



**5TH GENERATION END-TO-END NETWORK, EXPERIMENTATION,
SYSTEM INTEGRATION, AND SHOWCASING**

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5G Radio Components and User Equipment (Release B)

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Version History

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1.0	Release of D3.12	I Koffman (RunEL)	11.8.2021

LIST OF ACRONYMS

Acronym	Meaning
3GPP	3 rd Generation Partnership Project
5GC	5G Core network
AC	Alternating Current
AMF	Access and Mobility Management Function
ASA	Authorized Shared Access
CBRA	Contention Based Random Access
CBRS	Citizens Broadband Radio
CFRA	Contention Free Random Access
CN	Core Network
COTS	Commercial Off-The-Shelf
COVID-19	Coronavirus Disease 2019
CPU	Central Processing Unit
CR	Cognitive Radio
CU	Central Unit
DC	Direct Current
DL	Down Link
DRAN	Distributed Radio Access Network similar as DU
DRB	Dedicated Radio Bearer
DU	Distributed Unit
E2E	End-to-end
E-RAB	E-UTRAN Radio Access Bearer
eLSA	evolved Licensed Shared Access
eNB	e Node B (4G Base Station)
ENDC	E-UTRAN New Radio – Dual Connectivity
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
FAPI	Functional Application Platform Interface
FPGA	Field-Programmable Gate Array
GAA	General Authorized Access
gNB	G Node B (5G Base Station)
GPU	Graphics Processing Unit

GTP	GPRS Tunneling Protocol
HARQ	Hybrid Automatic Repeat Request
HDL	Hardware Description Language
HSS	Home Subscriber Server
IP	Internet Protocol
KPI	Key Performance Indicator
LAN	Local Area Network
LSA	Licensed Shared Access
LSTM	Long Short-Term Memory
LTE	Long Term Evolution
MAC	Medium Access Control
ML	Machine Learning
MME	Mobility Management Entity
NAS	Non-access stratum
NGAP	NG Application Protocol
NPN	Non Public Networks
NR	New Radio
NRF	5G Network Repository Function
NSA	Non-Standalone
NSMF	Network-Slice Management Function
NSSMF	Network-Slice Subnetwork Management Function
OAI	Open Air Interface
OS	Operative System
PAL	Priority Access Licenses
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PHY	Physical
PLMN	Public Land Mobile Network
PRB	Physical Resource Block
PUSCH	Physical Up Link Shared Channel
QoS	Quality of Service
RA	Random Access
RAN	Radio Access Network

RF	Radio Frequency
RL	Reinforcement Learning
RLC	Radio Link Control
RRC	Radio Resource Control
RRH	Remote Radio Head similar as RU
RTT	Round-Trip Time
RU	Radio Unit
SA	Standalone
SAS	Spectrum Access System
SBA	Service-Based Architecture
SCF	Small Cell Forum
SDN	Software-Defined Networking
SDR	Software-Defined Radio
SINAD	Signal-to-Noise and Distortion
SINR	Signal-to-Interference-plus-Noise Ratio
SGW	Serving Gateway
SMF	Session Management Function
SPGW	Serving and Packet Gateways
TCP	Transmission Control Protocol
TDD	Time Division Duplex
THD	Total Harmonic Distortion
TVWS	TV White Spaces
UE	User Equipment
UL	Up Link
UPF	User Plane Function
URLLC	Ultra-Reliable Low Latency Communication
USIM	Universal Subscriber Identity Module
USRP	Universal Software Radio Peripheral
UT	User Terminal
VLAN	Virtual Local Area Network
X2AP	X2 Application Protocol
UPF	User Plane Function
USRP	Universal Software Radio Peripheral
X2AP	X2 Application Protocol

Executive Summary

This document is the final report on the 5G Network architecture, access and backhaul components that are being developed and deployed in the different 5GENESIS Platforms as well as a new concept for spectrum management and sharing for 5G Networks.

The document describes the development, implementation, installation, and testing of a novel 5G LAN architecture that is perfectly matching the Non-Public-Networks (NPN) trend in the 5G industry for Private 5G Networks in Vertical Markets. The system was designed to meet the URLLC KPI requirements and outstanding Up Link and Down Link latencies of 750 microseconds each have been recorded.

