Bands

The VERT900 has a toroidal radiation shape similar to that of a doughnut. The form occurs because the antennae are omnidirectional on the vertical axis creating a null space at the top and bottom of the antenna. Figure 3.1 illustrates a toroidal radiation pattern similar to what the VERT900 antennae radiate.
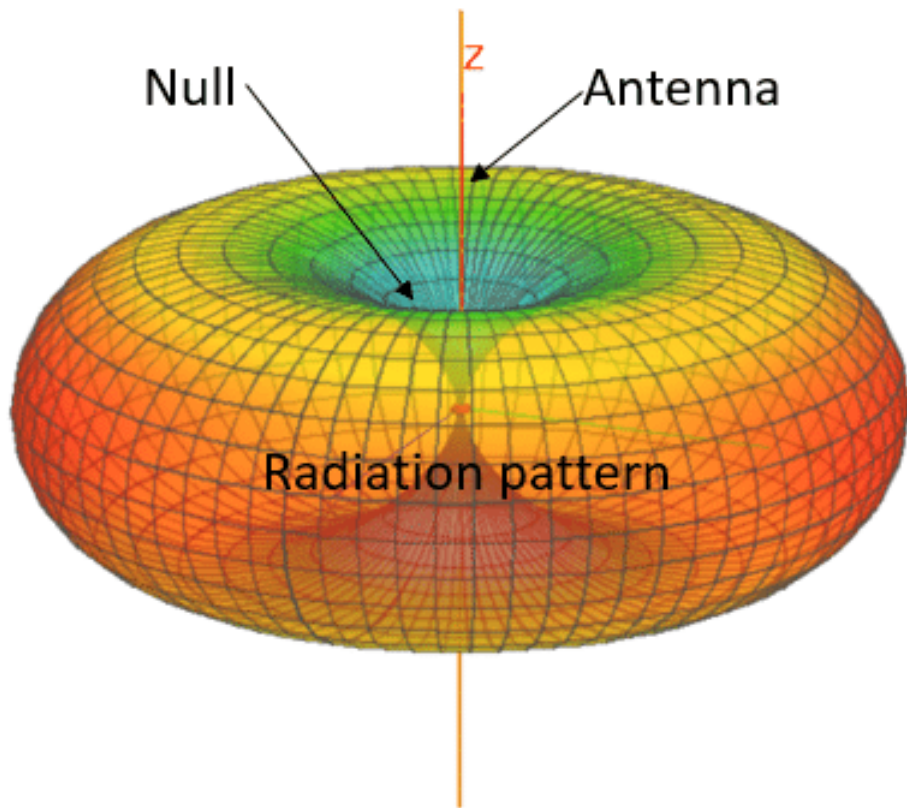
Figure 3.1. Example Toroidal Radiation Pattern. Source: [26].

L-com Roof Mount Antenna

We also tested a standard roof mount antenna from L-com [27]. These antennae have a 10-foot long, high-performance, low-loss 195 series cable, specifically for use in a vehicle. Our OAI network has the potential to be small enough for use in cars or tactical vehicles, making these roof mount antennas ideal for those scenarios. Table 3.2 provides parameters for the L-com antenna.

Table 3.2. L-com Roof Mount Antenna Parameters. Source: [27].

Specification	Value
Model	HG245803MGURB-NF
Antenna Profile	68.58 mm
Operating Frequencies	2.4 4.9-5.8 GHz
Polarization	Omni-directional
Gain	3 dBi
Diameter	25.4 mm
Band Type	IEEE 802.11 a/b/g/n/ac

During our tests, there was no measurable performance difference between each antenna regarding network speed, connection stability, or distance at which the connection held or dropped. We chose to use the L-com antenna based on preference.

3.1.3 Software Selection Rationale

The test network implemented the OAI open-source project instead of several other options considered for use, including FreedomFi, Open5GS, and SysLTE (now srsRAN). We selected OAI from among the available choices due to its compliance with 3GPP standards and robust set of features [11].

The EPC software developed by OSA implements system virtualization by using containers to host each network function; these containers act as stepping stones to transition from the 4G EPC to the 5G CN.

3.1.4   Software Utilities

This section discusses two software-based troubleshooting tools available within the OAI software build. The virtual oscilloscope (O-Scope) and the debugging T tracer utility are valuable tools for network operators' signal analysis. At the time of writing, we were unable to run the T tracer utility on our network build due to an unknown error within the software.

Virtual O-Scope

The virtual O-Scope provides a visual representation of the signal waveform for analysis in the time domain. The O-Scope utility built into the OAI software can monitor and display multiple signals in real-time. Specifically, the tool tracks the received signal in decibels (dB) across the time domain; the channel frequency response in dB across frequency channels; the Physical Uplink Shared Channel (PUSCH); log-likelihood ratio (LLR) magnitude in dB; the PUSCH In-phase and Quadrature (I/Q) of modulated frequency (MF) Output; the Physical Uplink Control Channel (PUCCH) Energy; and the PUCCH I/Q of the MF. The PUSCH carries the radio resource control (RRC) signaling messages, uplink control information (UCI), and the application data [28].

Figures 3.2 - 3.5 represent a sequence of screenshots taken as the Nokia 1A UE utilized the Google Chrome web browser to navigate to the NPS website. The screenshots aid in demonstrating the usefulness of the virtual O-Scope to troubleshoot by analyzing the signal health and strength across the network. Most noticeable is the PUCCH across the screenshots. The PUCCH channel carries information such as acknowledgments in response to the downlink transmission and quality control reports. Another prominent aspect of these figures is the differences in the PUSCH LLR, which constantly changes as data is sent between the network and UE. The screenshots cannot accurately depict the signal in real-time, where it is easy to see the signal move and change while the UE is in use. When the UE is idle, the signal movement is less noticeable.

Figure 3.2 represents a sample taken of the O-Scope as the Nokia 1A navigates to the NPS homepage, utilizing our testbed network.
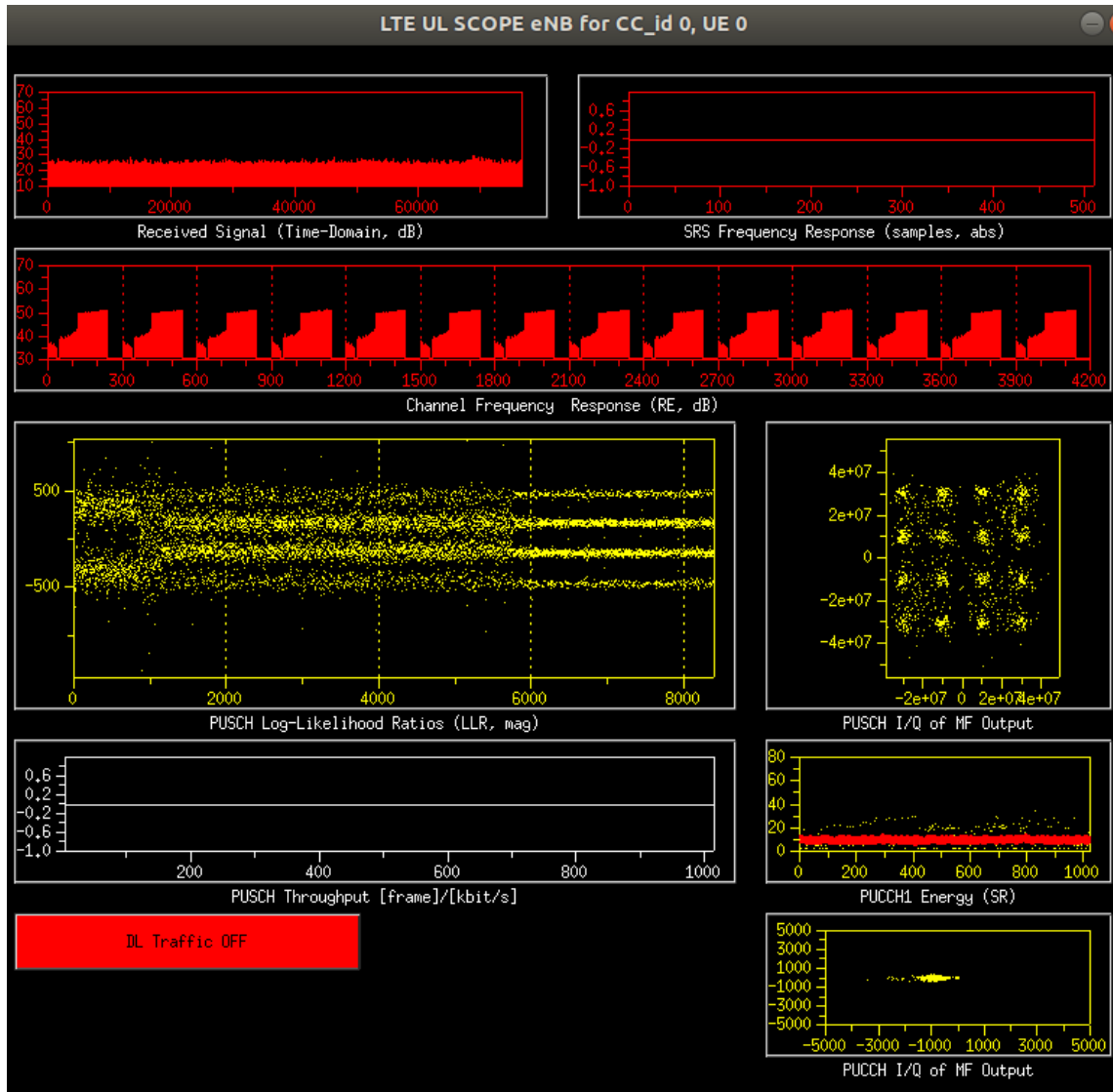
Figure 3.2. O-Scope Capture as Nokia 1A Navigated to NPS Homepage

A noticeable difference in Figure 3.3 from Figure 3.2 is the channel frequency response, which shows a spike off the left side of each channel; the cause did not require determination in this case but shows how the O-Scope could be useful for in-depth signal and channel analysis.
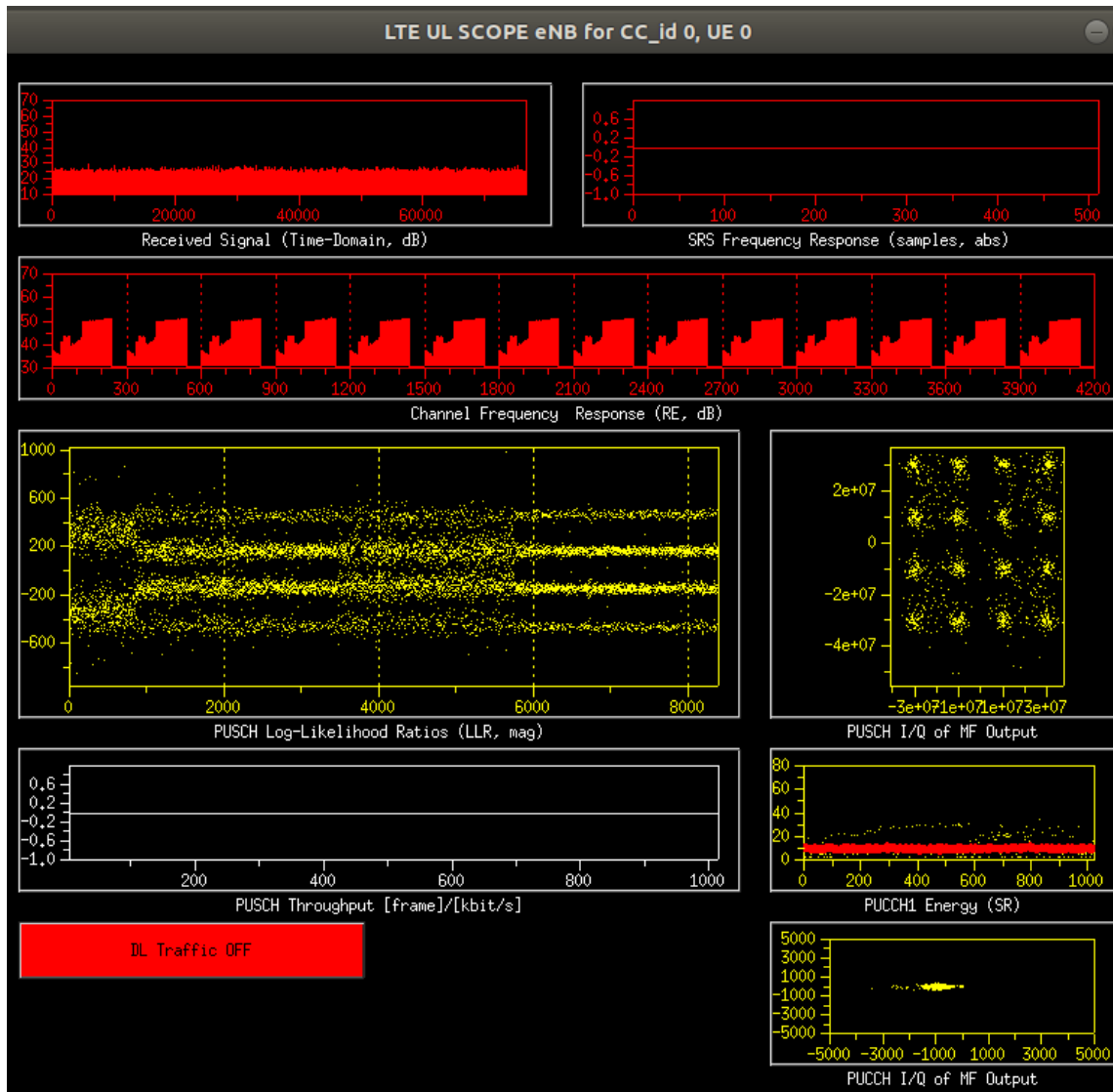
Figure 3.3. O-Scope Capture as NPS Homepage Continued to Load

Figure 3.4 aids in showing another change in the signal as the Nokia 1A phone is loading the NPS homepage. The PUSCH I/Q shows a more scattered signal pattern due to the changing amplitude of the signal across time as the signal traverses the network.
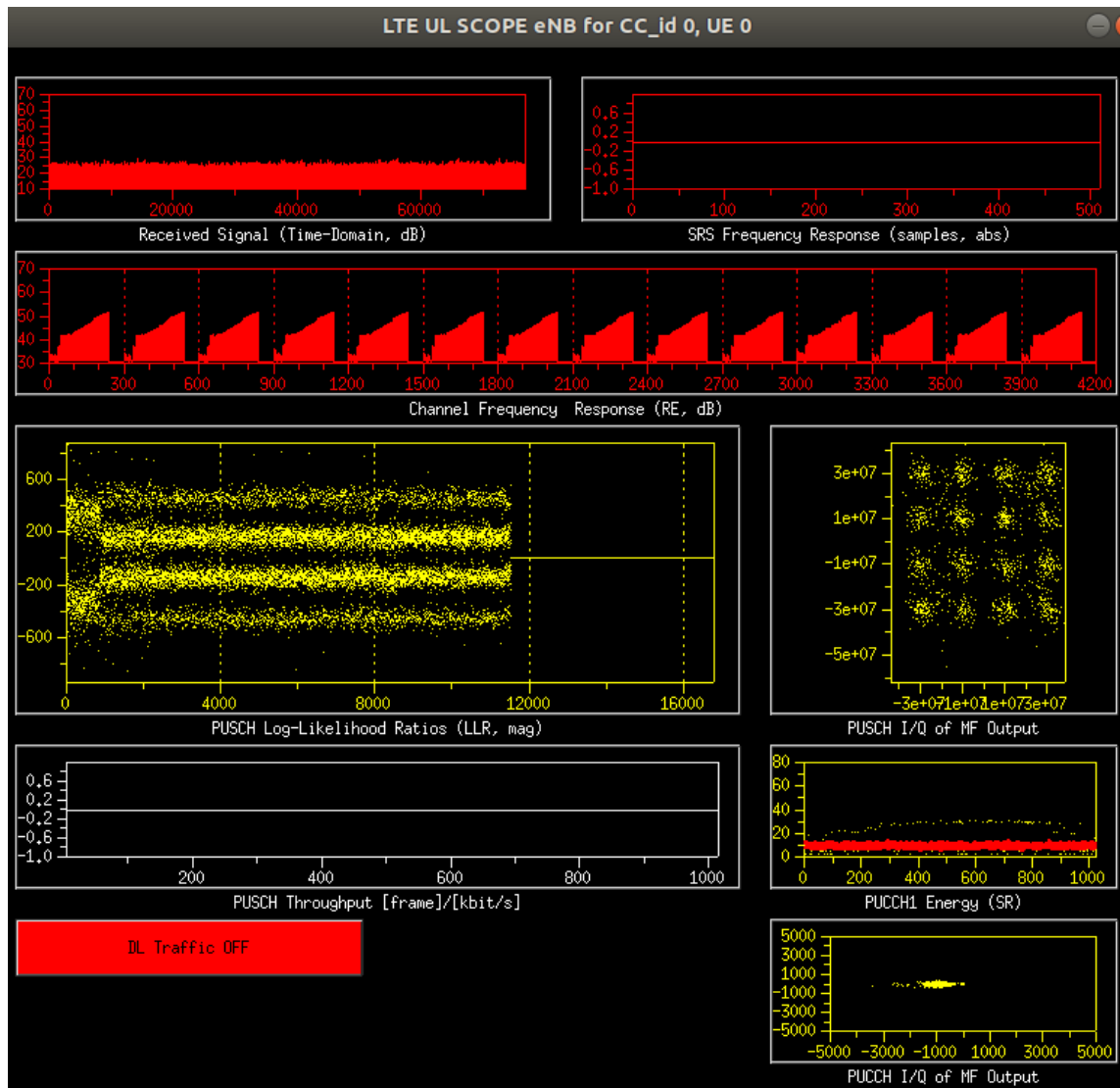
Figure 3.4. O-Scope Capture as NPS Homepage Finished Loading. Note the spike on the left edge of the channel is gone.

