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Investigation, Analysis and Implementation of Open Source Mobile Communication Software

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Problem Description

Title: Investigation, Analysis and Implementation of Open Source Mobile Communication Software

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With the emergence of open source mobile communication software such as openBTS and OpenBSC, it is claimed that it is possible to build a low cost GSM network. However, it is unclear about the scalability, reliability, openness and security of such a mobile network. The goal of this Master thesis work is to shed light on open source mobile communication software by practical installation and experiment of typical ones.

More specifically, the project consists of the following tasks:

- Investigation and analysis of available open source mobile communication software.
- Selection and installation of open source mobile communication software on generic computers.
- Evaluation of OpenAirInterface on scalability, reliability, openness and security.

Responsible professor: Do, Thanh Van

Abstract

Over the past few years, open source software has transformed the mobile communication networks. The development of VoIP technologies has enabled the migration of telco protocols and services to the IP network with help of open source software. This allows for deployment of mobile networks in rural areas with lower cost. The usage of open source GSM is very useful for developing countries which do not yet have full mobile coverage. Open source GSM allows very rapid and economical deployment of GSM. The companies like Range Networks and Osmocom have developed OpenBTS and OpenBSC respectively which offer varying network architecture and allow the user to implement GSM depending on their needs. Besides this, open source GSM is quite useful for students in order to understand 2G protocol stack.

Companies such as Fraunhofer FOKUS, Core Network Dynamics, and EURECOM have developed open source projects like OpenIMS, OpenEPC, OpenMTC, Open Air Interface (OAI) etc. These testbeds are essential for experimental evaluation as well as for product development. In the context of LTE networks, existing testbed platforms are limited either in functionality and/or extensibility or are too complex to modify and customize. Openairinterface is an open source platform for LTE experimentation designed for maximum modularity and code reuse and fully compliant with LTE Release 10. Today, testbeds are an essential platform for experimental research and prototype development. They enable researchers to test, validate and assess the performance of new technologies for wireless networks.

Software-Defined Radio (SDR) is a popular concept for implementing radio equipment in software, using low cost general purpose computers and radio frontends. In recent years, it is gaining popularity as a tool to build close-to-reality testbeds for experimental research. This flexibility and openness can be much more valuable for many research problems. The most popular open source LTE SDR software available for testbed today is Eurecom´s OpenAirInterface (OAI). The OAI currently provides a standard-complaint implementation of a subset of Release 10 LTE for UE, eNB, MME, HSS, SGW an PGW on standard Linux-based computing equipment.

Key Words: OpenBTS, OpenBSC, OpenLTE, OpenIMS, SDR, USRP, OpenAirInterface, NGN, SDN NFV

Acknowledgements

This thesis is submitted to the **Norwegian University of Science and Technology (NTNU)** for the partial fulfillment of the requirements for a Master degree. This work is done at the Department of Telematics, NTNU, Trondheim in the Autumn of 2016. The purpose of the work is to investigate, analyze and implement Open Source Mobile Communication Software.

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Furthermore, I would like to express my thankfulness to Linus AS for the supports and facilities provided to complete this thesis work. It is also important to express my gratitude to the Department of Telematics for all the facilities provided to finish this master thesis.

Finally, a special thanks to my family and friends who have always encouraged me.

September, 2016
Suresh Paudel

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List of Abbreviations

2G	Second Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
ADC	Analog to Digital Converter
AuC	Authentication Center
AS	Access Stratum
BSC	Base Station Controller
BTS	Base Transceiver Station
C-RAN	Cloud-Radio Access Network
CSCF	Call Session Control Function
D2D	Device to Device
DAC	Digital to Analog Converter
DDC	Digital Down Converter
DTAP	Direct Transfer Application Part
DUC	Digital Up Converter
DSP	Digital Signal Processor
EIR	Equipment Identity Register
eNB	Evolved Node B
EPC	Evolved Packet System
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved – Universal Terrestrial Radio Access
FPGA	Field Programmable Gate Array
GMLC	Gateway Mobile Location Centre
GNU	GNU´s Not Unix
GPRS	General Packet Radio Service
GPS	Global Positioning System
GRC	GNU Radio Companion
GSCL	Gateway Service Capability Layer
GSM	Global System for Mobile Communication

GTP	GPRS Tunneling Protocol
GTPU	GTP User Data Tunneling
HLR	Home Location Register
HSPA	Highs Speed Packet Access
HSS	Home Subscriber Server
I-CSCF	Interrogating Call Session Control Function
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IoT	Internet of Things
IP	Internet Protocol
LAPD	Link Access Protocol on D-Channel
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Mobile to Mobile Communication
MAC	Media Access Control
MCC	Mobile Country Code
MEC	Machine Edge Computing
MGCP	Media Gateway Control Protocol
MIMO	Multiple Input Multiple Output
MM	Mobility Management
MME	Mobility Management Entity
MMOG	Multimedia Online Gaming
MNC	Mobile Network Code
MS	Mobile Station
MSC	Mobile Switching Centre
MTC	Machine Type Communication
MTP	Message Transfer Part
NAS	Non Access Stratum
NFV	Network Function Virtualization
NGMN	Next Generation Mobile Network
NGN	Next Generation Network
NITB	Network in The Box
NOS	Network Operating System
NSCL	Network Service Capability Layer

OAI	Open Air Interface
OP	Operator Key
OSA	Open Air Interface Software Alliance
OSMOCOM	Open Source Mobile Communication
OTG	OpenAirInteface Traffic Generator
PCRF	Policy Control and Charging Rules Function
P-CSCF	Proxy-Call Session Control Function
PDCP	Packet Data Conversion Protocol
PDN	Packet Data Network
PDN-GW	Packet Date Network-Gateway
PLMN	Public Land Mobile Network
QoS	Quality of Service
RAN	Radio Access Network
RANAP	Radio Access Network Application Part
RLC	Radio Link Control
RNC	Radio Network Controller
RR	Radio Resource
RRC	Radio Resource Control
R&D	Research and Development
RRM	Radio Resource Management
S-CSCF	Serving-Call Session Control Function
SDN	Software Defined Network
SDP	Service Delivery Platform
SDR	Software Define Radio
SGW	Serving Gateway
SIM	Subscriber Identity Module
SIP	Session Initiation Protocol
SISO	Single Input Single Output
SMQueue	SIP Message Queue
SR	Subscriber Registry
TAC	Tracking Area Code
TCP	Transport Control Protocol
TDMA	Time Division Multiple Access
TEM	Telecommunication Equipment Manufacturer

TMSI	Temporary Mobile Subscriber Identity
TSP	Telecommunication Service Provider
UDP	User Datagram Protocol
UE	User Equipment
UHD	USRP Hardware Driver
UICC	Universal Integrated Circuit Card
UMTS	Universal Mobile Telecommunication System
USIM	Universal Subscriber Identity Module
USRP	Universal Software Radio Peripheral
USSD	Unstructured Supplementary Service Data
vBBU	Virtual Base Band Unit
vIMS	Virtual IMS
VLAN	Virtual Local Area Network
VLR	Visiting Location Register
VoIP	Voice Over IP
vRRH	Virtual Remote Radio Head

1. Introduction

The emergence of open source mobile communication software has transformed the telecommunication industries in recent years. A movement to bring open source to telecommunication has started when Mark Spencer created an open source telephone switch called Asterisk in 1999. Since then, others have followed Spencer's foot steps (Bloomberg, 2006). A number of companies and research institutes have been developing open source projects. Range Networks, Sysmocom, Core Network Dynamics, Fraunhofer FOKUS, and EURECOM are some of the more notable companies and research institutes who have been producing open source mobile communication software project over the past few years. The combination of open source mobile communication software with Software Defined Radio (SDR) provides potential to realize a minimum cost cellular system, in terms of cost, time and flexibility.

SDR has changed radio system engineering. In traditional wireless communication, different wireless device can not communicate with each other due to their different hardwired radio systems. In SDR, many radio system components are implemented in software and the users can enable the radio to support different wireless communication protocols by simply configure the waveform software. Such a paradigm change has converged the cellular system from a slow-moving proprietary and expensive hardware platforms towards an open source software platform (Mao, Huang, Li, & Agrawal, 2013). The Universal Radio Software Peripheral (USRP) which is the SDR platforms provides access network and core network functionality on standard Linux-based PCs. If anyone has commodity PCs and an USRP which allows him to connect those PCs to conventional telecommunication network, then he can make telephone system in a box which dramatically reduces the cost.

Open source projects make the laboratory and trial environment where Telecommunication Service providers (TSPs), Telecommunication Equipment Manufactures (TEMs), R&D departments, Universities as well as other research institutes around the world can test newest generation of communication architecture, concept and equipment. It provides a significant opportunity for students and research communities to interact with next generation of

telecommunication architectures. Companies such as Fraunhofer FOKUS, Core Network Dynamics, and EURECOM have developed open source projects like OpenIMS, OpenEPC, OpenMTC, OpenAirInterface etc. These open source projects help the companies to stop wasting time on testing their prototype, product, solution and keep concentrating on their core business.

Companies like Range Networks and Sysmocom have moved their projects from typical research and development environments to the enterprise sector, where they are competing against very successful telecommunication industries. Despite the recent deployment of 4G networks, they have focused on replacing a traditional infrastructure involved GSM cellular network with software. GSM is still the prevalent standard for cellular communications with over six billion users in 2011 according to GSMA (GSMA, 2016). Usually mobile operators are committed to the government to deploy new LTE cellular standard in the country, however, the deployment always started in the city first. They are not going to replace the GSM infrastructure in rural locations in near future due to high deployment cost. The usage of open source GSM is very useful for developing countries which do not have full mobile coverage. Open source GSM allows very rapid and economical deployment of GSM. The open source projects like OpenBTS and OpenBSC are quite helpful for this purpose. These small scale networks are operated at very low cost with more customization and control.

The EURECOM´s OpenAirInterface (OAI) is an open source based experimentation and prototyping platform. It is developed to enable the innovation in the field of mobile communication. It is the first open source software-based implementation of the LTE system including the full protocol stack of 3GPP standard both in E-UTRAN and EPC. It can be used to build and customize an LTE base station and core network on a PC and connect a commercial UEs to test different configurations and network setups and monitor the network and mobile device in real-time. It a Software Defined Radio (SDR) based solution in open source which provides both UE, eNB, and core network functionality. EURECOM believes that OAI can be useful in the development of the 5G technologies research like Machine to Machine (M2M) communication, CloudRAN, Heterogeneous Cellular Networks and Device to Device (D2D) communication, Shared Spectrum, Millimeter Waves, and Software Defined Mobile networks (Nikaein, et al., 2014).

1.1. Objectives

With the emergence of open source mobile communication software such as OpenBTS and OpenBSC, it is claimed that it is possible to build a low cost GSM network. However, it is unclear about the scalability, reliability, openness, and security of such a mobile network. The principle objective of this thesis is to shed light on open source mobile communication software by practical installation and experiment of typical ones. More specifically, the thesis consists of the following tasks:

- Investigation and analysis of available open source mobile communication software.
- Installation and experiments on OpenAirInterface.
- Evaluation of OpenAirInterface on scalability, reliability, openness and security.

1.1.1. Research Questions

The thesis work is designed to answer following research questions.

RQ1: How to investigate and analyze the available open source mobile communication software?
RQ2: What are the relevant works and state-of-arts on the field of open source mobile communication software?
RQ3: How to install and experiment OpenAirInterface 4G on a generic computer?
RQ4: How to evaluate the scalability, easiness of installation, reliability, openness and security of these open source software?

1.2. Motivation

Over the past few years, open source mobile communication software has made a very significant impact in mobile communication networks. It has been used as a momentum to increase the importance of testbed and prototype for validation, performance evaluation and

pre-deployment system test. Prior to the advent of such software, mobile communication system was too complex for academia and research communities.

The concept and technologies used in this thesis are very new. Some of projects using these concepts and technologies have been moved from typical research and development environments to the enterprise sector, where they are competing against very successful telecommunication industries. And some other projects act as flexible platform to accelerate innovation in 5G cellular system. These new technologies in mobile communication interest me most.

Open source GSM allows very rapid and economical deployment of GSM. The open source projects like OpenBTS and OpenBSC are quite helpful this purpose. These small scale networks are operated at very low cost with more customization and control. These projects are useful for developing countries which do not have full mobile coverage.

EURECOM has developed OpenAirInterface (OAI) to enable innovation in the area of mobile/wireless networking and communication. It can be use in the development of 5G technology research like M2M, CloudRAN, Heterogeneous Cellular Network, Device to Device (D2D) communication, Shared Spectrum, Millimeter Waves and Software Defined Network.

As a result of this thesis, I can gain good theoretical and practical knowledge about GSM, LTE and some of the key enabler technologies of 5G such as SDN, NFV, CloudRAN, M2M and massive MIMO. This is very helpful for me to understand upcoming technology in mobile communication networks.

1.3. Approach

The first part of this thesis contributes on investigation and analysis of available open source mobile communication software and their scalability, reliability, openness and security.

The final and the main part of this thesis work focuses on installation of OpenAirInterface 4G on a standard Linux-based PC with USRP B210, followed by the evaluation of OAI in terms of usability, easiness of installation, scalability, reliability, openness and security.

1.4. Report Outline

The thesis work is structured as follows:

- Chapter 1 **Introduction:** This chapter gives general overview of the thesis, problem domains motivation, approaches used and report outline.
- Chapter 2 **Background:** This chapter focuses on relevant theoretical background related to OpenAirInterface 4G.
  Chapter 3 **Overview of Available Open Source Mobile Communication Software:** This chapter gives brief overview of available open source mobile communication software and their scalability, reliability, openness and security.
- Chapter 4 **Open Air Interface:** This chapter gives a brief introduction of OpenAirInterface, describes it as a reference platform for innovation in the field of 4G/5G and provides installation procedures of OAI on PCs.
- Chapter 5 **Results and Discussion:** This chapter discusses findings obtained from the project.
- Chapter 6 **Conclusion:** Presents final conclusions drawn from the results and suggestions for further work.

2. Background

This chapter gives the necessary theoretical background related to OpenAirInterface 4G. Section 2.1 presents a brief introduction of Long Term Evolution (LTE), and is followed by the description of Software Defined Radio in section 2.2.

2.1. Long Term Evolution (LTE)

LTE commonly referred to as 4G, is a standard for wireless communication of high speed data for mobile phones and data terminals. It was designed by a collaboration of national and regional telecommunications standards bodies known as the Third Generation Partnership Project (3GPP). LTE evolved from an earlier 3GPP system known as the Universal Mobile Telecommunication System (UMTS), which in turn evolved from the Global System for Mobile Communications (GSM) (Cox, 2012). The specifications for LTE are specified by 3GPP in its Release 8, with the added benefit of enhancements having been introduced in all subsequent 3GPP Releases.

After the introduction of the Apple iPhone and other mobile devices based on Google´s Android operating system, mobile phone users have grown rapidly worldwide in recent years. Moreover, the demand on bandwidth and quality of services have been increased by these users (Cox, 2012). The rapid increase in use of Internet has moved Internet based services to the mobile devices. As a result of this, 2G and 3G network´s data traffic has increased dramatically and started to become congested. Even with the introduction of High Speed Packet Access (HSPA), evolution of UMTS has not satisfied the user´s needs. The migration of broadband services to mobile devices is a prime driver for the evolution of LTE. A rapid increase of mobile data usage and emergence of new applications such as MMOG (Multimedia Online Gaming), mobile TV, Web 2.0, streaming contents have motivated the 3GPP to work on the LTE on the way towards fourth-generation mobile (Tutorials Point, 2016).

A study into the long term evolution of UMTS was began in 2004. LTE or the E-UTRAN (Evolved Universal Terrestrial Access Network) has been designed to support only Packet Switched (PS) services. It is designed to provide seamless Internet Protocol (IP) connectivity between User Equipment (UE) and the Packet Data Network (PDN), without any disruption to the end user´s applications during mobility. Along with LTE that applies more to the radio access technology, there is also an evolution of the core network under the term System Architecture Evolution (SAE) which includes the Evolved Packet Core (EPC) network (Sesia, Toufik, & Baker, 2011). SAE has also been developed so that it is fully compatible with LTE technology. It is an evolution of the packet switched architecture used in GPRS/UMTS. It distributes all types of information to the user, voice as well as data, using the packet switching technologies that have been traditionally been used for data alone. Officially, a complete end-to-end system which includes UE, E-UTRAN and Core Network (EPC) is known as Evolved packet system (EPS) (Cox, 2012). The figure below shows new architecture that is evolved from UMTS.

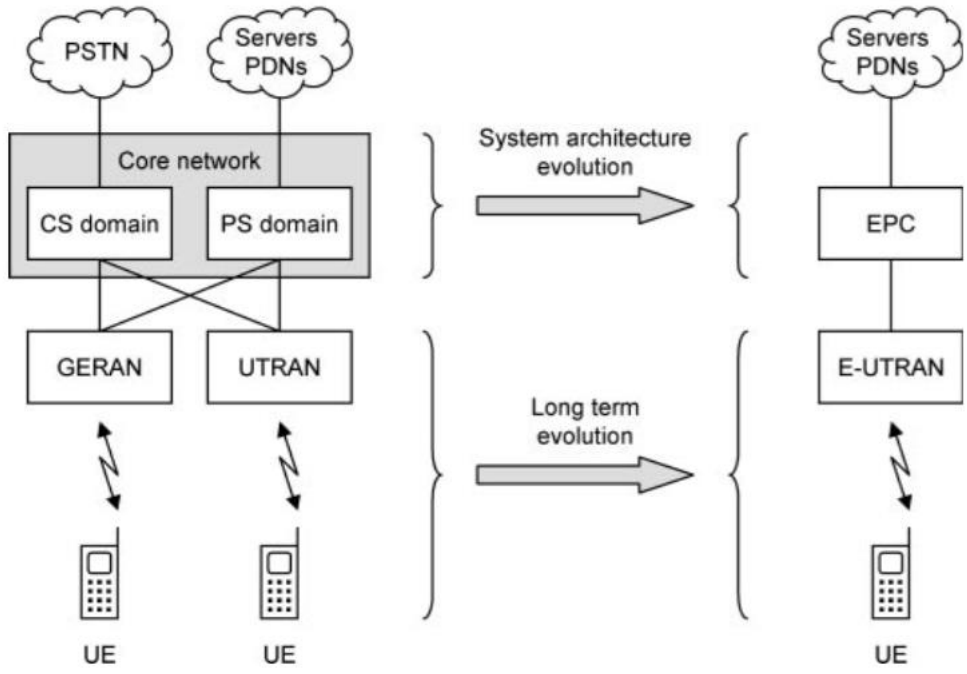

Figure 2.1: Evolution of the system architecture from GSM and UMTS to LTE (Cox, 2012)

2.1.1. Architecture of LTE

The high level architecture of EPS consists of mainly three components: user equipment (UE), E-UTRAN, and EPC. The figure shows the overall network architecture of EPS where the core network (EPC) consists of many logical nodes and the access network E-UTRAN is made up of a single node, the evolved NodeB (eNB) which connects to the UEs. Each of these network elements is interconnected by means of interfaces that are standardized in order to allow multi-vendor interoperability (Sesia, Toufik, & Baker, 2011). This gives network operators a freedom in implementations to split or merge these logical network elements depending on their commercial needs.

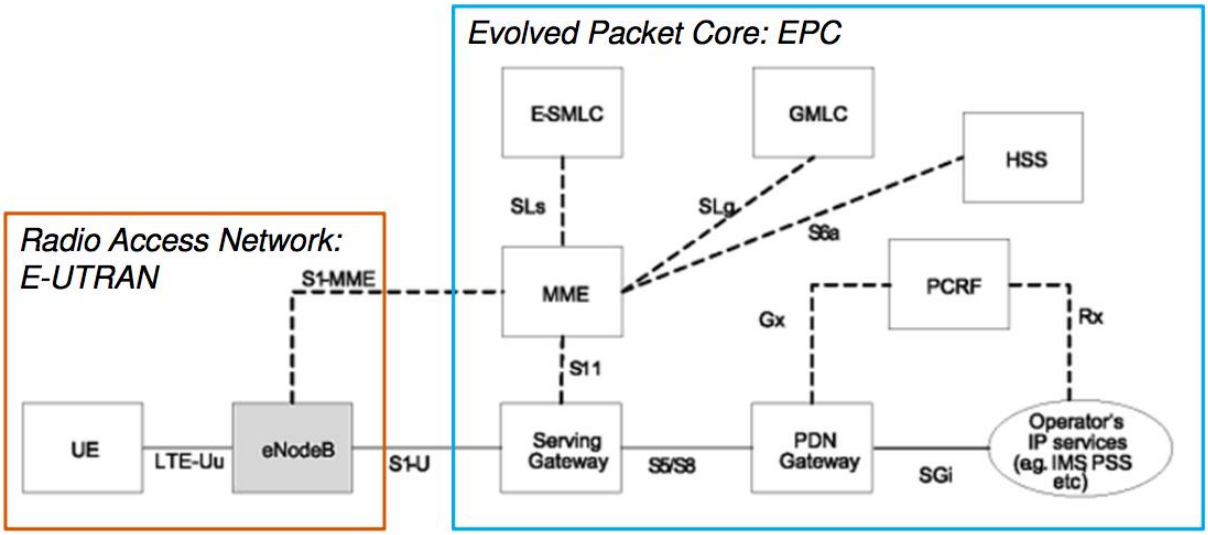

Figure 2.2: The EPS network elements (Sesia, Toufik, & Baker, 2011)

The functional split between the EPC and E-UTRAN for an LTE network is shown in Figure. This functional split is helpful for the operators who can dimension and adapt their network easily.

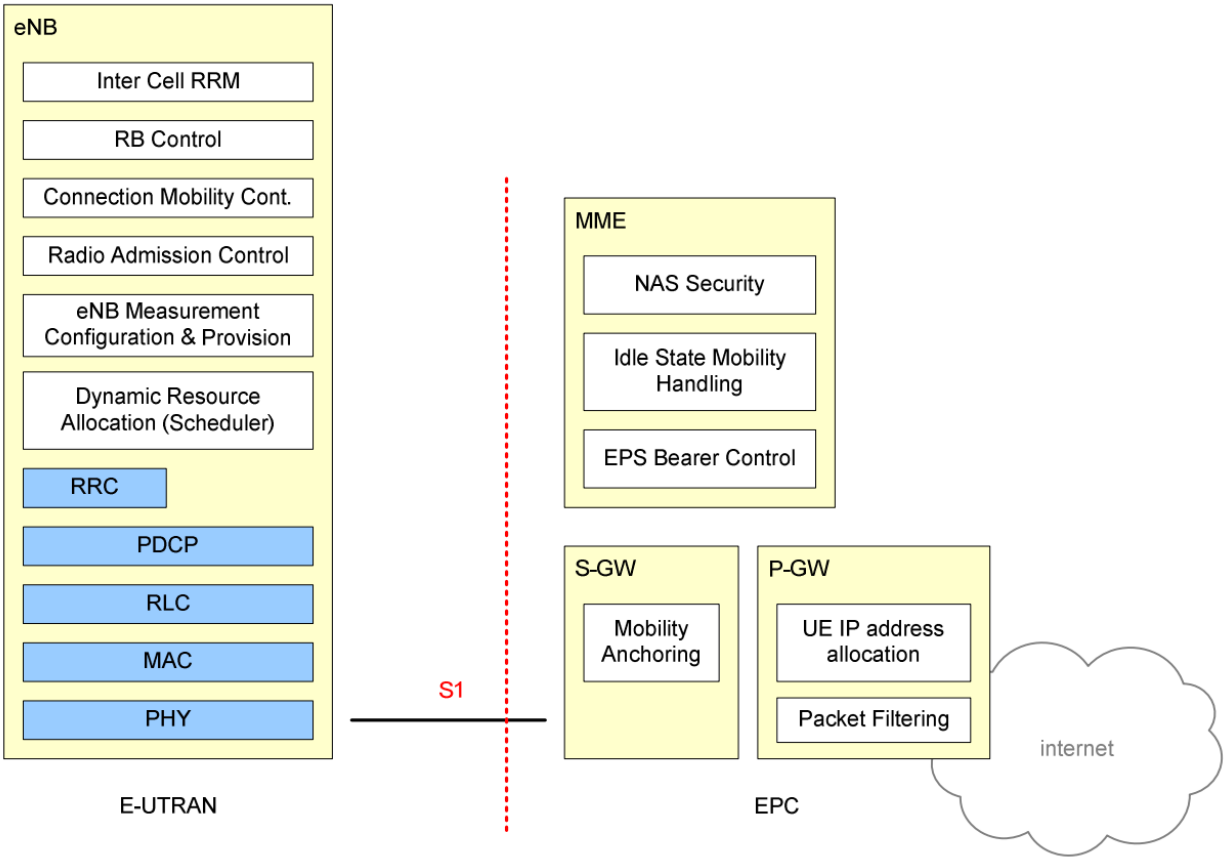

Figure 2.3: Functional Split between E-UTRAN and EPC (ETSI, 2015)

2.1.1.1. User Equipment

User Equipment (UE) is a device used by an end-user to communicate directly with mobile networks. The architecture UE used in LTE is identical to the one used by UMTS and GSM. The figure 2.4 shows the internal architecture of UE. The main device used for actual communication is the mobile equipment (ME). It is further divided into two components: mobile termination (MT) and terminal equipment (TE). The MT handles all the communication functions whereas TE terminates the data streams. The universal integrated circuit card (UICC) is a smart card which is known as SIM card runs an application known as the universal subscriber identity module (USIM). It stores subscriber information such user´s phone number and home network identity (Cox, 2012).

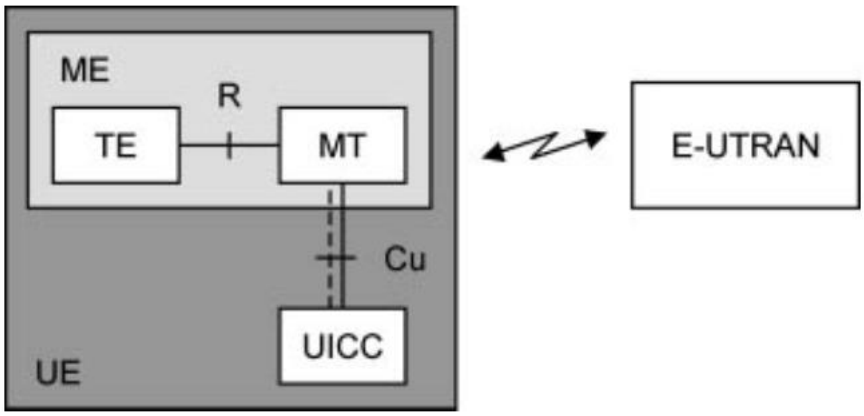

Figure 2.4: Internal architecture of the UE *(Cox, 2012)*

2.1.1.2. Architecture of E-UTRAN

E-UTRAN is an access part of an LTE system which handles the radio communication between user equipment and the EPC. It is basically a collection of evolved Node B (eNB) which serve as base station that controls the mobiles in one or more cells. The figure 2.5 shows an overall E-UTRAN architecture. The eNBs are inter-connected with each other and hence there is no centralized controller in E-UTRAN. So E-UTRAN architecture is said to be flat.

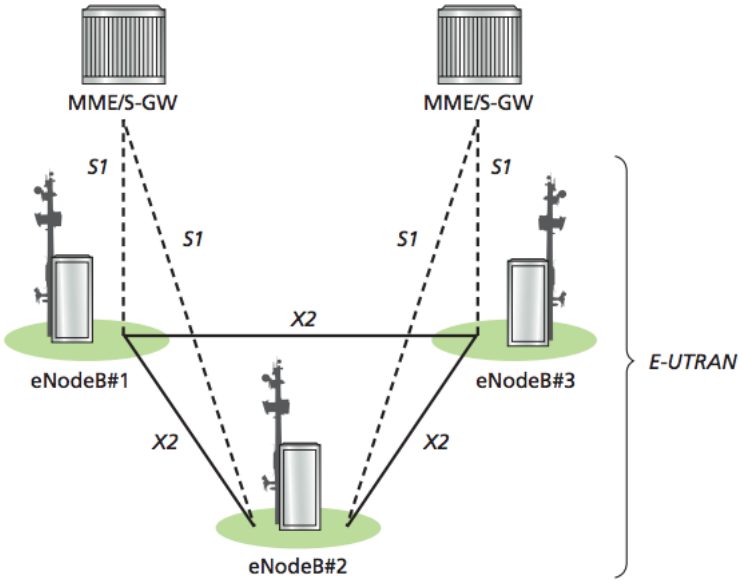

Figure 2.5: EUTRAN architecture (Alcatel.Lucent, 2013)

The main function of eNB is to send radio transmissions to mobile devices on the downlink and receives transmission from them on the uplink. The eNB also controls the low level operation of all its mobiles by sending them signaling messages such as handover commands that relate to those radio transmissions (Cox, 2012). The eNBs are interconnected by means of the X2 interface and to the EPC by means of the S1 interface. The protocols which runs between eNBs and UE are known as Access Stratum(AS) protocols. Overall, the EUTRAN is responsible for all radio related functions such as radio resource management, header compression, security, positioning and connectivity to the EPC (Sesia, Toufik, & Baker, 2011)

2.1.2. Architecture of Evolved Packet Core

EPC is the latest evolution in the core network architecture of the 3GPP´s LTE wireless communication standard. It has a flat, all-IP architecture with the separation of control plane and user plane traffic. This separation makes the network scaling independent and the network operators can dimension and adapt their network easily. It was decided to have a flat architecture to improves the network performance and through a flattened IP architecture, few network nodes are involved in the handling of the traffic (Firmin, 2016). The figure 2.6 shows the main components of EPC.