The Open-Air-Interface offer many advantages to 5G networks developers in terms of standardization, interoperability and cost. This report includes a detailed description of the design, implementation, installation and testing of an E2E Non-Standalone and a Standalone platform using OAI and commercial 5G User Equipment

The mm-Wave spectrum will be widely used in 5G Networks for Access and Backhaul due to the availability of large bandwidth that can transport the massive amount of data required to be transferred by the 5G Networks. This document includes a detailed description of the design implementation and testing of a 5G terrestrial backhaul system at 60GHz that includes a proprietary FPGA hardware platform for high-speed data communication with Software-Defined Radio (SDR) capability. The SDR allows to evaluate signal processing algorithms in hardware-in-the-loop manner prior to their HDL implementation on the same hardware platform

To minimize ‘wasting’ of spectrum by worse-case allocations, 5GENESIS proposes to analyse the opportunity to abandon the fixed allocation of spectrum and pursue an aggressive and dynamic allocation of spectrum both in time and space, according to the traffic demand. To achieve this goal, 5GENESIS slice template is extended with spectrum-related information, and a hierarchical spectrum management architecture is proposed, so the radio resources can be efficiently coordinated between any number of networks and further optimized within each 5G mobile network. The exploitation of dynamic allocation of radio resources will not be trivial especially in 5G due to the high number of service combinations, radio parameters and deployment options, which makes dynamic spectrum allocation by traditional rule-based techniques to become inefficient or difficult to implement in 5G. Hence, 5GENESIS spectrum management architecture uses Machine Learning (ML) algorithms for spectrum management in 5G, with these algorithms continuously adapting to every change in network conditions.

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1. INTRODUCTION

5G is an important new technological innovation that has the potential to transform the European economy by enabling the digitization of a wide range of sectors.

In practice, there will be several considerations relevant to businesses seeking to harness 5G connectivity. These include their understanding of the availability of the different solutions, the capabilities and cost of each solution and how these will meet the needs of their core business.

In this deliverable we explore four different aspects of the 5G Radio Architecture, components and Air Interfaces that can enable the rapid digitization of different industry sectors:

- The 5G LAN architecture
- The Open-Air Interface implementation of 5G Standalone and Non-Standalone Networks
- The mm Wave Terrestrial Backhaul
- The 5G Spectrum Management.

1.1. Purpose of the Document

The main target of this deliverable is to summarize the 5GENESIS third term activity in the area of 5G Access Components (5G Base Stations) and User Equipment. These activities are defined under the scope of Task T3.6, which deals with the “design and development of the 5G gNB (5G Base Stations) for the needs of 5GENESIS platforms, including the Physical and MAC (Layer-1 and Layer 2) layers, as well as its interfaces, structure and processing”. The gNB will be able to communicate with 5G User Terminals (UTs) in different demonstration scenarios and will be connected northbound to EPC and/or 5GC networks, operating at 3.5GHz or 28GHz and being able to support different scenarios in URLLC, eMBB and mMTC applications. The implemented 5G air interface will be presented, including potential compliance with standards beyond the 3GPP Rel-15. The performance of the gNB will be defined including special options and extensions which will be available at the time of the task activities. During the course of the project, the gNB will be upgraded from time to time considering the development of 3GPP 5G NR Specifications and profiles targeting new 3GPP 5G releases. Finally, the roadmap for further enhancements of the RRH and the air-interface performance will be presented and evaluated. When the 5G NR UE and gNB become available, this task will also develop aggregation methods for LTE, with 5G NR and WiFi.”

As indicated in the Task T3.6 definition above, this document describes different developments and 5G Network enhancements that have been implemented in the 5GENESIS test beds including Architecture enhancement (5G LAN), low latency KPI measurements (URLLC), Layer1 and Layer 2 (PHY and MAC) development using Open Air Interfaces, connection of commercial User Equipment to Non-Standalone (NSA) and Standalone (SA) 5G Networks, mm-Wave Backhaul/Midhaul/Fronthaul implementation and testing as well as new concept for spectrum management and spectrum sharing in the 5GC was developed

1.1.1 Document Dependencies

The document at hand has been produced in accordance to the specifications, requirements and assumptions discussed in the 5GENESIS deliverables related to both the requirements of the test platforms and the architecture.

The infrastructure elements described here belong to the 5GENESIS Infrastructure Layer and to the radio part of the infrastructure, whether it is the Radio Access Network (RAN) or the Terrestrial Backhaul. These elements are part of several platforms, as indicated in the deliverables of WP4. Table 1 summarizes the relevance towards the deliverables produced by WP2.