Once on the NPS webpage, we navigated to the "Students" link, and a noticeable change occurred on the PUCCH Energy between slots 100 and 300, as depicted in Figure 3.5. This is the visual representation of the PUCCH message being sent across the network and is typical of an in-use 4G connection. The change occurs because of the control information that is sent along with the signal increases the overall energy of the transmitted signal.
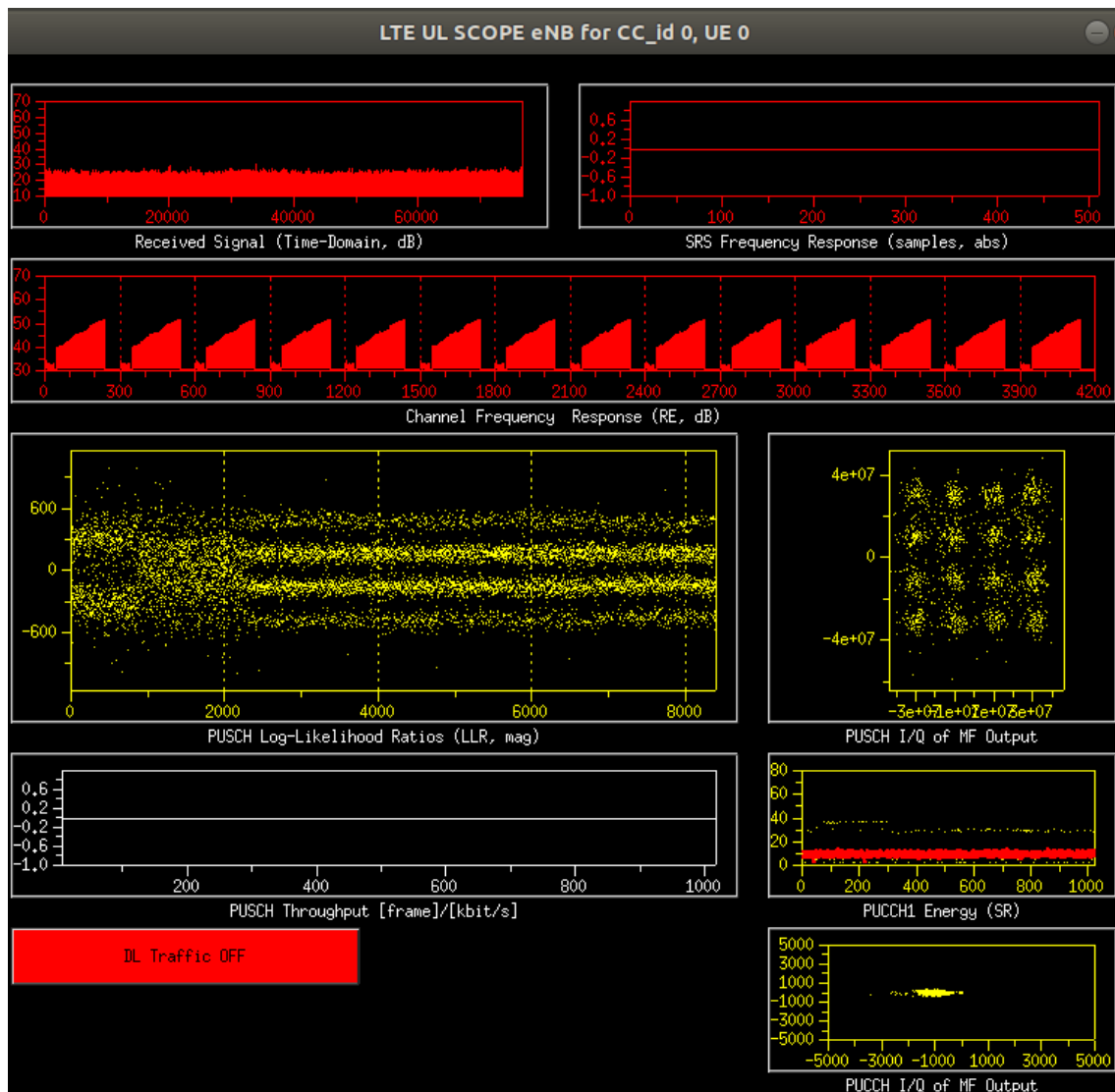
Figure 3.5. O-Scope Capture as Nokia 1A Navigated to "Students" Page. Note the increase in the PUCCH Energy.

T Tracer Utility

This tool provides a framework to monitor, debug, and analyze the softmodem on the network. The T tracer utility is comprised of two main parts; the first part is a real-time processor used to collect information and log separate events. The second part uses multiple programs that perform various functions, such as receiving and recording certain network events [29].

A few use cases would help to illustrate the functionality of the T tracer tool. First, "buf_test" tests the limit for a buffer overflow to occur. Next, testing data flow across the eNB can determine any latency issues within the network. Finally, the graphing function provides visual representations to analyze signal health over time.

Before executing the tracer, the operator must complete a few steps to prepare the utility. In a terminal window, change the directory to *"/common/utils/T/tracer."* Once in the folder, execute the *"make"* command to build and prepare the utility for execution. In the case that an error of *"/usr/bin/ld: cannot find -lxft"* is encountered after executing the *"make"* command, the operator should run the following: *"sudo apt-get install libxtf-dev"* [30].

The tracer utility executes from the eNB or the EPC; to run the tracer from EPC, assign the remote IP address in the CLI.

To execute the tracer from the eNB terminal, utilize the following command:

./enb -d ../T_messages.txt

To execute the tracer from the EPC terminal, utilize the following command, where the IP address is that of the eNB terminal:

./enb -d ../T_messages.txt -ip 192.168.13.1

Once called, the T tracer utility brings up an event selector menu from which the user can select desired events for analysis. The menu allows users to toggle between multiple UEs to specify which should be analyzed. The tracer utility GUI offers the following list of features to analyze the softmodem:

- The Time Signal Power provides a characterization of the signal.
- The PUSCH I/Q Modulation, much like the O-Scope, shows the signal amplitude modulation for the evaluated signal.
- The Channel Delay Spread measures the multipath richness of a communications channel. To calculate channel delay spread, take the difference between the time-of-arrival (TOA) of the earliest significant multipath component and the TOA of the last multipath components [25].
- The Selected UE Energy is the energy emitted by the UE across the network.
- The PUCCH Modulation shows the modulation of the control channel on the network.
- The Graphs for selected UE are displayed at the top of the GUI. The graphs include UE input signal, PUSCH I/Q, uplink estimated channel, PUCCH1 energy, PUCCH1 I/Q, Downlink mobile cellular system (MCS), Uplink MCS, Downlink physical layer (PHY), and Uplink PHY. These graphs provide practical visual interpretations of the signals and allow more in-depth analysis.
- The Traces provide network traces across the various layers: Physical, medium access control (MAC), radio link control (RLC), Packet Data Convergence Protocol (PDCP), RRC, and LOG x traces.

Our attempts to execute the T tracer debugging tool were unsuccessful. The GUI would load on the laptop; however, the tracer did not function, although we had a strong connection with the UE. We attempted to execute the tool from the eNB and the EPC utilizing the steps provided. We researched how to use the T tracer debugging tool; however, we found limited documentation on the OAI Wikipedia page. Our research also did not find any documented successful implementation.

3.1.5 Software Configuration

The OAI projects require an unusual method to configure and run their software [11]. The RAN Project repository resides on Github; the repository needs to be downloaded, and then the installation scripts must be executed within the repository to create the executable files. As outlined in [11], the CN project is similar, but instead, the scripts make containers for each component residing on the CN using Docker. Prior work on this project outlined the OAI software projects, the steps to implement the software, and the process for optimizing the laptops via low latency kernel configurations for both the RAN and CN. Appendix B contains our installation guide, adapted from [11].

3.2 Open Stack Network Configuration

This section discusses the revisions made to the pre-existing testbed network created from work done in [11].

3.2.1 Updated Physical Network Configuration

The main network components from [11] remain unchanged. Figure 3.6 shows the original network configuration before removing the simulated UE on the bottom left and the attenuators in the top center [11]. We then added the UE with a configured SIM card and antennae to the Ettus B200 SDR. Figure 3.7 shows the current network setup with our changes. The Ettus B200 SDR provides wireless connectivity to the Open Stack Network via the eNB. The eNB then connects to the EPC laptop through the switch, and the EPC connects to the internet via the campus wireless network. The EPC utilizes the campus 802.11 connection to permit mobile phones to access data services provided by the OAI stack.

Figure 3.6. Previous Wired 4G LTE Open Stack Network with Simulated UE and Attenuators. Source: [11]
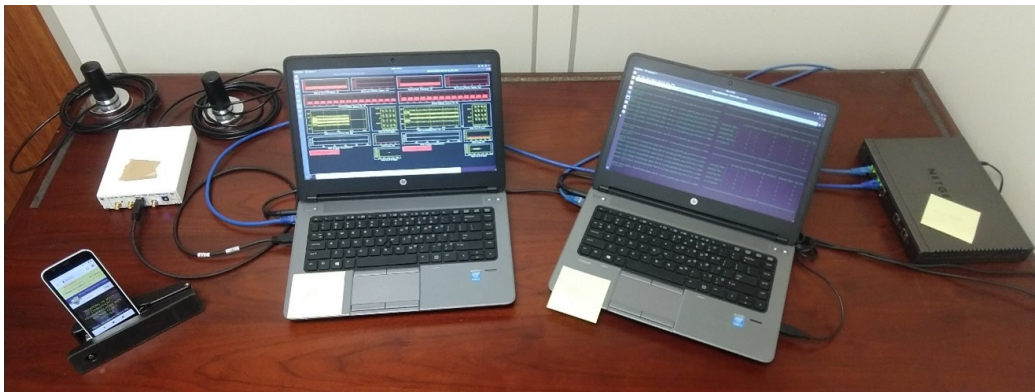
Figure 3.7. Our Current 4G LTE Open Stack Network with UE Smartphone and Antennae

3.2.2 Network Diagram and Software Commands

Lanoue described five different partial network set-ups to troubleshoot the open stack network [11]. The network's current state has moved beyond these partial network set-ups; however, these configurations are still helpful for troubleshooting issues as we could quickly reestablish any of the four configurations. We describe the five partial networks in the following list (adapted from [11]):

1. eNB and Soft UE over Ethernet. This operation mode ensures proper installation of the OAI RAN software by transmitting LTE packets over an Ethernet interface without RF devices. This configuration does not require an EPC.
2. eNB and Soft UE over RF. This operation mode tests the wireless interface between the eNB and UE without the EPC. To avoid the need for a Faraday cage, this set-up used SubMiniature version A (SMA) cables. The transmitter of one SDR connected to the receiver of the other SDR with 30 dB of in-line attenuation to prevent accidental damage to the radio interfaces.
3. eNB, EPC, and Soft UE over Ethernet. This operation mode tests the network interfaces between the eNB and EPC and checks that the soft UE and EPC have matching subscriber information. Communication gets passed via Ethernet.
4. eNB, EPC, and Soft UE with Wireless Link. This mode tests the network interfaces between all devices and includes the wireless link between the UE and eNB. This set-up tests the entire open stack network using the soft UE instead of a commercial UE.
5. eNB, EPC, and COTS UE. This mode tests the entire open stack network with a fully functional UE. A computer passes commands to the modem for UEs without displays and attaches the UE to the network.

The current state of the network used in our work most closely aligns with configuration 5 from the preceding list. We have a COTS UE wirelessly connected to the network with working displays.

3.3   SMS Integration into the OAI Open Stack

Successful integration of SMS software into the OAI network required research to determine specific changes and how to implement those changes within the software architecture.

Open5GS provides an overview of its network, identifying where a potential SMSC could be connected and implemented into its network [19]. Figure 3.8 displays the Open5GS network, and the upper left side of the image shows where a multimedia service center (MSC) integrates into the network. As shown, the MSC connects through an SGS interface to the MME. The interface would need to be assigned an IP address and a port number unique to each network.
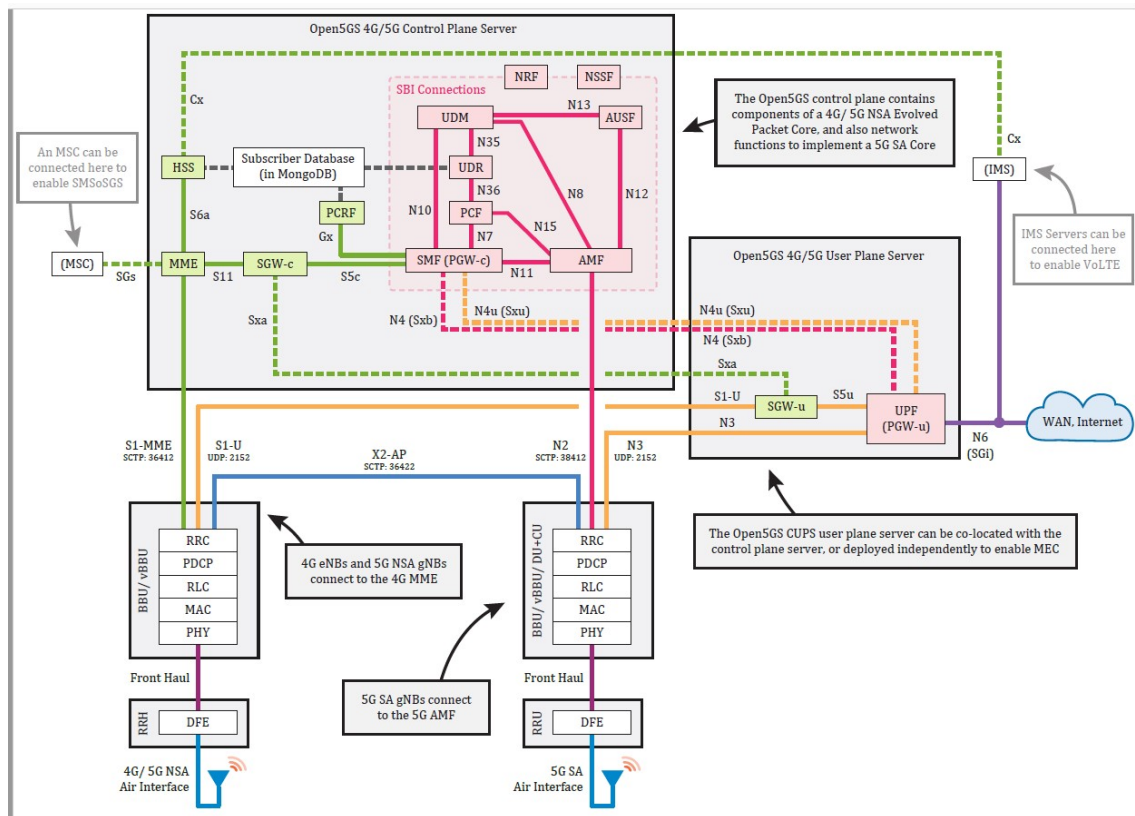
Figure 3.8. Open5GS Network Architecture Depicting MMS Integration. Source: [5].

3.3.1   SMS Software Selection Rationale

We chose to integrate the open-source JasminSMS software into the OAI network. We selected JasminSMS because the enterprise-level features support future scalability, and

the implementation does not require additional software. The JasminSMS software gives network administrators two options for transmitting and receiving text messages. The first is via the HTTP protocol, which utilizes a web server not locally managed on the network. The second option is via the SMPP protocol, which operates locally on the network, and SMPP was the implementation attempted in this thesis.

Our efforts focused on implementing the SMPP server API vice the RESTful or HTTP APIs. The benefit of this option is that all messages are stored on an internal network server and text messages can be sent and received through HTTP. The SMPP server has various elements, each listed in Table 3.3 with default values and a description [18].