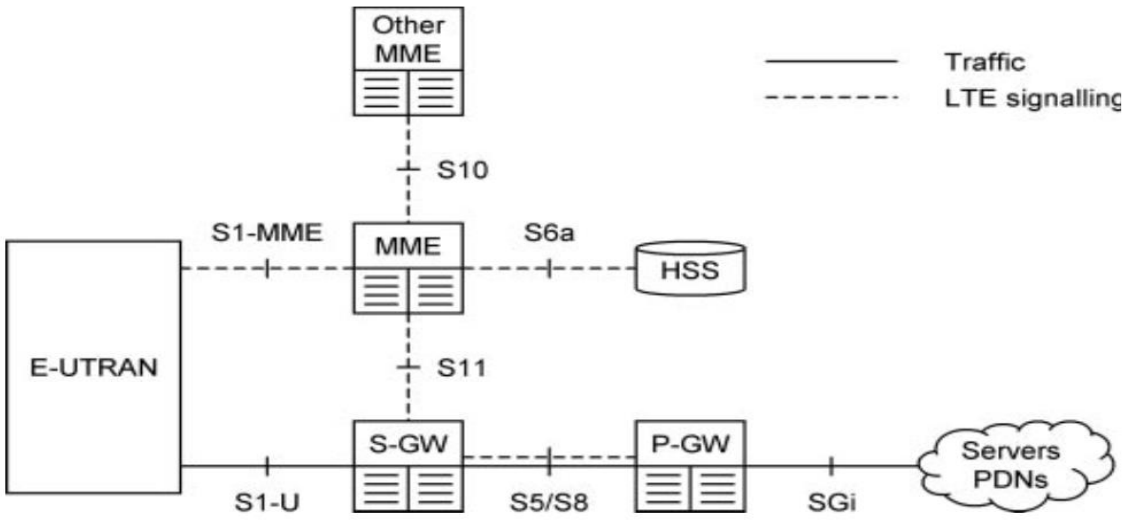

Figure 2.6: Main components of the EPC (Cox, 2012)

2.1.2.1. User Plane – Data Flow

The main components involved in user plane side are shown in figure 2.7 below. The functions of each component is described below.

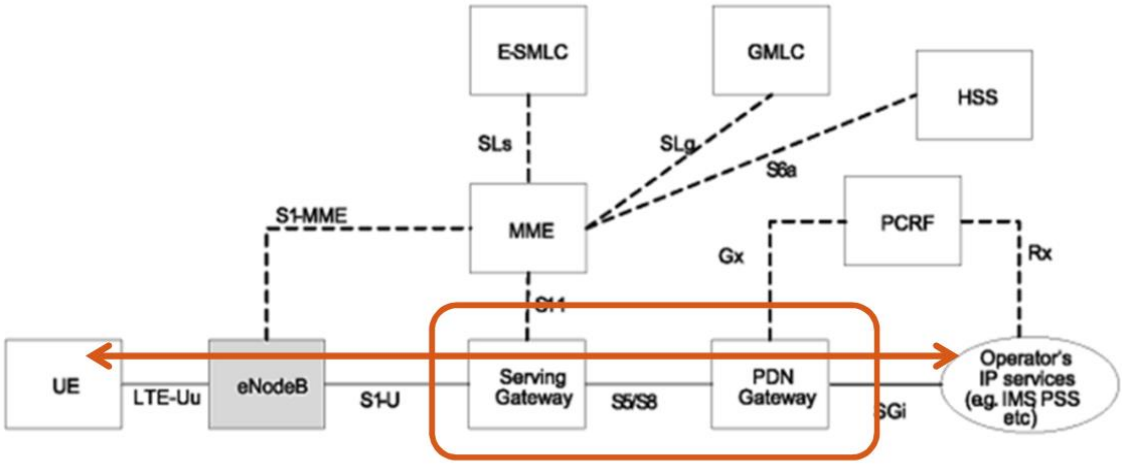

Figure 2.7: The EPS network elements- data flow (Lehne, 2015)

- **Serving Gateway (S-GW).** SGW manages user-plane mobility and serves as the local mobility anchor for the data bearers when the the UE moves between eNodeBs. It maintains the data paths between eNodeBs and the Packet Data Network Gateway (PDN GW). It also gets the information about the bearers when the UE is in idle state which is know as EPS connection Management IDLE. In addition, the SGW performs some administrative functions in the visited network such as collecting information for charging and legal interception (Sesia, Toufik, & Baker, 2011).
- **Packet Data Network Gateway (PDN GW).** The PDN GW is the point of contact between the EPC and external IP networks. It routes the IP packets to and from the external networks. Through the SGi interface, each PDN GW exchange data with one or more external device or Packet Data Networks. Each packet data network is identified by an access point name (APN) (Cox, 2012). It also performs other functions such as IP address allocation, Policy control and charging.

2.1.2.2. Control Plane – Signaling Flow

Control plane in LTE consists of HSS, MME, PCRF and GMLC. The functions of each are outlined below.

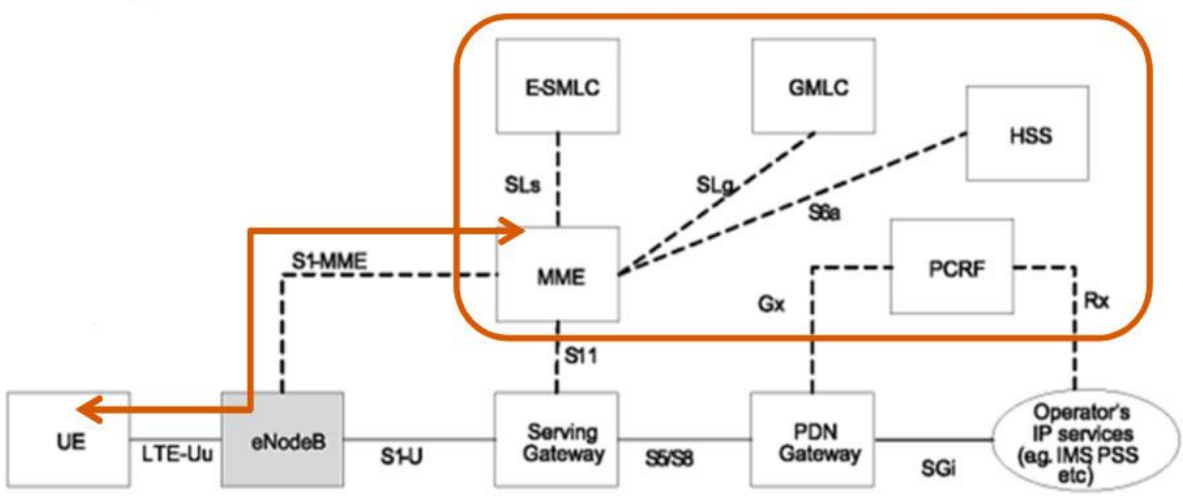

Figure 2.8: The EPS network elements-control flow (Lehne, 2015)

- **Home Subscriber Server (HSS).** HSS is a database that contains subscriber related information. It may include the Authentication Center (AC) which generates the vectors for authentication and security keys. It also provides the support in mobility management and call session setup.

- **Mobility Management Entity (MME).** MME is the main signaling node in the EPC. It is responsible for initiating paging and authentication of the mobile device. MME maintains location information at the tracking area level for each user and then selects the appropriate gateway during the initial registration process. MME is the key element for gateway selection within EPC (Serving and PDN) and also plays a vital role in handover signaling between LTE and 2G/3G networks. Multiple MMEs can be grouped together in a pool to meet increasing signaling load in the network (RCR Wireless News, 2014).

In addition to these components, EPC also have two other nodes such as Gateway Mobile Location Center (GMLC) and Policy Control and Charging Rule Function (PCRF).

- **Policy Control and Charging Rule Function (PCRF):** PCRF is the part of policy and charging control (PCC) function that supports service data flow detection, policy enforcement and flow based charging.
- **Gateway Mobile Location Center (GMLC):** GMLC interfaces the GSM core network, UMTS core network and the LTE evolved packet core network, and provides location based services. It may request routing information from the HSS and sends positioning requests to visited MSC, SGSN or MSC server and receives final location of the devices (Wikipedia, 2016).

2.1.3. Protocol Architecture

In this section we will discuss about the radio protocol architecture of E-UTRAN. The radio protocol architecture for LTE can be separated into control plane architecture and user plane architecture. The user plane consists of a set of protocols used to transfer the actual user data through the LTE network, whereas the control plane consists of protocols used to control and establish the user connections and bearers within the E-UTRAN.

Data packets created at the user plane side are processed by protocols such as TCP, UDP and IP while the the radio resource control (RRC) protocol writes the signaling messages that are exchanged between the base station and the mobile in the control plane. In both cases, the information is processed by the packet data conversion protocol (PDCP), the radio link control (RRC) protocol and the medium access control (MAC) protocol, before being passed to the physical layer for transmission (Obaidat, Zarai, & Nicopolitidis, 2015).

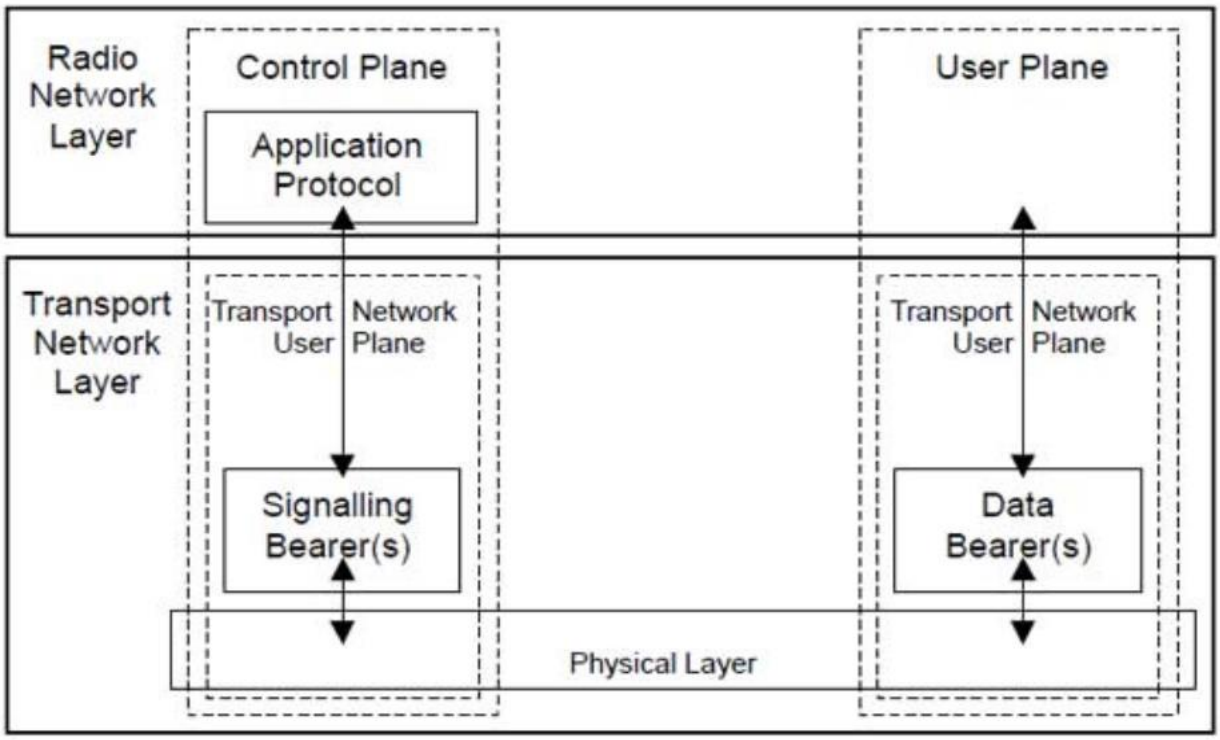

Figure 2.9: LTE protocol Architecture (Tutorialspoint, 2016)

2.1.3.1. User Plane Protocol Stack

The user plane protocol stacks for E-UTRAN composed of three sub-layers: Packet Data Conversion Protocol (PDCP), RLC and MAC sub layers. On the user plane, packets for the UE is encapsulated in a specific EPC protocol tunneled between the P-GW and eNodeB. Different tunneling protocols are used depending on the interface. GPRS Tunneling Protocol (GTP) is used on the S1 interface between eNBs and S-GW and on the S5/S8 interface between the S-GW and P-GW (Sesia, Toufik, & Baker, 2011). Packets received by a layer is called Service Data Unit (SDU) while the packet output by a layer is called protocol Data Unit (PDU). At user plane, packets flow from top to bottom layers. The greyed region of the figure below shows the E-UTRAN user plane protocol stack. The role of each of these layers are explained below.

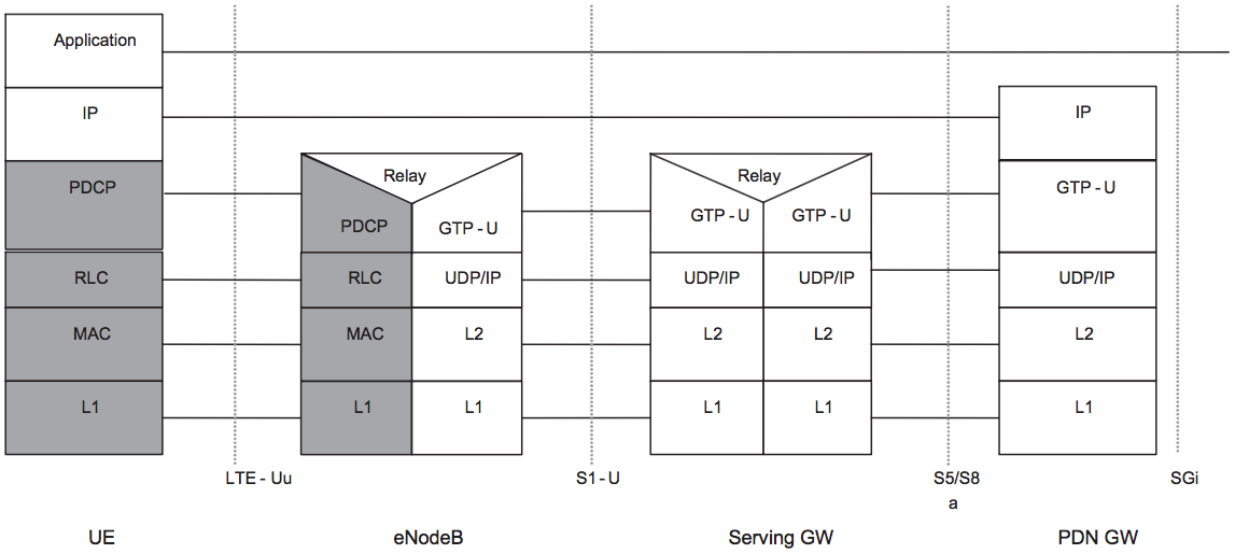

Figure 2.10: The E-UTRAN user plane protocol stack (Sesia, Toufik, & Baker, 2011)

- **Packet Data Conversion Protocol (PDCP):** PDCP layer processes IP packets in user plane. The main functions of this layer are header compression, security, and support for retransmission during handover.
- **Radio Link Control (RLC):** The main functions of this layer are segmentation and reassembly of upper layer packets to fit them for transmission over the radio interface. It also performs retransmission to recover from packet losses for radio bearers requiring error free transmission. Additionally, RLC layer performs reordering to compensate for out of order reception due to Hybrid Automatic Repeat request (HARQ) operation in layer below (Sesia, Toufik, & Baker, 2011).
- **Medium Access Control (MAC):** MAC layer is responsible for mapping between logical channels and transport channels, multiplexing of data from different radio bearers, error correction through HARQ, and aims to achieve the QoS for each radio bearers.

2.1.3.2. Control Plane Protocol Stack

The control plane includes all the user plane sub-layers with additional Radio Resource Control (RRC) layer which is responsible for configuring the lower layers. There is no direct path

between the MME and the UE through which data and signaling messages can be transported. The air interface is therefor divided into two levels, known as the access stratum (AS) and the non access stratum (NAS). The control plane handles radio related functions which depends on UE state. When UE is in idle mode, AS performs cell selection and reselection and monitors paging channel to detect incoming calls and acquires the system information. In figure 2.11, the greyed region of the stack indicates the AS Protocols. The lower layers perform the same functions as for the user plane with the exception that there is no header compression function for control plane (Sesia, Toufik, & Baker, 2011). PDCP protocol processes RRC messages in control plane. Transfer of control plane data, ciphering and integrity protection are the main services and functions of the PDP for the control plane.

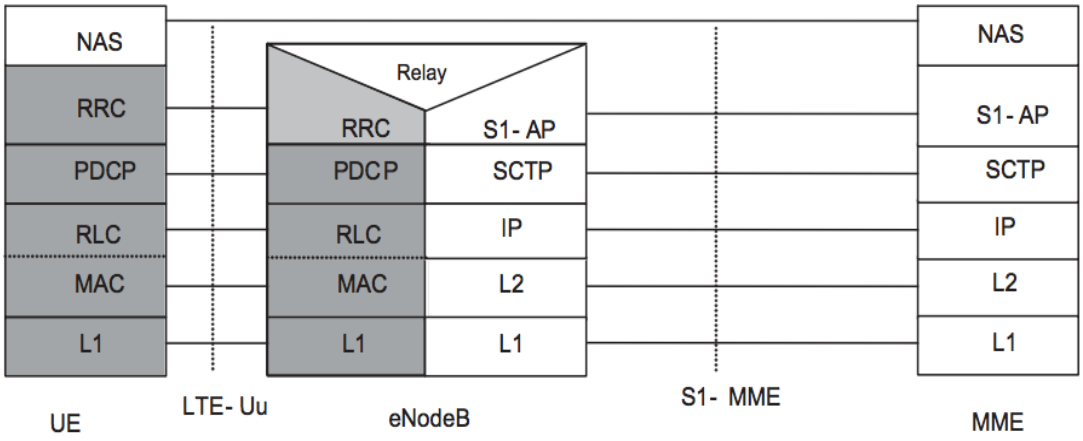

Figure 2.11: Control Plane Protocol Stack (Sesia, Toufik, & Baker, 2011)

NAS is the highest stratum of the control plane between UE and MME at the radio interface. The support of mobility of the UE and the support of session management procedures to establish and maintain IP connectivity between the UE and a PDN GW are the main functions of the NAS protocols. These protocols handle Public Land Mobile Network (PLMN) selection based on a list of available PLMNs provided by the AS. Other functions that are performed by NAS control protocols are: authentication, security control, EPS bearer management, and paging. To receive paging messages from E-UTRAN, UEs in idle mode monitor the downlink control channel (PDCCH) (Ques10, 2016).

2.1.4. LTE radio interface

The LTE radio access network is the collection of eNBs, each of which is connected by an S1 interface to the EPC core network. Specifically, the control plane is connected to the MME via an S1-MME interface, and the user plane is connected to the S-GW via an S1-U interface. Both interfaces are based on IP and include separate control and user plane protocol stack. Neighboring eNBs are connected via an X2 interface. Each eNB preforms Radio Resource management (RRM) tasks such as call admission control, handover control and bearer management and terminates all the radio interfaces protocols used for communication with the UE. (Okubo, Umesh, Iwamura, & Atarashi).

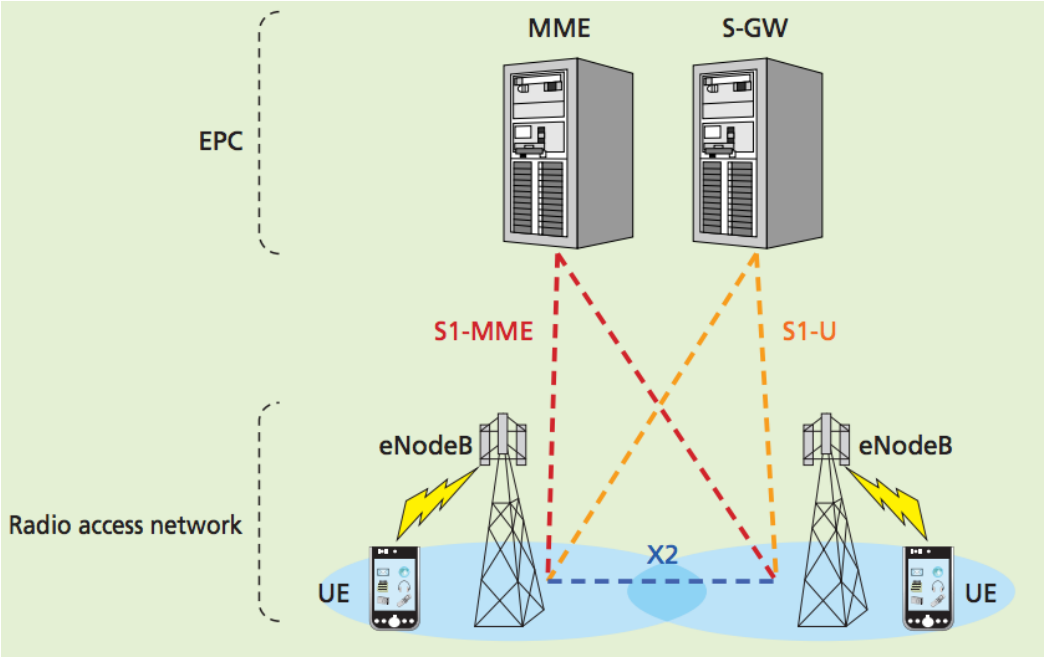

Figure 2.12: LTE Radio access network (Okubo, Umesh, Iwamura, & Atarashi)

2.1.4.1. S1 Interface

S1 interface lies between eNBs and MME and S-GW. In the user plane, this interface will be based on GTP User Data Tunneling (GTP-U). In the control plane, the interface is more similar

to Radio Access Network Application Part (RANAP), with some simplifications and changes due to the different functional split and mobility within EPS. The S1 interface is split into a S1-CP (control plane) and S1-UP part (User Plane). The signaling protocol for S1 is called S1-AP (ASCOM Tools, 2016).

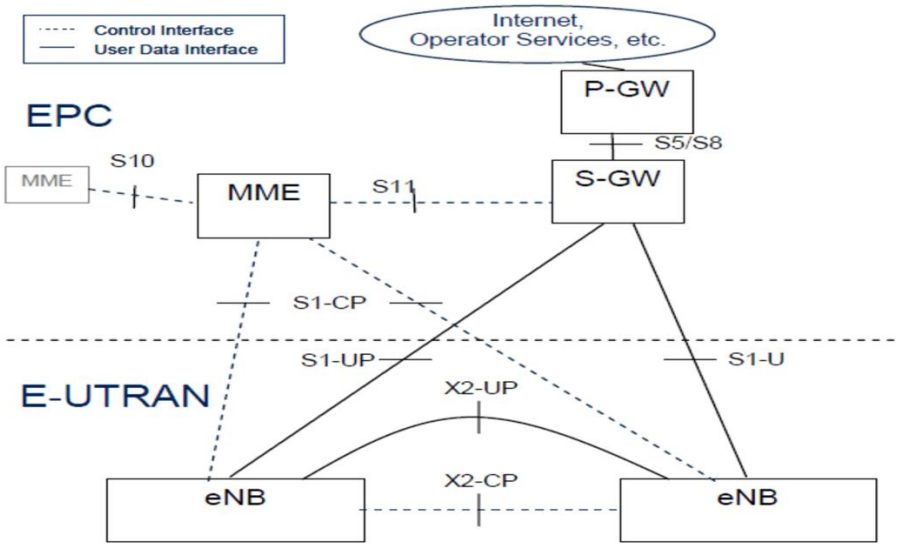

Figure 2.13: LTE S1 Interface (ASCOM Tools, 2016)

The S1-U interface is responsible for delivering user data between eNB and the S-GW. While the S1-MME interface is responsible for delivering signaling protocols between eNB and the MME. The S1-MME interface consists of a Stream Control Transmission Protocol (SCTP) over IP and supports multiple UEs through a single SCTP association. It provides guaranteed data delivery and is responsible for EPS bearer management, handover signaling procedure, paging and the NAS transport procedure. Similar to the user plane, LTE transport network layer is built on IP transport but for reliable transport of signaling messages SCTP is added on top of the IP (Teletopix, 2014).

2.1.4.2. X2 Interface

In UMTS networks, Node Bs could not communicate with each other. They had to communicate through Radio Network Controller (RNC). However, in LTE there is X2 interface for direct communication. The X2 interface is used for direct communication between eNBs which supports the exchange of signaling information between eNBs and also supports forwarding of PDUs to tunnel endpoints. It is a point to point interface and it works even if two eNBs may not be connected physically. It facilitates the interconnection of eNBs supplied by different manufactures (3GPP TS 36.420 V8.0.0, 2008).

Similar to S1 interface, X2 also has two planes: Control Plane and User Plane. User plane is based on GPT-U, UDP and IP and control plane uses SCTP and IP. The X2 interface is established between one eNB and some of its neighbor eNBs in order to exchange signaling information. To be exchanged over X2, two types of information is needed: load and handover related information. The initialization of the X2 interface starts with the identification of a suitable neighbor followed by the setting up of the Transport Network Layer (TNL). After the TNL has been set up, the initiating eNB must trigger the X2 setup procedure. Once the X2 Setup procedure has been completed, the X2 interface is operational (Alcatel.Lucent, 2013).

2.2. Software Defined Radio (SDR)

SDR has changed the radio system engineering. Traditional hardware radios implement radio protocols using static electrical circuit. Different wireless devices can not communicate with each other due to their hardwired radio systems. SDR implements many radio system components using software programs and users can enable the radio to support different wireless communication protocols by simply configure the waveform software. This makes the SDR devices tremendously versatile and has converged the cellular system from a slow moving proprietary and expensive hardware platforms towards an open source software platform (Lee, 2012).

SDR makes it possible to use the electromagnetic spectrum in new ways. Most radio standards today are designed to use a fixed narrow standard band. In contrast, SDR devices can tune into many different frequencies simultaneously (Lee, 2012). SDR now becomes the heart of the 4G mobile communication to access any network at any time basis. It is the main device for a user terminal to access different wireless network using individual IP address. The figure 2.14 shows a block diagram of a software defined radio receiver.

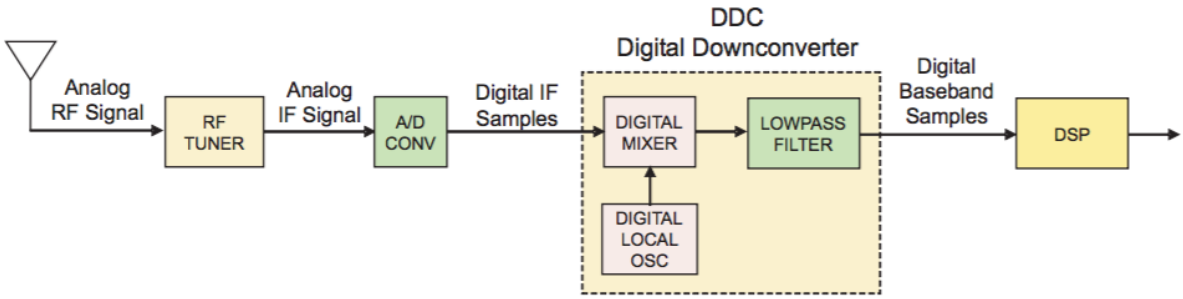

Figure 2.14: Software Defined Radio Receiver (Hosking, 2016)

It consists of mainly two parts, one analog part and another digital part. The analog part consists of antenna and RF Tuner. At the digital part, the received analog signal is digitized by the analog to digital converter (ADC) immediately after the analogy processing (Alam & Sobhan, 2010). These signals are then fed to the Digital Down Converter (DDC). The DDC has sub sections: a digital mixer, a digital low oscillator and a low pass filter. The digital mixer and local oscillator translate the digital intermediate frequency (IF) samples down to baseband and the low pass filter limits the signal bandwidth. The digital baseband samples are then fed to a block called digital signal processor (DSP) which performs the tasks such as demodulation, decoding, security and other processing tasks (Hosking, 2016).

The transmitter side of an SDR system is similar to the SDR receiver. The input to the transmitter SDR is a digital baseband signal which are then translated to the IF frequency by the digital up converter (DUC). Finally, Digital to Analog (DAC) converter converts the digital IF samples into the analog IF signal.

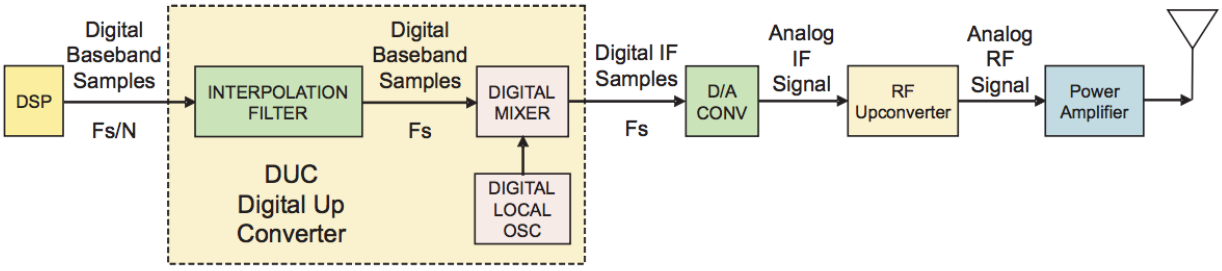

Figure 2.15: SDR Transmitter System (Hosking, 2016)

As SDRs have become more commonplace, many companies and organizations have developed hardware front-ends and software packages to help in software radios development. The most prominent hardware front ends to date have been the USRP hardware boards. Additionally, many software packages exit for SDR development, including the open source GNU Radio and OSSIE (Open Source SCA Implementation- Embedded) and closed source Simulink and LabView SDR packages. Using these development tools, researchers have developed many of the most relevant radio standards. Finally, we can say that the advantage of SDR is in the deployment. It allows us to change the modulation schema without necessarily throwing the hardware design away which save development cost (Haldren, 2014).