Table 1 Document dependencies

id	Document title	Relevance
D2.1 [26]	Requirements of the Facility	The document sets the ground for the first set of requirements related to supported features at the testbed for the facilitation of the Use Cases.
D2.2 [27]	5GENESIS Overall Facility Design and Specifications	The 5GENESIS facility architecture is defined in this document. The list of functional components to be deployed in each testbed is defined.
D2.3 [28]	Initial planning of tests and experimentation	Testing and experimentation specifications that influence the testbed definition, operation and maintenance are defined.

1.2. Structure of the Document

The implemented 5G radio components and Open Air interfaces are presented in the following chapters of this deliverable as follows:

- **Section 2** offers a description of 5G LAN Network Architecture implementation and test.
- **Section 3** describes the implementation of an Open Air Interface based End-to-End 5G Non Stand Alone (NSA) Network.
- **Section 4** describes the implementation of an Open Air Interface-based End-to-End 5G Stand Alone (SA) Network.
- **Section 5** is focused on the implementation of a Terrestrial Backhaul System.
- **Section 6** describes a new concept for spectrum management and spectrum sharing for 5G networks based on Artificial Intelligence.
- **Section 7** is a summary of the deliverable including future plans.
- **Section 8** includes the conclusions from the document reported activities.

1.3. Target Audience

This deliverable is mainly addressed to:

- The Project Consortium researchers to validate that all objectives and proposed technological advancements have been analysed and to ensure that, through the identified requirements, the next actions can be concretely derived.
- The Research Community and funding EC Organisation to: i) summarise the 5GENESIS scope, objectives and intended project innovations, ii) detail the 5GENESIS Facility testbeds and target use cases that shall be demonstrated and measure provided technological advancements and iii) present the related requirements and associated KPIs that must be tackled to achieve the expected results.
- The general public for obtaining a better understanding of the framework and scope of the 5GENESIS project.

Last but not least, the content of this deliverable is in-line with the guidelines of Deliverable 1.2 “Legal aspects and data management (Release A)”.

2. 5G LAN NETWORK

2.1. Background

5G LAN (Local Area Network) is one of the most promising technologies in 3GPP Release 16. It can address the three types of needs of enterprises and industries network communication: convenient management, flexible interoperability, and reliable communication. The 5G LAN technology is used to build an enterprise cloud office network for enterprise customers. As enterprises do not need to build a network, it can save network construction and maintenance costs for the campus.

With the support of 5G LAN technology, the network can allocate IP addresses of the same network segment to the enterprise cloud according to the needs of enterprises. The network can also establish an end-to-end tunnel from the wireless to the core network, to the enterprise cloud. Furthermore, enterprise administrators can flexibly manage these terminals. The terminals will be perceived as if they are within the intranet, enabling seamless management by the enterprises [4].

This chapter describes the implementation and testing of an Ultra-Reliable-Low-Latency-Communication (URLLC) 5G LAN network from RunEL that was deployed and tested in the 5G testbed in the University of Malaga

2.2. Architecture, Implementation, Integration and Testing in UMA 5G Platform

A 5G Local Area Network is a major step towards industries and private enterprises digitalization (driven by Industry 4.0).

5G mission-critical support and flexibility provides high performance including ultra-low latency and high reliability (URLLC) which holds one of the best answers to implement this digitalization trend.

The drawing below (Figure 1) depicts possible architecture options of 5G private networks (taken from 5G Alliance for Connected Industries and Automation, White paper[4]).

Functional architecture of private 5G networks can be implemented by using:

- Standalone private deployment (with an option for a link with the public network),
- Public-private shared RAN deployment
- Public-private shared RAN and Control-plane
- NPN deployed in public Networks