Table 3.3. Default JasminSMS SMPP Settings. Source: [18].

Element	Default Setting	Description
id	smpps_01	The SMPP server id, used to identify the instance in case multiple servers per Jasmin process are used
bind	0.0.0.0	The SMPP Server API listener will only bind to the specified address, given 0.0.0.0 the listener will bind on all interfaces
port	2775	the binding TCP port
sessionInitTimerSecs	30	Protocol tuning parameter: timeout for a bind request
enquireLinkTimerSecs	30	Protocol tuning parameter: timeout for an enquire_link request
inactivityTimerSecs	300	Protocol tuning parameter: inactivity timeout
responseTimerSecs	60	Protocol tuning parameter: global request timeout
pduReadTimerSecs	30	Protocol tuning parameter: binary pdu ready timeout
log_*		Python logging module configuration

3.3.2 JasminSMS SMPP Server Implementation

This section outlines the process and results of implementing the software on the OAI stack network. A workaround was required to successfully install the SMS server due to system requirements.

3.3.3 JasminSMS Installation and Set-up

The JasminSMS open-source software requires Ubuntu 20.04 (or newer). Our research network EPC operates on Ubuntu 18.04 for configuration stability and could not support the latest version of JasminSMS. The mismatch created some hurdles.

The first attempt to upgrade the EPC laptop to Ubuntu 20.04 failed. We attempted to follow the installation steps provided in Appendix B. However, during installation, we could not get past step three of B.5, which begins install of images for the network components begin to install. The command to download the docker builds expressly points to an Ubuntu 18.04 docker file. Our research did not find a version available for download on Ubuntu 20.04. The HSS is the first component to be built, and the components must be installed in order, meaning we could not get past this step in the process.

Unable to move forward with a newer OS, we sought a new approach. We created a virtual machine (VM) with JasminSMS installed to alleviate the need for the EPC upgrade. Once the VM was installed, we began to configure the JasminSMS software.

3.3.4 JasminSMS Configuration

Once the JasminSMS software was installed, configured, and running, the next step was to add users, groups, filters, and routes. The Jasmin documentation is not ordered according to installation precedence. After a few attempts, it became apparent that we needed to create our "group" before the "user." The following sequence of commands show the steps to successfully add a group, user, routes, and SMPP server.

The following commands execute within the Jasmin CLI (jcli) [18]. User input is in "blue."

To add a group, use the following sequence of commands:
jcli : group -a
Adding a new Group: (ok: save, ko: exit)
> gid npsnet
> ok
Successfully added Group [npsnet]

To enable the group, utilize the following command:

jcli : group -e npsnet

To add a user, utilize the following command sequence:

jcli : user -a

Adding a new User: (ok: save, ko: exit)

> username nokia1

> password nokia1

> gid npsnet

> uid 5307

> ok

Successfully added User [8088675307] to Group [npsnet]

To enable the user, utilize the following command:

jcli : user -e 5307

Successfully enabled User id:5307

The following commands will update user information for messaging parameters and SMPP user access:

jcli : user -u 5307

Updating User id [5307]: (ok: save, ko: exit)

> mt_messaging_cred valuefilter sr_addr ĴASMIN$

> mt_messaging_cred quota balance 44.2

> mt_messaging_cred quota sms_count none

> mt_messaging_cred quota smpps_throughput 2

> smpps_cred authorization bind yes

> smpps_cred quota max_bindings 2

> ok

Successfully updated User [5307]

The following commands will create a filter within the JasminSMS messaging architecture:

jcli : filter -a

Adding a new Filter: (ok: save, ko: exit)

> type TransparentFilter

> fid TF

> ok

Successfully added Filter [TransparentFilter] with fid:TF

The following command sequence will add an SMPP server to JasminSMS:

jcli : smppccm -a

Adding a new connector: (ok: save, ko: exit)

> cid npsnet

> bind transmitter

> ok

Add routes to the JasminSMS server with the following command sequence:

jcli : morouter -a

Adding a new MO Route: (ok: save, ko: exit)

> type StaticMORoute

<class 'jasmin.routing.Routes.StaticMORoute'> arguments: filters, connector

> order 15

> filters TF

> connector smpps(nokia2)

> ok

Successfully added MORoute [StaticMORoute] with order:15

The JasminSMS software will not automatically save the configuration and requires the following command to ensure the configuration remains intact after reboot:

jcli : persist

The final step was to establish an interface to the OAI network stack. However, our efforts fell short because of time and software constraints. Configuring the JasminSMS server was straightforward and was done quickly. The complications arose while attempting to interconnect the JasminSMS server into the stack. We attempted several configurations to establish an interface, but none were successful. While working on connecting the server through the VM, the certificates used by OAI to authenticate the network access to its backhaul on the OAI network expired. Re-installation of the certificates was successful; however, the connection between the MME and the HSS never fully restored for a reason we could not identifiy within the time constraints for this thesis. This connection complication prevented research from fully implementing SMS functionality.

3.4 Testbed UE Configuration

Multiple aspects of connectivity regarding the UE and our network bear discussion, including custom configuration of SIM cards and configuring APN settings on the UE handset itself.

3.4.1 SIM Card Configuration

Specific parameters were required to configure the SIM cards used on the network. Research led to the software and hardware configurations described in the following sections.

SIM Cards

OpenCells-SIM cards are 4G/LTE compatible and are re-programmable; however, version three, which is what we used, is not compatible with 5G NR technology. This incompatibility led us to research other SIM cards compatible with NR technology. OSA recommends the sysmoISIM-SJA2 with its network. Because our desired end-state is a fully operational 5G NR mobile ad hoc network, migration to this SIM card was necessary. We purchased new re-programmable SIM cards from Systems for Mobile Communications (SYSMOCOM). A dedicated and proficient ability to program and reprogram SIM cards is a requirement for network customization to support the changing requirements and dynamic nature of military operations; two theses have now proven that SIM programming is a challenging art [11].

SIM Card Programming Software

Open-source SIM card programming software is available and the two programs utilized to read and program the SIM cards for the network were pySIM and OYSIMWrite. pySIM is a small command-line utility program written in python [31]. OYSIMWrite is software that utilizes a simple GUI to allow faster and more accessible data manipulation [32]. Instead of reading and writing the SIM cards through the CLI, we used the GUI to program one SIM card and then created a template to program the remaining SIM cards. The test network can support up to 200 international mobile subscriber identifier (IMSI) numbers; to program these through the pySIM CLI, however, would take a significant amount of time compared to using the OYSIMWrite GUI, depicted in Figure 3.9.
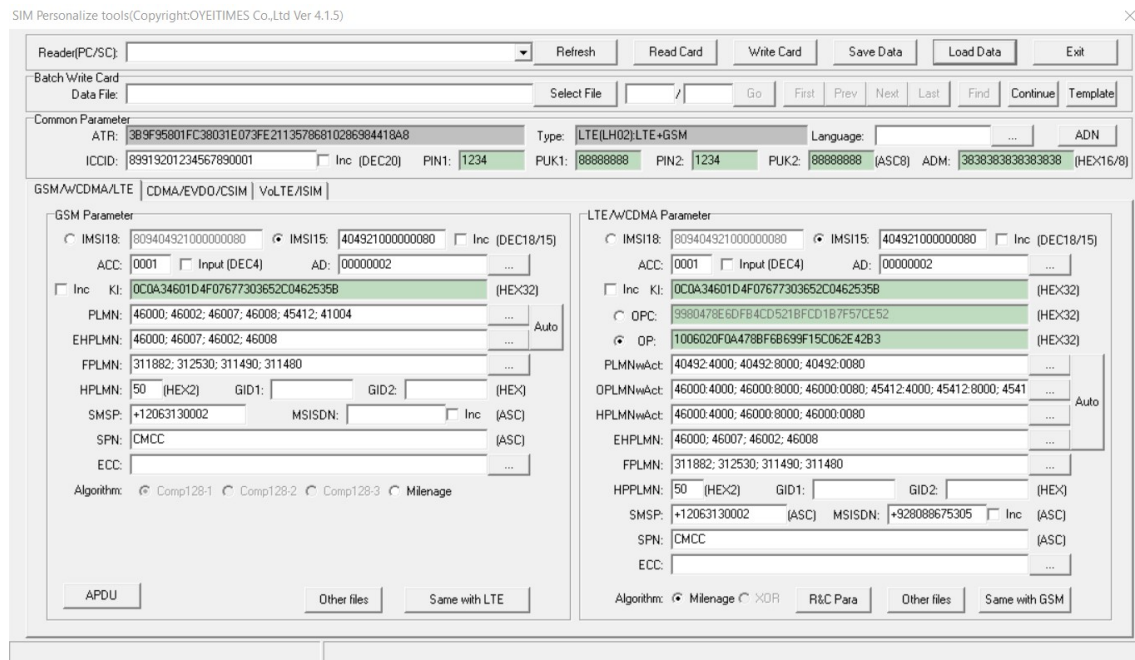
Figure 3.9. OYSIMWrite SIM Card User Interface. Source: [32].
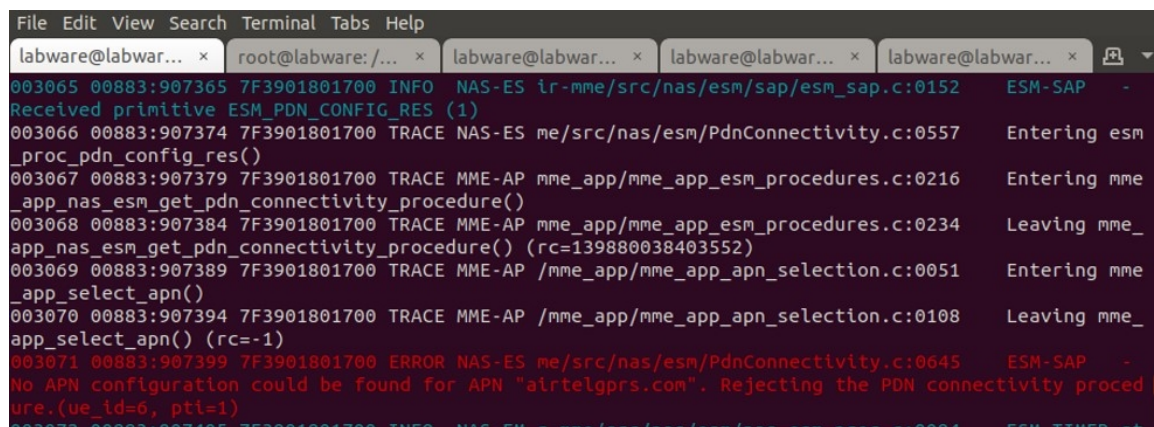
SIM Card Hardware

Card readers are readily available for reading and programming SIM cards. The card reader utilized in our research was from Advanced Card Systems Ltd., Model ACR39U. This model

is compatible with various smart card technologies and supports personal computer/smart card (PC/SC) and chipcard terminal API (CT-API) (through a wrapper on top of PC/SC). This feature allows application programming and enables customization of SIM cards [33].

3.4.2 Mobile Devices Used on Network

In selecting mobile devices to connect to the network, we tested a variety of makes and models, outlined in further detail in Chapter IV. However, once we successfully wrote the custom parameters onto the SIM card, we placed two of the programmed SIM cards into two Nokia 1A smartphones. In our research, the mobile devices were viewed attempting to connect to the network but did not achieve a connected state. After completing an analysis of logs on the EPC, we identified an error regarding a misconfigured APN preventing the UE from successfully connecting and maintaining a connection to the network. Figure 3.10 shows the error in the terminal window. Further research discovered that APN settings were configured on the MME and needed updating through the process outlined in the following sections. Once configured, the two UEs could access data services by connecting to the eNB, which routed the UEs to the internet through the gateway components on the EPC laptop.

Figure 3.10. Screenshot of Misconfigured APN Error Received on Our Network. Note the Lines in Red Text.

3.4.3 APN Settings

A critical factor that allowed COTS UE devices to connect wirelessly to the network was a proper configuration of device APN settings. We outline specific details regarding the process in the following sections.

APN Purpose

According to TS 23.003, an APN is a reference to a General Packet Radio Service (GPRS) Gateway Support Node (GGSN). For an APN to support inter-Public Land Mobile Network (PLMN) roaming, the internal GPRS DNS functionality translates the APN into the IP address of the GGSN, which means that the APN is the gateway that connects cellular networks to the internet. The two primary functions of an APN are to ensure privacy and security in the internet connection and provide a means of connectivity to the internet. Each provider uses its own gateway, with specific settings that need to be correctly implemented for the end-user to access the providers' services [34]. APN configuration is transparent to mobile users through large telecom providers, such as T-Mobile or Verizon, and typically does not need user configuration.

APN Structure

According to [34], the APN has two sections; the first is the APN Network Identifier, which defines the connection between the GGSN/Packet Data Network Gateway (PGW) and a specific external network. The APN Network Identifier is optionally requested by the Mobile Subscriber (MS), if desired. The second section is the APN Operator Identifier; it determines the location of the GGSN/PGW on a specific PLMN GPRS/evolved packet system (EPS) backbone; this piece is optional [34]. APN encoding must follow RFC2181, RFC1035, and RFC1123, which define name syntax. The following items, adapted from [34], are the guidelines that the APN structure must adhere to:

- The APN shall consist of one or more labels
- Each label is coded as a one octet length field followed by that number of octets coded as 8-bit ASCII characters
- All labels shall consist of only the alphabetic characters (A-Z and a-z), digits (0-9), and the hyphen (-)
- Each label shall begin and end with either an alphabetic character or a digit

- The labels are not case sensitive
- The labels cannot be terminated by a length byte of zero [34]

For ease of presentation and readability, the APN is a string in which dots separate each label (e.g., "Label1.Label2.Label3"). Table 3.4 below outlines the standardized structure for the APN utilized for our network, formatted per TS 23.003 [34].

Table 3.4. APN Network Specific Addresses

APN	Server IP	Purpose
apn1.carrier.com	192.168.17.2	4G/LTE networks
NPS4G.apn.epc.mnc092.mcc404.3gppnetwork.org	192.168.17.2	GSM Networks

Other Pertinent Settings

Although the primary function of the APN is to provide internet connectivity, several other settings offer the end-user access to additional service options from a cellular provider, such as a proxy server. Table 3.5 outlines these settings and their purpose.

Table 3.5. Other Pertinent APN Settings

Setting	Parameter
APN	Server IP Address
Name	Used to name APN (no specified format required)
MCC	Identifies the country in which the network resides
MNC	Identifies network the within country
MMSC	IP address or URL for carrier multimedia server
MMS proxy	The IP address for proxy, if applicable
MMS port	Port that the multimedia messaging service (MMS) utilizes for service

Network APN Settings

Not every APN setting is needed to connect the mobile device to the test network. However, to connect to our network, we needed to add an APN to the individual SIM card through settings on the mobile device. The following selections enable a user to add an APN to the Nokia 1A smartphone running Android version 10:

1. "Settings"
2. "Mobile network"
3. Expand the "Advanced" option
4. "Access Point Names"
5. Select three dots menu icon
6. "New APN"

Once on the screen for adding the new APN, the specific settings that need to be added or changed are "Name," "APN," "Server (IP address)," "MCC," "MNC," "APN Type," "APN protocol," "APN roaming protocol," and the "Bearer" fields. The annotated fields are unique

to the private network. Once filled out, the user must save the APN to ensure connectivity to the data services by the network. Table 3.6 provides the specific settings used for our test network.

Table 3.6. Minimum APN Settings to Enable Connectivity

Number	Setting Name	Setting Details
1	Name	MYAPN
2	APN	apn1.carrier.com
3	Server	192.168.17.2
4	MCC	404
5	MNC	92
6	APN type	default,supl,mms
7	APN protocol	IPV4/IPV6
7	APN roaming protocol	IPV4/IPV6
8	Bearer	LTE

The settings in Table 3.6 can be further explained as follows:

1. Name: The setting is arbitrary and named as the network operator desires.
2. APN: given by the OAI software settings.
3. Server: the setting is the Cassandra server IP address that the MME utilizes to communicate between the HSS and MME.
4. Mobile Country Code (MCC): the setting is customizable; we recommend using an MCC outside of the network operating region for deconfliction purposes; for example, our network utilized 404, which is an Indian country code; for a complete list of mobile network operator (MNO) names, see Appendix C.
5. Mobile Network Code (MNC): the setting is also customizable and should be an MNC within the MCC operators' range, which also ensures deconfliction.
6. APN type: the field dictates the capabilities of the APN. In our research network,

we set APN type to "default,supl,mms." Default is for general internet data. Supl stands for Secure User Plane Location, which allows the phone to determine its geographic location from the carrier. The MMS type is for Multimedia Messaging and will need additional fields configured for use (MMSC and, in some cases, MMS proxy/MMS port) [35].