2.2.1. Universal Software Radio Peripheral (USRP)

USRP is a software radio platform developed and sold by Ettus Research and its parent company, National Instruments. The basic idea behind the USRP is to do all the signal processing functions on the hosts CPU. Its main goal is to enable users to create their own SDRs, and it is used predominantly by researchers and universities. The key advantages of USRP are its versatility, large development community, and high amount of associated software (Dickens, Dunn, & Laneman, 2008).

The USRP comes with a small motherboard containing up to four analog to digital converter (ADC), four digital to analog converter (DAC), a field programmable gate array (FPGA), and an antenna connected to a radio frequency (RF) front end. In addition to a motherboard, there are up to four different kinds of daughter boards that are supported by the motherboard.

Varieties of daughter boards are available as either transmitter, receiver or both, and are designed to handle different frequency bands (Blossom, 2004). However, the daughterboard currently on the market are wideband enough that one daughterboard can suffice for many different radio protocols (Haldren, 2014). The USRP connects to a host computer via either a USB or Gigabit Ethernet connection, depending on the USRP model. It is compatible with Window, Mac OS X and many of the UNIX distributions operating systems (OS). Linux OS is the most commonly used OS with the USRP because of its open source nature. After connecting to the computer, the USRP device communicate with the host computer using the USRP Hardware Driver (UHD).

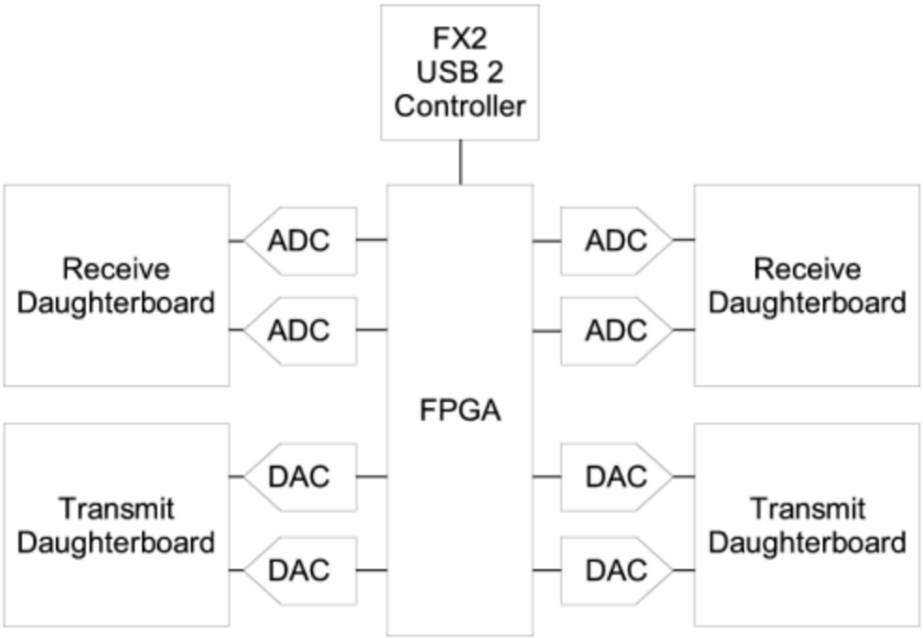

Figure 2.16: Block diagram of USRP (Blossom, 2004)

The USRP is not merely one product but is actually a family of products which includes a variety of models that use a similar architecture. Each of these USRP boards differs in terms of features offered and supported (Haldren, 2014). Currently, Ettus Research produces four main USRP models. The USRP X series are high-performance, scalable software defined radio platforms for designing and deploying next generation wireless communication system. The Bus series is designed for applications that do not require the higher bandwidth and the dynamic range. Bus series use a USB 2.0 or USB 3.0 interface to transfer samples to and from the host computer. The USRP N series are high performance USRP devices that provide higher

dynamic range and higher bandwidth than the bus series. Finally, embedded series is designed for applications that require stand-alone operation (Ettus, 2016).

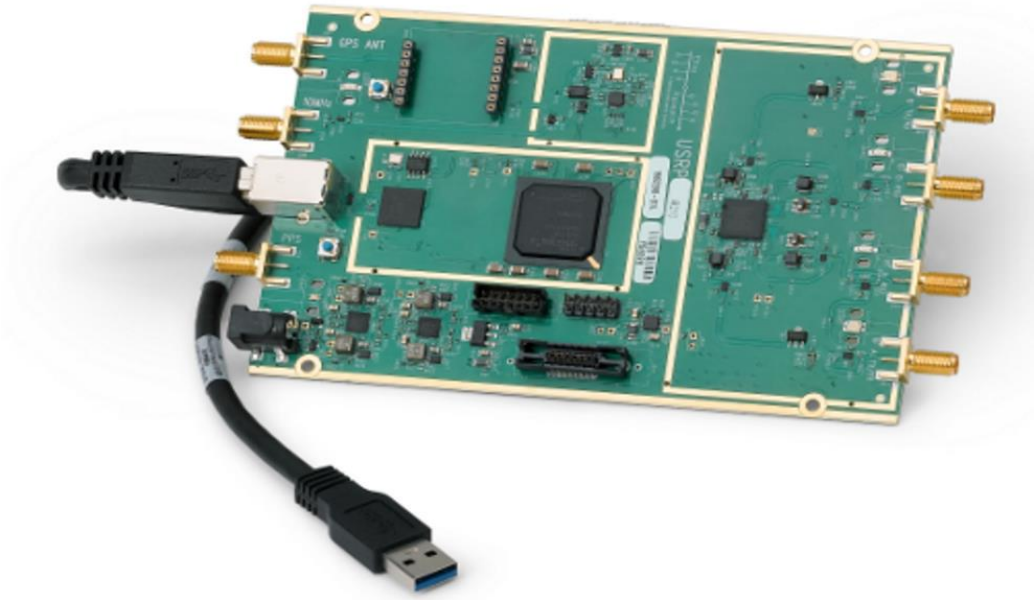

Figure 2.17: USRP B210 Board

The entire USRP design is open source, including schematics, firmware, drivers, and even the FPGA and daughterboard designs. When combine with the open source GNU radio software, we get a completely open software radio system enabling host-based signal processing on commodity platforms (Ettus Research , 2014). The USRP uses the GNU Radio framework for PHY layer processing on the PC. Description about the GNU Radio is given in the next section.

2.2.2. USRP Hardware Driver (UHD)

The USRP hardware driver (UHD) is the device driver provided by Ettus Research for use with the USRP product family (Ettus Research, 2016). It is an open source library which runs on all major operating systems Linux, Mac OSX, and Windows. The goal of UHD is to provide a host driver and API for current and future Ettus Research products. Users will be able to use the UHD driver standalone or with 3rd party applications (Kirkland, 2010).

2.2.3. GNU Radio

GNU Radio is an open source software development toolkit used to design and implement software radios. It is specifically designed and maintained for use with the USRP platform. However, GNU Radio is also compatible with many other hardware front-ends (Haldren, 2014). It can also be used without hardware in a simulation-like environment. It is widely used in hobbyist, academic and commercial environments to support both wireless communication research and real world radio systems (GNU Radio, 2013).

GNU Radio has been used for real world radio applications, including audio processing, mobile communications, tracking satellites, radar systems, GSM networks, and much more. GNU Radio works by breaking down digital signal processing into blocks and connections between those blocks. The signal processing library of GNU Radio provides signal processing blocks for modulation, demodulation, filtering, and I/O operation such as file access. In addition, it also provides blocks for communicating with the USRP. A radio is built by connecting these blocks to form a flow graph through which the signal flows on a systems level. The flow graphs can either be represented through source code by an executable Python script or through a graphic user interface known as GNU Radio Companion (GRC) (Dhar, George, Malani, & Steenkiste, 2006). The GRC is the front end to the GNU Radio libraries for signal processing. It is basically a Python code generation tool. When a flow graph is compiled in GRC, it generate Python code that creates the desired GUI windows and widgets, and creates and connects the blocks in the flow graph (Wikipedia, 2016)

Programming in the GNU Radio platform uses a combination of C++ and Python programming languages. The flow graphs and applications that sit on top are written in Python while the processing blocks are implemented in C++.

3. Overview of available Open Source Mobile Communication Software

This chapter provides an overview of some well-know open source mobile communication software which have made a significant impact on mobile communication networks. In addition to describing these software, the chapter illustrates their scalability, reliability, openness and security.

3.1. OpenBTS

OpenBTS is a software based GSM system that uses a Software Defined Radio (SDR) as a transceiver to present a GSM air interface to standard 2G handsets. On the backend, OpenBTS uses a SIP soft-switch to connect calls, so it can be integrated with VoIP phone systems (Gallagher, 2014). Instead of forwarding the call traffic towards Mobile Switching Center (MSC), it delivers call via SIP to a soft switch such as Asterisk or FreeSwitch. The combination of SDR transceiver with low cost VoIP soft switch forms the basis of a new type of cellular network that can be deployed and operated at very lower cost than the existing technologies. It looks like a simplified version of IP Multimedia Subsystem (IMS) that works with 2G features handsets (OpenBTS , 2014).

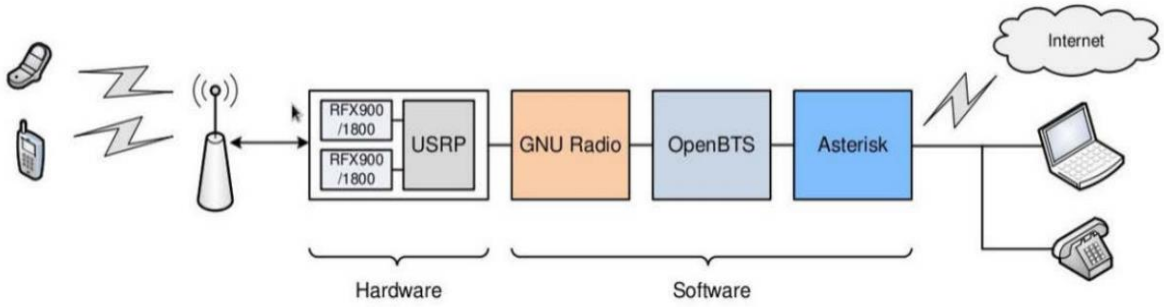

Figure 3.1: Openbts (Bongiorni, 2010)

The OpenBTS project is a collection of open source software components. The main software components are OpenBTS, Asterisk, SMQueue and SIPAuthServe. These four open source software encompass an entire GSM infrastructure needed to run a complete GSM network. OpenBTS is the main component of the project which is responsible for implementing the GSM air interface in software and communicating directly with GSM handsets over it. Asterisk is an open source PBX/SIP switch that routes all SIP traffic in the network. SIP Message Queue (SMQueue) is an application that processes SIP message requests generated by OpenBTS when a handset sends an SMS. SIP Authorization Server (SIPAuthServe) is a Home Location Register (HLR) that maintains the Subscriber Registry (SR). When a handset authenticates successfully, SIPAuthServer is responsible for updating the subscriber registry database with the IP address of the OpenBTS instance that initiated it, allowing other subscribers to call the handset (Iedema, 2015).

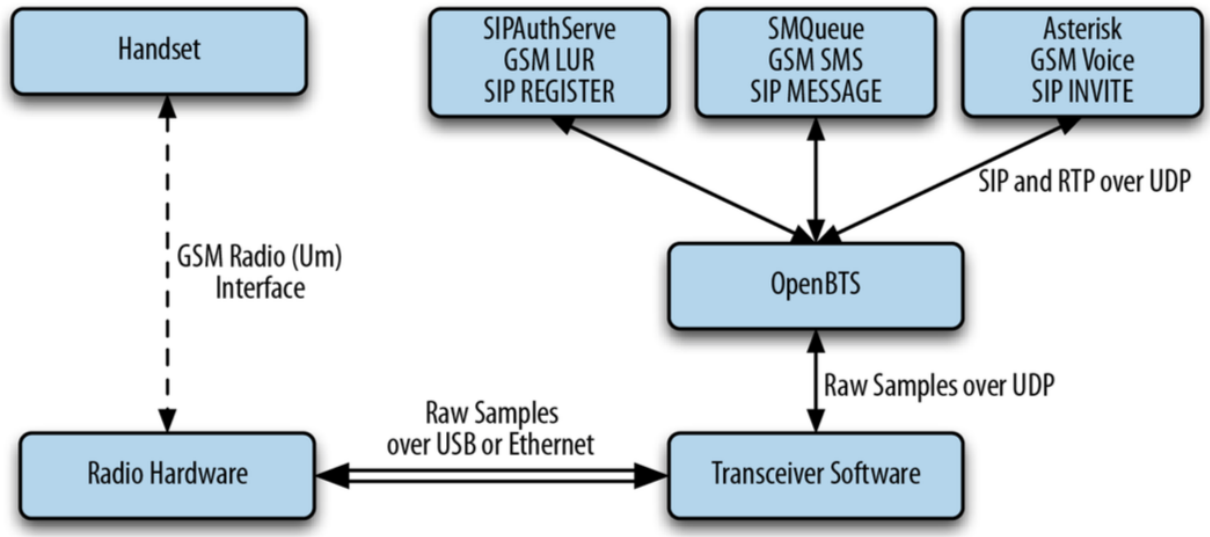

Figure 3.2: Components of OpenBTS (Iedema, 2015)

OpenBTS project was started by developers Harvind Samra and David A. Burgess with the intension of reducing the cost of GSM service which can deploy in remote areas with low populations. Now it is maintained by Range Networks. Big telecommunication companies are not interested to build GSM network in such places as they would not be profitable. Range

networks is able to bring the technology to the rural areas in the developing countries in Africa and Asia where people live in a small towns and village and have low income. Though OpenBTS is typically used in remote areas with low populations, it is intended for experimentation, education, and proof-concept uses.

3.1.1. Scalability, Reliability, Openness and Security

OpenBTS is an open source software implementation of a base station that runs on a Linux PC. It can even be run on virtualized servers in the cloud. The combination of OpenBTS and Software Defined Radio changes the way we think about the mobile networks. Anyone can cheaply build, operate, and learn how cell networks work. A mobile user within such a network can place calls to each other even if the system is not connected to the Internet, but an Internet connection requires to make call anywhere in the world (Naone, 2010).

The latest release of OpenBTS 4.0 offers significant improvements in processing capacity and system management features, including multi-node network scaling enhancement to the commercial systems. According to Edward Kozel, CEO of Range Networks, Range Networks has improved the OpenBTS software with an aim toward taking the technology out of lab and into the commercial world. The new software release is also focused on deployability, quality, stability, and scalability in order to extend Range Network's technology deeper into the service provider market (Parker, 2014).

OpenBTS was considered as a fun lab project but the company scaled it and released the commercial version which will enable the product to benefit from testing and innovation by the open source community. The conversion of the network from legacy telco protocols to Internet protocols gives the operator new opportunities to implement speech, text and unstructured supplementary service data (USSD) applications using web service technologies like Apache and Ruby or through cloud –based application platforms like Tropo or Twilio (Range Networks01, 2014). The figure 3.3 shows a full scale OpenBTS Network.

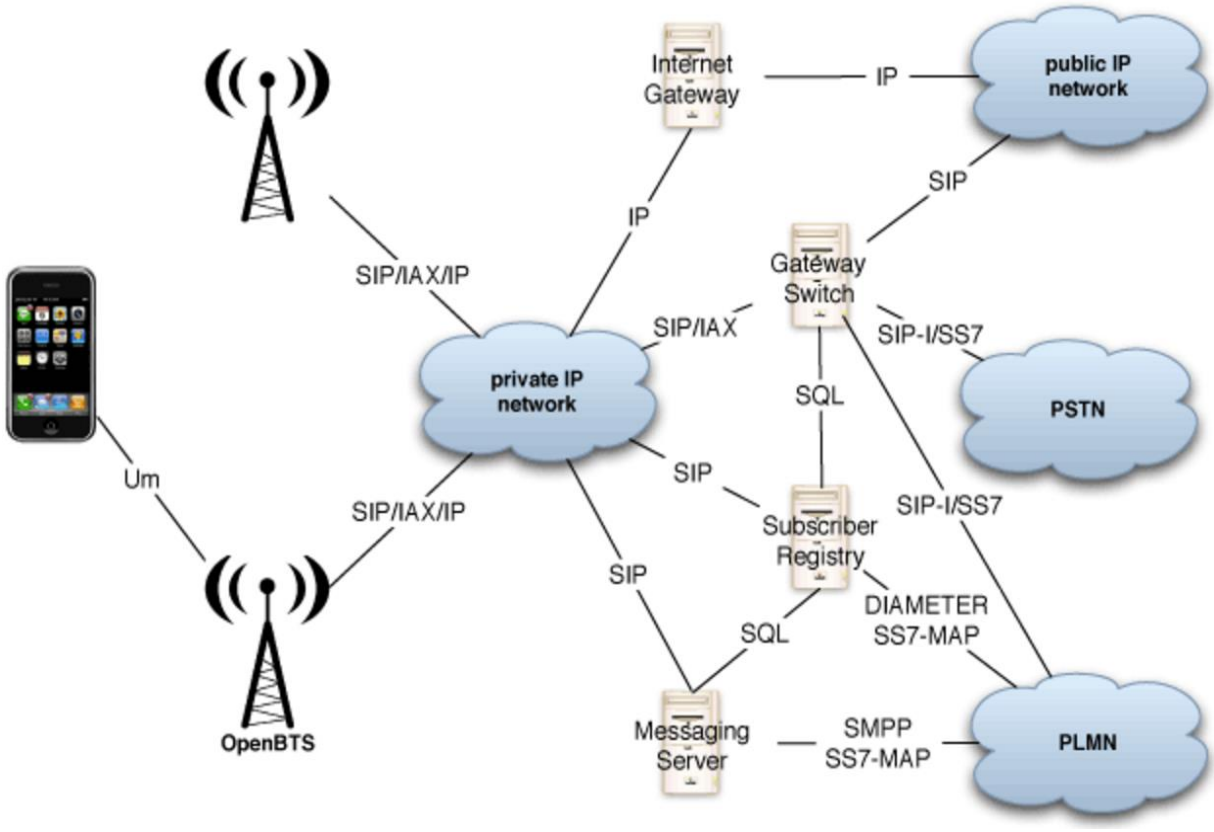

Figure 3.3: Full Scale openBTS network (Range Networks, 2016)

The radio interface used by cellular phones in OpenBTS is same as the conventional 2G and 2.5G networks support. On the network side, OpenBTS unit uses SIP/RTP or IAX for call signaling and SIP for mobility management and SMS. The subscriber registry (SR) is responsible for mobility and authentication functions associated with GSM. It is required to translate between 2G SIM and 3G/4G USIM authentication procedures. This compatibility allows OpenBTS operates in 3G and 4G networks in the coming days. OpenBTS units communicate with the SR via SIP while the other network elements access the SR directly with SQL. The gateway switch (GS) communicates with OpenBTS units using SIP/RTP or IAX and communicates with outside networks using an existing SIP switch with an ISDN/SS7 gateway functions (Range Networks, 2014).

As OpenBTS is SIP-based network, it allows easy integration of next-generation IMS core networks. OpenBTS-UMTS 1.0 code was released by Range Network but for now it supports

data transmission only. Ettus Research and Nuand have shown support for this 3G project and plan to develop SDRS that support OpenBTS-UMTS (Callon, 2014). According to the Kozel, for LTE the company need to develop a new radio, and that the radios it currently is using are fine for 2G and 3G networks, but do not have enough throughput for LTE. So the company is developing its own in house radios and working with others (Goldstein, 2014).

By using the Internet protocol and software architecture, OpenBTS has revolutionized the Mobile network industries. It can run on any simple computer which Linux operating system and connects with commonly used TCP/IP and UDP protocols. It can even run on a virtualized server in the cloud. The notable improvements to the latest release of OpenBTS 4.0 are expanded capacity, better battery life, built-in channel scanning, SMS processing etc.

The OpenBTS now supports more than 1000 subscribers in a single node because of the improved processing capacity. It has the better air interface security through the support of the A5/3 encryption algorithms. A new Layer 3 architecture has significantly improved scalability, including improved handover for multi-node networks. It is now implemented with a JSON API which enables mobile network operators to configure and manage a set of base stations via the web. There is a built-n channel scanning tool in order to identify the best transmission channel and SMS processing capacity has been improved in the latest release (Range Networks, 2014). With its improved performance, it becomes a platform for open source innovation. It also becomes a great tool for experimentation and education on 2G cellular protocols.

3.2. OpenBSC

OpenBSC is an open source implementation of the BSC features of a GSM network. It was mainly developed by Harald Welte and Holger Frether with the original intension as a platform for research and experimentation. The motivation behind the project came in 2006 when Harald Welte bought Siemens BS-11 BTC hardware via eBay. In 2008, Dieter Spaar and Harlad Welte were able to make a software BS11- Init which was capable of controlling the BS-11 via the A-bis protocol that is used between a BTS and BSC (Andrew Back). BS11-Init marks a major mile stone into the field of open source GSM software and is considered as a stepping stone for the start of OpenBSC (OSMOCOM, 2015).

OpenBSC project mainly focuses on GSM related components, libraries and tools in Open Source Mobile Communication (OSMOCOM). There are two mode of operations for BSC application; either as a classic BSC or as Open-BSC-Network in The Box (NITB).

NITB mode of operation is very different from classic GSM network. OpenBSC itself provides the functionalities of BSC, MSC, HLR, EIR and AuC. We only need at least one BTS and OpenBSC and there is no need for other parts of the GSM Network. The A-bis interface connects via IP or E1 to one of the available BTSs like Siemens BS-11, ip.access nanoBTS, sysmocom symoBTS fairwaves umSITE or osmoBTS plus SDR hardware (Cooper, 2012).

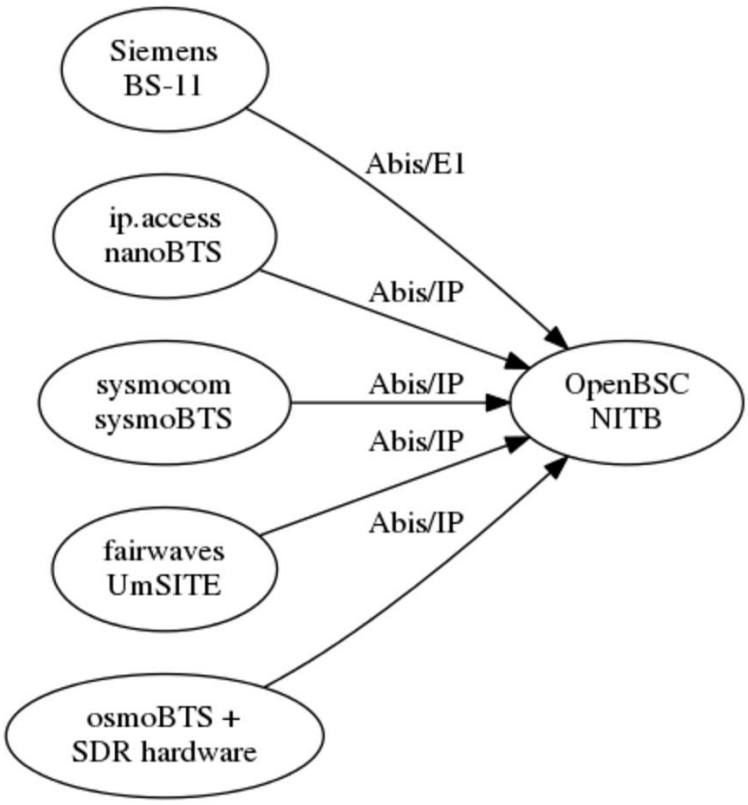

Figure 3.4: OpenBSC in NITB mode (OSMOCOM, 2015)

We can use OpenBSC as a classic GSM BSC. However, in this mode of operation we need all other components of GSM network and openBSC is situated between a BTS and MSC that can provide an A-over –IP interface using SCCP-lite (OSMOCOM, 2015).

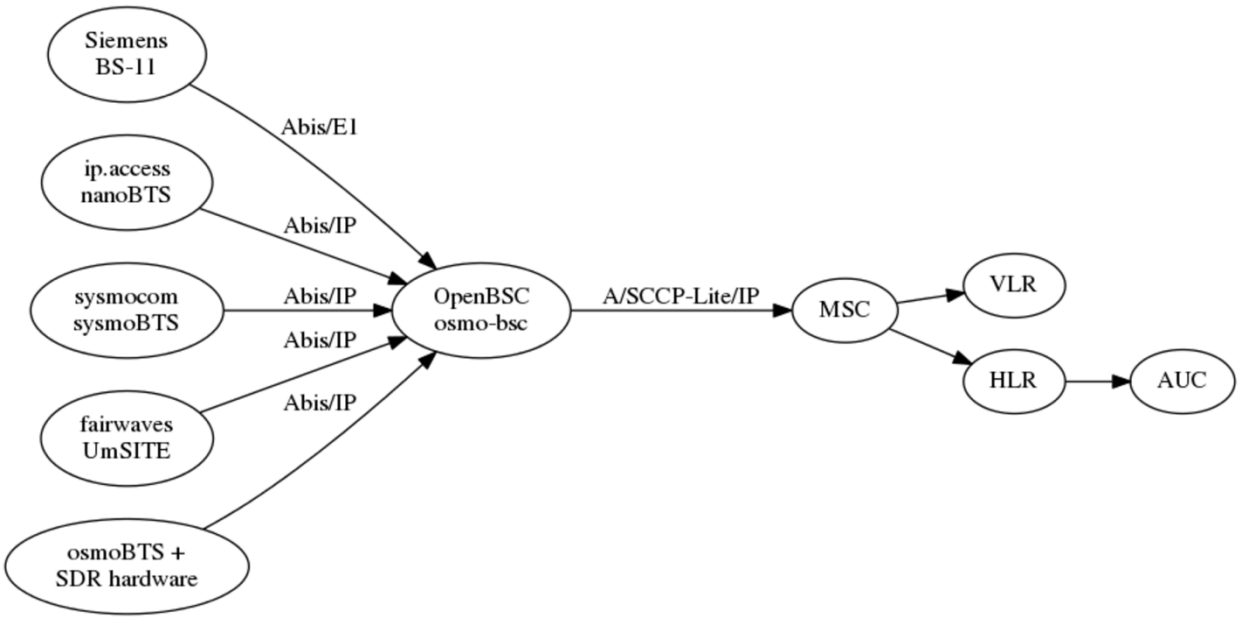

Figure 3.5: OpenBSC in only BSC-mode (OSMOCOM, 2015)

3.2.1. Scalability, Reliability, Openness and Security

OpenBSC is a project which was originally developed as a platform for research and experimentation purposes, but has moved way beyond the original intensions. Now it has been put to use in real world applications that include the network for the emergency services and disaster relief and the provision of maritime mobile phone networks for passengers and crews. It reduces the cost of building and operating traditional GSM networks through creating new products and services to provide cost effective solutions for developing nations (Back, Building a GSM network with open source, 2012). It is not just a standard BSC, but a GSM network in a box which includes the functionality performed by Base Station Controller (BSC), Mobile Switching Center (MSC), Home Location Register (HLR), Authentication Center (AUc), Visitor Location Register (VLR), and Equipment Identity Register (EIR). In addition to these

functionalities, the project also develops and maintains the osmo-sgsn and OpenGGSN in order to provide support for GPRS data service and EDGE capabilities (OSMOCOM, 2016).

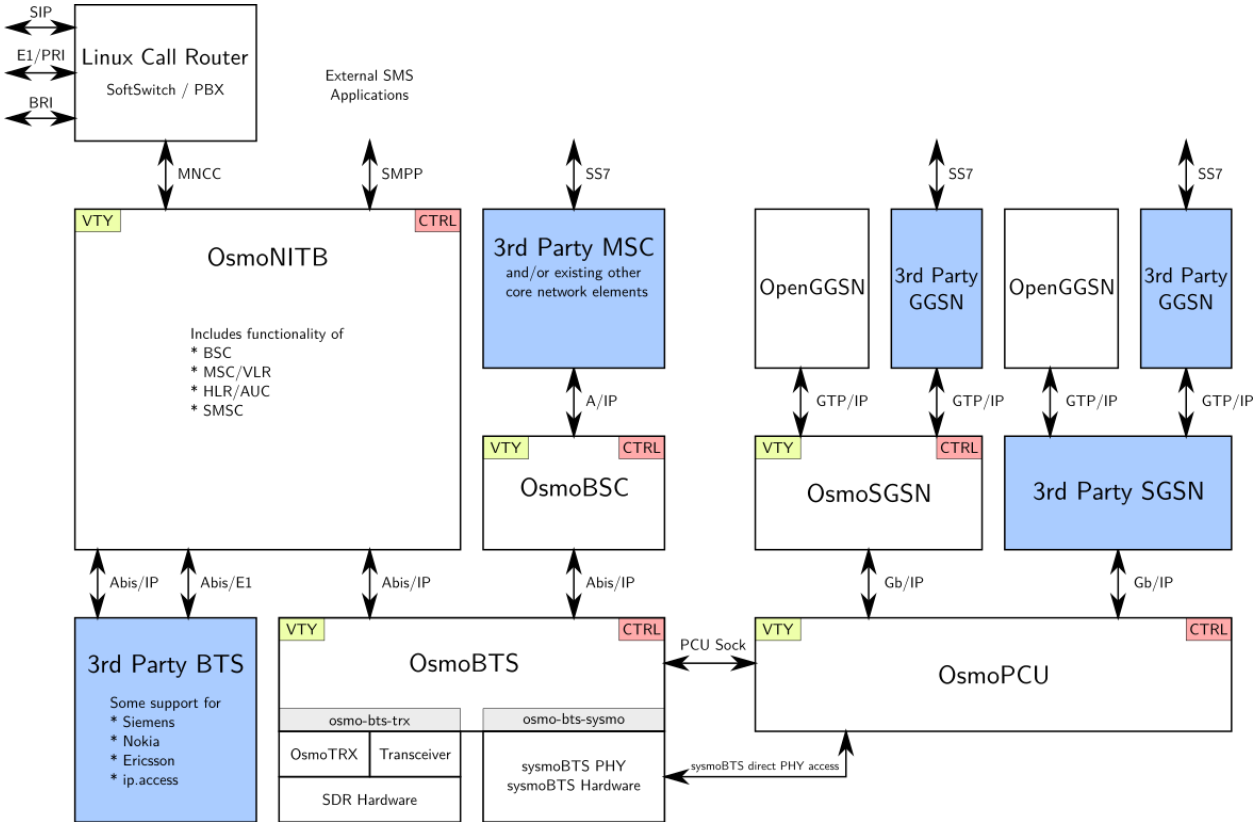

Figure 3.6: OpenBSC GPRS support (OSMOCOM, 2016)

OpenBSC also includes support for mobility management and authentication and intra-BSC handover, SMS and voice calls. GPRS and EDGE support are also possible if combined with OsmoSGSN and OpenGGSN as shown in the figure 3.6.