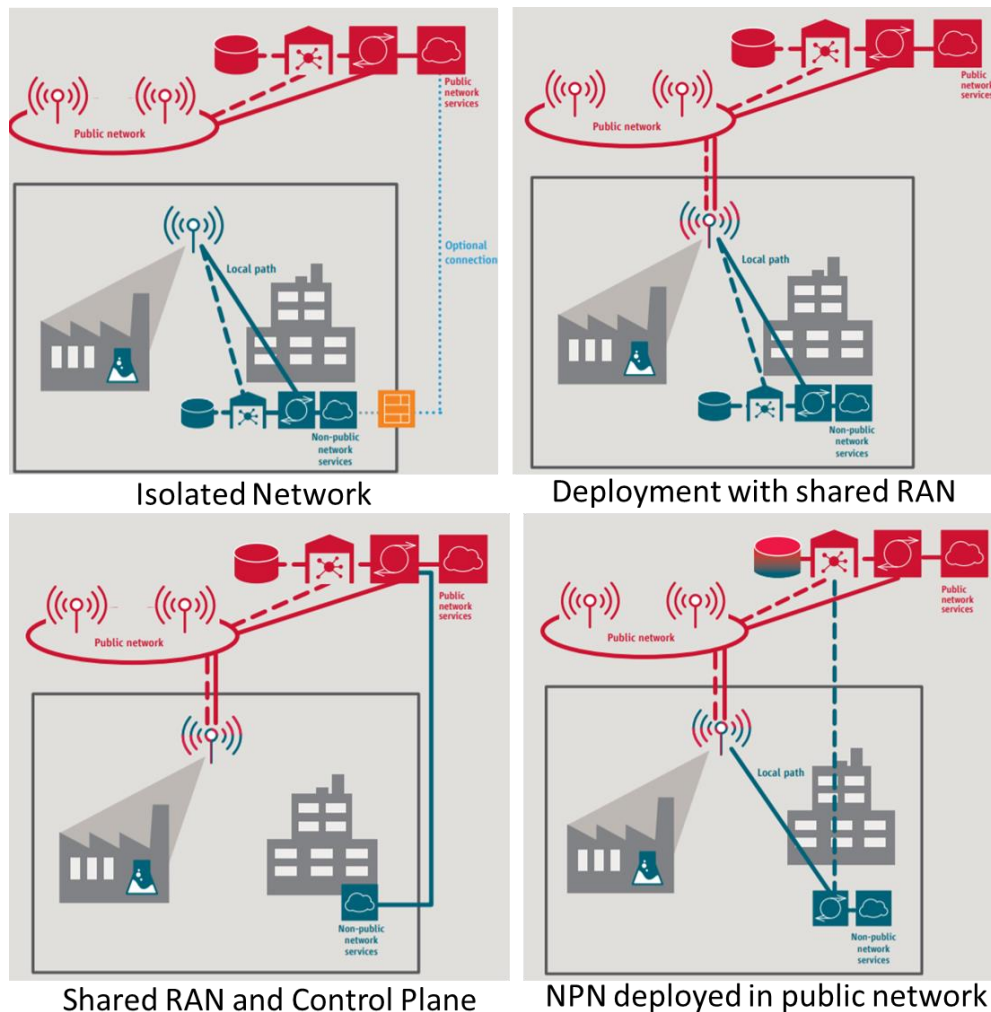


Figure 1 Types of Private Networks

Testing in UMA platform is executed as an Isolated private local area network deployment at 3.5GHz 5G n78 spectrum.

2.3. Ethernet over 5G LAN in industrial environments from 3GPP documents

The 3GPP TR 22.821 V16.1.0 (2018-06) document [4] named “Feasibility Study on LAN Support in 5G” describes new use cases and potential requirements applicable to the 5G system for a 3GPP network operator to support 5G LAN-type services over the 5G system (i.e., UE, RAN, Core Network, and potential application to manage the LAN-style service). In this context, 5G LAN-type services with 5G capabilities (e.g., performance, long distance access, mobility, security) allow a restricted set of UEs to communicate amongst each other.

This document also describes 5G LAN-type service support for an ethernet transport services and Possible Deployment Scenarios such as Residential Environment, Enterprise Environment and Industrial Automation Environment.

We choose to explore and test one of the use cases in the 5G LAN Industrial Automation Environment called Factory Automation (chapter 5.17 in the document [4]).

In this use case a factory producing electronic goods using highly precise automated robots coordinated by tight closed-loop control, has used 5G infrastructure to replace some of the wired Ethernet connections. There are several drivers to replace wired links with wireless links. For example, devices are mobile, cables need to go through hazardous areas, or moving parts in a machine need connectivity. Further, providing wireless connectivity can enable rapid reconfiguration of a factory, which can yield improvements in productivity. Figure 2 describes a small section of the factory deployment where 5G is used to connect devices T, C and S.