7. APN (roaming) protocol: these settings identify whether to use IPv4 or IPv6 for the APN internet connection and the roaming connection. Our network settings allow for either protocol for greater flexibility.

8. Bearer: the setting provides the type of network used. The suggested setting is LTE for the network, but other options include GSM and NR, depending on the capability of the network.

This chapter described the configuration of the testbed network, selected SMS, the UE, SIM cards, and APNs. Chapter IV provides detailed results from experimentation and testing of the implemented OAI architecture on the research network created for this thesis.

CHAPTER 4:
Results

This chapter details the results of our research and experimentation with the OAI stack to determine the feasibility of using our network for military applications. Part of our work sought to discover what UE devices could connect to the testbed network; guided by a list of incompatible phones from [36], we evaluated the compatibility of various other devices. Other experiments and tests included network speed tests on UE devices, the RAN, the EPC, link budget analysis, signal strength, and data throughput. These results informed our analysis of network suitability for military applications and will inform future research into the use of open-source 5G technology.

4.1   Devices that Could not Connect to Network

We thought it was critical to begin with this topic because having a variety of devices to use on the network would provide a greater diversity in capabilities and allow us to choose the UE best suited to our research needs. Additionally, the ability to connect, on demand, a diverse range of devices in terms of manufacturer and operating systems would provide a powerful military use case for open-stack 5G technology.

To determine compatibility, we attempted to connect various mobile devices to our testbed network once we established wireless connectivity, as described in Chapter III. OAI provides a list of models that are not compatible with their software, and we tested additional models not evaluated by OAI. Table 4.1 represents models we tested that failed to connect to our research network, while Table 4.2 provides OAI's list for comparison [36].

Table 4.1. UEs that Did Not Connect to Our Testbed Network

Make/Model	Reason (if known)	Version
OnePlus 6	Unable to add/remove APNs	Oxygen 11.1.2.2
Apple iPhone 11	APN options Not Available	Apple iOS 13.3.1
Samsung Galaxy A5	"SIM Not Provisioned" Message	Android 6
Google Nexus 5	Unknown Reason	Android 6

For all of the devices we attempted to connect to our testbed, we followed the same SIM and APN procedures as outlined in Chapter III. Based on the reasons provided in Table 4.1, we can infer that the incompatibility is partly due to the model-specific restrictions of each device. For example, the iPhone 11 did not provide any available options for modifying the APN settings. A potential workaround is "rooting" the UEs to permit control of the settings that require alteration.

The other issue likely stems from the OAI software. The OAI list in Table 4.2 is not exhaustive and only contains models that the contributors have tested. The software may not be sufficiently developed to connect every UE.

Table 4.2. Devices Listed as Incompatible by OAI. Source: [36].

Make	Model	Version
Motorola	Moto G	Android 4.4.4
Samsung	GS5	Android 5.0.1
Samsung	GS6	Android 5.0.1
Sony	Xperia Z2 Tablet	Android 4.4.4
Huawei	e392	Unknown

Table 4.3 represents the UEs that could not obtain data services, despite being connected to our testbed. In all, we identified six additional devices that did not appear to be supported by the OAI stack.

Table 4.3. UEs Able to Connect to Network; No Data Services Available

Make/Model	Reason (if known)	Version
Google Pixel 4a	Domain Name Resolution Error	Android 10
Huawei P8Lite	Unknown	Android 5.0.1

Our research also discovered an issue specific to our Google Pixel 4a device regarding the DNS resolution of a website Uniform Resource Locator (URL) to an IP address. Troubleshooting indicated, however, that the UE could navigate to a website if the IP address was typed into the web browser. For example, entering: "https://52.42.202.22" into the browser enabled the device to access the NPS website.

Because our testbed network resides on the internal NPS campus network, the original build was created with an internal primary DNS server. The internal IP address prevented successful DNS resolution. Through troubleshooting, we discovered that the DNS settings need to be corrected during the initial network build, as attempts to alter the code created instability with the network.

4.2   Testbed Network Speed Tests

Answering our research questions regarding network reliability required us to define the capabilities and limitations of our testbed. We wanted to determine the cost, or (network) speed loss, as the signal transited our network. We expected that as we moved the measurement location further away from the backhaul connection, the speed of our network would drop.

The experiment we used to test this hypothesis was simple: connect to the backhaul and test each component including the RAN, the EPC, and finally, the UE. The testbed network

connects to the NPS 802.11 network. Our testing utilized the free network speed test tool provided by Measurement Lab [10]. We chose to use [10] because the site is readily accessible. When we searched "test my internet speed" via Google, the search engine returned an embedded version of the Measurement Lab speed test application. The application sends packets to a test server and then measures the download speed, upload speed, packet latency, and packet retransmission rate.

4.2.1 RAN Network Speed Test

The primary purpose of conducting speed tests directly from the RAN laptop is to determine impacts on speed as traffic traverses network components, not including the UE. The RAN connects to the EPC through the switch, and the network has an established IP route created for the network, which provides the RAN laptop internet access via the EPC. The results in Figure 4.1 represent the speed across the network from the RAN.
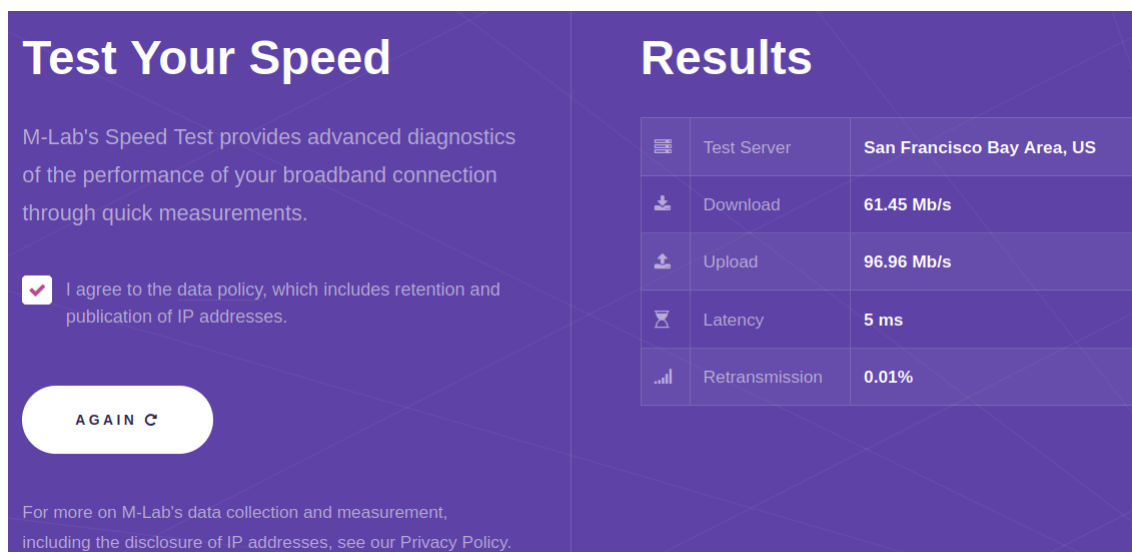
Figure 4.1. Testbed RAN Speed Test Results. Source: [10]

4.2.2 EPC Network Speed Test

We also conducted a speed test via the EPC to determine if there would be a difference in speed between the RAN and EPC. The EPC laptop is connected to the NPS 802.11 network and utilizes it as the backhaul connection. Figure 4.2 shows the results of the speed test across the EPC.
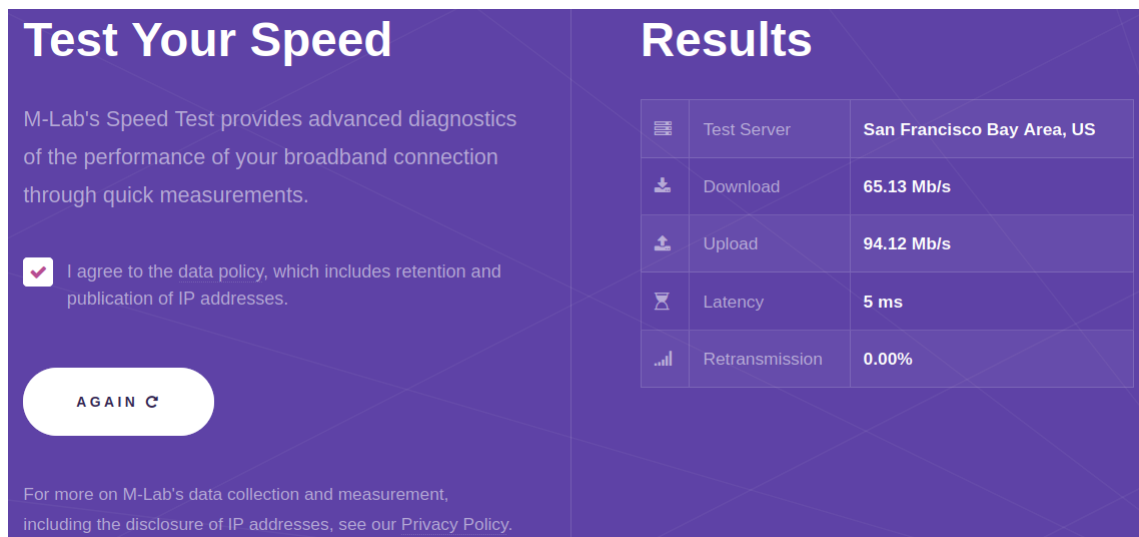
Figure 4.2. Testbed EPC Speed Test Results. Source: [10].

4.2.3 EPC and RAN Network Speed Test Results

When comparing the internet speed tests, the results are similar between the EPC and RAN. Each test used the same test server. The EPC has a slightly faster download speed, 65.13 Mbps, compared to the download speed for the RAN at 61.45 Mbps. This slight difference could result from the traffic crossing all the components of the EPC before reaching the RAN itself. The results were more similar when comparing upload speed with the RAN at 96.96 Mbps and the EPC at 94.12 Mbps. Each component had 5 ms of latency across the connection. The latency reading identifies lag in the network path, and the result is negligible. The last category on the speed test is retransmission, which measures how many packets out of the total sent need retransmitted due to packet loss. The EPC had a retransmission percentage of zero, and the RAN retransmission was 0.01 percent of its total

packets. Putting this in perspective, the rate of loss is the equivalent of losing one packet in every 10 000 sent across a network, which is indicative of a reliable network.

The next section explains our UE test, how it supports our research question, the results, and our analysis of those results.

4.2.4 Testbed UE Speed Tests

Next, we tested our UE to assemble a complete picture of our network. We conducted our tests in two scenarios with the Nokia 1A running Android 10. The first scenario tested the device speed while connected to our testbed network, and the second tested the device while connected to the NPS 802.11 network. To provide a comparison, other UEs that have data connections to commercial networks were tested on their data network and then again on the NPS 802.11 network. The purpose of testing the speeds on the 802.11 network is to determine differences between the commercial data network speeds and an alternate backhaul option. Although Wi-Fi is not a likely option for backhaul in remote or forward operations, it provides a good baseline for evaluating slowdowns due to the testbed network. Table 4.4 gives the results of the 4G data network speed tests, while Table 4.5 provides the results from the NPS 802.11 network.

Table 4.4. 4G Data Network Services Speed Comparison Results

UE/Network	Test Server	Download	Upload	Latency	Retransmission
Nokia 1A / Testbed	SF, Bay Area	12.74Mbps	6.17Mbps	20ms	0.80%
Moto X4 / Google Fi	SF, Bay Area	29.84Mbps	6.57Mbps	33ms	0.01%
Microsoft Surface Duo / Verizon	SF, Bay Area	7.60Mbps	6.71Mbps	24ms	0.08%
iPhone 11 Pro / AT&T	SF, Bay Area	7.23Mbps	8.12Mbps	10ms	0.00%

The devices in Table 4.4 utilized different data networks, but each had a 4G/LTE connection. We ran speed tests on the fourth floor of our building in an office environment. Table 4.4 compares data rates between all networks to which the UEs were connected. The most noticeable difference between devices was the download speed; the Google Fi download rate was 17.10 Mbps faster than the test network. However, our testbed download speed was almost twice as fast as Verizon and AT&T. A reasonable assumption for the disparity could be that distance from the servicing tower and network saturation with the major telecoms reduce throughput. Also, our testbed is physically closer to its backhaul (the NPS 802.11 network). Google Fi is a mobile virtual network operator (MVNO) that uses major network providers such as T-Mobile to provide data services to its users. Carrier aggregation combines two or more LTE carriers into a single carrier signal; this aggregation of services could be a reason for the significant disparity between the Moto X4 and the other three UEs.

Table 4.5. NPS 802.11 Speed Comparison Results

Device	Test Server	Download	Upload	Latency	Retransmission
Nokia 1A	SF, Bay Area	38.76Mbps	21.81Mbps	5ms	0.85%
Moto X4	SF, Bay Area	45.51Mbps	37.40Mbps	5ms	0.00%
Microsoft Surface Duo	SF, Bay Area	71.30Mbps	70.09Mbps	5ms	0.02%
iPhone 11 Pro	SF, Bay Area	17.41Mbps	30.91Mbps	5ms	1.98%

For the Nokia 1A in Table 4.5, the download speed is 38.76 Mbps, and the upload speed is 21.81 Mbps. This compares to a download speed in Table 4.4 of 12.74 Mbps and upload speed of 6.17 Mbps. The wireless network on campus was approximately 26 Mbps faster on download and 15 Mbps faster on the upload than our testbed. This is likely due to NPS utilizing commercial grade wireless access points vs. our low-cost network equipment.

When further analyzing the results in Table 4.5, we notice that the Microsoft Surface Duo had the highest download and upload speeds. We could not confidently discern why the rates were so much faster than the other devices we tested. Likely causes include that the

Microsoft Surface Duo is equipped with the Qualcomm SM8150 Snapdragon 855 chipset and the Octa-core CPU [37]. This chipset is powerful and is required because the Microsoft Surface Duo is intended to function as a mobile phone/tablet hybrid to provide the user with more capability.

UE Retransmission

Another result to note is the retransmission rate for the Nokia 1A on the testbed network compared to the other service providers. As highlighted in Table 4.4, the retransmission rate for our testbed is 0.80 percent compared to 0.01 percent on Google Fi, 0.08 percent on Verizon, and 0.00 percent on the AT&T network. The retransmission rate is an indicator of overall network reliability. Although the retransmission rates seem low, the testbed rate is an order-of-magnitude higher than the closest commercial network. This could be a result of the technology on our UE, as the antennae were low-cost and different on the two networks tested. Compared with the retransmission rate from the speed test conducted on the RAN and EPC components, which was 0.01 percent, the retransmission rate across the wireless connection between the Nokia 1A and RAN increased dramatically. This sharp increase could be caused because the Nokia 1A is a less-capable device, with less processing power than the other devices tested, or it could be due to the RAN transmission and reception components. We were unable to conduct additional troubleshooting because we did not have alternative UE or RAN antennae and radios.

One result that bears further discussion is the retransmission rate for the Apple iPhone 11 Pro on the NPS campus network. As shown in Table 4.5, the iPhone 11 retransmission rate was the highest at 1.98 percent. The high retransmission rate is an outlier in our testing, and we conducted research into possible reasons why this occurred, as the iPhone 11 Pro was the slowest of all devices we tested on the campus network.

We found on multiple forums that iPhone 11 Pro, Pro Max, and even newer model users experienced problems utilizing Wi-Fi. On the Apple Developer Forums, a user complained the phone continuously dropped its 802.11 connection, along with other users who experienced similar issues with slow and inconsistent 802.11 connections [38]. The forum posts are from July 2021 and refer to iOS 14.0 and 14.2. The iPhone 11 Pro we tested had iOS 15.3.1 installed. On another Apple discussion forum, around the time we tested our device,

users had similar issues using iPhones with iOS 15.3.1 installed on 802.11 connections [39]. It appears that newer iOS versions have not fully addressed the problems with 802.11 connectivity, and this could explain the low numbers across the board for the iPhone, or at least be a contributing factor.

UE Latency

At 20 ms, the latency of our testbed network came in at just under the average latency in this experiment of 21.75 ms. As discussed in Chapter I, reduced latency is a major benefit of 5G. Considering the open-source nature of our network and its 4G implementation, the latency improvement was notable and outperformed both the Google Fi and Verizon networks, though it could be due to the small network size and relatively light load. Further evaluation on a larger testbed capable of supporting more devices is required and an item of future work.

In summary, our 4G testbed network is not as fast in terms of data rate or latency as the Wi-Fi backhaul, yet future iterations of software and improvements in hardware may lead to faster, more reliable network builds.