3.3. OpenIMSCore

The IP Multimedia Subsystem (IMS) is an architectural framework for delivering IP multimedia services (Wikipedia, 2016). The Open Source IMS Core project is an IP multimedia system for IMS technology testing. It was developed by the Fraunhofer Institute

FOKUS. It has to be noted that this Open Source IMS Cores System is not for commercial product development activities. Its purpose is to provide an IMS core reference implementation for IMS technology testing, IMS application development and prototyping (Core Network Dynamic, 2015). Open IMS is in a constant process of evolving. It is open for new partners, new components, new technologies, as well as new concepts and paradigms. It is a test laboratory where different partners can carry out component test, conformance test, interoperability test and deploy and operate their own development (Fraunhofer FOKUS, 2015).

The Open Source IMS core consists of Call Session Control Functions (CSCFs), the central routing elements for any IMS signaling, and a Home Subscriber Server (HSS) to manage user profiles and associated routing rules (University of Patras, 2012) . The central components of Open Source IMS Core are IMS Call Session Control Functions (CSCFs) and a Home Subscriber Server (HSS). Most of the key components are same in both IMS and Open IMS Core but SIP2IMS gateway is only exits in open IMS Core.

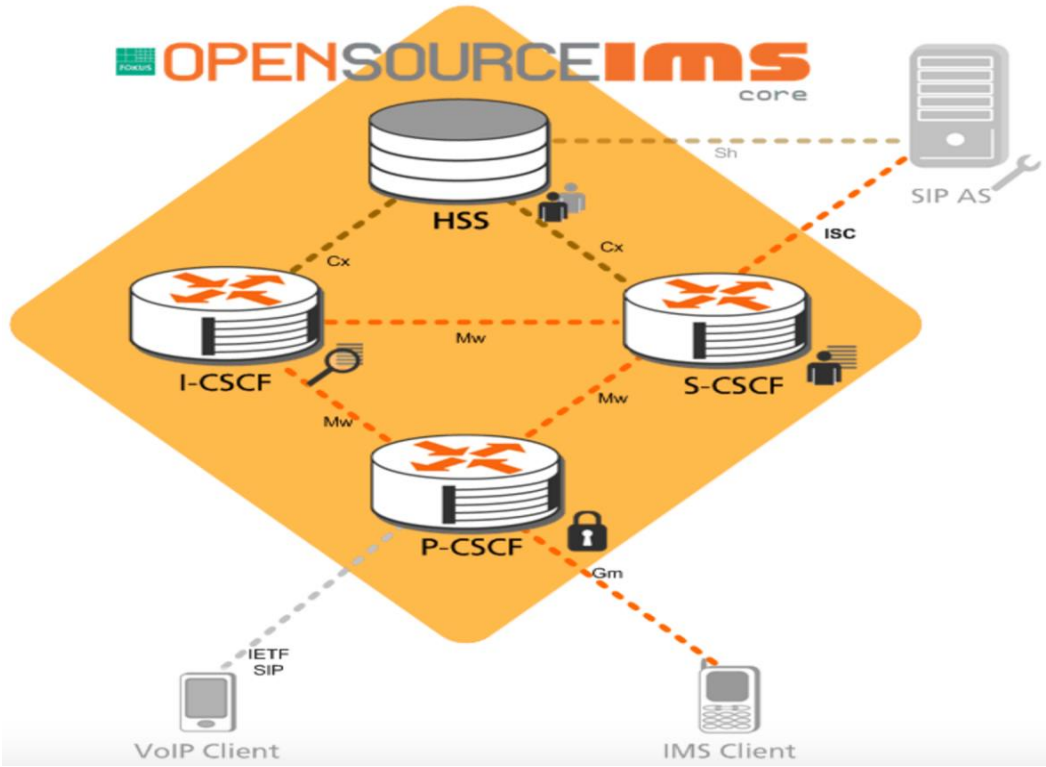

Figure 3.7: OpenIMSCore (Core Network Dynamic, 2015)

3.3.1. Open IMS Core Network Elements

Call Session Control Function (CSCF)

The CSCFs are built upon the SIP Express Router (SER) which can act as SIP registrar, proxy or redirect server and is capable of handing many thousands of call per second. SER is an open source SIP server widely used to implement Voice over IP (VoIP) services. Each CSCF entity of the Open IMS Core is implemented as a SER (Umair, 2013). Proxy-CSCF (P-CSCF), Serving-CSCF(S-CSCF) and Interrogating-CSCF(I-CSCF) play a role during registration and session establishment. P-CSCF and S-CSCF are also able to release session on behalf of the user. They are able to check the content of the SIP request or response and conforms the operator's policy and user's subscription (Poikselka & Mayer, 2009)

Home Subscriber Server (HSS)

HSS is the user database contains subscriber related information and user's initial filter criteria. It performs authentication and authorization of the user and can provide information about the subscriber's location and IP information (Wikipedia , 2015)

Application Server

Application Server handles and interprets the SIP messages forwarded by the S-CSCF and translates end-users service logic into sequences of SIP messages. It is then sends back to the parties again through the S-CSCF (Khlifi & Gregoire, 2008). IMS architecture does not pose any limitation to deploy multiple application server in the same domain. Different application servers can be deployed for different application types. Thus FOKUS supports several IMS SIP Application Server (Magedanz, Witzszek, K, & Weik, 2015).

SIP Application Server

SIP application server can act as redirect server, proxy servers, originating user agents, terminating user agents, or back to back user agents (Khlifi & Gregoire, 2008).

SIP2IMS Gateway

The SIP2IMS Gateway is designed to facilitate the migration of non-IMS device to IMS network and extend the number of client that can use IMS network. It sits between user agent and P-CSCF and access the Open IMS Core through the P-CSCF. SIP2IMS can enable the developers to access Open IMS Core and test multimedia services by using a non-IMS client (Johnson & John, 2007)

3.3.2. Scalability, Reliability, Openness and Security

Before releasing any hardware/software it is necessary to test the product in real world like environment by running a systematic test. The Open IMS Core constitutes such an environment, where various experiments can be run. It is an open and vendor-independent Next Generation Network (NGN)/IMS test environment that can be used as a testbed by academic and industrial institutions for prototyping of new NGN/IMS related components, protocols, and applications, as well as for testing and benchmarking of components. The interconnection to other IMS testbeds worldwide is in progress in order to allow the experience of IMS concepts and IMS services to be shared with partners (Eurescom, 2016)

In Open Source project, tools are regarded as common and shared effort. The existing tools can be reused for other projects. Reusing the existing code for specific need is often less expensive than developing the project from scratch. Unlike commercial products, open source projects do not act as black-boxes. OpenIMS has offers a clear view on how it is implemented and provides detail information about installation and optimization. It provides a secure environment in order to prevents a rouge UE to access the network by providing client identification, authentication and key exchange mechanism. Open IMS Core can be integrated with Cloud computing. Such integration will bring explosive growths in Telecom industries as IMS now is evolved to be the core signaling architecture of Next Generation Networking (NGN) for multimedia services. And it has been widely deployed by telecom operators throughout the world (Zhang, Lei, Chen, & Liu, 2014) .

As previously mentioned, the openIMSCore is an open source implementation of IMS CSCFs, a lightweight HSS and Application Servers (ASs). Each Core IMS component, including P-CSCF, I-CSCF, S-CSCF and HSS, runs on a Linux Debian server. The Cloud Service Control Function (SCF) AS was also implemented based on OpenIMSCore. The Cloud Service Notification Function (SNF) AS has been developed based on OpenSIPS Project. The Cloud PCF AS has been developed based on OpenXCAP, which is an open source XCAP server. XCAP protocols allows a client to read, write, and modify application configuration data stored in XML format on a server using HTTP protocol. The cloud client, consisting of the IMS signaling part and cloud service interaction part, has been developed based on Doubango project. Doubango is an open source 3GPP IMP client for both embedded and desktop systems. The Cloud PCF AS is used to provide configuration interface for cloud clients to manage user own profiles. Cloud SCF AS interacts directly with HSS in order to get user profiles with all user subscriptions and preferences (Zhang, Lei, Chen, & Liu, 2014).

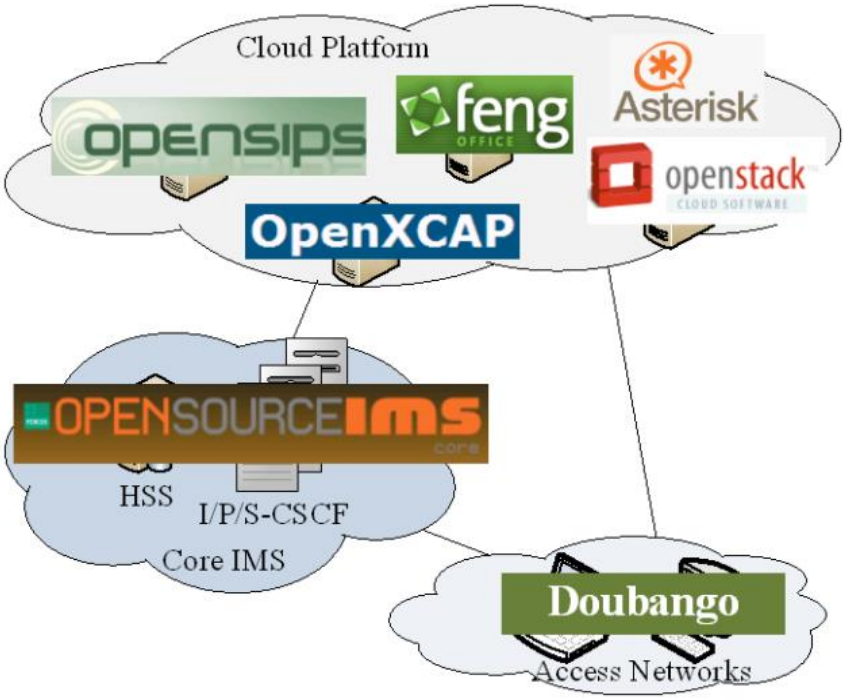

Figure 3.8: Prototypical Implementation of the IMS-based Cloud Computing (Zhang, Lei, Chen, & Liu, 2014)

3.4. OpenEPC

OpenEPC project has been developed by Fraunhofer FOKUS since 2008. It covers all the functional elements in the 3GPP Evolved Packet System (EPS) specifications, formerly known as System Architecture Evolution (SAE). As the Fraunhofer FOKUS now moves toward on 5G system, OpenEPC project has been taken over by Core Network Dynamic, a spin off company of Fraunhofer FOKUS, which continues development and maintenance of the OpenEPC projects (Core Network Dynamic, 2015).

The future of the wireless technology lies in the Next Generation Mobile Network (NGMN). OpenEPC can be used to create NGMN test-beds which are then used to prototype, measure, monitor, test, and perform research and development for NGMNs. The future massive broadband communication will be realized through multi-access support (LTE, 2G, 3G, WiFi, fixed networks etc.) and multi-application domains (OTT, IMS, P2P, M2M, Cloud etc.). EPC is the central IP connectivity control platform of wireless broadband technologies for NGMNs. Core Network Dynamic is developing OpenEPC, enabling to integrate various network technologies and application platforms into a single testbed (Vlad & Magedanz, 2013). This platform is a set of software components offering advanced IP mobility schemes, policy based QoS control, and integration with different application platforms in converging network environments. In addition to fostering research and development, OpenEPC toolkit enables academic and industry researchers to rapidly realize state-of-art NGMN infrastructure and application testbeds (FOKUS Fraunhofer Institute for Open Communication System, 2010).

As LTE is a new wireless technology, advanced features of EPC still need much research and testing. After the successful development of OpenIMS, Fraunhofer FOKUS launched OpenEPC by utilizing the knowledge learned from the OpenIMS Core project. OpenEPC is a Prototype implementation of the 3GPP Evolved Packet Core (EPC). It is not a replacement of OpenIMS core but it integrates well with it, one providing operator optimized services and the other providing the high performance connectivity. So, today in every deployment and test-bed of OpenEPC project includes the OpenIMS Core platform (Fraunhofer FOKUS, 2015).

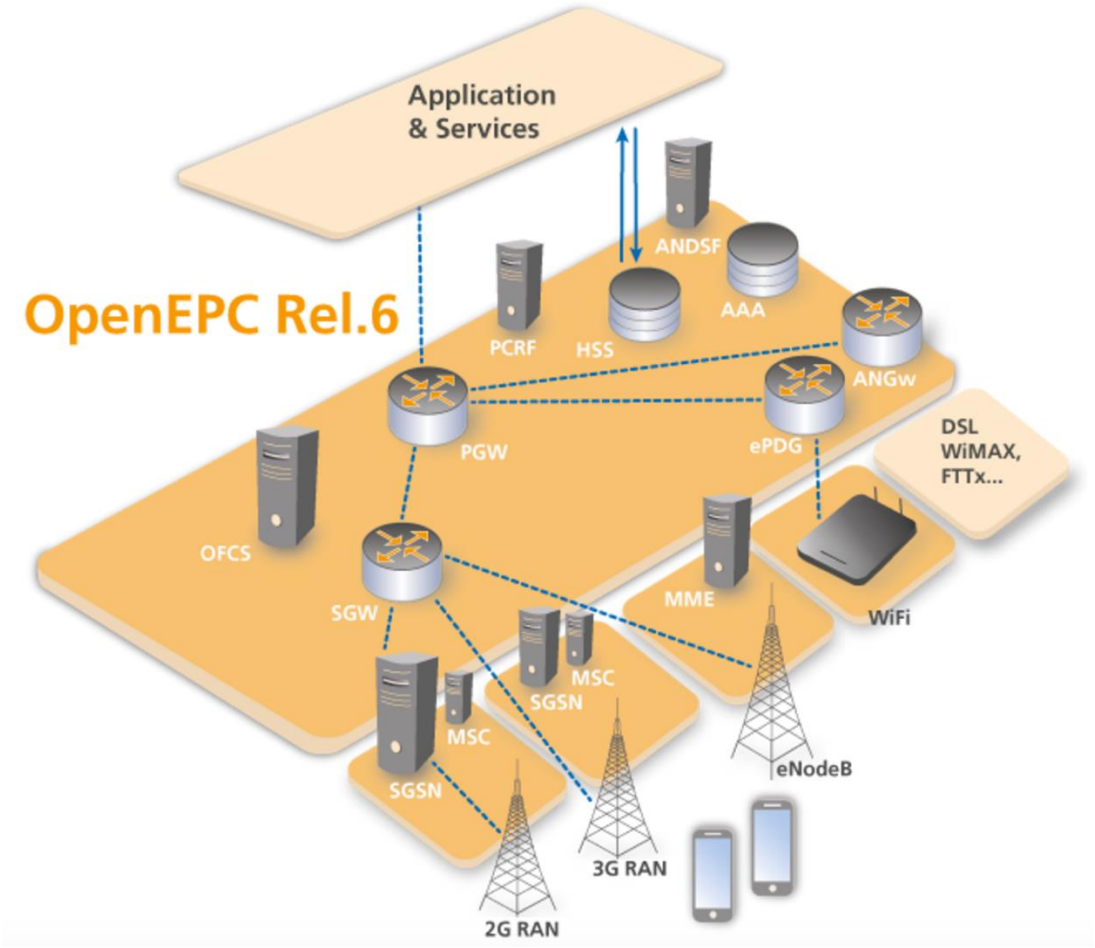

Figure 3.9: OpenEPC (Core Network Dynamics, 2016)

3.4.1. OpenEPC Components

OpenEPC includes all the components and a major part of the functionality of the 3GPP EPC standards.

- **The Gateways**: A variety of gateways are used in EPC in order to forward the data traffic of mobile devices and ensure access control, QoS and mobility management. Serving Gateway (SGW) is access network specific gateway which is used to manage user-plane mobility. It acts as a router and maintains data path between eNodeBs and the Packet Data Network Gateway (PDN-GW). All packets are transferred through it. When terminals move between eNodeBs, the SGW serves as a local mobility anchor.

The evolved Packet Date Gateway (ePDG) and the generic Access Network Gateway(ANGW) provide the interconnection with the various Radio Access Technologies (RATs). The PDN-GW acts as an interface between the EPC and the packet data networks and routes packets to and from the PDNs. The PDN-GW also performs a various functions such as allocation of IP-address for UE, QoS enforcement, policy control and flow based charging. (Firmin, 2016).

- **The Policy Engine and Control Entities**: The policy and Charging Rules Function (PCRF), the Mobility Management Entity (MME), the Serving GPRS Support Node (SGSN) and the Access Network Discovery and Selection Function (ANDSF) make policy based decisions for the connectivity, the access control and the resource allocated for mobile devices (Core Network Dynamics, 2016).
- **The Subscription Data Entities**: The Home Subscriber Server (HSS) and AAA server has replaced the Home Location Register (HLR) concepts that used in previous mobile technologies. HSS is the main subscriber information database that store, update and transmit notifications on the subscription profile of the users. The AAA server provides authorization and authentication of mobile devices.

3.4.2. Scalability, Reliability, Openness and Security

OpenEPC integrates with various access network technologies and different services platforms to provide a complete mobile broadband core network solution. It is available for licensing with full source code either as a complete testbed or as individual components for research and development purposes (FOKUS Fraunhofer Institute for Open Communication System, 2010)

The company has recently announced the upcoming release of its OpenEPC 7 software, a carrier-grade package that now can handle thousands of users per network cell. It includes the support for LTE-M which is beneficial for the IoT market and the critical communications features necessary for public safety. According to Carsten Brinkschulte, the CEO of Core Network, IoT is a key use case for OpenEPC 7, letting mobile operators enhance and extend their LTE networks at the edge and capitalize on this fast growing market without having to

replace their existing infrastructure. “We are delivering on our first public safety contract in Europe to build a secure, private LTE mess network that aims to put a radio cell running OpenEPC into vehicles and attach an antenna to the roof, so that every vehicle will effectively become a mini mobile operator”, said Brinkschulte (Houser, 2016).

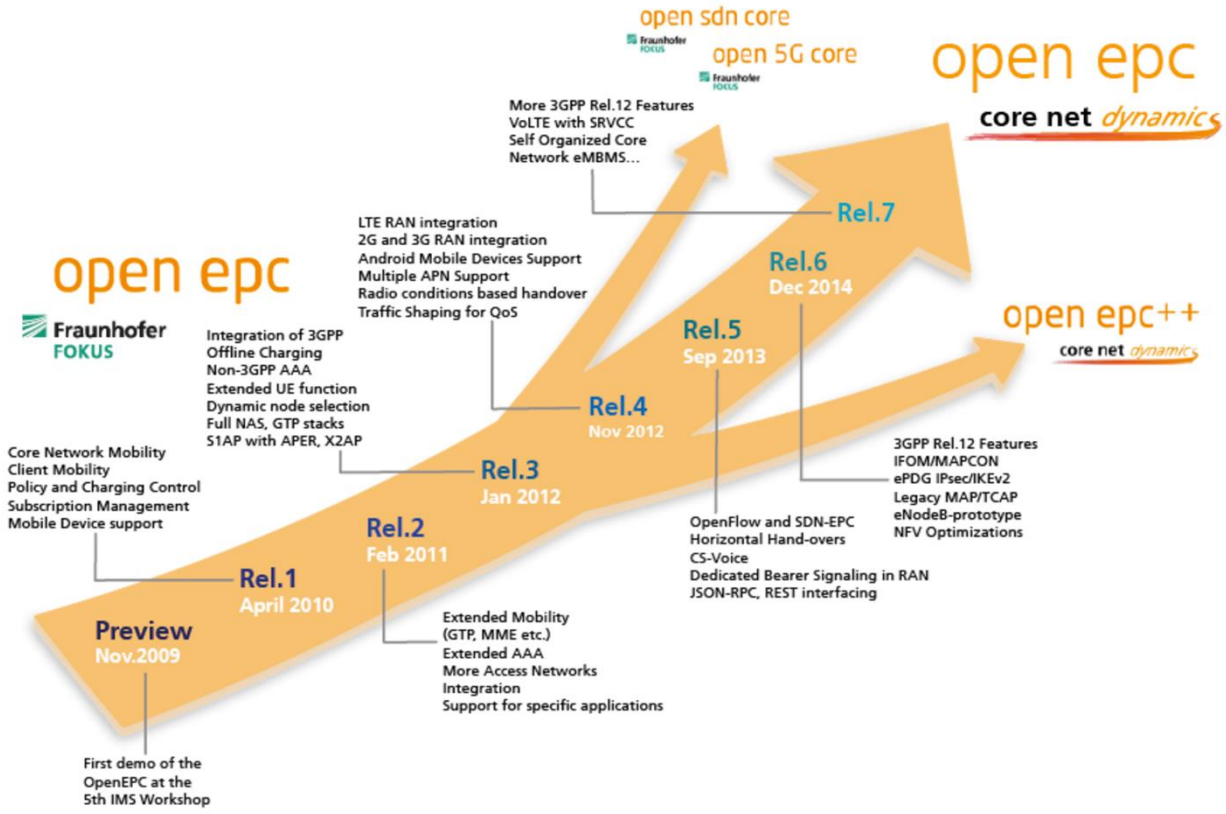

Figure 3.10: OpenEPC releases and roadmap (Core Network Dynamics, 2016)

3.5. Amarisoft LTE 100

Amarisoft LTE 100 is a software-based LTE Base Station running on a PC. It is the world´s first fully software-based LTE Base Station which is more flexible and cheaper than any other expensive hardware based solution (Amarisoft, 2015). It allows to build a real 4G LTE base station using a standard PC and a low cost software radio frontend. All the physical layer and

protocol layer processing is done in real time inside the PC. So other dedicated LTE hardware is not necessary (Bellard, 2012).

The Amarisoft core network software is known as LTEMME which is a MME implementation. It has built-in SGS, PGW and HSS. It can be used with the Amarisoft LTE 100. By combining LTE 100 with LTEMME, a highly configurable LTE test network can be built. Amarisoft LTE implements LTE release 8 with Frequency Division Duplexing (FDD) configuration. Core Network emulation is implemented so that no LTE network infrastructure is needed to use the base station. It supports test USIM cards using the standard XOR authentication algorithm and has flexible configuration system to support various LTE parameters. It implements the LTE PHY, MAC, RLC, PDCP, RRC and NAS layers (George, Sivabalan, Prabhu, & Prasad).

3.5.1. Scalability, Reliability, Openness and Security

Amarisoft LTE is a flexible platform that supports commercial UEs. These commercial UEs can directly connect to it and access the Internet. All parameters of PHY layer are accessible through the configuration file. It is possible to test all kind of setups to see how Base Station and mobile behave in real-time. It is an affordable solution for students and researchers who can build their own Base Station to work on their project. An LTE base station can be set up on a PC with lower investment than using traditional hardware. They can instantly compare theoretical behaviors with the practical one. With Amari LTE 100 stack, the 4G support can be added to the existing wireless solution in a matter of days. Without heavy investment, anyone can remain on the top of 3GPP releases and can take the benefit of them (Amarisoft, 2015).

3.6. PhantomNet

PhantomNet is an end to end mobile networking testbed that provides educators and researchers with a set of hardware and software resources that they can use to develop, debug,

and evaluate their mobility ideas. It is a realistic playground where researchers can explore mobile network architecture in an end to end manner. It is an end-to-end testbed meaning that it supports experimentation not only with mobile end user devices but also with a cellular core network that can be configured and extended with new technologies (Banerjee, et al., 2015). It is based on Emulab, a testbed control suite that has been developed by the Flux Research Group at University of Utah, USA (PhantomNet, 2016). The researchers and educators from all around the world can access and share the PhantomNet through the Internet with free of charge. It provides a single environment where experimenters can combine mobile networking, cloud computing and software defined networking technologies (Banerjee, et al., 2015).

The PhantomNet consists of diverse mix of hardware and software resources. Users can request hardware and software resources for their experiment. The hardware components consist of compute nodes connected by switches, programmable attenuation, off-the-shelf mobile handsets, and off-the-shelf small cell base stations. For off-the-shelf small base stations, we can use either ip.access or SDR hardware such as Ettus Research USRP B210. Hardware resources are connected to a programmatically controlled attenuator matrix to enable controlled RAN experimentation (PhantomNet, 2016). Software resources available in PhantomNet include EPC software such as OpenEPC, OpenLTE and Open Air Interface (OAI). OAI includes SDR-based user equipment (UE) and access point (eNodeB) implementations and an emerging 3GPP LTE implementation. OpenLTE is similar to OAI but it deals with radio access layers of LTE only. The OpenEPC, developed by Fraunhofer FOCUS, is the main software components of PhantomNet. It includes most of the functionality defined by 3GPP LTE version 12 specification (Banerjee, et al., 2015).

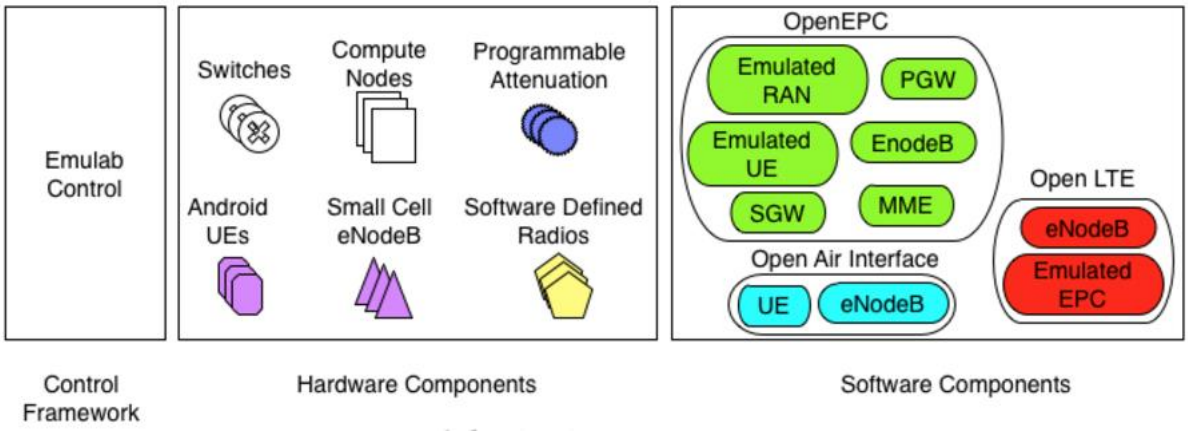

Figure 3.11: PhantomNet infrastructure (PhantomNet, 2016)

PhantomNet is a flexible platform where we can explore an EPC setup with emulated endpoints and access points. We can use EPC core software with real, off-the-shelf eNodeBs and UEs. If we want to experiment both RAN and EPC core, then we can use OAI software. If we do not like 3GPP EPC core, then it is not necessary to use it. We can use our own clean-slate core components with OpenLTE (PhantomNet, 2016).

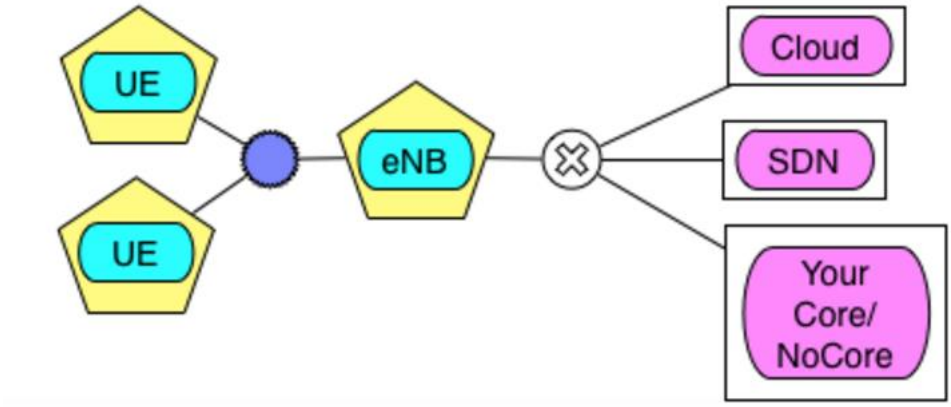

Figure 3.12: Clean-slate mobile network architecture (PhantomNet, 2016)

3.6.1. Scalability, Availability, Openness and Security

Most of the PhantomNet resources are freely available to experimenters worldwide. But OpenEPC functionality is only available in binary form because of its licensing restriction. PhantomNet can support different networking setups. It is a flexible platform where various combinations and configurations are possible. It combines mobile networking, SDN and NFV which are the key enabler for future mobile network.