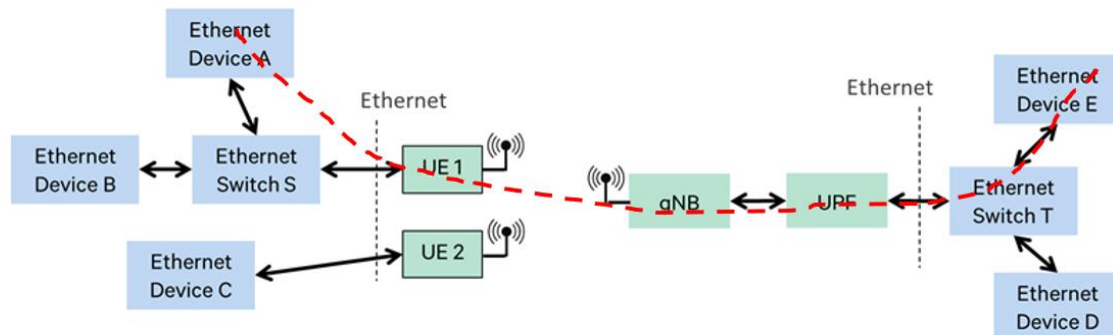


Figure 2 5G LAN architecture for factory automation

As can be seen from the above drawing, the logical long-distance connections of the private network are implemented by using a private 5G network infrastructure which bridges the two (or more) ends of the network.

5G can support the end-to-end KPIs required for running modern and future industrial environment. Such KPIs include latency, reliability, positioning (for mobile elements) throughput (for high-rate devices) among others.

The red dashed line in Figure 2 represents the portion of the 5G LAN implemented in the UMA test bed which is described in the following subsections.

2.4. 5G LAN Test Preparations

The 5G LAN KPI tests will be accomplished using the hardware configuration in Figure 3 below:

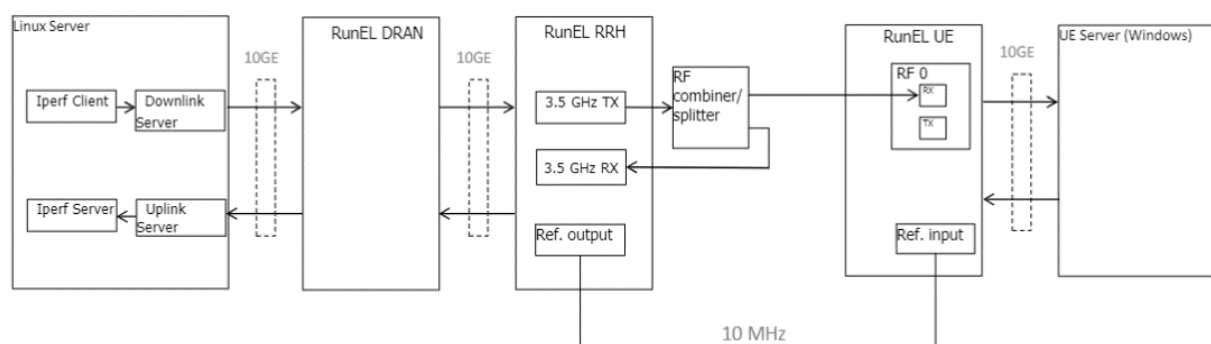


Figure 3 5G LAN Loop Back Test Set Up

The block diagram describes a loop-back configuration where the Down Link (DL) RF signal (3.5GHz) is injected back to the Up Link (UL) in order to be able to measure the round-trip latency of the base station alone without the UE. An Example of the RF combiner is depicted in Figure 4.

The 5G system configuration is static using preconfigured slot resources allocation.

For testing the KPI's two data units are allocated and delivered over each slot. For both the same data content (IPERF PDU) will be driven.

The first allocation (symbols 4 and 5) is for Down Link. The second (symbols 11 and 12) is used for Up Link.

The server provides the control plane information (descriptors) for DL and UL enabling the DRAN and RRH to process the data.



Figure 4 RF Combiner

The data (UDP) is driven by IPERF application. IPERF version and set up is selected to enable transparent UDP data delivery.

The data server runs over LINUX OS.

For the tests Wireshark sniffer tool is used. Time stamps for the DL PDU and UL PDU are compared to derive the data round trip latency performance.

RunEL upgraded remotely the RRH firmware at UMA to include the 5G Up Link to test the round-trip latency among other KPIs.

For the tests the following equipment is required:

- RunEL DRAN
- RunEL RRH
- UE or RunEL UE Emulator
- Oscilloscope
- SPECTRUM ANALYZER
- PC with USB (For IP setting or debugging via RS232)
- 1G Ethernet switch
- PC Monitor
- TX UDP Server
- RX UDP Server
- VLC Video player

The tests configuration is depicted in Figure 5 below and includes the following system main parameters: TDD, 100MHz BW, 3.5GHz Center Frequency.