4.3   Network Link Budget Analysis

We sought to estimate outdoor performance of our network. To establish this baseline, we utilized a link budget calculator from Rohde-Schwarz [40]. We then compared network tests to this baseline. Finally, we provided another link budget analysis tool from MathWorks to provide an example of a tool with more options, including atmospheric conditions [41].

4.3.1   Estimated Network Performance: The Rohde-Schwarz Link Budget Calculator

Compared to the analyzer provided by MathWorks, the Rohde-Schwarz calculator is much simpler and requires fewer parameters. However, it gives helpful feedback. The calculator measures the signal power, noise power, noise limit, and the Signal to Noise Ratio (SNR) of the network [40]. Table 4.6 provides parameters, with a brief explanation, that are required to calculate the results for the device under test (DUT).

Table 4.6. Parameter Explanations for Rohde-Schwarz Link Budget

Parameter	Explanation
Frequency	Frequency network uses
Bandwidth	Total allowed for UE
Equivalent Isotropically Radiated Power (EIRP)	Power at transmitter (Tx)
Transmitter SNR	Ratio of signal to noise floor level
Distances	between Tx and receiver (Rx)
FSPL	Expected frequency loss
Receiver Antenna Gain	Signal gain, varies by antenna
Cable Loss	Signal loss from transiting via cable
Displayed Average Noise Loss	Loss from noise levels

Figure 4.3 presents an example output of the Rohde and Schwarz calculator using default parameters.
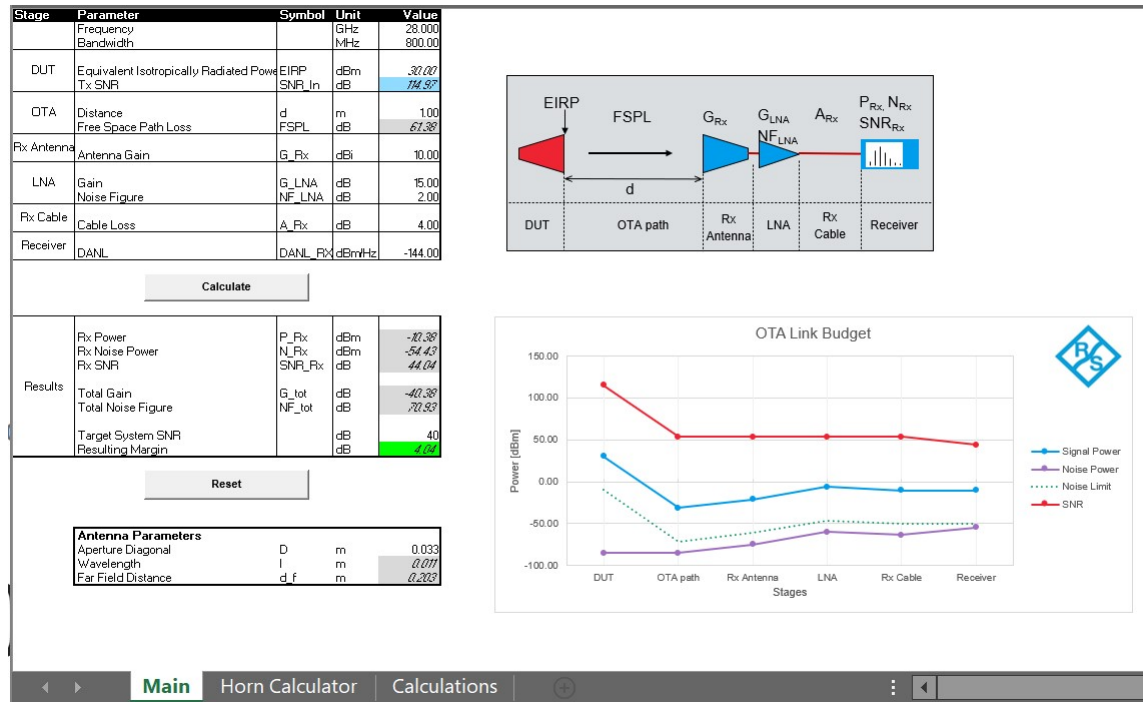
Figure 4.3. Main Page, over the air (OTA) Link Budget Calculator. Source: [40].

We used the parameters from Tables 3.1 and 3.2 from Chapter III to complete estimations using the Rohde-Schwarz calculator [40]. Weather and other atmospheric data are not inputs to this tool. The calculator already takes the Free Space Path Loss (FSPL) into account while determining the network performance, based on the entered parameters. For comparison, FSPL was also estimated using Equation (4.1).

We used the FSPL equation to estimate the signal performance of our testbed network in dB,

$$FSPL = 20log_{10}(d) + 20log_{10}(f) + 20log_{10}(\frac{4\pi}{c}) - G_t - G_r,$$ (4.1)

where d is the distance between antennas, f is the frequency, $G(Tx)$ is the gain of the transmitting antenna, $G(Rx)$ is the gain of the receiving antenna, and c is the speed of light in a vacuum (in meters per second). Figure 4.4 shows the results of the FSPL estimation for our testbed network in normal operating conditions.

Figure 4.4. Nokia 1A FSPL Estimate

As can be seen in Figure 4.4, the expected loss at 13 m is 23 dBm. This result provides the estimate to which we compare our network performance results in Section 4.3.2.

Network performance was also estimated utilizing the Rohde-Schwarz Link Budget calculator at the exact distances used in the FSPL estimation shown in Figure 4.4. The parameters used in this calculation are given in Table 4.7.

Table 4.7. Parameters for Rohde-Schwarz Link Budget

Item	Parameter	Value
1	Frequency	2.87 GHz
2	Bandwidth	120 MHz
3	EIRP	38.14 dBm
4	Transmitter SNR	151.35 dB
5	Distances	Figure 4.4
6	FSPL	Figure 4.4
7	Receiver Antenna Gain	3 dBi
8	Cable Loss	4 dB
9	Displayed Average Noise Loss	-144 dBm/Hz

We determined the settings in Table 4.7 as follows:

1. The frequency is the eNB operating frequency of our testbed network.
2. The bandwidth is the offset frequency assigned to in our eNB configuration.
3. The EIRP can either be left blank if unknown and the Rohde-Schwarz calculator will use the input power, cable loss, and Tx Antenna Gain to calculate it. We used this option because we did not know the EIRP of our antenna [40].
4. The Tx SNR was also left blank; the calculator uses the thermal noise floor if left empty [40].
5. We used the distances from Figure 4.4 in our calculations.
6. We used the FSPL results from Figure 4.4 in our calculations.
7. The Rx antenna gain is derived from the antenna parameters on our network [25]
8. The cable loss was the default value in the calculator [40]
9. The displayed average noise loss is a default calculation done in the calculator [40].

Figures 4.5, 4.6, and 4.7 depict the output for a distance of 1 m, 5 m, and 10 m, respectively. The results from the Rohde-Schwarz calculator show that the expected margin begins to go negative at 10 m, indicating that the signal is not useable after this distance. The calculator assumes a desired SNR of 40 dB at the target system (e.g., UE). The estimation was not exact, and after conducting the tests discussed in the next section, we show that our testbed network outperformed the Rohde-Schwarz estimate.

Results				
	Rx Power	P_Rx	dBm	-4.46
	Rx Noise Power	N_Rx	dBm	-63.21
	Rx SNR	SNR_Rx	dB	58.75
	Total Gain	G_tot	dB	-42.60
	Total Noise Figure	NF_tot	dB	72.60
	Target System SNR		dB	40
	Resulting Margin		dB	18.75

Reset

Antenna Parameters			
Aperture Diagonal	D	m	0.033
Wavelength	l	m	0.105
Far Field Distance	d_f	m	0.021
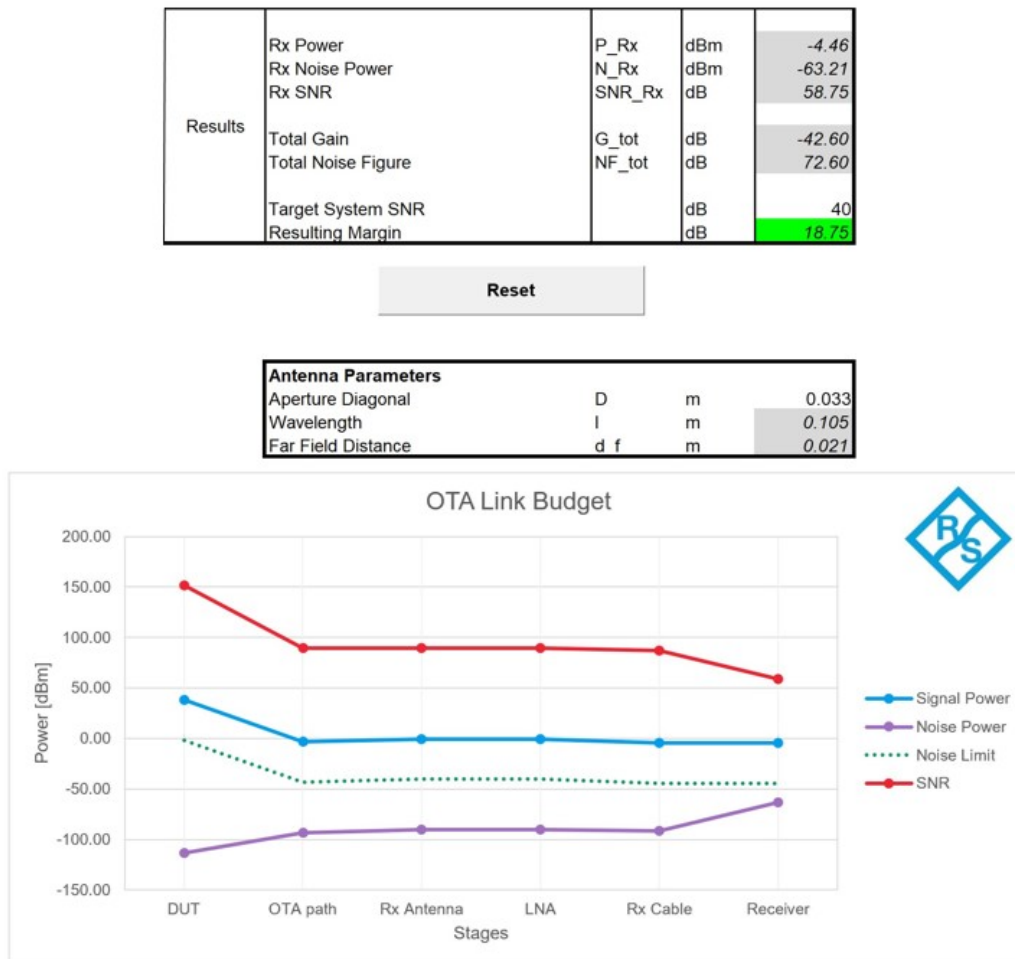
Figure 4.5. Rohde and Schwarz Link Budget Results at 1m

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Results	Rx Power	P_Rx	dBm	-18.44
	Rx Noise Power	N_Rx	dBm	-63.21
	Rx SNR	SNR_Rx	dB	44.77
	Total Gain	G_tot	dB	-56.58
	Total Noise Figure	NF_tot	dB	86.58
	Target System SNR		dB	40
	Resulting Margin		dB	4.77

Reset

Antenna Parameters			
Aperture Diagonal	D	m	0.033
Wavelength	I	m	0.105
Far Field Distance	d_f	m	0.021
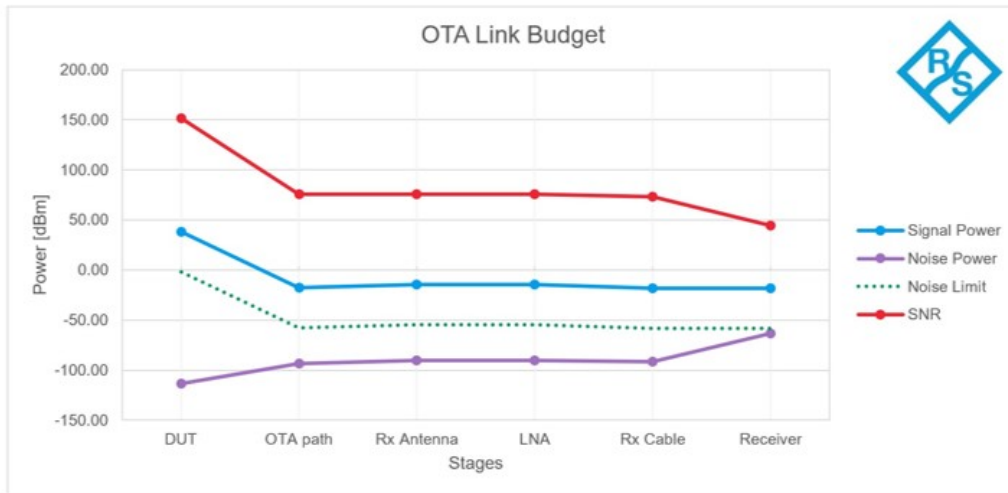
Figure 4.6. Rohde and Schwarz Link Budget Results at 5m

Results	Rx Power	P_Rx	dBm	-24.46
	Rx Noise Power	N_Rx	dBm	-63.21
	Rx SNR	SNR_Rx	dB	38.75
	Total Gain	G_tot	dB	-62.60
	Total Noise Figure	NF_tot	dB	92.60
	Target System SNR		dB	40
	Resulting Margin		dB	-1.25

Reset

Antenna Parameters			
Aperture Diagonal	D	m	0.033
Wavelength	l	m	0.105
Far Field Distance	d f	m	0.021
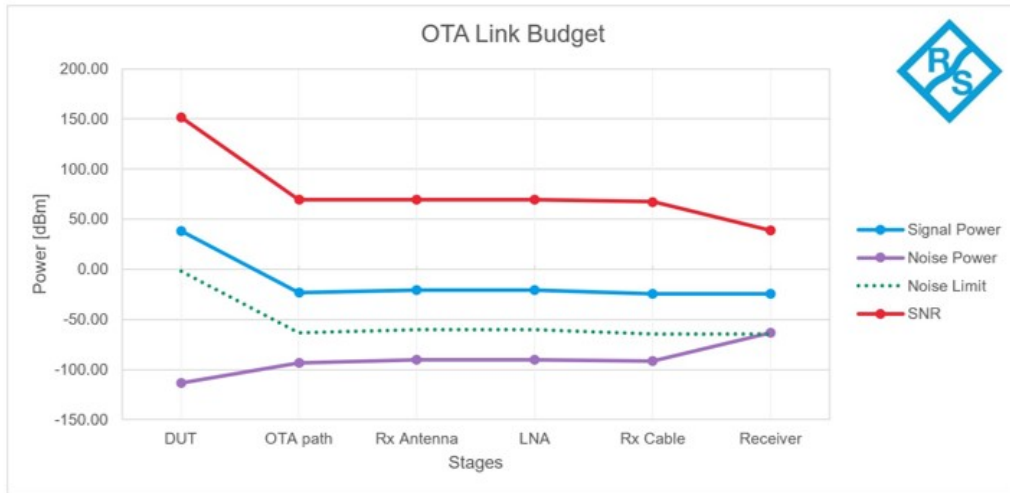
Figure 4.7. Rohde and Schwarz Link Budget Results at 10m

4.3.2 Testbed Network Performance

Signal propagation and connection range of the first open-source 4G network at NPS were important features to measure. As expected, FSPL and link budget analysis predict a drop in signal strength, but experimentation was required to map expected signal strength to observed data rate.

We conducted two network experiments in our office lab environment; the first tested the signal strength vs. distance, and the second tested data throughput vs. distance. We marked distances on the floor at increments of 1, 5, 12, 16, 19, and 22 meters. Figure 4.8 represents our test results for signal strength vs. distance.
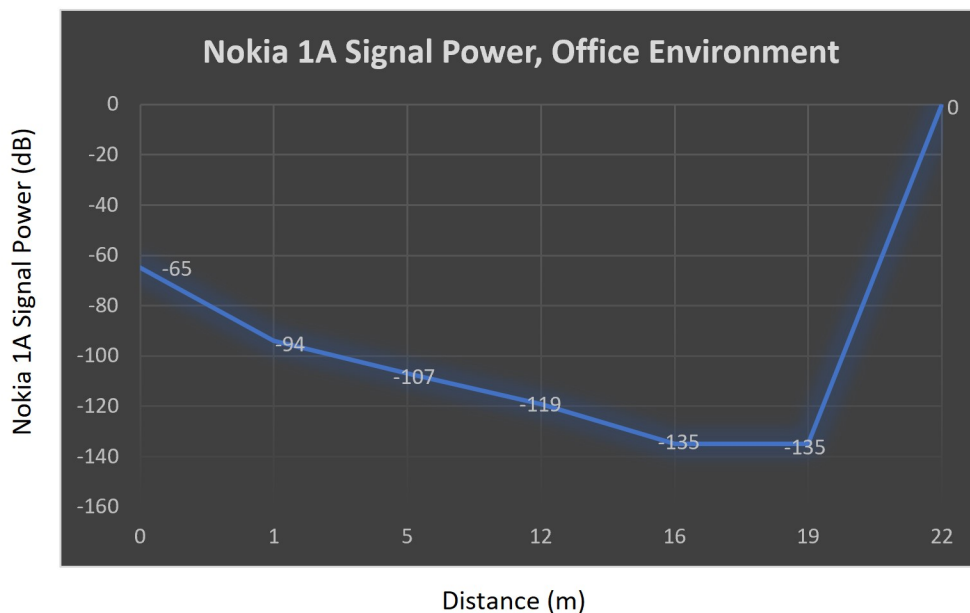
Figure 4.8. Nokia 1A Office Signal Performance, in dB vs. Distance

As the UE approached 16 m during the experiment, the signal strength significantly dropped. As represented in Figure 4.8, the UE signal displayed -135 dBm at 16 m and 19 m before the UE was disconnected. We could not determine if the Nokia 1A device could register a reading lower than -135 dBm. Due to these factors and our measured data rate, we assess the limit for a usable signal to be 16 m if using equivalent equipment.