PhantomNet continually add more feature and components and makes available for users. They typically introduce new functionality by providing pre-configured profiles and accompanying self-help tutorials to get users up and running quickly. As already mentioned, PhantomNet is based on Emulab. Now it is transforming its classic Emulab interface to web

portal. This portal provides easy interface for developing profiles, instantiating and interacting with experiments (PhantomNet, 2016).

PhantomNet´s OpenEPC components run from disk images with restricted user environments. User are not given root privilege and can not access to the actual OpenEPC binary components. They may interact with these components only through control scripts, configuration files, and service consoles. PhantomNet also set limited privilege for operations such as capturing network interface traffic and node shutdown/reboot, and disable node console access and custom image creation operation (Emulab, 2016).

3.7. Software Defined Networking (SDN)

Software Defined Networking (SDN) is an emerging network architecture that allows network administrator to manage network services through abstraction of lower-level functionality. This is done by separating the network control plane and data plane enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services (Open Networking Foundation, 2016). SDN requires some method for the control plane to communicate with the data plane. OpenFlow protocol is such a mechanism which is fundamental for building SDN solutions.

Current networks are hierarchical, built with tires of Ethernet switches arranged in a tree structure. This design is not appropriate to the dynamic computing and storage of today´s enterprise data centers, R&D departments and Universities (Wikipedia, 2016). Today´s networks are fragile and difficult to manage. The root of these problems lies in the complexity of the control and management planes. The increasing number of mobile devices, social medias, data centers, and cloud computing has strained the capabilities of traditional networking technologies. With data center and cloud environments, number of end stations that connect to a single network have grown exponentially. The limitation of MAC address table sizes and number of VLANs have become difficult to network installation and deployment. Server virtualization has also caused the scale of networks to increase and this increased scale has put pressure on layer two and layer three networks as they exist today. Advances in data center, could computing, mobile communication, and video streaming have

caused weaknesses in the current networking technology. This situation has demand for better ways to construct and manage networks, and that demand has driven innovation of the SDN (Goransson & Black, 2014).

SDN gives us new ways to design, build and operate networks. SDN method centralizes control of the network by removing complicated control logic from the device and places into a centralized controller. This controller is capable of seeing the entire network and able to make forwarding and routing decisions. It makes decision about how packets should flow through the network from the data plane. SDN actually attempts to segregate network´s activities forwarding, filtering, and prioritization. The administrator can change any network switch´s rules when necessary by prioritizing, de-prioritizing or even blocking specific types of packets with a very granular level of control. This is especially helpful in a cloud computing architecture because administrator can manage traffic loads in a flexible and more efficient manner. Essentially, SDN allows the administrator to use less expensive commodity switches and have more control over network traffic flow than ever before (Rouse, 2015). By converging the management of network and applications services into centralized platform, SDN enhances the benefits of data center virtualization, resource flexibility, and reducing infrastructure costs and overhead. Common centralized IT policies bring together disparate IT groups and workflows. As a result, modern infrastructure can deliver new applications and services in a minutes, rather than days or weeks required in the past. When deploying new applications and business services, SDN delivers speed and agility. Flexibility, policy, and programmability are the main properties of SDN solutions, which is capable of handling the most demanding networking need of today and tomorrow (Cisco, 2016).

All SDN models have some basic components: the SDN Controller as well as southbound APIs and northbound APIs, SDN Devices, and the applications. The figure 3.13 describes the operation of the SDN.

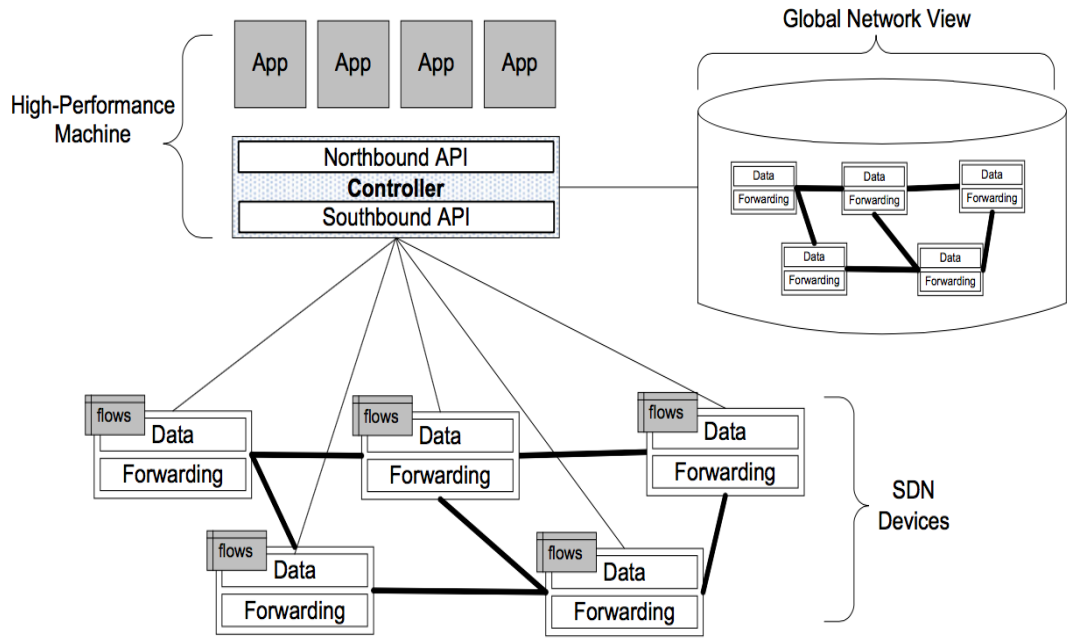

Figure 3.13: SDN operation overview (Goransson & Black, 2014)

- **Controller:** SDN Controller is the brain of the network which maintains a view of the the overall network. It is responsible for controlling and presenting an abstraction of these network resources to the SDN application running above it. The controller allows the SDN application to define flows on devices and to help the application the application respond to packets that are forwarded to the controller by the SDN devices. It also implements policy decisions regarding routing, forwarding, redirecting, load balancing (Goransson & Black, 2014).
- **Southbound APIs:** Southbound APIs are used to relay information to the switches and routers.
- **Northbound APIs:** SDN uses northbound APIs to communicate with the applications and business logic.
- **Flows:** A flow describes a set packets transferred from one network end point to another endpoint. All packets belonging to that flow have a set of rules which describes the forwarding actions that the device should decide what to do with each incoming packet.
- **SDN Devices:** SDN device is composed of an API for communication with the controller. It contains forwarding functionalities for taking appropriate action for each incoming packet. Flow tables are the fundamental data structure in an SDN device which allows devices to evaluate incoming packets and take the proper decision. Flow

table consists of a number of prioritized flow entries, each of which consist of two components: match fields and actions (Goransson & Black, 2014). Match fields are used to compare against incoming packets. If an incoming packet matches the match fields specified for that flow entry, then the network device should perform appropriate actions.

- **Applications:** SDN applications are programs that runs above the SDN controller and communicate their network requirements and desired network behavior to the SDN controller via the controller´s northbound API. They are responsible for managing the flow entries that are programmed on the network devices. Other functions that are performed by SDN applications are load balancing and firewalling. The core functionality of the application will vary from one application to another, but application behavior is driven by events coming from the controller as well as external inputs (Goransson & Black, 2014).

3.7.1. OpenFlow

OpenFlow is a programmable communication protocol that enables the SDN controller to directly interact with the forwarding plane of the network devices such as switches and routers. With OpenFlow, the packet moving decisions are centralized, so that the network can be programmed independently of the individual switches and routers. The concept of SDN came into existence after OpenFlow appeared on the scene in 2008. So, the arrival of OpenFlow is the point at which SDN was actually born (Goransson & Black, 2014). The investors of the protocol consider OpenFlow an enabler of SDN. OpenFlow based SDN architecture is today´s need for mobile and wireless networks.

OpenFlow was developed and designed to allow researchers to run experimental protocols and innovate with new protocols in the network we use everyday. A number of network switch and router vendors have implemented OpenFlow in their products. OpenFlow enabled switches are now commercially available in the market. Packet forwarding and routing occur on the same device in a traditional switch but an OpenFlow enabled switch separates the data plane from the control plane. The data plane resides on the switch itself while a separate controller makes high-level routing decisions (Wikipedia, 2016). The switch and controller communicate by

means of the OpenFlow protocol. The figure 3.14 illustrates the simple architecture of an OpenFlow solution.

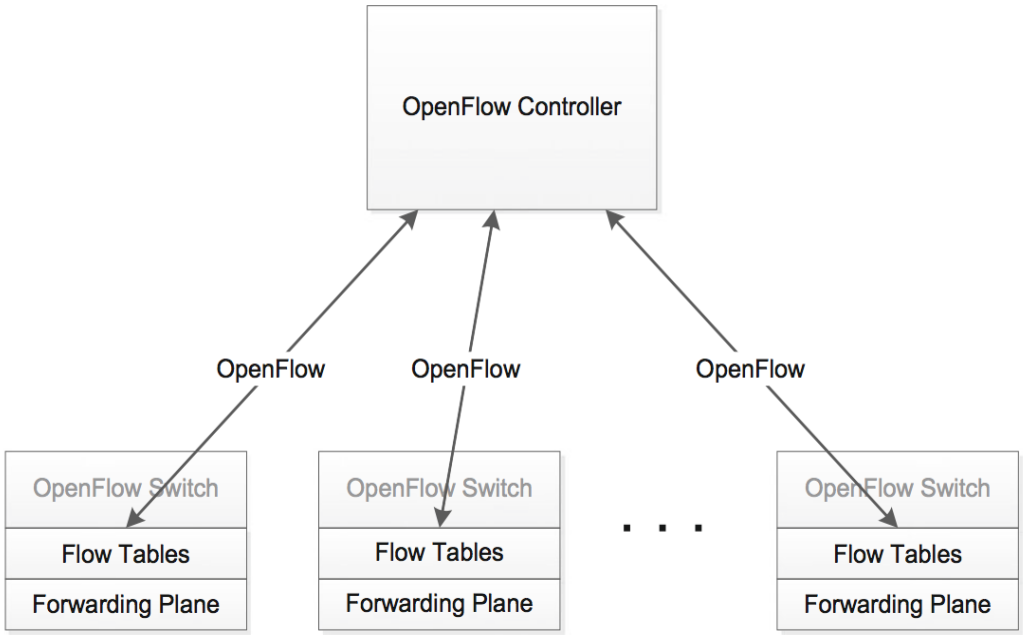

Figure 3.14: General OpenFlow Design (Goransson & Black, 2014).

3.7.2. SDN for Cellular Networks

The growing popularity of mobile devices and broadband mobile network deployment with LTE /LTE-A have increased mobile data traffic on today´s cellular networks. Mobile and wireless technologies are growing continuously. As wireless becomes the main option for people to communicate with others, mobile operators must carry much volumes of traffic and at the same time provide a number of facilities or services. The increasing number of wireless technologies 3G, 4G cellular as well as Wi-Fi and Bluetooth are in use simultaneously. To support these various types of technologies, mobile operator usually has to increase the budgets required to address the new demands and handle operational headaches. LTE have supported network operator to maintain the stability of traffic growth by increasing the radio access

volume. However, they now face a number of challenges of keeping up with the increasing demand in their core network (Kabir, A Novel Architecture for SDN-Based Cellular Network, 2014). This is a serious problem for today´s highly centralized cellular network where all the mobile traffic is handled at central gateways.

The massive growth in mobile data, the need to simultaneously operate over multiple wireless technologies, and the rapidly evolving mobile services market impose significant challenges for today´s architecture. OpenFlow-based SDN architecture is suitable for highly scalable mobile and wireless networks, from access to backhaul and core for addressing these challenges (Open Networking Foundation, 2013). SDN offers a logically centralized control plane which enables better coordination among network elements. It can enable common control protocol across diverse wireless technologies for seamless mobility support within and across the 3G, UMTS, WiMAX, 4G/LTE, Wi-Fi, and Bluetooth technologies. Due to its centralized control plane, SDN architecture can give cellular operators greater control over their equipment and simplify the network management while enabling the network services (Sebastian, 2015).

Cellular networks need an SDN architecture that handles and manages the full network from a central location and offers frequent mobility, fine grained measurement, real time control and at the same time supports many subscribers. The future SDN architecture should address real-time adaptation scalability challenges that today´s cellular network usually fails (Kabir, SDN in Cellular Network and Implementatio Challenges, 2016). A simplified SDN-based cellular network architecture could be represented as shown in Figure 3.15.

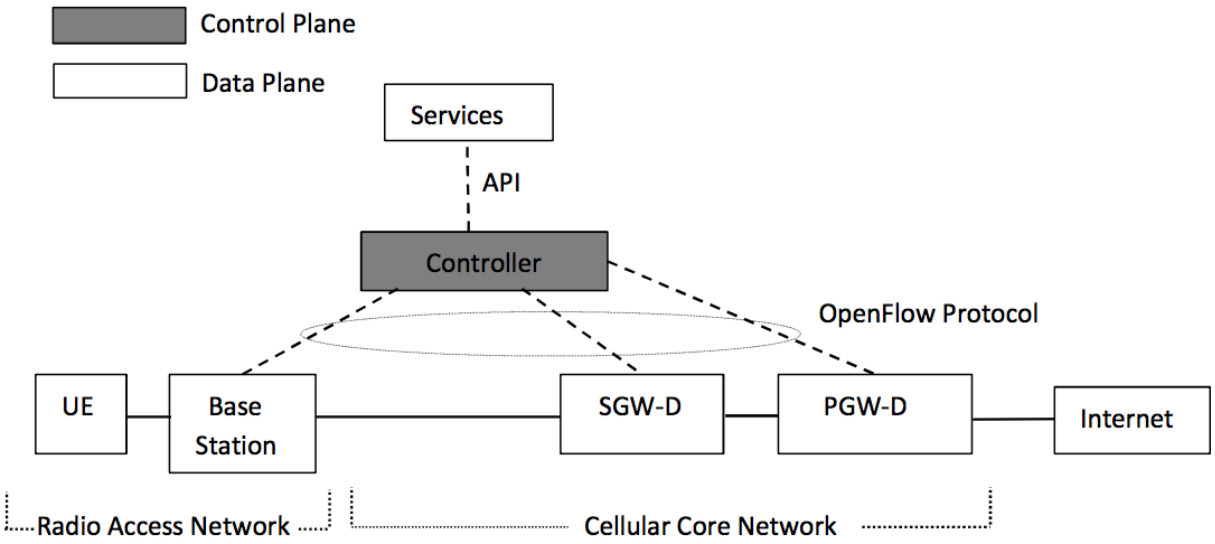

Figure 3.15: A simplified architecture of SDN-based cellular network (Kabir, SDN in Cellular Network and Implementatio Challenges, 2016)

The central controller handles and operates all the network control operations. It consists of a Network Operating System (NOS) running application modules, such as radio resource management, mobility management, and routing. The SDN controller instructs other components to operate and forward traffic with the help of these application modules that reside usually on top of the central controller (Jin, Erran, Vanbever, & Rexford, 2013). OpenFlow protocol is used to communicate with other networking components.

3.8. Network Function Virtualization

Today´s networks are populated with varieties of physical proprietary hardware appliances. Service provision within the telecommunication industry has been based on network operator´s proprietary devices. Due to the proprietary nature of these appliances, it is difficult to bring the new services into the networks. However, users are demanding more diverse and new services with high data rates. Therefore, service provider must continuously purchase, store and operate new physical equipment (Mijumbi, Serrat, Gorricho, & Bouten, 2016). This does not only increase the cost of energy, and capital investment, but also requires skilled technicians

necessary to design, integrate and operate increasingly complex hardware-based appliances. Therefore, service providers are looking to build more dynamic and service aware networks so they can deliver new and innovative services to subscribers.

NFV aims to reduces the deployment and operating cost and increases the manageability and innovation in service space of the network function. It offers a new way to design, deploy and manage networking services by decoupling the network functions from proprietary hardware appliances, so that they can run in software (Garg, 2014). The implementation of network functions through software virtualization can run on an industry standard server hardware, and that can be moved to, or instantiated in, various locations in the network as required, without the need for installation of new equipment (Chiosi, Clarke, Benitez, & Damker, 2012). Figure 3.16 illustrates the vision for NFV.

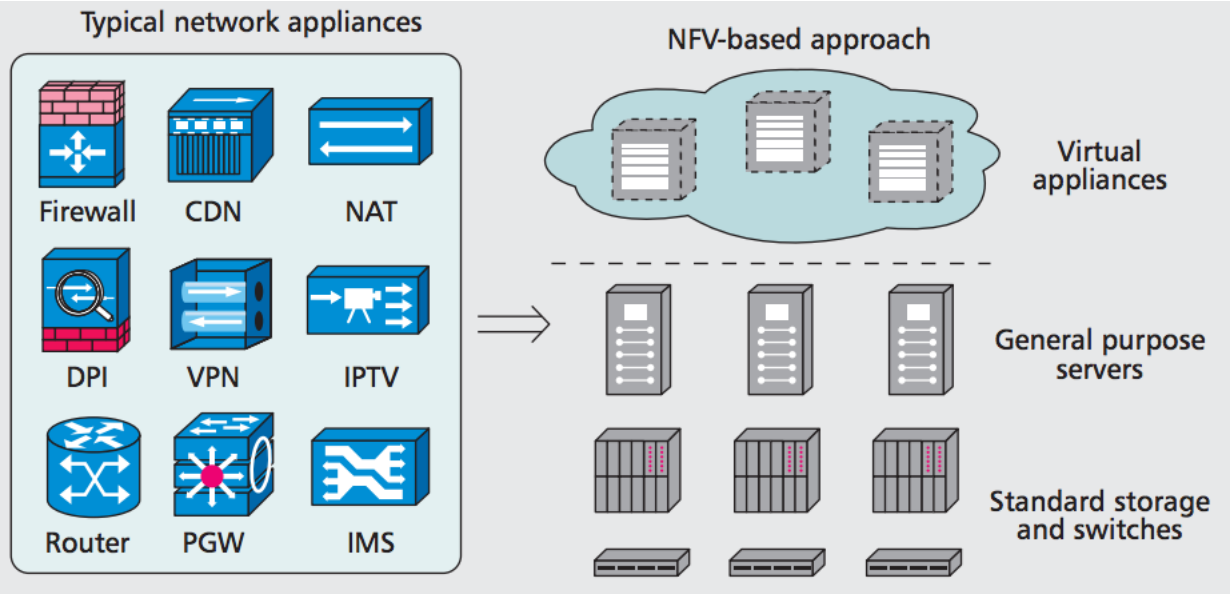

Figure 3.16: Vision for Network Functions Virtualization (Han, GopalaKrishnan, Ji, & Lee, 2015)

SDN and NFV are complementary approaches. They offer a new way to design, deploy, and manage the network and its services. But they do not dependent on each other. NFV can be implemented without SDN. However, two solutions can be combined to create greater value (Chiosi, Clarke, Benitez, & Damker, 2012).

3.8.1. Virtualization of Mobile Core Network

The ETSI has proposed a number use cases for NFV (ETSI ISG, 2013). In this subsection we will discuss how NFV applicable to EPC, the Core network of LTE. In current EPC, all its functions are based on proprietary equipment. When a specific function is not available, operators have to replace existing equipment. Virtualization of EPC can solve these problems to meet changing market requirements. It could potentially lead to better flexibility and dynamic scaling, and hence allow mobile operators to respond easily and cheaply to meet changing market requirements (Mijumbi, Serrat, Gorricho, & Bouten, 2016). The figure 3.17 shows both the normal architecture of LTE and the one in which EPC is virtualized.

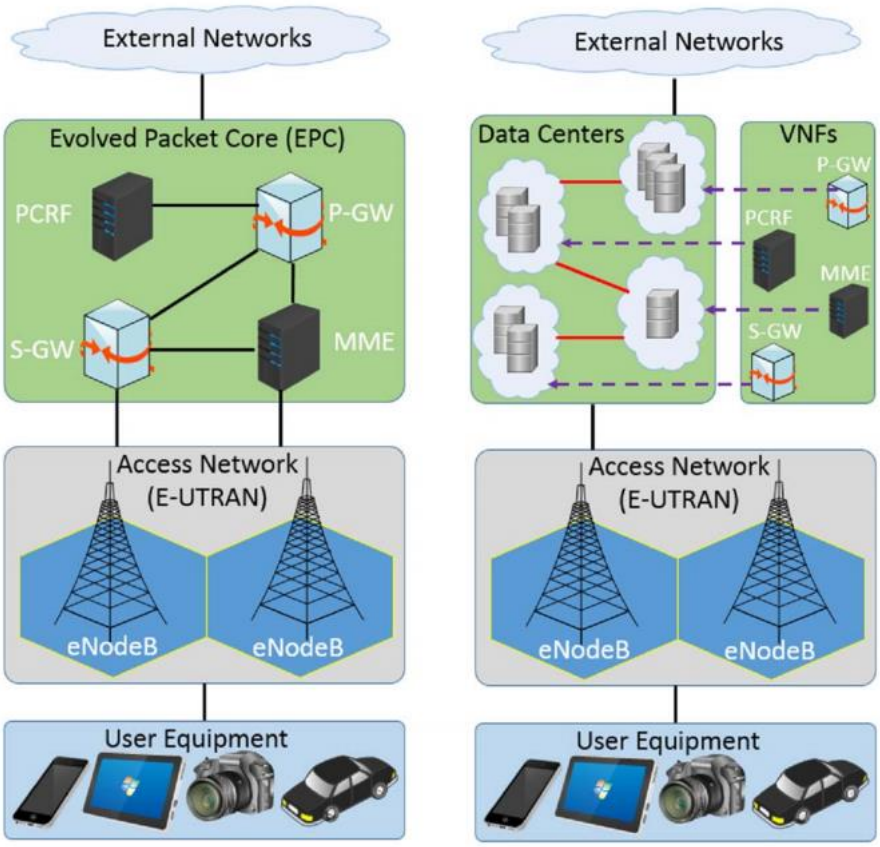

Figure 3.17: Virtualization of EPC (Mijumbi, Serrat, Gorricho, & Bouten, 2016)

The virtualization of EPC includes MME, HSS, SGW, PGW and PCRF. It allows us to move toward a more intelligent, resilient, and scalable core architecture and enables flexible distribution of hardware resources to eliminate performance bottlenecks and rapid launch of innovative services to generate new revenue sources like M2M and Internet of Things (IoT) applications (Han, GopalaKrishnan, Ji, & Lee, 2015).

3.9. Cloud Radio Access Network (CloudRAN)

With the growing data traffic in mobile networks and deployment of of 4G/LTE, the current radio access network becomes dense and heterogeneous. As a result, congestion occurs in RAN by increasing the number of base stations for user equipment to connect to the base stations. This denser deployment of BS brings new challenges in interference management and inter cell coordination that need new approaches to manage (Dawson, Marina, & Garcia, 2014). In order to handle this scaling capacity and to manage the dense infrastructure, a new architecture require to tackle interference management and inter cell coordination.

ClouldRAN is a centralized, cloud computing-based architecture for radio access networks that supports 2G, 3G, 4G and future communication standards (Wikipedia, 2016). CloudRAN uses virtualization technologies in the radio access networks. As NFV has already emerged as a viable approach to increase network flexibility for mobile core network, this can be applied to the radio access part of the cellular network. CloudRAN allows for the use of two principles: centralization and virtualization of base station (BS) baseband processing in mobile network. By applying NFV, the network operator can dynamically allocate processing resources within a centralized baseband pool to different virtualized base stations and different air interface standards. This allows the operator to efficiently support the variety of air interfaces. In this case, a base station can be easily built up through the flexible resource combination. The real time virtualized operating system would adjust, allocate and re-allocate resources based on each virtualized base station requirements in order to meet its demands (Upperside Conferences, 2014). By utilizing CloudRAN, operators can centralize the control plane which brings RAN functionality closer to applications, or further distribute the physical layer closer to the antenna to enable massive beam forming. Centralizing BS processing with CloudRAN simplifies network management and enables resource pooling and coordination of radio resources (Ericsson, 2015). The figure 3.18 shows an examples of functional splits of the radio

access protocol layer in a CloudRAN. Therefore, a CloudRAN architecture combines virtualization, centralization and coordination techniques which are interact with each other within the network.

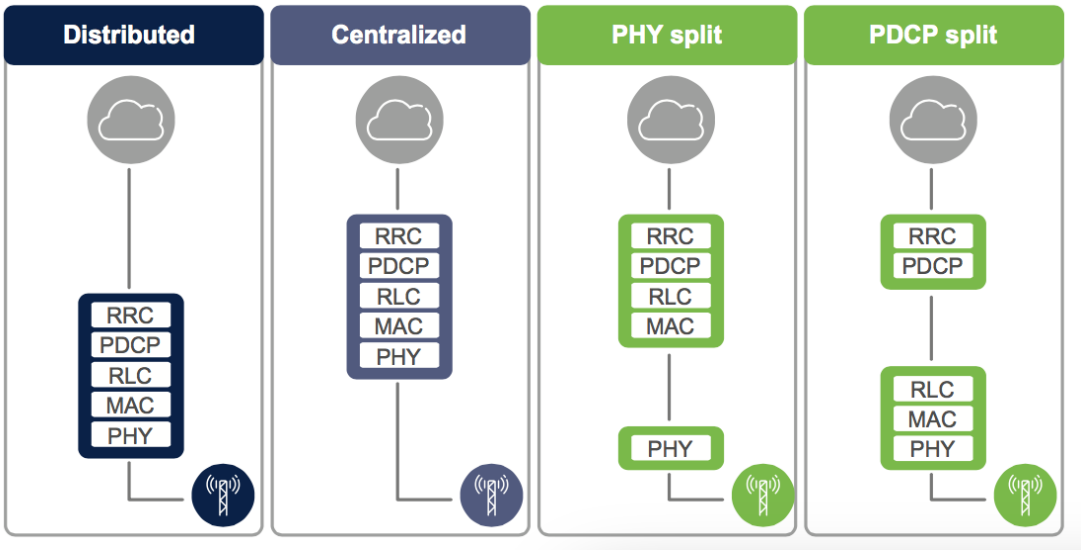

Figure 3.18: Functional splits of the radio access protocol layer in a Cloud RAN (Ericsson, 2015)

In current cellular systems, each physical base station (BS) combines baseband processing and radio functions. With the recent advancements in software defined radios, it is possible to split the base station into radio front-end and software implementation of baseband processing. With the CloudRAN, the baseband processing for many cells is centralized. By combing multiple BSs into a centralized server, CloudRAN improves the performance due to the ability to coordinate between cells, and also increase the demand for resource control (Beyene, Jantti, & Ruttik, 2014).

The figure 3.19 illustrates the the architecture of CloudRAN. It replaces the BSs with shared processing and distributed radio elements. The core components of CloudRAN are: Base Station Pool, Optical Fronthaul and Remote Radio Heads (RRH). Base station pool provides signal processing and coordination functionality required by all cells within the area. Optical fronthaul is a fiber links which carries baseband data and RRHs are light weight radio units and antennae that user equipment connects to via the RAN. RRHs can be used in anywhere unlike a traditional base station which requires a mast and housing for the baseband processing

unit. All remote radio heads in a given area is handled by a single BS pool so that inter cell coordination becomes easier as communication occurs directly within the pool (Dawson, Marina, & Garcia, 2014).

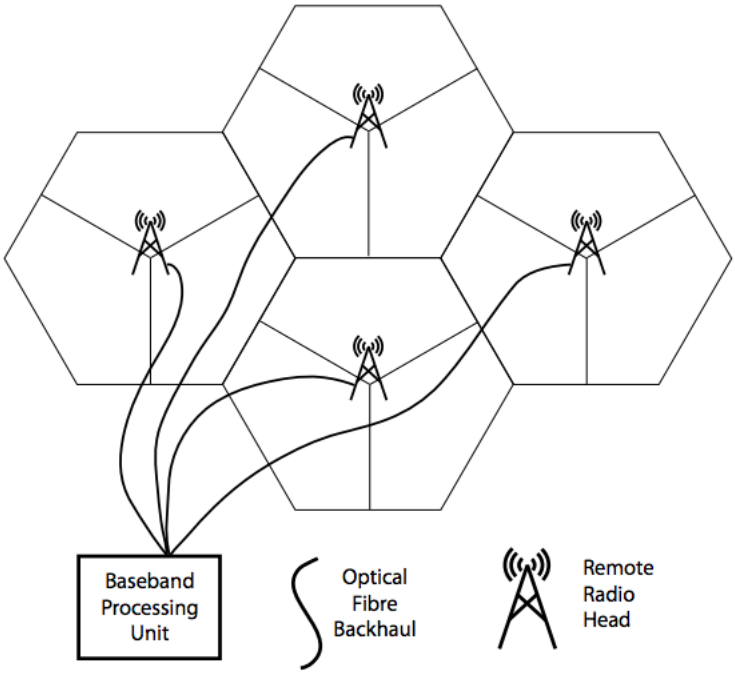

Figure 3.19: CloudRAN architecture (Dawson, Marina, & Garcia, 2014)

3.10. Software Defined Radio Access Network (SoftRAN)

As mentioned earlier, cellular network is becoming dense and heterogeneous with the deployment of variety of radio access networks. The advantage of these networks is that they can enable seamless communication. But the complexity in heterogeneous RANs creates serious problems in radio resources sharing and management of sharing of spectrum. Due to limited spectrum, it becomes difficult to allocate radio resources, implement handovers, manage interference, and balance the load between cells. LTE network has the flexible spectrum allocation. However, current distributed solutions adopted by LTE macro-cells are

not scalable for dense small cell deployments (Chen & Nikaein, 2016). A SDN approach for RAN could be a suitable solution to address the above challenges.