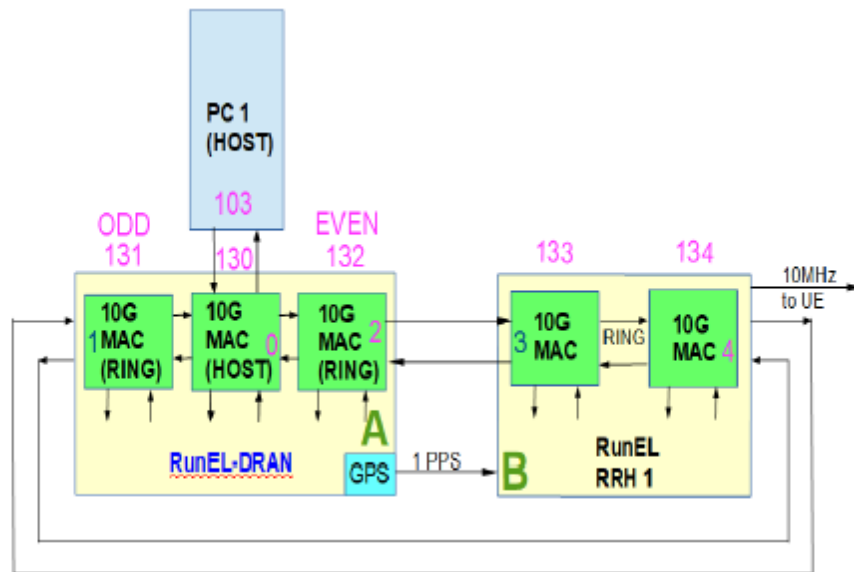


Figure 5 5G LAN Configuration Diagram

Step by step instructions for the 5G LAN Loop Back test configuration are described at Annex-1 at the end of this document

2.5. 5G LAN KPIs Test Results

In the tests performed at UMA a round trip latency of 1.3 milliseconds was measured representing an **outstanding average DL and UL latency of 650 microseconds each**.

Figure 6 and 7 below shows a picture of the latency traces recorded via Wireshark, showing a round-trip latency of 0.001249465 sec and 0.001350687sec respectively.

731	1.848728422	10.0.0.103	10.0.0.130	UDP	562	59254 → 1234	Len=520
752	0.001249465	10.0.0.134	10.0.0.103	UDP	538	1234 → 1236	Len=496
774	0.000498317	10.0.0.134	10.0.0.103	UDP	538	1234 → 1236	Len=496

Figure 6 Round trip latency trace record-1

No.	Time	Source	Destination	Protocol	Length	Info
38	0.000000000	10.0.0.103	10.0.0.130	UDP	562	59254 → 1234 Len=520
458	0.001350687	10.0.0.134	10.0.0.103	UDP	538	1234 → 1236 Len=496
459	0.000496060	10.0.0.134	10.0.0.103	UDP	538	1234 → 1236 Len=496

Figure 7 Round trip latency trace record-2

Further results of the 5G LAN network will be provided in Delivery D6.3.

3. OAI BASED E2E 5G NSA NETWORK

3.1. Background

The OSA is the home of Open-Air-Interface, an open software organization that gathers a community of developers from around the world, who work together to build wireless cellular Radio Access Network (RAN) and Core Network (CN) technologies.

For 5GENESIS release A components, Eurecom had provided an intermediary version for an NSA setup based only on Open Air Interface (OAI) gNB and UE components. In this first version, there was no Core Network and eNB, and hence all the required configuration that would normally take place over the LTE links to establish a 5G connection was preconfigured, so that data plane IP traffic over the 5G NR stack could be demonstrated.

With the first NSA COTS UE devices becoming available in the market, Eurecom worked on providing a real NSA solution based on OAI eNB and gNB components for 5GENESIS release B, during the second and third year of the project. The first E2E version of the NSA setup based on OAI RAN and COTS UEs, interoperable with OAI and other commercial Core Networks became available at the beginning of the third year of the project. Since then, significant enhancements with respect to the stability of the setup, supported radio configurations, resources scheduling, and performance improvements have gradually been integrated.

3.2. Architecture, Implementation, Integration and Testing

3.2.1. Supported NSA architecture

OAI supports NSA architecture option 3a as per 3GPP Rel.15. As depicted in Figure 8, according to this deployment, all the control plane traffic is exchanged with the UE through the eNB. To add successfully the COTS UE to the NR cell (gNB), the eNB acts as the intermediary node that communicates with the gNB over X2-C interface to convey all required NR configuration to and from the UE. S1-C interface is responsible for the exchanges between the eNB and the 4G EPC (MME component) for the successful attachment of the UE. Once the UE is attached to the Core Network (CN) and connected to the 5G cell, the end-to-end user-plane traffic is delivered to the UE and the core network (S1-U interface to the SGW) exclusively through the gNB. It is noted that as per this architecture option, there is no delivery of user-plane traffic through the X2 interface (i.e., no split bearer option).