Referring back to our FSPL results from Figure 4.4, where the expected loss in signal was 23 dBm from 1 m to approximately 13 m, the measured signal loss (as shown in Figure 4.8) was 25 dBm from 1 m to 13 m. We assess that the FSPL prediction was relatively accurate at these short distances, even in an office environment.

The signal strength readings from the UE matched the recorded trends in data rate vs. distance. We observed a significant drop in data rate at 16 m, as shown in Figure 4.9. Data rates were obtained from the Measurement Lab site [10].
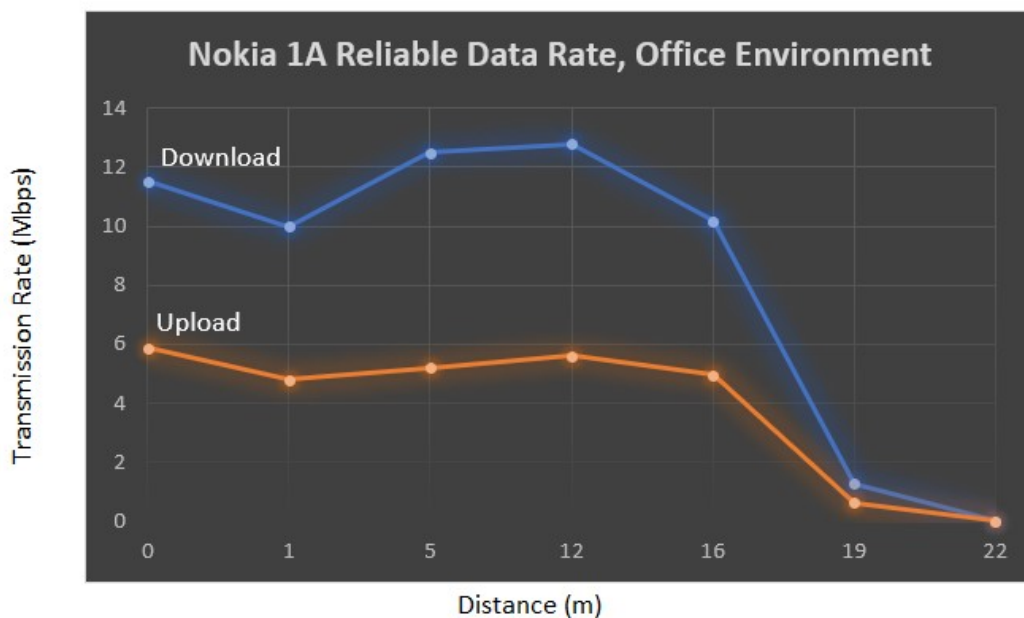
Figure 4.9. Nokia 1A Office Data Rate, in Mbps vs. Distance

FSPL leads us to expect the signal loss to increase as distance increases; the results in Figure 4.8 and Figure 4.9 corroborate this. As shown in Figure 4.8, the dB level went from -135 dBm to 0 dBm at approximately 22 m, representing a complete signal loss as the network disconnected the UE. Figure 4.9 shows that the highest recorded data rates for download and upload occurred at approximately 12 m, while the data rate dropped to 0 Mbps at 22 m.

We did not conduct an outdoor network test due to the inability to resolve issues with network certificates. The network performed well in an environment where the signal had to penetrate walls, windows, and doors; it is reasonable to presume that our network would

perform much better outdoors and treat the connection ranges discussed above as a lower bound. We can estimate the impact of atmospheric conditions using options available in the Mathworks Link Budget Analyzer to provide estimates of signal loss.

4.3.3   MathWorks Link Budget Analyzer

The Link Budget Analyzer is an application built in MATLAB code that provides a user-friendly GUI that allows the network architect to input parameters. Of the two examined link budget analyzers, MATLAB offers more parameter options for the analysis of the DUT [41].

The MATLAB analyzer also considers weather and atmospheric conditions. Atmospheric analysis can allow network architects to determine whether the signal strength will be sufficient in adverse weather conditions such as rain, sleet, snow, or fog. These atmospheric properties have an enormous impact on millimeter-wave (mmW) technology and lesser impacts on the higher frequency bands of 4G and 5G. Figures 4.10 and 4.11 show the GUI and the large number of user-defined parameters in the MATLAB tool.
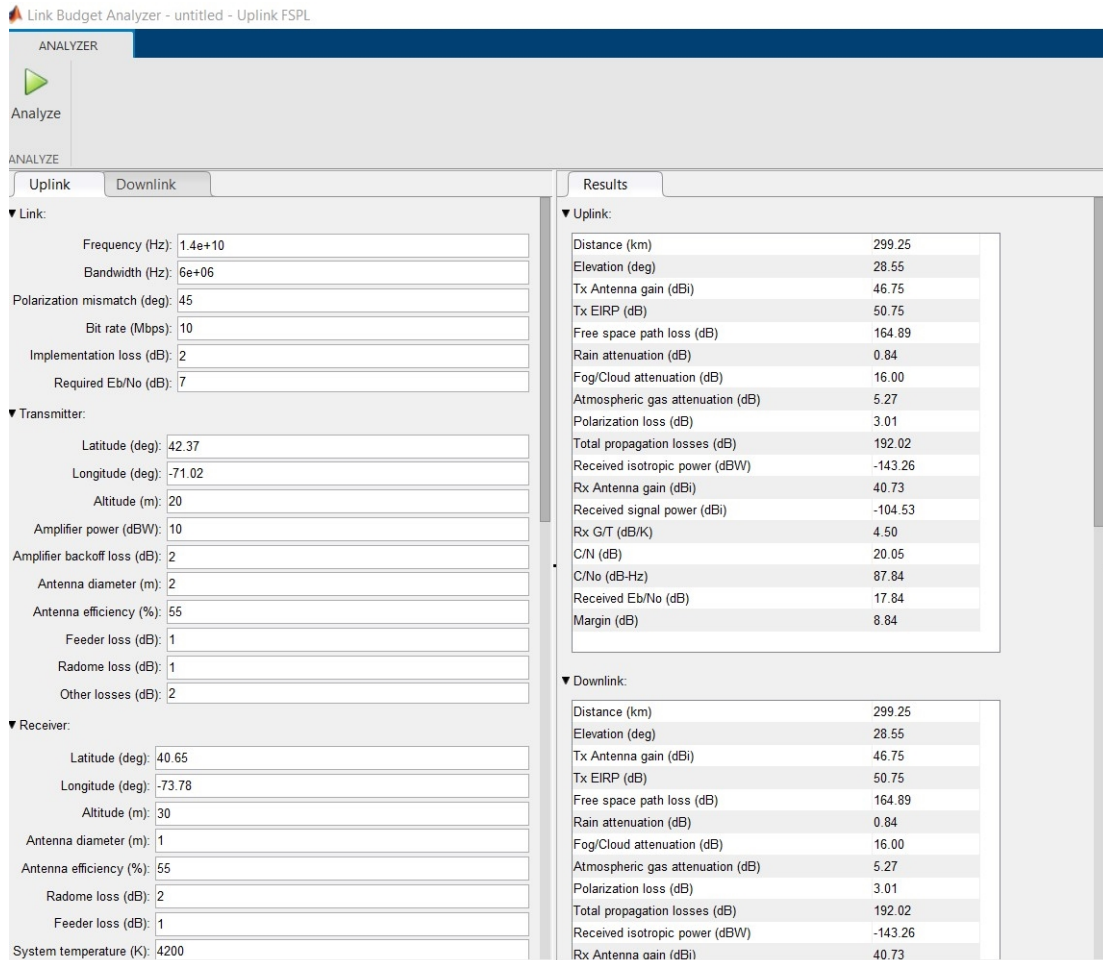
Figure 4.10. MathWorks Link Budget Analyzer Parameters Section GUI
Source: [41].
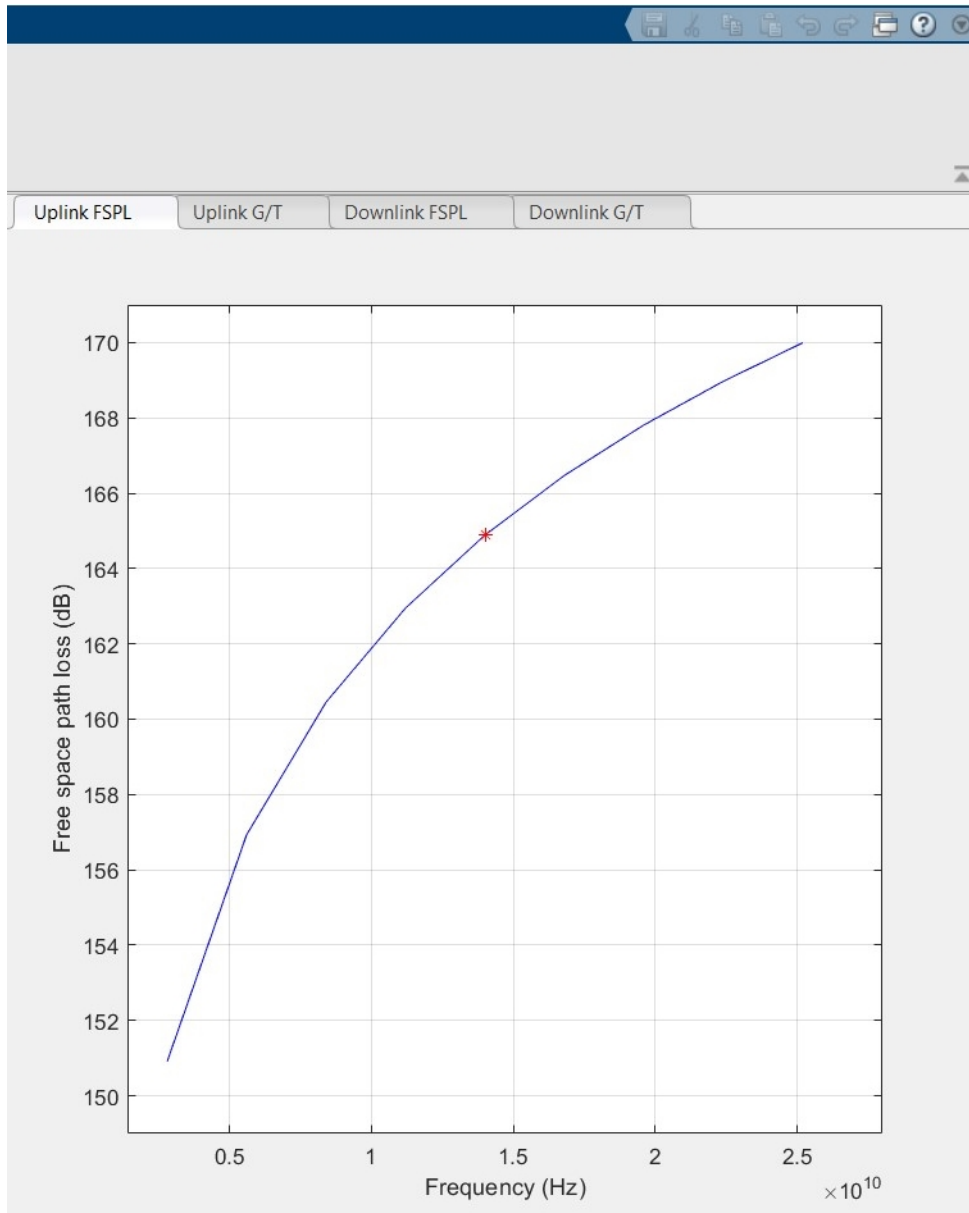
Figure 4.11. MathWorks Output Display of GUI. Source: [41].

4.3.4 MathWorks Outdoor Link Budget Analysis

To illustrate the network capability in an outdoor environment, the MathWorks Link Budget Analyzer accounts for weather and atmospheric conditions. We did not test the research network in an outdoor environment; however, we used this link budget analysis to estimate performance. Figures 4.12 and 4.13 depicts the uplink (U/L) and downlink (D/L) parameters utilized for testing.

When considering the weather impact on the network results, we utilized the weather conditions in Monterey, California, on April 26, 2022, at noon [42]. The weather for the day was sunny and clear, with slight haze or cloud cover. We obtained the coordinates of Spruance Plaza between Spanagel and Root Hall on the NPS campus from Google Maps [43].

Shortly after running the first link budget, it became apparent that this tool was not ideal for small networks, and we did not conduct further testing. The immediate concern was the granularity of the latitude and longitude. Because the research network is small, with a limited range, accurate latitude and longitude representation require many decimal places. The latitude, for example, taken from the online map was +36.595268; however, the link budget analyzer changed the latitude to +36.5953.

The Mathworks application limits decimal places to four and rounds the fourth decimal position based on the fifth decimal spot. The limited decimal places take away from the granularity and make it difficult to measure distances to compare previous tests. Another concern relative to latitude/longitude representation is that the minimum distance that the application can calculate is 0.02 km, or 20 m. We tested our network out to a maximum distance of 22 m, and found a maximum effective distance of 16 m. The MATLAB tool does not have the ability to compare distances shorter than the maximum effective range of our testbed. Although we cannot use our results to compare against distances previously tested, we provide the results in Tables 4.8 and 4.9.

Figure 4.12. Testbed Uplink Parameters

Figure 4.13. Testbed Downlink Parameters

Table 4.8. Testbed Uplink Results from MATLAB Link Budget Analyzer Application

Parameter	Test A	Test B
Latitude, Longitude (deg)	36.5953, -121.875	36.5954, -121.875
Distance (km)	0.02	0.02
Elevation (deg)	7.19	17.36
Tx Antenna gain (dBi)	-24.93	-24.93
Tx EIRP (dB)	-27.93	-27.93
FSPL (dB)	66.69	67.02
Rain Attenuation (dB)	0	0
Fog/Cloud attenuation (dB)	0	0
Atmospheric gas attenuation (dB)	0	0
Polarization loss (dB)	3.01	3.01
Total propagation losses (dB)	71.7	72.03
Received isotropic power (dBW)	-101.63	-101.96
Rx Antenna gain (dBi)	-27.04	-27.04
Received signal power (dBi)	-129.67	-130
Rx G/T (dB/K)	-63.27	-63.27
C/N (dB)	-18.09	-18.43
C/No (dB-Hz)	62.7	62.36
Received Eb/No (dB)	-4.29	-4.63
Margin (dB)	-13.29	-13.63

Table 4.9. Testbed Downlink Results from MATLAB Link Budget Analyzer Application

Parameter	Test A	Test B
Latitude, Longitude (deg)	36.5953, -121.875	36.5954, -121.875
Distance (km)	0.03	0.03
Elevation (deg)	36.6	57.54
Tx Antenna gain (dBi)	-25.56	-25.56
Tx EIRP (dB)	-20.56	-20.56
FSPL (dB)	70.19	70.79
Rain Attenuation (dB)	0	0
Fog/Cloud attenuation (dB)	0	0
Atmospheric gas attenuation (dB)	0	0
Polarization loss (dB)	3.01	3.01
Total propagation losses (dB)	75.2	75.8
Received isotropic power (dBW)	-95.77	-96.36
Rx Antenna gain (dBi)	-27.67	-27.67
Received signal power (dBi)	-125.44	-126.03
Rx G/T (dB/K)	-63.9	-63.9
C/N (dB)	-13.86	-14.46
C/No (dB-Hz)	66.93	66.34
Received Eb/No (dB)	-3.86	-4.46
Margin (dB)	-12.86	-13.46

The most critical parameter in Tables 4.8 and 4.9 is the "Margin." The "Margin" typically needs to be around 20 dB to ensure a stable connection. In both tests, the U/L and D/L margins were around -13 dB. These test results, at a distance of 20-30 m, support the observed outcomes of the network tests in the indoor environment, where significant signal loss observed at 16 m.