SoftRAN is a software defined control plane for radio access networks that abstracts all base stations in a local geographical area as a virtual big base station comprised of a central controller and radio elements (Gudipati, Perry, Erran, & Katti, 2013). The architecture of SoftRAN is shown in figure 3.20. It has a centralized controller as an alternative to the distributed control plane currently implemented in LTE networks and control APIs to group existing cell into CloudRAN like a big base stations. The controller maintains a global view of the radio access network. The 3D resource grid is an abstraction of radio resource in the network that offer mapping of resources based on time, frequency and end point as well as monitoring interference between end points and devices (Dawson, Marina, & Garcia, 2014).

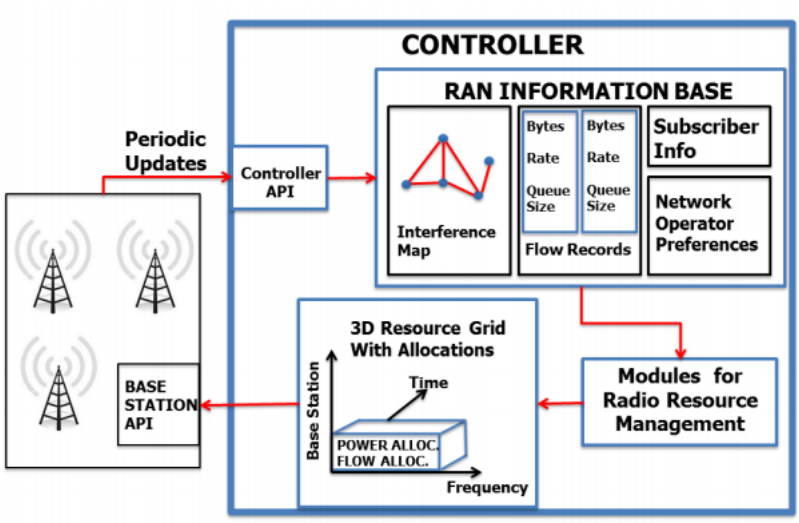

Figure 3.20: SoftRAN architecture (Gudipati, Perry, Erran, & Katti, 2013)

SoftRAN mainly focusses on balancing the loading of cells through its logically centralized control plane. Through the global view of network, a big base station can manage interference, load, quality of services, smooth handover and also improve utility and power usage (Gudipati, Perry, Erran, & Katti, 2013).

3.11. Machine to Machine (M2M) Communication

Today´s communication network is focused on human communications such as voice call, messaging and Internet browsing. As IPv6 system is already rolled in, every device on the Internet can have its own IP address. Cisco Internet Business Solution Group (IBSG) predicts that the number of connected devices will reach over 50 billion by 2020 (Cisco IBSG, 2011). As a result, M2M communication has emerged to address new kinds of services and technologies and is expected to be the next revolution in the mobile communication.

In M2M communication, machines autonomously communicate with each other without human interfacing or interaction. In addition to exchanging data, it allows devices to monitor systems themselves and automatically respond to changes in the environment, with much reduced need for human involvement. Three very common technologies: wireless sensors, the Internet and server computers are coming together to create M2M communication (Crosby, 2016). With M2M technology, it is possible to create a common network of communication among all physical devices around us. M2M is an inevitable part of Interne of Things (IoT) technology, which is expected to be the next revolution in the mobile communication technology (Nokia, 2015). With the rise of IoT, M2M communications has become a driving force for innovation in cities, homes, cars, and workplace. It has the power to reinvent the business and turns remote objects into intelligent assets (Vodafone, 2016).

3.11.1. How M2M Works

In M2M communications, a remote sensor attached with device gathers data and sends it wirelessly from a SIM integrated in the device to a central server where it is translated into meaningful information, for example, as shown in figure 3.21. At that point, the data is analyzed and acted upon, according to the software in place (Crosby, 2016).

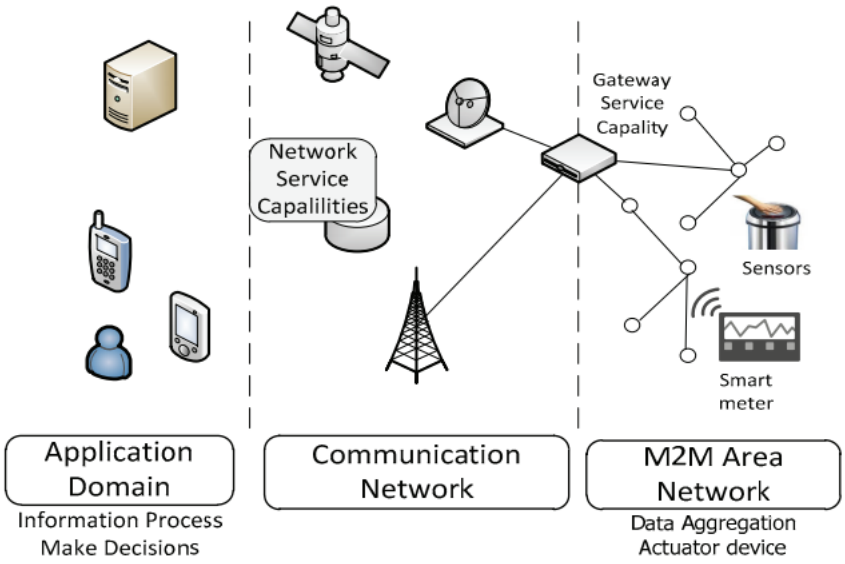

Figure 3.21: ETSI M2M Network architecture (Corici, Coskun, Mao, Kurniawan, & Wahle, 2012)

The data transfer patterns in the M2M communication is different from current mobile communication system. In order to be able to fully use machine type communication (MTC) which permits the deployment of novel machine-oriented services, a set of challenges have to overcome. ETSI has defined a set of requirements to achieve an efficient end to end delivery of the services. Many M2M applications will need to deliver and process information in real time or near real time and many nodes will have to be extremely low power or self powered device. The communication of the devices and the network core should be secured against a large variety of security threats. In order to be able to manage the overall system, the M2M system should include a middleware layer which facilitates the communication between the devices and network application. Likewise, MTC applications can send receive packet switched data only during defined time interval. Based on these general requirements, ETSI has developed M2M middleware architecture which is the basis for further development of M2M applications (Corici, Coskun, Mao, Kurniawan, & Wahle, 2012). Now MTC has become an important part of the infrastructure of LTE which connects all other new technologies in mobile communications. This aims to increase the level of system automation in which device can exchange and share data, addressing requirements and challenges of the emerging world of Smart cities and the Internet of Things.

3.11.2. OpenMTC

OpenMTC has been designed by Frauhofer Institute FOKUS and Technische Universitat Berlin as an open source software which provides test environment for Machine Type Communication. It is a middleware platform which resides between packet core network and applications and implements specific M2M service capabilities such as generic communication, application enabling, and remote management (Technische Universitat Berlin, 2015). OpenMTC helps academia and industry to integrate various machine devices and applications into a single local testbed, so that they can focus on research and development of M2M systems without constructing a real system, which ultimately reduces the development cost.

OpenMTC platform has been designed to act as a middleware between application domain and M2M area Network, inspired by ETSI M2M, oneM2M and Open Mobile Alliance (OMA) standards as shown in figure 3.22 (Corici, Coskun, Mao, Kurniawan, & Wahle, 2012). OpneMTC mainly consists of three components: M2M Network Area, M2M capabilities layers, and application domains. Devices are located in M2M Network Area and are connected through a variety of networks infrastructure such as ZigBee, Wi-Fi, GPRS, FS20, and Bluetooth. Two common M2M capability layers are: a gateway service capability layer (GSCL) and a network service capability layers (NSCL). The GSCL connects the devices located in Network Area with the server where as NSCL mediates the interactions between applications in the M2M network area (Abdurohman, Sasongko, & Herutomo, 2015).

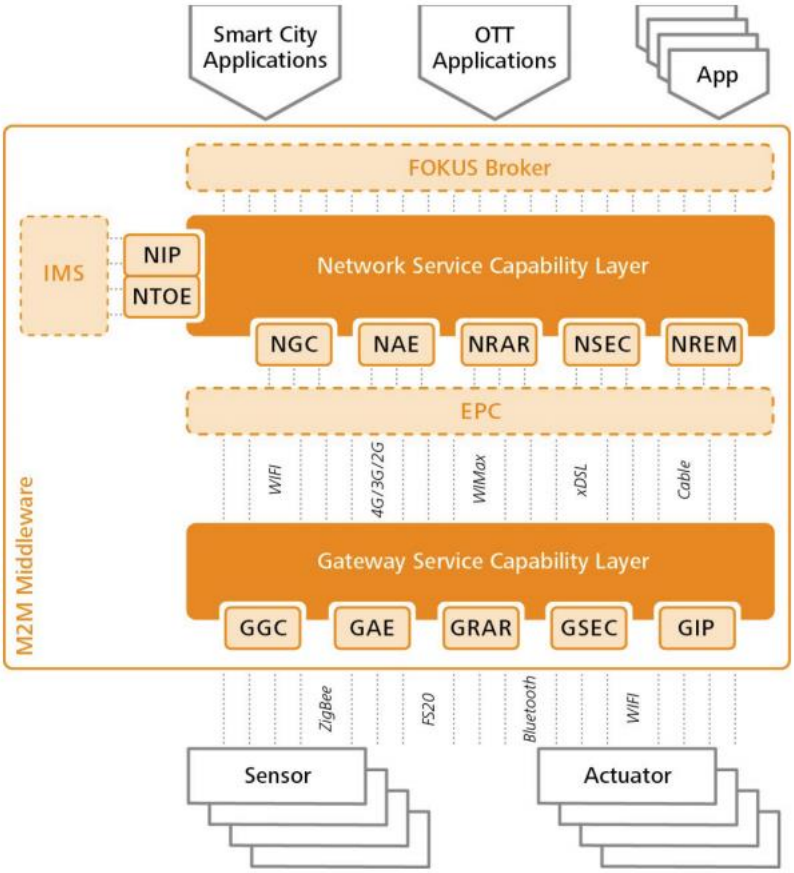

Figure 3.22: OpenMTC architecture (Corici, Coskun, Mao, Kurniawan, & Wahle, 2012)

OpenMTC platform as a middleware has an ability for handling thousands of sensors, actuators and M2M applications. OpenMTC has capabilities to support interworking with other telecommunication cores, such as the IMS and EPC. Translating the information exchanged from sensors and devices into SIP messages enables the usage of IMP for various M2M applications. This means the M2M communication rely on the security and reliability of IMS. OpenMTC relay on OpenEPC for connectivity selection management and carrier grade Quality of Service, as EPC provides advanced networking capabilities such as policy and charging control. Therefore, OpenMTC helps to be prepared for the upcoming all-IP NGN and M2M world using open and vendor independent testbed infrastructure (Fraunhofer FOKUS, 2012).

4. Open Air Interface

This chapter gives a brief introduction of OpenAirInterface and describes it as a reference platform for innovation in the field of 4G/5G. It also describes how to install and configure OpenAirInterface on a Linux-based PC.

4.1. Introduction

Cellular data traffic has exponentially increased in recent years due to the rapid adaptation of Internet connected mobile devices such as smart phones, tablets, and other M2M devices. As cellular technology offers variety of services and uses different type of topology, it ultimately makes network more complex and costly to deploy, operate, maintain and upgrade. While 4G LTE networks have been already deployed worldwide, research for the next generation mobile networks have been begun by EURECOM using open source software called OpenAirInterface (OAI).

OpenAirInterace is an open source based experimentation and prototyping platform created by the Mobile Communication Department at EURECOM, a France based research institute, to enable innovation in the area of mobile/wireless networking and communication (Nikaein, et al., 2014). Researchers can rapidly prototype and test systems using OAI which would be infeasible with proprietary equipment. Prior to the development of OAI, 4G LTE was too complex and esoteric technology for a community of open source developers to manage. OAI is an open forum that aims on improving the emerging industrial air interface standards such as LTE and 5G regarding spectral, algorithmic and protocol efficiency research (Ravali, Vasudevan, & Sundaram, 2016). EURECOM believes that OAI can be useful in the development of the 5G technologies research like M2M communication, CloudRAN, Heterogeneous Cellular Networks and Device to Device (D2D) communication, Shared Spectrum, Millimeter Waves, and Software Defined Mobile networks (Nikaein, et al., 2014).

OAI offers an open-source software-based implementation of the LTE system spanning the full protocol stack of 3GPP standard both in E-UTRAN and EPC (OpenAirInterface, 2016). It can be used to build and customized an LTE base station and core network on a PC and connect a commercial UEs to test different configurations and network setups and monitor the network and mobile device in real time. OAI is based on a PC hosted software radio frontend architecture (Nikaein N. , 2015). With OAI, the transceiver functionality of a base station, access point, mobile terminal, core network etc. are realized via a software radio front end connected to a host computer for processing. OAI provides a rich development environment with a range of built-in tools such as highly realistic emulation modes, soft monitoring and debugging tools, protocol analyzer, performance profiler, and configurable logging system for all layers and channels (OpenAirInterface, 2016). EURECOM has recently created the OpenAirInterface Software Alliance(OSA) with the aims of providing an environment for EUTRAN and the EPC of 3GPP cellular systems to interoperate with the closed source equipment in both part of the network.

4.2. OAI Components

The OAI consists of two main components of the LTE system architecture: the radio part, the E-UTRAN and the core part, the EPC. The transceiver part i.e. a base station, access point and mobile terminal is achieved by using Software Define Radio. The EPC core part is an OpenEPC elements i.e. SGW, PGW, MME, HSS etc. It is said that OAI is the only SDR based solution that is fully open source and provides a complete software implementation of all elements of 4G LTE system architecture. OAI equipment is the combination of software and hardware platforms. Besides the real-time operation over hardware components, OAI can be run on emulation mode too.

4.2.1. Software Platform

The OSA´s software packages for core network is known as openairCN while the access network software for base stations and terminals goes under the name of openair5G. The core

part can be integrated with other open source software packages such as openIMS, Clearwater IMS, OpenDayLight etc. on a generic cloud computing platform OpenStack. In order to ease with integration within an OpenStack environment, openairCN is distributed under an Apache V2.0 license. On the other hand, openair5G is freely distributed by the OSA under the terms stipulated by a new open-source license, the OAI Public License, catering to the intellectual property agreements used in 3GPP and allowing contributions from 3GPP members holding patents on key procedures used in the standard (Knopp, 2016). The combination of these two sets of software packages currently includes a standard compliant implementation of a subset of Release 10 LTE for UE, eNB, MME, HSS, SGW, and PGW on standard Linux-based computing equipment. At the physical layer, it provides the following feature (Nikaein N. , Latency, Cooperation, and Cloud in Radio Access Network, 2015):

- LTE release 8.6, with a subset of Release 10;
- FDD and TDD configuration in 5, 10, and 2o MHz band-width;
- Transmission mode: 1 (SISO), and 2, 4, 5, and 6 (MIMO 2x2),
- CQI/PMI reporting;
- All DL channels are supported: PSS, SSS, PBCH, PCFICH, PHICH, PDCCH, PDSCH, PMCH;
- All UL channels are supported: PRACH, PUSCH, PUCCH, SRS, DRS;
- HARQ support (UL and DL),
- Highly optimized baseband processing (including turbo decoder).

For the E-UTRAN protocol stack, it provides:

- LTE release 8.6 and a subset of Release 10 features;
- Implements the MAC, RLC, PDCP and RRC layers;
- Protocol service for Release 10 eMBMS (MCH, MCCH, MTCH)
- Priority-based MAC scheduler with dynamic MCS selection;
- Fully reconfigurable protocol stack;
- Integrity check and encryption using the AES and Snow3G algorithms;
- Support of RRC measurement with measurement gap;
- Standard S1AP and GTP-U interfaces to the Core Network;

- IPv4 and IPv6 support.

Features of OAI EPC implementation include:

- SGW, PGW, MME and HSS implementation;
- NAS integrity and encryption using the AES and Snow3G algorithms;
- UE procedures handling: attach, authentication, service access, radio bearer establishment;
- Transparent access to the IP network- no need of external SGW and PGW;
- IPv4 and IPv6 support.

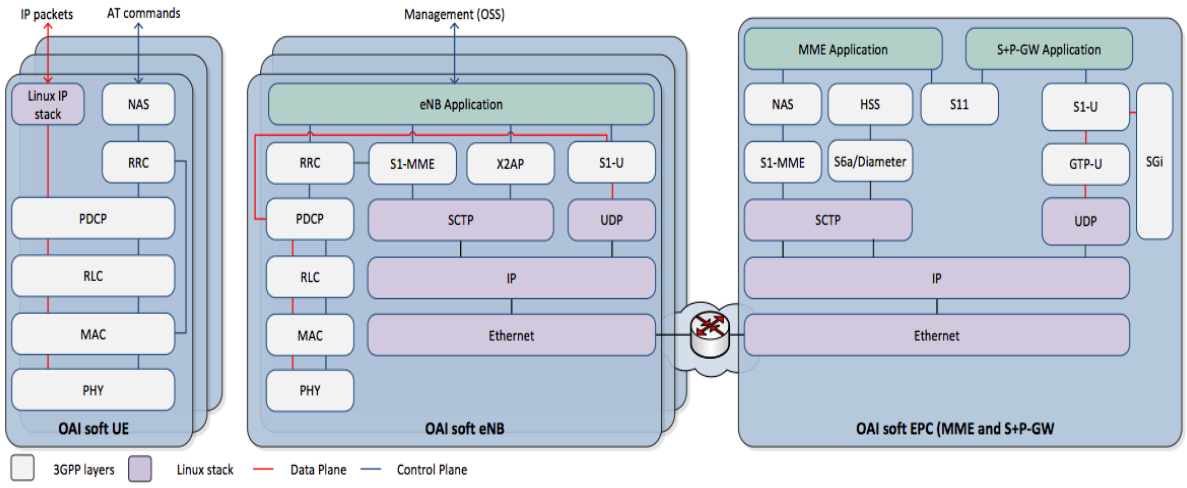

Figure 4.1: OpenAirInterface LTE software stack (Nikaein, et al., 2014)

Figure 4.1 shows the entire LTE protocol stack in OAI. The OAI can be used with a rich software development environment including Aeroflex-Geisler LEON/GRLIB, RTAI, Linux, GNU, Wireshark, control and monitoring tools, message and time analyzer, low-level log processing, traffic generator, profiling tools and soft scope (Nikaein, et al., 2014). It also provides tools for protocol validation, performance evaluation and pre-deployment system test (OpenAirInterface, 2016).

4.2.2. Hardware Platform

The OAI equipment consists of two types of hardware components: CardBus MIMO and Express MIMO. The CardBus MIMO is a software defined radio. USRP B210 platform is widely used software radio frontend in research community. The OAI supports the USRP Hardware Driver (UHD) for use with the recent version of USRP PC-hosted software radio platform (Nikaein, et al., 2014). Express MIMO is a default software radio frontend for OAI. It is a baseband processing board for high performance radio signal processing. It uses a standard PCI-express interface which can be controlled through PC. Currently newer version ExpressMIMO2 is available in the market. The embedded system on the ExpressMIMO2 is based on a LEON3 microcontroller. The LEON3 has a large DDR3 memory for data and program storage. The embedded software for the FPGA is booted via the PC or can reside entirely in the boot ROM which is part of the FPGA design. In the current design, the embedded software is booted by PCIexpress dynamically under control of the PC device driver (EURECOM, 2016).

The OAI platform can be used in several different configuration including commercial components to varying degrees (Nikaein, et al., 2014):

- OAI UE <--> OAI eNB + OAI EPC
- OAI UE <--> OAI eNB + Commercial EPC
- OAI UE <--> Commercial eNB + OAI EPC
- OAI UE <--> Commercial eNB + Commercial EPC
- Commercial UE <--> Commercial eNB + OAI EPC
- Commercial UE <--> OAI eNB + Commercial EPC
- Commercial UE <--> OAI eNB + OAI EPC

4.2.3. Emulation Platform

Besides the real time operation and simulation of OAI software over the hardware components, the full protocol stack can be run in a laboratory environment in emulation mode. It is a next

generation framework for real time wireless 4G systems and networking experimentation applicable to evolving cellular technologies such as LTE-Advanced. The objective of this platform is to fill the gap between the simulation and real experimentation by providing the baselines for protocol validation, performance evaluation and pre-deployment system test (EURECOM, 2016).

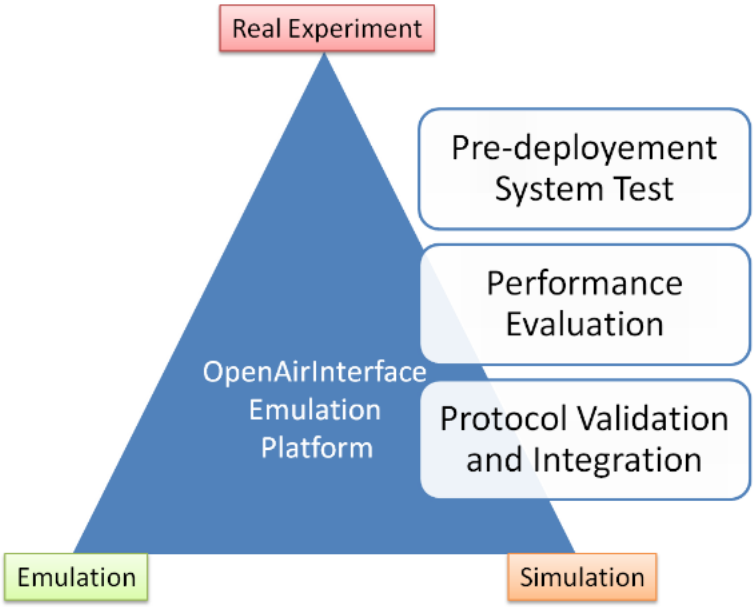

Figure 4.2: OAI Platforms (EURECOM, 2016)

4.3. OAI Towards 5G Research

The fifth generation of mobile network is going to support a wide range of new applications and services, which demands higher data rate, reduced energy consumption per service, reliable connectivity with very low latency and the possibility to handle extreme device densities. As LTE gradually deployed worldwide, cellular system is still slow in moving towards this direction thus locks to expensive HW/SW platforms (Yeoh, Mokhtar, Rahman, & Samingan, 2016). However, with the help of OAI, we can build and support an open cellular ecosystem that can use the commodity hardware or general purpose processor for open LTE system for future 5G. RAN virtualization or CloudRAN, SDN and NFV are the solutions to avoid the

costly deployment, operation and maintenance of future mobile network. In this regard, the OAI, an open source base LTE implementation is definitely speeding CloudRAN, SDN, and NFV and also realizing the possibility of low cost LTE network deployment in future (Virdis, Iardella, Stea, & Sabella, 2015).

The concept of CloudRAN evolved from a distributed base station (DBS) architecture where a BS server is responsible for baseband processing (Hossain & Hasan, 2015). In CloudRAN, functions of eNBs is split into two main parts: radio access part called Remote Radio Head (RRH) which is deployed in the territory generally according to coverage policies and base band function called Base Band Unit (BBU) that can be centralized and remotely connected with the RRH (Virdis, Iardella, Stea, & Sabella, 2015). A BBU pool serves a particular area with a number of RRH of macro and small cells. Based on baseband signals received from the cloud, the transmissions of radio signals to users are performed The emulation mode is designed for experimentation in wireless access technology in a real network setting. This emulation environment can help the researchers to experiment their ideas quickly and verify them in a realistic environment. The current development targets generic Linux-based hardware environment ranging form a single PC to sophisticated cluster or even a GPU workstation (Romdhanne, Nikaein, Knopp, & Bonnet, 2011). It provides a complete wireless protocol stack and implements the PHY, MAC, RLC, PDCP, RRC, as well as providing an IPv4/IPv6 network device interface under Linux (Anouar, Bonnet, Câmara, Filali, & Knopp, 2008). It has different modes of operation including single machine and multi-machine emulation. The single machine mode is the virtualization of network nodes in a single machine while the multi-machine emulation is distributed deployment on a local network to transmit information via the IP address. For the PHY layer of the platform, it has two operating modes: full PHY layer and PHY abstraction. The Full PHY layer mode which is more detailed and intensive involves convolution by the RRHs (Hossain & Hasan, 2015).

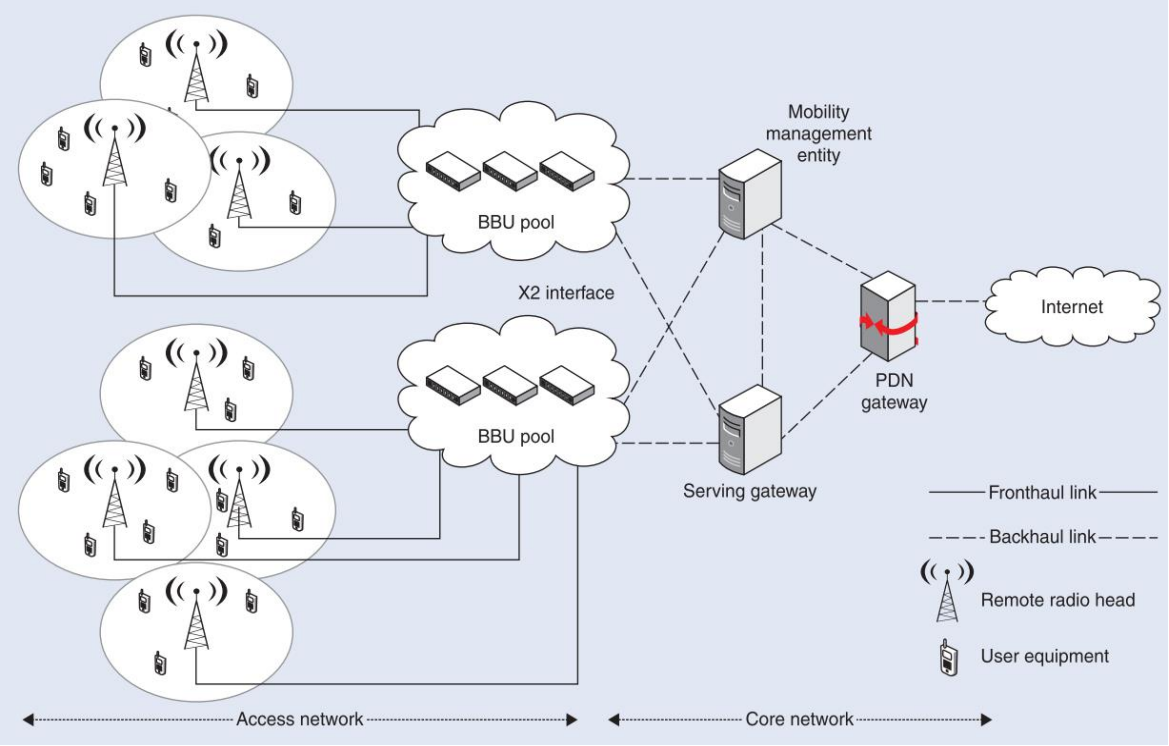

Figure 4.3: An LTE-A system enhanced with cloud-based radio access network (Hossain & Hasan, 2015)

The radio and baseband processing functionality is integrated inside the BS in LTE-A based cellular system and the inter-BS communication is performed over X2 interface. In CloudRAN, as shown in figure, the baseband processing is performed in the cloud (e.g. BBU pool). A BBU pool is a virtualized server which can consist of general-purpose processors to perform baseband processing (Hossain & Hasan, 2015). Figure 4.3 shows an example of a CloudRAN mobile LTE network. The fronthaul part of the network spans from the RRHs sites to the BBU Pool. The backhaul connects the BBU Pool with the mobile core network. At a remote site, the radio unit e.g. RRH is co-located with the antennas and performs digital processing, digital to analog conversion and performs digital conversion, power amplification and filtering (Checko, et al., 2015). This approach provides several research opportunities. Centralization of access network processing will allow the implementation of smart algorithms for cooperation among the base stations in terms of radio resource allocation, QoS-aware traffic management and power saving (Virdis, Iardella, Stea, & Sabella, 2015).

CloudRAN will enhance the scalability, improve network capacity, and extend the coverage of future 5G systems. In order to carry out research on these topics, we need a software platform

capable of emulating cellular network on general purpose hardware. Due to its emulation capacity, OAI appears to be the most promising and complete project for 5G research which allows one to conduct performance evaluation campaigns on LTE networks with a protocol stack entirely implemented in software. In addition, OAI allows one to carry out experiments using hardware equipment and commercial terminals, by ensuring real-time performances, validation and prototyping (Virdis, Iardella, Stea, & Sabella, 2015). Thus, the OAI is a suitable platform for an open cellular ecosystem both for 4G experimentation and 5G research.

4.4. OAI Installation

This section describes installation of OAI on a Linux-based PC as well as materials and methods required for installation.

4.4.1. Building, Installing, and Running OAI

The OpenAirInterface software consists of two main components of LTE system Architecture: the radio part, the E-UTRAN and the core part, the EPC part. The EURECOM´s access network software is known as openairinterface5G while the EPC software goes under the name of openairCN. The transceiver part (a base station, access point, mobile terminal) is achieved by using USRP SDR. The EPC part is a bundle of software components that provides the MME, SGW, PGW and HSS functions of the LTE core EPC architecture.