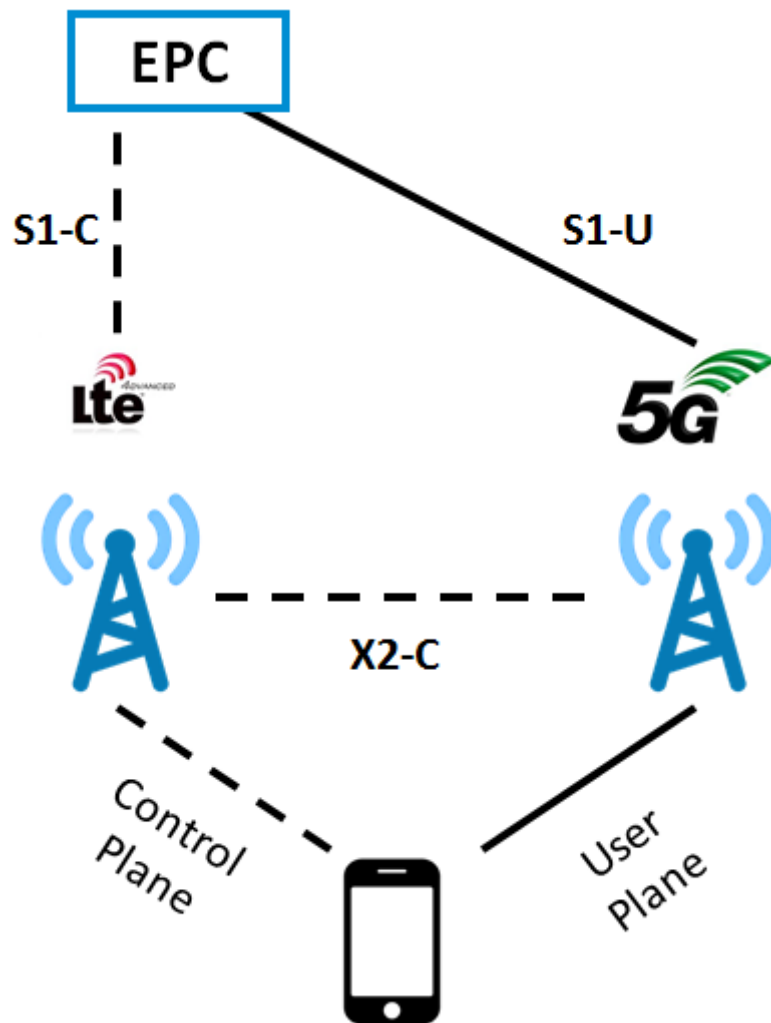


Figure 8 NSA architecture deployed in OAI (option 3a)

3.2.2. Implementation and software architecture

The developments that took place in OAI eNB and gNB components to support the NSA setup can be grouped per layer as follows:

- **MAC/PHY:**
 - Integration of 5G NR Contention Free Random Access (CFRA) procedures to enable successful 5G connection of the UE to the 5G cell according to [3] and [4].
 - Complete integration of SCF 5G FAPI interface between MAC and PHY layer according to [5].
 - Integration of dynamic scheduling and capability to support multiple users.
 - Integration of HARQ procedures on top of Down Link and Up Link physical channels to provide support for data acknowledging and retransmissions according to [4].
- **PDCP/RLC:** Complete implementation of NR PDCP and RLC AM (Acknowledged Mode) and UM (Unacknowledged Mode) according to [6] and [7], in order to support data plane traffic over 5G established DRBs.

- **RRC** extensions according to [8] and [9] :
 - Integration of the LTE eNB procedures triggering the UE addition/release request to the 5G cell and the data path switch procedures towards the 5G cell,
 - Extensions of LTE RRC messages with NR message containers originating from the gNB
 - Integration of all the gNB NSA configuration procedures for a UE added to the NR cell and construction of the corresponding NR message containers conveyed to the UE through the eNB.
- **X2AP** extensions according to [10]: Integration of the required X2AP messages and interfacing with RRC to support the establishment, maintenance, and release of an ENDC X2 connection between the eNB and gNB and the addition/release of a UE to the 5G cell.
- **S1AP** extensions according to [11]: Integration of the E-RAB Modification procedures initiated from the LTE cell (eNB) to trigger the data path switch towards the NR cell (gNB) at the core network.