Overall, our research into open-stack networks yielded potentially promising results, and the use cases for private use in military applications are apparent. The connection, once established, was reliable and provided the user with similar data functionality as commercial service providers. However, we need to conduct further research and experimentation into the network capabilities including expandability (in terms of compatible devices) and reliability (in terms of isolating causes of retransmissions). Inconsistency in obtaining the initial connection plagued our research, and software stability and integrating additional capabilities proved very challenging. Chapter V discusses our conclusions, research contributions, and areas for future research opportunities.

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CHAPTER 5:
Conclusions, Contributions, and Future Work

In this work, we conducted a variety of tests. These included testing compatible UEs, network and device speed, and data throughput and reliability for our OAI testbed implementation. We also explored a link budget analysis to provide a reference comparison to our field tests. Finally, we experimented with another link budget analysis application with more input options to include atmospheric conditions. We outline our conclusions from our tests and experimentation, our contributions to the 5G NR research field at NPS, and future work possibilities.

5.1 Conclusions

Based on our results, we address the initial problem statement and research questions in the following sections. Our findings show the potential value of an open-source private 4G/5G mobile ad hoc network to support military operations, but we raise concerns about the functionality and maintenance of the network.

5.1.1 Is the OAI Open Stack Network Feasible for Military Application?

The benefits are apparent, but we discerned that the OAI architecture is not a feasible option in its current state. We based our conclusion on the network performance we observed during our tests and the findings of our other research questions in the following sections.

5.1.2 Would a private 5G Mobile Ad Hoc Network be Reliable for Tactical Military Operations?

With the evaluation of our test results and the apparent benefits that 5G cellular technology provides, we see great potential for utilizing open-source technology to support tactical military operations. The OAI software is still under heavy development and is not ready for application in real-world military scenarios. However, the various open-source software

options and the low-cost COTS equipment available enable us to widen the scope of considered networks and pursue other viable 5G options in the future.

Promising Network Results

If we only consider our data speed and reliability tests, the network performed admirably. The data rate was comparable to large telecom providers. Equally impressive is the range at which the UE, attached to our testbed, reliably sent data within our office lab environment. The network was stable until the UE reached approximately 13 m away from the network antenna. Our lab environment is a typical office area with physical barriers, such as cubical walls and solid wood doors. It is reasonable to believe that the distance at which the network provided a reliable connection would increase in an outdoor environment.

5.1.3   Areas of Concern

The instability of obtaining a connection with our testbed network is the largest area of concern observed during our research. We alluded to this difficulty in Chapter I, but we need to further explain the challenges we encountered.

Inconsistent Initial Connection

Throughout our research, we spent countless hours troubleshooting connectivity issues. We reviewed the connection logs on the EPC, verified the device APN settings, and configured and reconfigured numerous SIM cards in attempts to determine the causes preventing connections between our device and the testbed. The inconsistent connection hindered our progress and negatively impacted the number of tests conducted in our thesis.

Specifically, the eNB laptop often crashed as we attempted to connect our UEs to the network. We continually needed to restart the eNB and EPC to clear the cache and allow new connections to occur. However, clearing the cache alone did not typically lead to a successful connection.

Limited Connection Capacity

Another concern that became apparent was that the network could not handle more than two UE connections at one time and, most of the time, the network could only handle one. We

attempted to document a standard process to ensure we followed the same steps to connect two devices. Our efforts to distill this process fell short, as we could not identify a single best way to achieve the connections. One device would connect, and when the network attempted to connect the second device, the eNB would crash.

The Number of Compatible Devices is Lacking

Another connectivity concern that we identified was the number of devices the network allows to connect needs improvement. Due to the device limitation, we could only test one UE model, the Nokia 1A smartphone. The lack of compatible devices is concerning and stands out as a severe limitation of the OAI software. Limiting the UEs to one model left us tied to the limited capabilities of the Nokia 1A. Newer, more powerful, and more secure devices exist. Looking towards a fully functional 5G network, we need recent and 5G compatible devices, and the Nokia 1A does not meet that requirement.

Difficulty Modifying the Underlying Code

A benefit that we highlighted regarding open-source software for 5G private networks was the ability to modify or change code to tailor the network to the user's needs. However, another area of concern that we identified is it is very difficult to manipulate the code to integrate additional network capabilities. Changes made to the code create significant issues, likely due to dependencies to other services. We experienced these problems modifying the code while attempting to incorporate the JasminSMS software into our testbed network.

OAI Certificate Issues

The OAI network utilizes digital certificates to allow a secure connection to its domain. Our research encountered a hurdle when we realized that the certificate had expired on the HSS and MME. Little documentation exists on the OAI Wiki pages for renewing the certificates. Due to the lack of documentation, we began troubleshooting a way to reinstall the certificates. The network operates on Docker containers, and the HSS and MME component certificates need renewing in each separate container. We successfully downloaded the certificates for each component, but the certificates failed to promulgate across the network. Because of this, we could not restore the connection between the MME and the HSS.

5.2 Contributions

In this work, we established a framework to continue testing and experimenting with cellular technology as it advances. Our testbed network is the first iteration of a fully open-source functional cellular network at NPS using COTS hardware. This testbed can be foundational for the 5G technology field of study and should assist in further understanding the software and hardware system of systems used in next-generation wireless communications.

Thus, the contributions of this work are as follows:

- Implemented the first fully wireless open-source 4G/LTE cellular testbed network built on COTS equipment at NPS.
- Performed a preliminary assessment of the reliability of OAI software as an open-source option to support tactical military operations.
- Uncovered additional incompatible devices beyond the list OAI provides.
- Evaluated possible additional network capabilities for integration into the OAI open stack architecture.

5.3 Future Work

Options for future work are bountiful because of the availability of software in open-source form. This section discusses the possibilities and justification for pursuing these research topics.

5.3.1 Successfully Implement a next-generation NodeB (gNB)

Another student in the Master of Science in Applied Cyber Operations (MACO) program conducted research into a 4G-assisted 5G network implementation. This student successfully built the gNB and connected the gNB to his network [44]. Although unsuccessful in getting the gNB to connect a UE to the network and pass traffic, his effort was essential in progress toward a successful transition to a fully functional 5G private network. We need continued research in building a 4G-assisted 5G networks to achieve the desired end-state as OAI continues to work on implementing its 5G CN software.

5.3.2 Integrate IMS for VoLTE Services on the Testbed Network

Voice calls over non-data networks will soon be, if not already, obsolete. 5G brings a network with enough bandwidth, capacity, and throughput to allow communication solely over a data network. The OAI software does not come with the IMS capability, which means the only method of voice communication over the OAI network is if a user has a messaging application, such as Signal or WhatsApp. Building in an IMS capability into the OAI implementation would allow a user to dial a landline, for example, as most applications do not allow calls to landlines.

5.3.3 Incorporate Additional eNBs into the Testbed Network

Scaling out the network to include more eNBs is another area of research to pursue. Adding modems, extending the range of the network, and adding in other eNBs would allow the network to be built out as a a true, useful cellular network and create the opportunity for multiple groups of users to communicate across the network.

5.3.4 Transition Our RAN and EPC Laptops to the Raspberry Pi

Technology is shrinking with the abundance of internet-of-things devices and 5G technology, and our small-scale network implementation fits this theme. There are opportunities to make our testbed network even smaller. Research is underway, and a team put an OAI network into a backpack-sized case utilizing a combination 5G/4G build [45]. Miniaturization is a viable area of pursuit here at NPS because of the utility a smaller network would provide to military operations. Potential concern areas would be the memory size needed for the network and a reliable power source in mobile conditions.

5.3.5 Experiment with Different Cloud-based Servers for Data Backhaul

Further research into backhaul options for private 5G networks, to provide a reliable way to transfer data over the network from forward operating bases back to upper echelon commanders, is a vital need. Integration into the Navy Operational Architecture (NOA) is ideal for our testbed network; the process, however, for network validation to meet the standards required to plug into the NOA would be rigorous. There are, however, commercial

options for a backhaul, such as Amazon Web Services (AWS). Considering the DOD secured a contract with AWS, this could potentially be an option to utilize a more open network with the ability to encrypt traffic as needed.

APPENDIX A:
USRP B200 DATASHEET

This appendix contains relevant data about the USRP B200 and B210; Table B.1, adapted from [11].

Table A.1. USRP B200 and B210 Product Specifications

Parameter	USRP B200	USRP B210
Channels	1 Tx and 1 Rx	2 TX and 2 Rx
FPGA	Xilinx Spartan 6 XC6SLX75	Xilinx Spartan 6 XC6SLX150
Instantaneous Bandwidth	56 MHz	56 MHz in 1x1 30.72 MHz in 2x2
Frequency Coverage	70 MHz - 6 GHz	70 MHz - 6 GHz
Power Output	Over 10 dB	Over 10 dB
Receiver Noise Figure	Less than 8 dB	Less than 8 dB
Max ADC/DAC Sample Rate	61.44 MS/s	61.44 MS/s
ADC/DAC Resolution	12 bits	12 bits

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APPENDIX B:
KERNEL AND SOFTWARE CONFIGURATION

This appendix is taken in whole from [11] and provides a detailed guide for each of the steps required to install and configure the OAI RAN and EPC software. The steps shown reflect a specific configuration of the OAI EPC with the QuectelEC20 UE and may require changes for other open stack network implementations.

B.1   RAN Kernel Configuration

The RAN Kernel was configured using the recommendations on the OAI wiki for Ubuntu 16.04 as a guide, since the computers used for this work were configured with Ubuntu 18.04. The major steps required were to install the low-latency kernel, remove all power management features such as P-states and C-states, disable CPU frequency scaling, and disable hyperthreading. The commands to accomplish each step and verify the step was completed are now presented. While ultimately unnecessary, the BIOS for the RAN computer was also updated to the latest version using a removable thumb-drive configured for the HP laptops.

B.1.1   Install low-latency kernel

The low-latency kernel is installed using (1) and can be verified with (2). If installed correctly, then the system should display "low-latency" instead of "generic" attached to the kernel version number. If the system fails to boot into the low-latency kernel, then hold "shift" after the computer reboots and before the OS loads the log-in page to enter the grub menu. In this menu, the low-latency kernel can be selected as the preferred kernel.

1. sudo apt-get install linux-image-lowlatency linux-headers-lowlatency
2. uname -a

B.1.2   Remove all power management features

To disable p-states and c-states, the following command is added to the file /etc/default/grub before updating that boot options with "update-grub."

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GRUB_CMDLINE_LINUX_DEFAULT="quiet intel_pstate=disable processor.max_cstate=1 intel_idle.max_cstate=0 idle=poll"

Then, to check that p-states and c-states are disabled, install the i7z utility with "sudo apt-get install i7z" and verify that only c-state c0 is utilized when "sudo i7z" is run.

Next, the Intel powerclamp module is disabled by adding "blacklist intel_powerclamp" to the end of the file /etc/modprobe.d/blacklist.conf. If the file does not exist, then an empty file with the same name should be made before adding the blacklist command.

B.1.3   Disable frequency scaling

The following commands are used to disable frequency scaling. First, install cpufrequtils with "sudo apt-get install cpufrequtils." Then run "sudo systemctl disable ondemand" to prevent the CPU governor from switching modes. Next, set the governor with "sudo cpufreq-set -g performance" and restart the process with "sudo /etc/init.d/cpufrequtils restart." If done successfully, then when "cpufreq-info" is run, all cores should show the governor as set to "performance." Another check is to verify with "sudo i7z" that all cores are operating at the maximum frequency.

B.1.4   Disable hyberthreading

On the HP laptops, hyperthreading is disabled in the BIOS menu. During computer booting, press "F10" to enter the BIOS menu. Log in to the BIOS as an admin. This may require entering or making a password. Next, deep sleep was disabled so that the Intel HT (hyperthreading) technology could be toggled off.

B.2   CN Kernel Configuration

The CN Kernel configuration guide recommends installing the generic tunnel protocol (GTP) kernel modules. However, this step is likely a relic of the EPC project before it shifted to using containers. If necessary, the GTP kernel modules can be installed with:

wget http://kernel.ubuntu.com/ kernel-ppa/mainline/v4.8/linux-headers-4.8.0-040800-generic_4.8.0-040800.201610022031_amd64.deb

wget http://kernel.ubuntu.com/ kernel-ppa/mainline/v4.8/linux-image-4.8.0-040800-generic_4.8.0-040800.201610022031_amd64.deb

sudo dpkg -i linux-headers-4.8.0-040800-generic_4.8.0-040800. 201610022031_amd64.deb

sudo dpkg -i linux-image-4.8.0-040800-generic_4.8.0-040800. 201610022031_amd64.deb

After rebooting, the kernel module and version can be checked with "uname -a," "sudo modprobe gtp," and "dmesg | tail."

B.3 Software Configuration

This section describes the steps needed to install and then build the OAI software.

B.3.1 RAN Software Build

Despite requiring a more complex kernel configuration, the RAN software build is simple and straightforward. A repository containing the 4G and 5G RAN is available on GitLab. If not already installed on the computer, git can be installed from the Ubuntu repositories via package manager with "sudo apt-get install subversion git cmake." Once git is installed, the repository is cloned with "git clone https://gitlab.eurecom.fr/oai/openairinterface5g.git." For this work, the 2020.w47 tag from the developer branch was utilized. The user then navigates to the newly created directory with "cd openairinterface5g" and initializes some environment variables used by the software with "source oaienv." Next, the user navigates to the cmake directory with "cd cmake_targets." Finally, the user builds the desired RAN software with "./build_oai -I -w USRP –eNB –UE –buildlib enbscope –build-lib uescope." A summary of the flags used in the build script is provided in Table E.1.

Table B.1. OAI RAN Build Script Flag Summary

Flag	Purpose
-I	Install external dependencies using the package manager
-w	Select desired radio front-end (USRP, bladeRF, hackRF, etc)
- -UE	Build the UE executable and associated utilities
- -eNB	Build the eNB executable
- -build-lib	Used to build additional supported libraries such as the oscilloscopes for the eNB and UE
-c	Erase previously built files for target (UE or eNB) before starting new build
-C	Erase previously built files for all targets before starting new build
-g	3 Build binaries with support for gdb
-h	Display help information for script and list complete flag summary

Analysis of the build_oai script reveals that all instances of the USRP hardware driver (UHD) are first removed and then the latest version from the Ettus Research repositories is installed in the function "check_install_usrp_uhd_driver." This can cause software mismatch errors that prevent the OAI RAN software from executing properly if a different version of UHD is installed from source. The RAN software is executed from the " /openairinterface5g/cmake_targets/ran_build/build" directory after first executing "source oaienv" from the " /openairinterface5g" directory. A log file containing the information the eNB or UE script prints to the terminal window can be created by appending "| tee eNB.log" or "| tee UE.log" to the command used to execute the software.

B.3.2 CN Software Build

In contrast to the CN kernel configuration, the steps required to build the software are more complex. The OAI 4G LTE EPC uses the Docker platform to create individual containers for each of the EPC network functions. Docker containers are similar to virtual machines running on a host device, except they typically have less of the overhead and additional

services provided by an OS. In the Docker environment, images are used to build containers, just like how OS image files (.iso) are required to build virtual machines.

The OAI EPC implementation differs slightly from the textbook EPC architecture by combining the S-GW and P-GW into a single entity labelled the SP-GW that is then separated into a control plane and user plane container. Figure 20 depicts a network diagram for the OAI EPC with labels for the interfaces between network functions. The middle box containing the control-plane aspects of the S-GW and P-GW is instantiated as a singled container called the SPGW-C in the software. The bottom box containing the user-plane aspects of the S-GW and P-GW is called the SPGW-U in the software.

After installing the Docker software, base images are pulled from the Docker repository for Ubuntu 18.04 and the Cassandra database management system. The Ubuntu images are used as the basis for creating the EPC network function images and the Cassandra image is used to create a database that stores subscriber information. The Cassandra container operates exclusively with the HSS container. Additionally, the CN computer is configured to enable IP forwarding and the Docker network bridge is assigned an IP address on the desired network. The Docker network bridge is used to allow containers on one host machine to interact with other devices on the network.

First, additional docker images are built for each EPC network function using software downloaded from the OAI GitHub repository at https://github.com/OPENAIRINTERFACE/openair-epc-fed.git. Table E.2 provides the software versions used for each of the OAI EPC network-function images. The SPGW-U image is referred to as SPGW-U-tiny to reflect the fact that a limited number of users can be supported. No other size SPGW-U image is offered on the public-facing OAI websites.