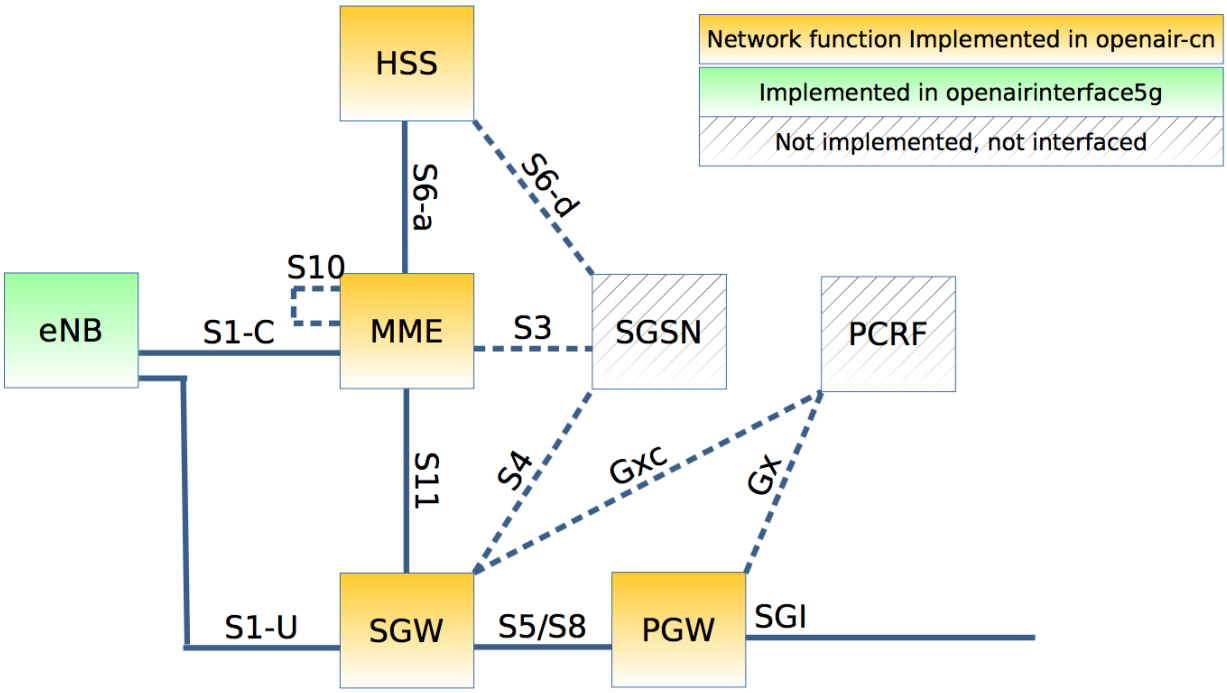

Figure 4.4: EURECOM core network entities overview (Bonnet, et al., 2016)

The MME is a network entity that can be deployed on its own host or can be co-located with any other LTE network entity such SPGW and HSS. But the EURECOM does not recommend the deployment of MME on a eNB even it works. The SPGW can be deployed on its own host or can be co-located with MME or/and with the HSS (Bonnet, et al., 2016). In a deployment scenario that I followed, there is no S5 and S8 interface as SGW and PGW are merged together.

The EURECOM eNB software comes with bundle of components that provides the eNB functions of the LTE on both radio interface i.e. Uu and the core network interfaces i.e. S1-C and S1-U. There are several deployment scenarios with the EURECOM eNB and UE. The figure 4.5 shows OAI eNB with S1 interface which describes a EURECOM eNB and EPC providing MME and GW functions, and interact with the EURECOM HSS. In this configuration, the S11 interface is virtual in the sense that S11 messages do not go through the network layer but through an inter-task interface message passing middleware (ITTI) (Gupta, et al., 2015).

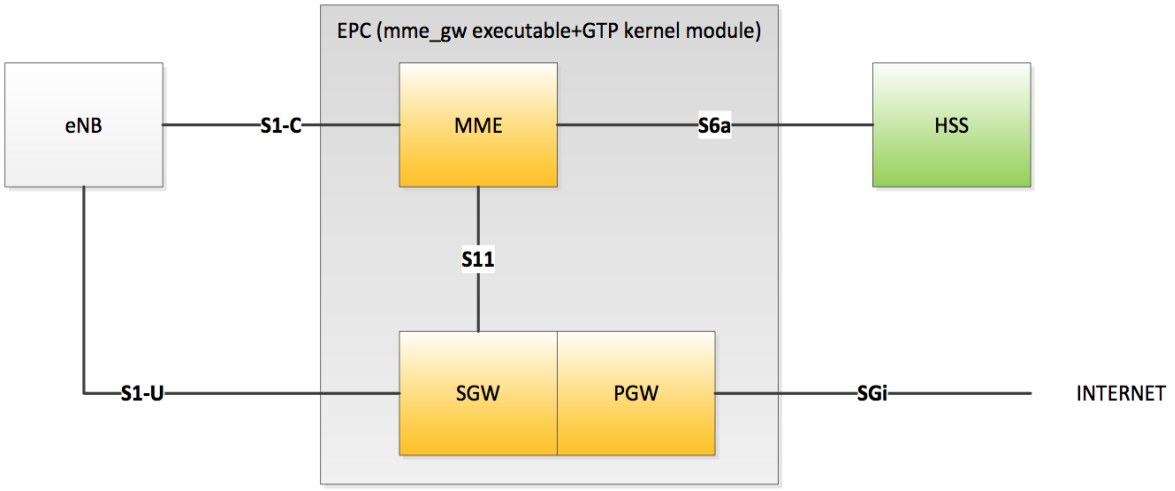

Figure 4.5: OAI eNB with S1 interface (Gupta, et al., 2015)

Several prerequisites are required before the system will be capable of building, installing, and running OAI software.

4.4.1.1. Hardware Components

EURECOM software currently supports Intel architecture based PCs for the eNodeB or UE targets. The software has been tested on Intel Core i5 and i7 processors. The operating system requires for these software is Ubuntu 14.04 LTS (32-bit or 64-bit). According to EURECOM, the OpenairCN EPC component should work on any 64 bits Linux machine.

The USRP B210, which acts as a transceiver, is a key component that makes OAI possible. The Express MIMO2 is a baseband processing board for high performance radio signal processing. It uses a PCI express interface which can be controlled through PC. For real time operation, these hardware targets have some constraints (EURECOM, 2015).

- ExpressMIMO2 PCIe card requiring a PC with a free 8/16-way PCIe slot.
- USRP B210 USB3 radio card requiring a PC with a free USB3 port.
- Ethernet transport requires a PC with a fast Ethernet port (10G or more).

4.4.1.2. Kernel Requirements for RAN

The openairCN does not require any special kernels and we can generally use Ubuntu distributions with generic kernels. The EURECOM currently supports Ubuntu14.04 LTS and Ubuntu 15.04 with a generic 3.19 kernel. But for openairinterface5G, we should install low-latency kernel. Currently OAI supports 14.04 LTS with a recent low-latency kernel 3.19.0-61-lowlatency. If someone wants to run OAI core network software on the OAI eNB, then a low-latency kernel is required. There are some other options we need to follow before the actual installation begins. We should disable the C-states from BIOS in order to reduce the processor power when not needing the full speed. Another option is disabling CPU frequency scaling which enables the operating system to scale the CPU frequency up and down in order to save power. A detail description about kernel requirements for OAI is given in Appendix 1.

4.4.1.3. Getting the Code

The OAI software can be obtained from EURECOM gitLab server. Before downloading the code, we need to install a modern version of subversion/git by executing the following command.

sudo apt-get update
sudo apt-get install subversion git

The EURECOM openairinterface5G (RAN) repository has source code for eNB RAN and UE RAN. The core network source code is placed in openair-cn repository. If someone wants to check in code to git server, then he needs to configure git with his name/email address. In order to get code, we need to add a certificate from www.gitlab.eurecom.fr to our Ubuntu 14.04 installation machine. The user can checkout the git repository by using following commands.

- Checkout RAN repository (eNodeB RAN + UE RAN):
  git clone https://gitlab.eurecom.fr/oai/openairinterfac5g.git
- Checkout EPC repository:

git clone https://gitlab.eurecom.fr/oai/openair-cn.git

By default, we are on the master branch which is most stable branch. The develop branch contains recent commits that are tested on OAI test bench.

4.4.1.4. Building the Code

Now we have two folders: openair-cn and openairinterface5g in our home directory. We use an automated build script located at the cmake-targets directory to build OAI eNodeB, EPC and HSS. The cmake tool automatically generates makefiles to build the system for OAI.

Building Script for openairinterface5g

cd ~/openairinerface
source oaienv # It sets the correct environment variables.
cd cmake_targets
. /build_oai –I –g –eNB –x --install-system-files –w USRP --install-optional-packages
(this command is for USRP)
. /build_oai –I –g –eNB –x --install-system-files –w EXMIMO --install-optional-packages
(this is for EXMIMO RF)
. /build_oai –I –g –eNB –x --install-system-files –w BLADERF --install-optional-packages
(this is for BladeRF)

We can use the . /build_oai –h option to understand the meaning of different options used in the above commands. Some of them are summarized as follows.

- -I: installs required packages.
- -g: adds debugging symbols to compilation directives.
- --eNB: installs eNB, i.e.; Lte-softmodem.
- -x: adds a software oscilloscope feature to the produced binaries.

- --install-system-files: installs OAI required files in Linux system.
- -w: adds the hardware support, which is USRP in my case.
- --install-optional-packages: Installs optional packages (EURECOM, 2016).

Building script for openair-cn

cd openair-cn

cd SCRIPTS

. /build_mme –i

. /build_hss –i

. /build_spgw –i

By default, we are on master branch. To change to develop branch, we need to use two more command after we are on openair-cn directory: git checkout develop and git pull.

4.4.1.5. Configuration

Basically there are two types of setup for OAI software: The first method is setting up OAI eNB, EPC and HSS on a single host and the second method is running OAI eNB and EPC plus HSS on different hosts. The building procedure is same for both types of setup, but configurations are different. Because of some unexpected real-time issues, the EURECOM recommends the second type of setup. Here I explain the setup for running eNB and EPC plus HSS on two different hosts.
The IP address of the PC which has eNB installed is 129.241.209.200 and the PC which has EPC + HSS is 129.241.208.190. Both the PCs are connected together with the Ethernet (eth0) interface.

In eNB configuration file, we need to change some network parameters like tracking area code (TAC), mobile country code (MCC), mobile network code (MNC), IP address of MME and eNB related network interface information. The eNB configuration file is located at the following directory: ~/openairinterface5g/targets/PROJECTS/GENERIC-LTE-EPC/CONF/enb.band7.tm1.usrpb210.conf.

```
tracking_area_code  =  "1";
mobile_country_code =  "208";
mobile_network_code =  "93";

        mme_ip_address = ({ipv4       = "129.241.208.190";


        NETWORK_INTERFACES:
        {
        ENB_INTERFACE_NAME_FOR_S1_MME         = "eth0";
        ENB_IPV4_ADDRESS_FOR_S1_MME           = "129.241.209.200/23";

        ENB_INTERFACE_NAME_FOR_S1U            = "eth0";
        ENB_IPV4_ADDRESS_FOR_S1U          = "129.241.209.200/23";
        ENB_PORT_FOR_S1U                  = 2152; # Spec 2152
        };
```

In the above code, mme_ip_address is network interface´s IP address of EPC/HSS and NETWORK_INTERFACE is the eNB related network interface information. A brief overview of all configuration file for OAI is shown in appendix

By default, OAI SQL database password is ´linux`. We can provide our own password during installation. In that case we need to change the password option in configuration file. The operator key for oai_db.sql must match to that of UE SIM card´s operator key. The appendix 5-2 shows all the configuration related to EPC machine.

4.4.1.6. Compiling and Running eNB, EPC and HSS

Before running OAI components, we need to install HSS and MME certificates into a directory /usr/local/etc/oai/freeDiameter as follows:

```
cd  ~/openair-cn/SCRIPTS
```

./check_hss_s6a_certificate /usr/etc/oai/freediameter/ hss.openair4G.eur
./check_mme_s6a_certificate /usr/etc/oai/freediameter/ shyamalpc.openair4G.eur

After installing, we always need to run HSS first and then after EPC is connected to HSS we need to compile and start the eNB.

- **Compile and run HSS:**
  cd ~/openair-cn
  cd SCRIPTS
  ./build_hss –c
  ./run_hss - i ~/openair-cn/SRC/OAI_HSS/db/oai_db.sql # this command needs to run only once which install the OAI database.
  ./run_hss # this command for all other subsequent runs

- **Compile and Run MME:**
  cd ~/openair-cn
  cd SCRIPTS
  ./build_mme –c
  ./run_mme

- **Compile and Run SP-GW:**
  cd ~/openair-cn
  cd SCRIPTS
  ./build_spgw –c
  ./run_spgw -r

- **Compile and Run eNB:**
  cd ~/openairinterface5g
  source oaienv
  ./cmake_targets/build_oai –w USRP –x c --eNB
  cd cmake_targets/lte_build_oai/build
  sudo –E ./lte-softmodem –o $OPENAIR_DIR/targets/PROJECT/GENERIC-LTE-EPC/CONF/enb.band7.tm1.usrpb210.conf –d

4.4.1.7. UE configuration and User Registration on HSS Database

For user registration on HSS database, the UE or USIM card must have the following information.

- MCC: 208
- MNC: 93
- TAC: 1
- IMSI:208930000000001
- Ki: 8BAF473F28FD09487CCCBD7097C6862
- OP (Operator Key): 11111111111111111111111111111111

The operator key in hss.conf file must be matched with SIM card´s OP key. To configure UE, we have to create an Access Point Name (APN) profile in our smartphone. The required fields in APN are name, APN, and bearer.

We need to register the user on HSS database to complete the UE attached procedure. For this purpose, we have to add user to oai_db.users table and have to update oai_db.mmeidentity and oai_db.pdn tables with necessary parameters. We can check out existing users in the database via phpmyadmin. However, we can not be able to insert a user record on phpmyadmin, because authentication key Ki as well as Operator key OPc are stored as binary in the database. For this purpose, we can use mysql –u root –p command from terminal and the password is ´linux´. The SQL commands that are used to add user to table oai_db.users and updating oai_db.mmeidentity and oai_db.phd tables are shown in Appendix 7.

4.4.2. Materials and Methods

The OAI team provides a lot of informations and tools required for implementing OAI software. Some of them are: git repository, twiki site, mailing lists, bulletin board forum and Bugzilla (EURECOM, 2016).

- **OAI Git Repository:** The OAI software can be obtained from git server hosted by EURECOM. Normal user can obtain code without login to the git server but for developer who wants to commit in code must login with user account.

- **OAI Mailing Twiki:** This contains practical information on software installation, machine configuration, code compilation and many more. This website is no longer maintained now, but it is still useful for lot of information. The new wiki is now available at EURECOM gitlab server.

- **OAI Mailing Lists:** Several mailing lists for developers and users are hosted on EURECOM´s sympa server. For example, openair5g-user is for the users of OpenAirInterface and openair5g-devel is for the developers of OpenairInterface. Similarly, openaircn-user is for the user of OpenairCN and openaircn-devel is for the developers of OpenairCN.

- **OAI Forum:** This is created for communication between developers and people curious about what is going on in EURECOM. This can be considered as a direct information exchange.

- **OAI Bugzilla:** This is created for reporting bugs but it is not used.

5. Results and Discussion

This chapter presents the results of my analysis. The first section describes the results obtained from analysis of each of open source mobile communication software. The second section describes the results obtained from the implementation of OpenAirInterface. Section 5.2 summarizes the thesis and discusses its findings.

5.1. Results

The results obtained from the study of open source mobile communication software show that they are quite useful for experimentation and testing of new generation of mobile communication architecture. They provide a significant opportunity for students and researchers to interact with next generation telecommunication architecture. In the past, projects OpenBTS and OpenBSC were considered as fun lab projects, but now companies scaled and released the commercial version. These open source GSM projects allow very rapid and economical deployment of GSM in rural of developing countries.

As LTE is a new wireless technology, OpenEPC can be used to create NGMN testbeds which are used to prototype, test, and perform research and development of NGMNs. It integrates various network technologies and application into a single testbed. The upcoming release of OpenEPC7 includes the support for LTE-M which is beneficial for IoT market. Another LTE project called Amarisoft LTE100 is the world´s first fully software based LTE Base Station which is more flexible and cheaper than other hardware based solution. The researchers and educators from all around the world can access and share PhantomNet Project through the Internet with free of charge, where they develop, debug and evaluate their mobility ideas.

The current cellular system is still slow and requires expensive HW/SW platforms. CloudRAN, SoftRAN, SDN, and NFV are the solutions to avoid the costly deployment, operation and maintenance of future mobile networks. CloudRAN and softRAN will enhance the scalability, improve the network capacity, and extend the coverage of future 5G systems. Future cellular networks nee an SDN which can handle and manages the network from the central location

and offers mobility and control. The results obtained from the installation of OAI is described in next sections.

5.1.1. OAI Experimental Testbed

As illustrated in figure 5.1, the OAI experimental testbed consists of OAI eNB installed in one machine and OAI EPC (MME, HSS and SPGW) installed in another machine. USRP B210 is connected with eNB machine for radio interface. Both the machines run Ubuntu 14.04 LTS in Intel x86-64 machines comprising 4 cores with Intel i7 processor core at 2.80GHz. The OAI EPC is connected with OAI eNB using Ethernet interface. The USRP B210 is connected with eNB through USB 3.0. The Samsung Galaxy S3 with EURECOM provided SIM card acts as UE.

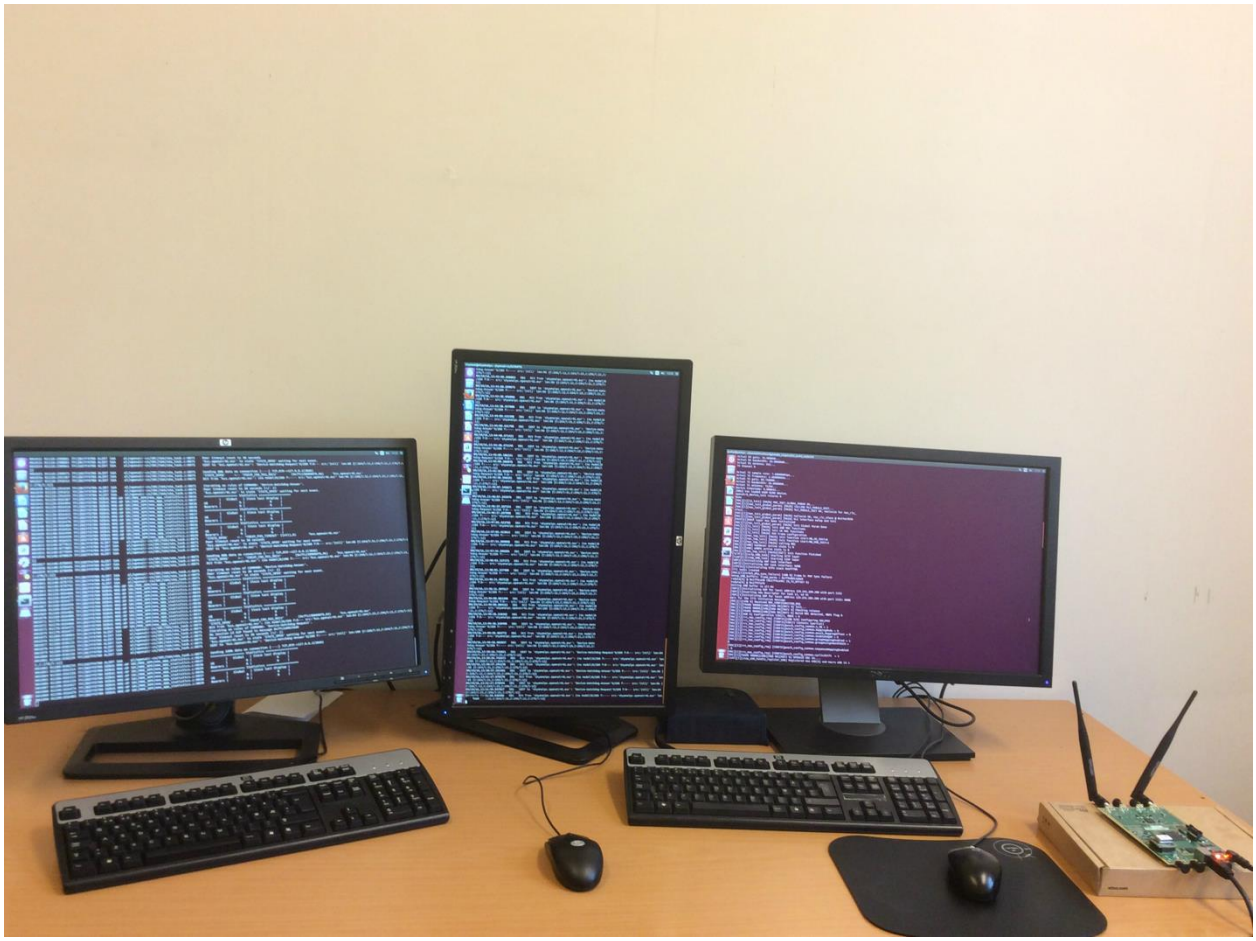

Figure 7.1: OAI experimental setup

Both EPC and HSS run successfully. After EPC is connected with HSS, we can see both enter STATE_OPEN from the terminal as shown in Appendix 8-4. The eNB is also successfully connected and shows something like the following in the figure 5.2 on eNB terminal. Unfortunately, eNB starts to crash after sometime due to some real time issues with USRP B210.

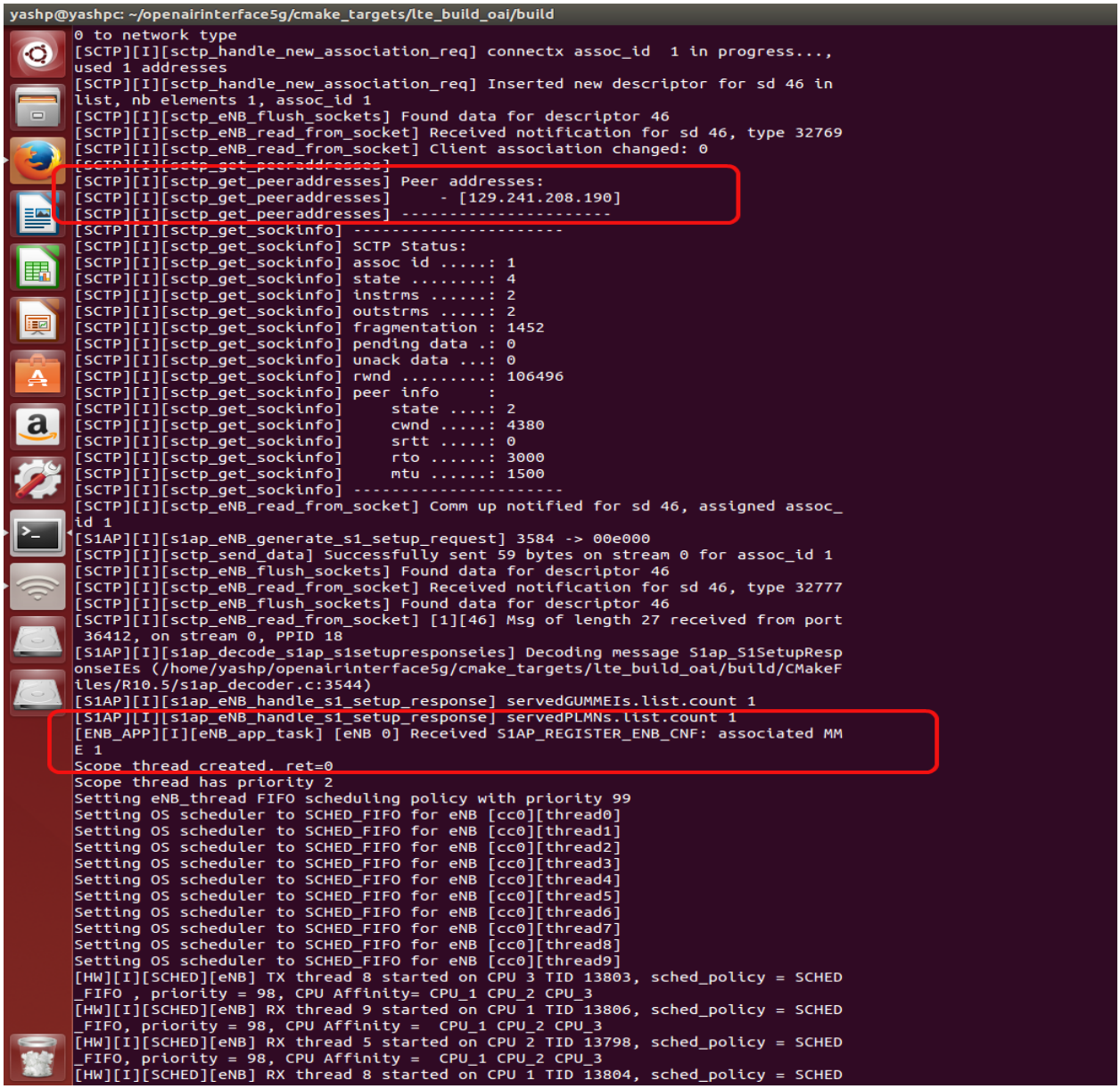

Figure 7.2: eNB successfully connected before crash

5.1.2. Real Time Issues

Unfortunately, eNB is not associated with MME because of some real time issues. It happens because eNB installed computer does not send data to USRP B210 fast enough. That means data transfer is not happing in real-time. According to the OAI team, this problem is radically improved in the upcoming merge from "enhancement-10-harmony" branch. Appendix 8-1 shows some unwanted character eNB crashed due to real time issues with USRP B210. From this experiment we can say that OAI software is not yet mature and still have some issues.

5.2. Discussion

Based on the above results, we see that open source projects have shown the feasibility of using open source components and low cost hardware platform to deploy GSM and LTE testbeds. By breaking the boundary of proprietary and closed systems, open source projects not only reduce the cost but also boost the innovation in the field of mobile communication networks. Open source GSM Projects such as OpenBTS and OpenBSC have been improved with the aims of taking them out of the lab and into the commercial world. They are already being implemented in rural areas of developing countries. The latest release of these projects offers significant improvements in processing capacity and system management features. They are highly scalable, reliable, secure and easy to use.

Open LTE projects such as OpenEPC, Amarisoft LTE 100 and PhantomNet are useful for testing and research the advanced features of EPC/LTE. The upcoming release of OpenEPC 7 supports LTE-M features which is beneficial for M2M communication. It integrates well with OpenIMS core and provides a complete mobile broadband core network solution. It is also possible to combine OpenEPC, Amarisoft LTE 100 and PhantomNet together and provides a complete end-to-end mobile networking testbed for educators and researchers where they can develop, debug and evaluate their mobility ideas.
Unfortunately, I could not implement OAI software completely due to some real time issue with USRP B210. But I think OAI can be instrumental in the development of key 5G technologies like CloudRAN, SDN, NFV, massive MIMO and M2M/IoT. These technologies

are the solutions to avoid the costly deployment, operation and maintenance of future mobile networks.

5.2.1. Answering Research Questions

This section answers the research questions as mentioned in section 1.1.1.

1. **What are the State of Art approaches to investigate and analyze the available open source mobile communication software?**

   There are several open source projects works in the field of mobile communication. Chapter 3 discusses some of the available open source projects. Section 3.1 describes about OpenBTS projects which is considered as an open cellular ecosystem. As OpenBTS is SIP based network, there are possibilities of integration with next generation mobile networks. Section 3.2 discuses about OpenBSC which was originally developed for research and experimentation, but now it has been put to use in real world applications. The openIMS core is discussed in section 3.3 whose purpose is to provide IMS core reference implementation for IMS technology testing. It can be integrated with cloud computing and now it is evolved as the core signaling architecture of Next Generation Networking (NGN) for multimedia services. Similarly, section 3.4 explain about OpenEPC which can be used to create Next Generation Mobile Networks (NGMNs) which are used to prototype, measure, monitor, test and perform research and development for NGMNs. Section 3.5 describes about Amarisoft LTE 100 which is a software based LTE Base Station and section 3.6 discusses about PhantomNet project. The PhantomNet is an end to end mobile networking testbed which provides a single environment where experimenters can combine mobile networking, cloud computing and software defined networking technologies. Finally, section 3.9 to section 3.11 as well as chapter 4 discusse how OpenAirInterface combine with Software Defined Network, Network Function Virtualization, CloudRAN/SoftRAN and Machine to Machine communication revolutionized next generation mobile communication networks.

2. **How to evaluate usability, easiness of installation, portability, scalability, reliability and openness of these open source mobile communication software?**

   The evaluation of open source mobile communication software in terms of usability, portability, scalability, reliability, easiness of installation and openness is discussed in different sections of chapter 3. Section 3.1.1 describes how new release of OpenBTS 4.0 extends Range Network´s technology deeper into the service provider market. Similarly, section 3.2.1 shows the possibility of OpenBSC supports GPRS and EDGE if combined with OsmoSGSN and OpenGGSN. The OpenIMS core project can be integrated with cloud computing. This integration will bring explosive growth in Telecom industries as IMS now the core signaling architecture of NGN for multimedia service. A description about its evaluation can be found in section 3.3.1. Section 3.4.1 describes the integration of OpenEPC with various access network technologies to provide a complete mobile broadband core network solution. It also provides features of upcoming release of OpenEPC7 and describes how LTE-M is beneficial for IoT market. Section 3.5.1 describes how the world´s first fully software based LTE Base Station is more flexible, scalable and reliable than any other expensive hardware based solution. And the section 3.6.1 describes the flexibility of PhantomNet where various combination and configurations are possible. Finally, chapter 4 describes OpenAirInterface as a reference platform that could be used by ETSI and other open source project workgroups for prototyping and validating the standards and shows the value of OAI for 5G related studies.

3. **How to install and experiment OpenAirInterface 4G on a generic computer?**

   Section 4.4 of Chapter 4 describes the installation procedures for OAI on a standard Linux-based computing equipment, system requirements, and kernel configuration as well as user registration on HSS database.