Table B.2. OAI RAN Build Script Flag Summary

Network Function	Branch	Tag
HSS	Master	V1.1.1
MME	Developer	2020.w47
SPGW-C	Master	V1.1.0
SPGW-U-tiny	Master	V1.1.0

Next, Python scripts are executed to generate configuration files for each of the containers. The configuration files are used with the images to create each of the four network function containers and the Cassandra database container. The containers are then connected to a private network so that the network functions can communicate with one another. During the configuration process, the MME, SPGW-C, and SPGW-U-tiny functions are made reachable through the Docker network bridge for devices external to the CN host machine. Also, the configuration process creates subscriber information for a specified number of users. Finally, the network functions can be started and stopped as desired to test the EPC. When the containers are started or secured, a specific order must be followed: HSS, MME, SPGW-C, and SPGW-U-tiny.

Scripts were created to facilitate each of the steps required to configure the EPC so that changes to network parameters could be made without manually reworking the software installation and configuration process. These scripts were divided between each of the steps described (i.e., image creation, container configuration, container launching, and container stopping) and an additional script to facilitate restarting each container after the host machine was rebooted. These scripts form each of the sections in Appendix E and are provided with the electronic source material for this work.

A final note about the OAI EPC software is that there are multiple ways to deploy the Docker containers. Instead of manually launching and stopping the containers after configuration as described, a separate process can be followed to configure and permanently launch the containers. This process is more appropriate for a permanently deployed EPC instead of one

used for research. When the permanent deployment was used, the resulting EPC log files overflowed the available memory on the host machine after 72 hours of continuous operation. A method of maintaining and storing large volumes of EPC logs generated by the software is not provided. Additionally, a recent developer branch has shifted towards integration of the OAI EPC software with Magma MME software from Facebook Connectivity. This branch utilizes the "docker-compose" set of commands to replace the scripts from the described approach.

B.4   Prerequisites and Initial Docker Set-up

Install Docker

1. Remove any old docker files if applicable

   sudo apt-get remove docker docker-engine docker.io containerd runc

2. Set-up the Docker repository

   sudo apt-get update

   sudo apt-get install apt-transport-https ca-certificates curl gnupg-agent software-properties-common

   curl -fsSL https://download.docker.com/linux/ubuntu/gpg | sudo gpg –dearmor -o /usr/share/keyrings/docker-archive-keyring.gpg

   echo "deb [arch=amd64 signed-by=/usr/share/keyrings/docker-archive-keyring.gpg] https://download.docker.com/linux/ubuntu $(lsb_release -cs) stable" | sudo tee /etc/apt/sources.list.d/docker.list > /dev/null

3. Install the Docker engine

   sudo apt-get update

   sudo apt-get install docker-ce docker-ce-cli containerd.io

4. Create a Docker hub account

5. Add the user to Docker group so that future commands do not require "sudo." In this step, replace $USER with the actual username. After completion, the user must log out, then log back in before continuing.

> sudo groupadd docker

> sudo usermod -a -G docker $USER

6. Verify Docker installation with "Hello World" example

> docker run hello-world

Check Python version

1. The installed Python version must be at least 3.6, which can be checked with the following command:

> python3 –version

2. If this condition is not met, then use the package manager to update or install Python version 3.0 with:

> sudo apt-get install python3

Pull Base Images

1. If not already done, log into the user's Docker account
2. Pull the base images for Ubuntu 18.04 and Cassandra

> docker pull ubuntu:bionic

> docker pull Cassandra:2.1

3. If desired, the user may now logout of their Docker account

Network Configuration

1. Enable IP address forwarding

> sudo sysctl net.ipv4.conf.all.forwarding=1

> sudo iptables -P FORWARD ACCEPT

In /etc/sysctl.conf, uncomment the line net.ipv4.ip_forward

    sudo sysctl -p /etc/sysctl.conf

Reboot the machine

2. Verify that IP forwarding is enabled by checking that the following command outputs a 1.

    sysctl net.ipv4.ip_forward

3. Alter the Docker network bridge to an IP address on the local network Add a file /etc/docker/daemon.json with the desired IP range as shown:

    {
    "bip": "192.168.17.2/24"
    }

4. Restart the Docker daemon for the changes to take effect

    sudo service docker restart

    docker info

    docker network inspect bridge

    docker pull ubuntu:bionic

    docker pull Cassandra:2.1

B.5 Build Images

The series of commands required to create each of the EPC network function image files are consolidated in the script "Create_4G_Images.sh." The script only requires an initial clone of the OAI EPC repository.

1. Clone the OAI EPC repository

    git clone https://github.com/OPENAIRINTERFACE/openair-epc-fed.git

2. Change directories to the downloaded openair-epc-fed folder

    cd openair-epc-fed

3. Change desired branch to master and synchronize files with the repository

> git checkout master
>
> git pull origin master
>
> ./scripts/syncComponents.sh

4. Build the HSS image

> docker build –target oai-hss –tag oai-hss:production –file component/oai-hss/docker/Dockerfile.ubuntu18.04 component/oai-hss
>
> docker image prune –force
>
> docker image ls

5. Build the MME image. This image is the only one that appears to stall for a significant period of time while building. The stall occurs around step 13 and 14, but it will successfully build if left alone.

> docker build –target oai-mme –tag oai-mme:production –file component/oai-mme/docker/Dockerfile.ubuntu18.04 component/oai-mme
>
> docker image prune –force
>
> docker image ls

6. Build SPGWC

> docker build –target oai-spgwc –tag oai-spgwc:production –file component/oai-spgwc/docker/Dockerfile.ubuntu18.04 component/oai-spgwc
>
> docker image prune –force
>
> docker image ls

7. Build SPGWU

> docker build –target oai-spgwu –tag oai-spgwu:production –file
> component/oai-spgwu/docker/Dockerfile.ubuntu18.04
> component/oai-spgwu
>
> docker image prune –force
>
> docker image ls

B.6   Create and Configure Containers

The series of commands required to create each of the EPC network function containers are consolidated in the script "Configure_4G_Containers.sh." The first three steps are not included in the script. The first step creates a network within the docker environment for the containers to communicate with each other. This step only needs to be completed once. The second step creates a route on the eNB machine to the OAI EPC network on the EPC machine. The third step is not required but is provided as a set of commands that can be used to permanently rename modern-style network interfaces to their more classical "eth0" style.

1. Create a network for the OAI EPC containers

   > docker network create –attachable –subnet 192.168.61.0/26 –ip-range
   > 192.168.61.0/26 prod-oai-public-net

2. Create a route for the eNB to reach the EPC containers

   > sudo ip route add 192.168.61.0/26 via 192.168.17.1 dev eth0

3. If desired, rename network interfaces similar to "enp0s25" to the more classical "eth0" style

   > sudo nano /etc/default/grub
   >
   > Edit the line GRUB_CMDLINE_LINUX="" to: GRUB_CMDLINE _LINUX="net.ifnames=0 biosdevname=0" sudo grub-mkconfig -o /boot/grub/grub.cfg

   Restart the computer

4. Create each container. This is the step where the "Configure_4G_Containers.sh" script begins and where a different approach for permanent deployment of the containers could be followed.

> docker run –name prod-cassandra -d -e CASSANDRA _CLUSTER_NAME="OAI HSS Cluster" -e CASSANDRA_ENDPOINT _SNITCH= GossipingPropertyFileSnitch cassandra 2.1
>
> docker run –privileged –name prod-oai-hss -d –entrypoint /bin/bash oai-hss:production -c "sleep infinity"
>
> docker network connect prod-oai-public-net prod-oai-hss
>
> docker run –privileged –name prod-oai-mme –network prod-oai-public-net -d –entrypoint /bin/bash oai-mme:production -c "sleep infinity"
>
> docker run –privileged –name prod-oai-spgwc –network prod-oai-public-net -d –entrypoint /bin/bash oai-spgwc:production -c "sleep infinity"
>
> docker run –privileged –name prod-oai-spgwu-tiny –network prod-oai-public-net -d –entrypoint /bin/bash oai-spgwu-tiny:production -c "sleep infinity"

5. Configure the Cassandra container

> docker cp component/oai-hss/src/hss_rel14/db/oai_db.cql prod-cassandra:/home
>
> docker exec -it prod-cassandra /bin/bash -c "nodetool status"
>
> Cassandra_IP='docker inspect –format= "range .NetworkSettings.Networks .IPAddressend" prod-cassandra'
>
> docker exec -it prod-cassandra /bin/bash -c "cqlsh –file /home/oai_db.cql $Cassandra_IP"

6. Configure the HSS container

> HSS_IP='docker exec -it prod-oai-hss /bin/bash -c "ifconfig eth1 | grep inet" | sed -f ./ci-scripts/convertIpAddrFromIfconfig.sed'
>
> python3 component/oai-hss/ci-scripts/generateConfigFiles.py –kind=HSS –cassandra=$Cassandra_IP

–hss_s6a=$HSS_IP –apn1=apn1.carrier.com

–apn2=NPS4G.apn.epc.mnc092.mcc404.3gppnetwork.org

–users=200 –imsi=404921000000001

–ltek=0c0a34601d4f07677303652c0462535b

–op=63bfa50ee6523365ff14c1f45f88737d

–nb_mmes=1 –from_docker_file

docker cp ./hss-cfg.sh prod-oai-hss:/openair-hss/scripts

docker exec -it prod-oai-hss /bin/bash -c "cd /openair-hss/scripts && chmod 777 hss-cfg.sh && ./hss-cfg.sh"

7. Configure the MME container

MME_IP='docker inspect –format="range .NetworkSettings.Networks .IPAddressend" prod-oai-mme'

SPGW0_IP='docker inspect –format="range .NetworkSettings.Networks .IPAddressend" prod-oai-spgwc'

python3 component/oai-mme/ci-scripts/generateConfigFiles.py –kind=MME

–hss_s6a=$HSS_IP –mme_s6a=$MME_IP

–mme_s1c_IP=$MME_IP –mme_s1c_name=eth0

–mme_s10_IP=$MME_IP –mme_s10_name=eth0

–mme_s11_IP=$MME_IP –mme_s11_name=eth0

–spgwc0_s11_IP=$SPGW0_IP

–mcc=404–mnc=92 –tac_list="5 6 7" –from_docker_file

docker cp ./mme-cfg.sh prod-oai-mme:/openair-mme/scripts

docker exec -it prod-oai-mme /bin/bash -c "cd /openair-mme/scripts && chmod 777 mme-cfg.sh && ./mme-cfg.sh"

8. Configure the SPGW-C container

    python3 component/oai-spgwc/ci-scripts/generateConfigFiles.py
    –kind=SPGW-C
    –s11c=eth0 –sxc=eth0 –apn=apn1.carrier.com
    –dns1_ip=172.20.20.12 –dns2_ip=8.8.8.8 –from_docker_file

    docker cp ./spgwc-cfg.sh prod-oai-spgwc:/openair-spgwc

    docker exec -it prod-oai-spgwc /bin/bash -c "cd /openair-spgwc && chmod
    777 spgwc-cfg.sh && ./spgwc-cfg.sh"

9. Configure the SPGW-U-tiny container

    python3 component/oai-spgwu-tiny/ci-scripts/generateConfigFiles.py
    –kind= SPGW-U
    –sxc_ip_addr=$SPGW0_IP –sxu=eth0 –s1u=eth0
    –network_ue_nat_option=yes –from_docker_file

    docker cp ./spgwu-cfg.sh prod-oai-spgwu-tiny:/openair-spgwu-tiny docker
    exec -it prod-oai-spgwu-tiny /bin/bash -c "cd /openair-spgwu-tiny &&
    chmod 777 spgwu-cfg.sh && ./spgwu-cfg.sh"

B.7 Start Network Functions

The series of commands required to start the network functions requires a specific ordering: HSS, MME, SPGW-C, and SPGW-U-tiny. These commands initialize the network functions and start packet captures in each container. Additionally, a colored display of the MME log is printed to the screen. The script that contains these commands is "Launch_4G_Containers.sh."

1. Launch tshark in each container to start packet captures

    docker exec -d prod-oai-hss /bin/bash -c "nohup tshark -i eth0 -i eth1 -w
    /tmp/hss_check_run.pcap 2>&1 > /dev/null"

    docker exec -d prod-oai-mme /bin/bash -c "nohup tshark -i eth0 -i lo:s10
    -w /tmp/mme_check_run.pcap 2>&1 > /dev/null"

> docker exec -d prod-oai-spgwc /bin/bash -c "nohup tshark -i eth0 -i lo:p5c -i lo:s5c -w /tmp/spgwc_check_run.pcap 2>&1 > /dev/null"
>
> docker exec -d prod-oai-spgwu-tiny /bin/bash -c "nohup tshark -i eth0 -w /tmp/spgwu_check_run.pcap 2>&1 > /dev/null"

2. Launch each network function

> docker exec -d prod-oai-hss /bin/bash -c "nohup ./bin/oai_hss -j ./etc/hss_rel14.json –reloadkey true > hss_check_run.log 2>&1"
>
> sleep 2
>
> docker exec -d prod-oai-mme /bin/bash -c "nohup ./bin/oai_mme -c ./etc/mme.conf > mme_check_run.log 2>&1"
>
> sleep 2
>
> docker exec -d prod-oai-spgwc /bin/bash -c "nohup ./bin/oai_spgwc -o -c ./etc/spgw_c.conf > spgwc_check_run.log 2>&1"
>
> sleep 2
>
> docker exec -d prod-oai-spgwu-tiny /bin/bash -c "nohup ./bin/oai_spgwu -o -c ./etc/spgw_u.conf > spgwu_check_run.log 2>&1"

3. Print the running MME log to screen

> docker exec -it prod-oai-mme tail -f mme_check_run.log

B.8   Stopping Network Functions

The series of commands required to stop the network functions requires the same ordering as the commands to start the network functions: HSS, MME, SPGW-C, and SPGW-U-tiny. These commands stop the network functions by sending each container a "killall" signal twice. Additionally, the logs, configuration files, and packet captures are consolidated into a compressed archive folder, which must be renamed after executing the script to prevent the archive from being overwritten. The script is called "Stop_4G_Containers.sh."

1. Send the "killall" signal to each container twice

> docker exec -it prod-oai-hss /bin/bash -c "killall –signal SIGINT oai_hss tshark tcpdump"

docker exec -it prod-oai-mme /bin/bash -c "killall –signal SIGINT oai_mme tshark tcpdump"

docker exec -it prod-oai-spgwc /bin/bash -c "killall –signal SIGINT oai_spgwc tshark tcpdump"

docker exec -it prod-oai-spgwu-tiny /bin/bash -c "killall –signal SIGINT oai_spgwu tshark tcpdump"

sleep 10

docker exec -it prod-oai-hss /bin/bash -c "killall –signal SIGKILL oai_hss tshark tcpdump"

docker exec -it prod-oai-mme /bin/bash -c "killall –signal SIGKILL oai_mme tshark tcpdump"

docker exec -it prod-oai-spgwc /bin/bash -c "killall –signal SIGKILL oai_spgwc tshark tcpdump"

docker exec -it prod-oai-spgwu-tiny /bin/bash -c "killall –signal SIGKILL oai_spgwu tshark tcpdump"

2. Remove the old archive folder and create a new archive folder

rm -Rf archives

mkdir -p archives/oai-hss-cfg archives/oai-mme-cfg archives/oai-spgwc-cfg archives/oai-spgwu-cfg

3. Copy the configurations, logs, and packet captures into the new archive

docker cp prod-oai-hss:/openair-hss/etc/. archives/oai-hss-cfg

docker cp prod-oai-mme:/openair-mme/etc/. archives/oai-mme-cfg

docker cp prod-oai-spgwc:/openair-spgwc/etc/. archives/oai-spgwc-cfg

docker cp prod-oai-spgwu-tiny:/openair-spgwu-tiny/etc/. archives/oai-spgwu-cfg

docker cp prod-oai-hss:/openair-hss/hss_check_run.log archives

docker cp prod-oai-mme:/openair-mme/mme_check_run.log archives

docker cp prod-oai-spgwc:/openair-spgwc/spgwc_check_run.log archives

docker cp prod-oai-spgwu-tiny:/openair-spgwu-tiny/spgwu_check_run.
log archives

docker cp prod-oai-hss:/tmp/hss_check_run.pcap archives

docker cp prod-oai-mme:/tmp/mme_check_run.pcap archives

docker cp prod-oai-spgwc:/tmp/spgwc_check_run.pcap archives

docker cp prod-oai-spgwu-tiny:/tmp/spgwu_check_run.pcap archives

4. Compress the newly created archive for storage

zip -r -qq docker_files.zip archives

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APPENDIX C:
EC20 NETWORK OPERATORS LIST

This appendix is taken in whole from [11] and contains the output from the execution of the AT+COPN command via the minicom utility and lists every MNO that is stored on the EC20. The results are presented in two columns. Entries contain the PLMN of the MNO and the operator's name in long alphanumeric format. Some MNOs have an additional short alphanumeric format to facilitate displaying on the UE, although this is not shown in this appendix.

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