5.2.2. Challenges

This section describes some of the challenges encountered when investing and analyzing some of the open source mobile communication software as well as limitation arising from implementation of OAI on a generic computer.

5.2.2.1. Evolve around the developer, not to the end users

The open source software tends to evolve around developer´s wishes than the need of end-users. During this thesis preparation, I have read a lot of open source projects related to telecommunication. Some of them have disappointing documentations and user guides. For this reason, they are less user friendly and not easy to use because less attention is paid to the end user. One of the biggest challenge I have faced during this thesis preparation is that I hardly got project related documents on web site. These open source projects also forget the new entry level user who needs introductory explanations out of the main part of the project. However, some of the project like OpenAirInterface and OpenBTS have excellent reading materials and wiki pages which explain in details about the projects but the code structure is complex and difficult for a user to modify and customize.

5.2.2.2. OAI installation challenges

- **Real time Issues with USRP B210:** The main challenge I have faced during OAI installation is the real-time issues that comes from USRP driver. When I have tried to run the OAI eNB, the screen printed some characters like ULLLLLULLLLLLL. I sent email to mailing list and Rohit Gupa, a member of OAI team said that it happens because computer does not send data to B210 fast enough. This means data transfer is not happing in real time and he further said this is radically improved in the upcoming merge from ´enhancement-10-harmony´ branch.

- **Mysql server and Oai_db database creation problem:** In several of my installations of Openairn-cn, I have encoutnerd problems related to Mysql server and oai_db creation. In tutorial, it is written to do `build_hss –i` first when installing complete EPC. It tries to install both mysql and phpmyadmin. During installation of phpmyadmin, it tries to configure sql database but fails as mysql is not installed. Although manually configure and install mysql and using script hss_db_create seem to make HSS work, we are not sure if all the necessary steps have been completed through these workarounds. Moreover, the phpmyadmin is not installed through these workarounds. OAI team has fixed these problems recently on develop branch on openair-cn but still we need to install Mysql server prior to build HSS, SPW, and MME.

- **Different system requirements for EPC/HSS and eNB:** It is not recommended to install OAI eNB and OAI EPC on a single host because of some real time issues, for example, both EPC/HSS and eNB require different kernel requirements and require different dependencies files. During implementation of OAI, I have also faced some conflicting package installation of asn1 from eNB. So OAI team suggested me not to install OAI enB and OAI EPC on the same host unless I know how to resolve real time issues that will arise. It can also create real-time issues which can interfere with USRP acquisition.

- **Complex code structure:** If we compare OAI with other LTE project like OpenLTE, OAI is well organized and comparatively very complete. However, the code structure is complex and difficult for a user external to the project to modify or customize.

- **Community dependent:** As OAI depends on community of developers and users, some times when the things go wrong, it takes longer than usual time responds to and fix the problems.

6. Conclusions

This chapter presents the conclusions drawn from the result of this thesis and some possible future extensions that could be interesting to analyze OAI in terms of performance and security.

6.1. Conclusion

This thesis started with the aim of analyzing some of the available open source mobile communication software followed on the practical installation of OpenAirInterface 4G software. Over the past few years, open source mobile communication software has made a very significant impact in mobile communication networks. It has been used as a momentum to increase the importance of testbed and prototype for protocol validation, performance evaluation and pre-deployment system test. The thesis tends to cover various topics including available open source mobile communication software, analyzing their scalability, reliability, openness and security, state of art works done so far in the field of LTE, and installing OpenAirInterface 4G on generic Linux based PC.

Some of the open source mobile communication software have been moved from typical research and development environments to the the enterprise sector, where they are competing against very successful telecommunication industries. As described in Chapter 2, the latest release of OpenBTS 4.0 from Range Networks offers significant improvements in capacity and system management features, including multi-node network scaling enhancement to the commercial systems. The OpenIMSCore project as, discussed in Chapter 2, has been designed as a testbed. As IMS is now evolved as the core signaling architecture of NGN for multimedia services, research labs around the world are now using OpenIMSCore to test and optimize for VoLTE deployments in near future. It also integrates well with OpenEPC platform and provide a complete mobile broadband core network solution. Other Open LTE testbeds such as Amarisoft LTE 100, PhantomNet and OpenEPC integrate well with each other and provide a complete testbed for next generation of mobile networks.

The thesis evaluates OpenAirInterface as a flexible platform towards an open LTE ecosystem. Prior to the development of OAI, LTE was too complex for a community of open source developers to manage. It is believed that OAI can be instrumental in the development of key 5G technologies like Cloud-RAN, SDN, NFV, massive MIMO, and M2M/IoT. It provides researchers with an environment in which they can rapidly prototype and test systems which would be infeasible with proprietary equipment (Nikaein, et al., 2014). In this regard, OAI is definitely accelerating the above technologies and providing the possibility of low cost LTE network deployments in future.

6.2. Future work

Several of the objectives defined in this thesis work are achieved and lay the groundwork for a good understanding of analyzing the open source mobile communication software. There are some interesting works that can be done using OpenAirInterface to bring it to the next level of real-time implementation. In the future OAI can be used for testing and evaluating the performance of emerging networking architecture. For the upcoming years, online gaming and M2M applications will continuously in growth and generate a lot traffic. Understanding and modeling of such traffic is very important for designing the next generation mobile communication networks. In this regards, OpenAirInterface Traffic Generator (OTG) tool will be helpful.

Another obvious possibility for future work is using OAI with SDN and Cloud-RAN to reshape the design of next generation mobile networks. As previously mentioned, the OAI works on the two main components of the LTE system architecture; first, the E-UTRAN; and second, the EPC.
Since SDN is purposed to simplify the core network complexity, the same principle of SDN can be used to minimize the complexity of heterogeneous RAN. By moving the base band processing to the data center and leaving only antennas on site, SDN and OAI is definitely accelerating RAN virtualization.

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Appendices

Appendix 1 Kernel Requirements for RAN

Ubuntu 14.04 LTS with Linux version 3.17 or 3.19 is recommended. Before installing correct version run:

sudo apt-get update
sudo apt-get install linux-image-3.19.0-61-lowlatency linux-headers-3.19.0-61-lowlatency

Appendix 1-1 Disable CPU Frequency Scaling

Install cpufrequtils:

sudo apt-get install cpufrequtils

Then edit the following file:

sudo nano /etc/default/cpufrequtils

Add the following line to this file:

GOVERNOR=“performance”

Save and exit

Disable ondemand daemon:

sudo update-rc.d ondemand disable

Appendix 2 Getting Source Code

Install subversion/git:

sudo apt-get update
sudo apt-get install subversion git

Check out the RAN repository:
git clone http://gitlab.eurecom.fr/oai/openairinterface5g.git

Checkout EPC:
git clone https://gitlab.eureocm.fr/oai/openair-cn.git

By default, we are on the master branch. If we want to select the develop branch, then the code is:

cd openair-cn
git checkout develop
git pull
cd SCRIPTS

Appendix 3 Specify FQDN for EPC

Fill the FQDN in /etc/hosts:

shyamal@shyamalpc:~$ cat /etc/hosts
127.0.0.1 localhost
127.0.1.1 shyamalpc.openair4G.eur shyamalpc
127.0.1.1 hss.openair4G.eur hss

Here the fully qualified name is shyamalpc.openair4G.eur. we can take any name. Relam is openair4G and shyamalpc is a hostname.

Appendix 4 Building OAI

Appendix 4-1 Building OAI eNB

cd ~/openairinterface
sorce oaienv
cd cmake_targets
./build_oai -I -g --eNB -x --install-system-files -w USRP --install-optional-packages #for USRP
./build_oai -I -g --eNB -x --install-system-files -w EXMIMO --install-optional-packages #for EXMIMO
./build_oai -I -g --eNB -x --install-system-files -w BLADERF --install-optional-packages #for BladeRF

Appendix 4-2 Building OAI EPC

```
cd openair-cn
git checkout develop
git pull
cd SCRIPTS
./build_mme -i          #( Run only once to install missing packages)
./build_hss -i   #(Run to run only once to install missing packages)
./build_spgw -i         #(Run to run only once to install missing packages)
```

Appendix 5 Configuration

Appendix 5-1 eNB Configuration

The eNB configuration file is located at the following directory:

~/openairinterface5g/targets/PROJECTS/GENERIC-LTE-EPC/CONF/enb.band7.tm1.usrpb210.conf.

```
tracking_area_code  =  "1";
mobile_country_code =  "208";
mobile_network_code =  "93";

////////// MME parameters:
        mme_ip_address = ({ipv4      = "129.241.208.190";
                           ipv6     = "192:168:30::17";
                           active   = "yes";
                           preference = "ipv4";
                         }
                         );

        NETWORK_INTERFACES:
        {
        ENB_INTERFACE_NAME_FOR_S1_MME         = "eth0";
        ENB_IPV4_ADDRESS_FOR_S1_MME           = "129.241.209.200/23";

        ENB_INTERFACE_NAME_FOR_S1U            = "eth0";
```

```
        ENB_IPV4_ADDRESS_FOR_S1U            = "129.241.209.200/23";
        ENB_PORT_FOR_S1U                    = 2152; # Spec 2152
        };
```

Appendix 5-2 Configure of EPC Machine

Before making any changes in EPC related configuration files we need to copy them into /usr/local/etc/oai folder.

sudo mkdir -p /usr/local/etc/oai/freeDiameter

sudo cp ~/openair-cn/ETC/mme.conf /usr/local/etc/oai

sudo cp ~/openair-cn/ETC/hss.conf /usr/local/etc/oai

sudo cp ~/openair-cn/ETC/spgw.conf /usr/local/etc/oai

sudo cp ~/openair-cn/ETC/acl.conf /usr/local/etc/oai/freeDiameter

sudo cp ~/openair-cn/ETC/mme_fd.conf /usr/local/etc/oai/freeDiameter

sudo cp ~/openair-cn/ETC/hss_fd.conf /usr/local/etc/oai/freeDiameter

In mme.conf file:

```
REALM                           = "openair4G.eur";

S6A:
        {
        S6A_CONF                = "/usr/local/etc/oai/freeDiameter/mme_fd.conf";
        HSS_HOSTNAME                = "hss";
        };
GUMMEI_LIST = (
        {MCC="208"; MNC="93"; MME_GID="4" ; MME_CODE="1"; }
        );
TAI_LIST = (
        {MCC="208"; MNC="93"; TAC = "1"; }
        );

NETWORK_INTERFACES:
        {
        # MME binded interface for S1-C or S1-MME  communication (S1AP)
        MME_INTERFACE_NAME_FOR_S1_MME       = "eth0";
        MME_IPV4_ADDRESS_FOR_S1_MME         = "129.241.208.190/23";
```

```
        # MME binded interface for S11 communication (GTPV2-C)
        MME_INTERFACE_NAME_FOR_S11_MME      = "lo";
        MME_IPV4_ADDRESS_FOR_S11_MME        = "127.0.11.1/8";
        MME_PORT_FOR_S11_MME                = 2123;
        };
S-GW:
{
        # S-GW binded interface for S11 communication (GTPV2-C), if none selected the
ITTI message interface is used
        SGW_IPV4_ADDRESS_FOR_S11            = "127.0.11.2/8";

};
```

In spgw.conf file:

```
S-GW :
{
        NETWORK_INTERFACES :
        {
        # S-GW binded interface for S11 communication (GTPV2-C), if noneselected the
ITTI message interface is used
        SGW_INTERFACE_NAME_FOR_S11          = "lo";
        SGW_IPV4_ADDRESS_FOR_S11            = "127.0.11.2/8";

        # S-GW binded interface for S1-U communication (GTPV1-U) can be ethernet
interface, virtual ethernet interface, we don't advise wireless interfaces
        SGW_INTERFACE_NAME_FOR_S1U_S12_S4_UP        = "eth0";
        SGW_IPV4_ADDRESS_FOR_S1U_S12_S4_UP  = "129.241.208.190/23";
        SGW_IPV4_PORT_FOR_S1U_S12_S4_UP     = 2152;

        # S-GW binded interface for S5 or S8 communication, not implemented, so leave it to
none
        SGW_INTERFACE_NAME_FOR_S5_S8_UP     = "none";
        SGW_IPV4_ADDRESS_FOR_S5_S8_UP       = "0.0.0.0/24";
        };

        INTERTASK_INTERFACE :
        {
        # max queue size per task
        ITTI_QUEUE_SIZE             = 2000000;
        };

        LOGGING :
        {
        # OUTPUT choice in { "CONSOLE", "`path to file`", "`IPv4@`:`TCP port num`"}
        # `path to file` must start with '.' or '/'
        # if TCP stream choice, then you can easily dump the traffic on the remote or local
host: nc -l `TCP
```

```
        OUTPUT      = "CONSOLE";

        # THREAD_SAFE choice in { "yes", "no" } means use of thread safe intermediate
buffer then a single thread pick each message log one
        # by one to flush it to the chosen output
        THREAD_SAFE     = "yes";

        # COLOR choice in { "yes", "no" } means use of ANSI styling codes or no
        COLOR       = "yes";                                # TODO

        # Log level choice in { "EMERGENCY", "ALERT", "CRITICAL", "ERROR",
"WARNING", "NOTICE", "INFO", "DEBUG", "TRACE"}
        UDP_LOG_LEVEL   = "TRACE";
        GTPV1U_LOG_LEVEL   = "TRACE";
        GTPV2C_LOG_LEVEL   = "TRACE";
        SPGW_APP_LOG_LEVEL = "TRACE";
        S11_LOG_LEVEL    = "TRACE";
        };
};

P-GW =
{
        NETWORK_INTERFACES :
        {
        # P-GW binded interface for S5 or S8 communication, not implemented, so leave it to
none
        PGW_INTERFACE_NAME_FOR_S5_S8            = "none";
        PGW_IPV4_ADDRESS_FOR_S5_S8      = "0.0.0.0/24";

        # P-GW binded interface for SGI (egress/ingress internet traffic)
        PGW_INTERFACE_NAME_FOR_SGI              = "eth0";
        PGW_IPV4_ADDRESS_FOR_SGI        = "129.241.208.190/23";
        PGW_MASQUERADE_SGI                  = "yes";
        };

        # Pool of UE assigned IP addresses
        IP_ADDRESS_POOL :
        {
        IPV4_LIST = (
                "192.188.0.0/24",
                "192.188.1.0/24"
                );
        };

        # DNS address communicated to UEs
        DEFAULT_DNS_IPV4_ADDRESS = "129.241.208.40";
        DEFAULT_DNS_SEC_IPV4_ADDRESS = "129.241.206.252";

        # Non standard feature, normally should be set to "no", but you may need to set to yes
for UE that do not explicitly request a PDN address through NAS signalling
```

```
        FORCE_PUSH_PROTOCOL_CONFIGURATION_OPTIONS = "yes";
        UE_MTU = 1428;
};
```

In HSS free diameter configuration file (hss_fd.conf):

Identity = “hss.openair4G.eur”;
Relam = “openair4G.eur”;

In MME free diameter configuration file (mme_fd):

Identity = “shyamalpc.openair4G.eur”;
Relam = “openair4G.eur”;

ConnectPeer= "hss.openair4G.eur" { ConnectTo = "127.0.0.1"; No_SCTP ; No_IPv6; Prefer_TCP; No_TLS; port = 3868; realm = "openair4G.eur";};

In HSS configuration file (hss.conf):

```
HSS:
{
## MySQL mandatory options
MYSQL_server = "127.0.0.1";
MYSQL_user   = "root";
MYSQL_pass   = "mspwroot";
MYSQL_db    = "oai_db";

## HSS options
OPERATOR_key = "11111111111111111111111111111111"; # OP key for oai_db.sql

RANDOM = "true";

## Freediameter options
FD_conf = "/usr/local/etc/oai/freeDiameter/hss_fd.conf";
};
```

Appendix 6 Running eNB, EPC and HSS

Install certificates:

cd ~/openair-cn/SCRIPTS

./check_hss_s6a_certificate /usr/local/etc/oai/freeDiameter/ hss.openair4G.eur

./check_mme_s6a_certificate /usr/local/etc/oai/freeDiameter/ nano.openair4G.eur

Compile & Run HSS:

cd ~/openair-cn

cd SCRIPTS

./build_hss -c

./run_hss -i ~/openair-cn/SRC/OAI_HSS/db/oai_db.sql # Run this command only once to install database

./run_hss #Run this for all subsequent runs

Compile and Run MME:

cd ~/openair-cn/SCRIPTS

./build_mme -c

./run_mme

Compile and Run SP-GW:

cd ~/openair-cn

cd SCRIPTS

./build_spgw -c

./run_spgw -r

Compile and Run eNB:

cd ~/openairinterface5g

source oaienv

./cmake_targets/build_oai -w USRP -x -c --eNB

cd cmake_targets/lte_build_oai/build

sudo -E ./lte-softmodem -O $OPENAIR_DIR/targets/PROJECTS/GENERIC-LTE-EPC/CONF/enb.band7.tm1.usrpb210.conf -d

sudo -E ./lte-softmodem -h #(to see help options

Appendix 7 User Registration on HSS Database

Adding user to table oai_db.users:

From the command line we can use mysql –u root –p command. The password is ´linux´.

mysql > use oai_db;
mysql > show tables;
mysql > select * from mmeidentity;
mysql > INSERT INTO users (´imsi´, ´msisdn´, ´imei´, ´imei_sv´, ´ms_ps_status´, ´rau_tau_timer´, ´ue_ambr_ul´, ´ue_amr_dl´, ´access_restriction´, ´mme_cap´, ´mmeidentity_idmmeidentity´, ´key´, ´RFSP-Index´, ´urrp_mme´, ´sqn´, ´rand´, ´OPc´) VALUES (´208930000000001´, ´33638060010`, NULL, NULL, ´PURGED´ ´120´, ´50000000´, ´100000000´, ´47´, ´0000000000´, ´3´, 0x8BAF473F28FD09487CCCBD7097C6862, ´1´, ´0´, ´ ´, 0x00000000000000000000000000000000, ´ ´);

Updating oai_db.mmeidentity and oai_db.pdn tables:

mysql > INSERT INTO pdn (´id´, ápn´, ´pdn_type´, ´pdn_ipv4´, ´pdn_ipv6´, ´aggregate_ambr_ul´, ´aggregate_ambr_dl´, ´pgw_id´, ´users_imsi´, ´qci´, `priority_level`, ´pre_emp_cap`, `pre_emp_vul`, ´LIPA-Permissions´) VALUES (´60´, ´oai.ipv4´, ´0.0.0.0´, `0:0:0:0:0:0:0:0´, ´50000000´, ´100000000´, ´3´, ´208930000000001´, ´9´, ´15´, ´DISABLED´, ENABLED´, ´LIPA-ONLY´);

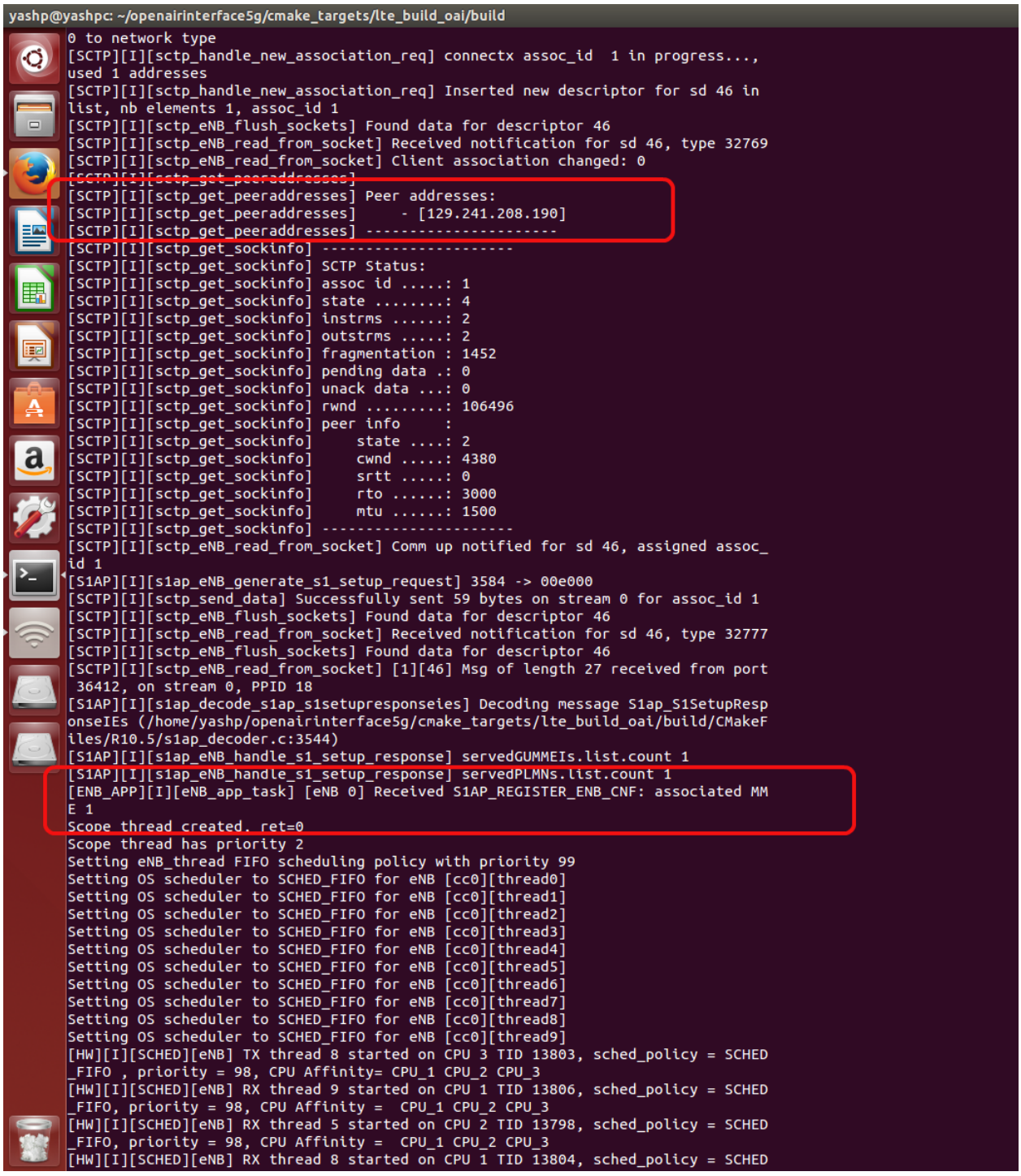
mysql > INSERT INTO mmeidentity (´idmmeidentity´, ´mmehost´, ´mmerelam´, ´UE-reachability´) VALUES (´6´, ´shyamalpc.openair4G.eur´, ´openair4G.eur´, ´0´);

Appendix 8 OAI Results

Appendix 8-1 eNB Real Time issues

```
[HW][I][SCHED][eNB] RX thread 0 started on CPU 1 TID 13788, sched_policy = SCHED
_FIFO, priority = 98, CPU Affinity =  CPU_1 CPU_2 CPU_3
[HW][I][SCHED][eNB] RX thread 6 started on CPU 3 TID 13800, sched_policy = SCHED
_FIFO, priority = 98, CPU Affinity =  CPU_1 CPU_2 CPU_3
[HW][I][SCHED][eNB] TX thread 0 started on CPU 1 TID 13787, sched_policy = SCHED
_FIFO , priority = 98, CPU Affinity= CPU_1 CPU_2 CPU_3
Creating main eNB_thread
[HW][I][SCHED][eNB] Started eNB main thread on CPU 1 TID 13807 , sched_policy =
SCHED_FIFO, priority = 99, CPU Affinity =  CPU_1  CPU_2  CPU_3
eNB_thread: mlockall in ...
eNB_thread: mlockall out ...
waiting for sync (eNB_thread)
Sending sync to all threads
TYPE <CTRL-C> TO TERMINATE
Entering ITTI signals handler
got sync (eNB_thread)
ULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL
ULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULULLLLLLLLLLLLLLLUL LLLLLLLLULLLLLLLLLLLLLLLLULLLL
LLLLLLLLLLLLLLLLLLLLLLLLLULLLLLLLLLLLLLLLULLLULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULL
LLLLLLLLLLLLLLLLLLLUUULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL
LLLLLLLLLLLLLLLUULLULLLLLLLULLLLLLLLLLLLLLLLLLLLLLLLLLLUULLLLLLLLLLLLLLLLLLLLLLL
LUUULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLULLLLLLLLLLLULLLLLLLLLLLLLU
LLLULLLLLLLLLLLLULLLULLLLLLLLLLLLLLLULLLLLLULLLLLLLLLLLLULLLLLLLULLLLLLLLLLLLLLL
LLLLLLLLLLLLLLLULLLLLLLLLLLLLULLLLLLLLLULLLLLLLLLLLLLLLLLLLLLLULLLLLLLLLLLLLLULL
LLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLLLLULLLLLULLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLLLLL
LLLLLLLLLLLLLLLLULULLLLLULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULLLLULLLLLLLLL
LLLLULLLLLLLLLLLLULLLLLLLLLLLLLLLLLULUUULLLLLLULLLLLLLLLLLLLULLLLLLLLLULLLLLLLLLU
LLLLLULLLLLLLLLLLLLLLULLLLLLLLLLLLULLLLLLLLLLLLLLLLLLLLULLLLLLLLLLLLLULLLLLLLLLU
LLLLLLLLLLLULLLLLLLLLLULLLULLLLLLLLLLLLLLLLUULLLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLULL
LLLLLLLLLLLLLULLLLLULULLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLULLLLLLLLLLULLL
LLLLLLLLULLLULLLLLLUUULLLLLLLLLULLLULLLLLLLLLLLLLLLULLLLLLLLLLLLLLULLLLLLLLLLULL
LULLLLLLLLLLLLLULLLLLLLLLLLLLLUULLLLLLLLLLLLLLLLLLULLLLLLLLULLLLLLLLLLLLLLLULLLLLLLLL
```

Appendix 8-2 OAI associated with MME before Crashed



Appendix 8-3 MME Screen

```
00884 00915:508900 7FC26D7FA700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Sending 88b data on connection {----} TCP,#39->127.0.0.1(3868)
00885 00915:509432 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'STATE_OPEN'     <-- 'FDEVP_CNX_MSG_RECV'       (0x7fc2380008f0,96)     'hss.openair4G.eur'
00886 00915:509463 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   RCV from 'hss.openair4G.eur': (no model)0/280 f:---- src:'hss.openair4G.eur' len:96 {C:268/l:12,C:264/l:25,C:296/l
:278/l:12}
00887 00915:509484 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Iterating on rules of COMMAND: 'Device-Watchdog-Answer'.
00888 00915:509500 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Peer timeout reset to 30 seconds (+/- 2)
00889 00915:509507 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'hss.openair4G.eur' in state 'STATE_OPEN' waiting for next event.
00890 00920:056460 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00891 00920:056478 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00892 00920:056483 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00893 00920:056489 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00894 00930:056450 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00895 00930:056468 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00896 00930:056474 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00897 00930:056479 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00898 00940:056450 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00899 00940:056466 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00900 00940:056472 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00901 00940:056478 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00902 00944:336949 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'STATE_OPEN'     <-- 'FDEVP_PSM_TIMEOUT' ((nil),0)      'hss.openair4G.eur'
00903 00944:336987 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Peer timeout reset to 30 seconds
00904 00944:336995 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'hss.openair4G.eur' in state 'STATE_OPEN' waiting for next event.
00905 00944:337138 7FC26D7FA700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   SENT to 'hss.openair4G.eur': 'Device-Watchdog-Request'0/280 f:R--- src:'(nil)' len:88 {C:264/l:31,C:296/l:21,C:278
}
00906 00944:337152 7FC26D7FA700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Sending 88b data on connection {----} TCP,#39->127.0.0.1(3868)
00907 00944:337651 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'STATE_OPEN'     <-- 'FDEVP_CNX_MSG_RECV'       (0x7fc2380008f0,96)     'hss.openair4G.eur'
00908 00944:337665 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   RCV from 'hss.openair4G.eur': (no model)0/280 f:---- src:'hss.openair4G.eur' len:96 {C:268/l:12,C:264/l:25,C:296/l
:278/l:12}
00909 00944:337686 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Iterating on rules of COMMAND: 'Device-Watchdog-Answer'.
00910 00944:337702 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Peer timeout reset to 30 seconds (+/- 2)
00911 00944:337705 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'hss.openair4G.eur' in state 'STATE_OPEN' waiting for next event.
00912 00950:056441 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00913 00950:056463 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00914 00950:056469 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00915 00950:056474 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00916 00960:056451 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00917 00960:056467 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00918 00960:056472 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00919 00960:056478 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00920 00970:056407 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0036   ================ Statistics ================
00921 00970:056423 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0037           |   Global   | Since last display |
00922 00970:056429 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0038   UE      |         0 |            0     |
00923 00970:056435 7FC2BEFFD700 DEBUG MME-AP SRC/MME_APP/mme_app_statistics.c:0039   Bearers |         0 |            0     |
00924 00972:496986 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'STATE_OPEN'     <-- 'FDEVP_PSM_TIMEOUT' ((nil),0)      'hss.openair4G.eur'
00925 00972:497026 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   Peer timeout reset to 30 seconds
00926 00972:497035 7FC2BCFF9700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   'hss.openair4G.eur' in state 'STATE_OPEN' waiting for next event.
00927 00972:497189 7FC26D7FA700 ALERT S6A    al/openair-cn/SRC/S6A/s6a_task.c:0075   SENT to 'hss.openair4G.eur': 'Device-Watchdog-Request'0/280 f:R--- src:'(nil)' len:88 {C:264/l:31,C:296/l:21,C:278
}
```

Appendix 8-4 MME, HSS, and SPGW connected successfully