3.2.3. Supported features and performance

Based on the OAI NSA setup, the main focus is on frequency range 1 configuration (below 6 GHz). More specifically, TDD configuration is used at the gNB side with 30 KHz subcarrier spacing and 106 PRBs. At the time of writing this document, the most stable performance at the gNB is achieved for 40 MHz channel bandwidth, reaching up to 75 Mbps Down Link and 7 Mbps Up Link throughput.

The project aims at achieving performance improvements in our upcoming contributions (100-200Mbps Down Link, 15-30 Mbps Up Link) and ensure stable performance for 80 and 100 MHz channel bandwidths.

3.2.4. Hardware architecture

The hardware platform required for the OAI NSA setup consists of two sets of computers and USRPs for the eNB and gNB components. Depending on the configuration used at the gNB side and the associated performance, the required hardware equipment and consequently the deployment cost can differ. Specifically, as shown in the following Table-2, to achieve higher NR performance for 80 or 100 MHz channel bandwidths, a USRP N3xx series must be used, together with a powerful server (>8 CPU cores). For a limited performance setup (40 MHz channel bandwidth), the cheaper USRP B210 board can be used. More information about the hardware and operating system requirements can be found in [18].

Table 2 Suggested hardware equipment supporting OAI NSA setup

	eNB	gNB/40MHz bandwidth	gNB/80 MHz bandwidth
PC/Server	≥4 cores processor (e.g., Intel® Core™ i5-6600K CPU @ 3.50GHz × 4)	≥4 cores processor (e.g., Intel® Core™ i5-6600K CPU @ 3.50GHz × 4)	≥10 cores processor and 2x10Gbit Ethernet (e.g., Intel(R) Xeon(R) Gold 6154 CPU @ 3.00GHz with 18 cores)
USRP	B210	B210, N310, N300	N310, N300

3.2.5. Testing and validation

In the following, we provide some snapshots of the NSA setup from Wireshark traces and OAI logs, to highlight the important steps for the establishment of a 5G connection and user plane traffic flow through the 5G cell.

During the initial attachment of the UE to the LTE cell and the core network, the UE reveals its capabilities for NR connectivity and the eNB provides information to the UE on how to perform 5G NR cell specific measurements on the NR frequencies. Based on this information, after its attachment to the core network, the UE sends RRC measurement reports including measurements from the NR cell (gNB). Upon reception of the NR measurement report, the eNB triggers the addition of the UE to the secondary node (gNB) by sending the *X2 sgNB Addition Request* message. This message includes RRC and radio bearer configuration, as well as security information elements and other information per layer regarding additional UE capabilities (Figure 9).

After performing the required configuration procedures for the addition of the UE, the gNB replies with the *X2 sgNB Addition Request Acknowledge* message. This message includes the *NR RRC Reconfiguration* container which provides the configuration information that the UE needs to know to successfully get connected with the gNB (Figure 10). The eNB then includes the *NR RRC Reconfiguration* container in the *LTE RRC Connection Reconfiguration* message sent to the UE. The UE replies with the *NR RRC Reconfiguration Complete* container (encapsulated in *LTE RRC Connection Reconfiguration Complete* message) indicating the successful outcome of the RRC Reconfiguration procedure. The eNB then forwards this information to the gNB through the *X2 sgNB Reconfiguration Complete* message (Figure 11).

No.	Time	Source	Destination	Protocol	Length	Info
106	12.196203	192.168.12.196	192.168.12.207	X2AP	370	SgNBAdditionRequest
107	12.201071	192.168.12.207	192.168.12.196	X2AP	470	SgNBAdditionRequestAcknowledge, RRC Reconfiguration
▶ Frame 106: 370 bytes on wire (2960 bits), 370 bytes captured (2960 bits) ▶ Ethernet II, Src: D-Link_b1:4e:df (5c:d9:98:b1:4e:df), Dst: Giga-Byt_9b:ea:5e (e0:d5:5e:9b:ea:5e) ▶ Internet Protocol Version 4, Src: 192.168.12.196, Dst: 192.168.12.207 ▶ Stream Control Transmission Protocol, Src Port: 36422 (36422), Dst Port: 36422 (36422) ▶ EUTRAN X2 Application Protocol (X2AP) ▼ X2AP-PDU: initiatingMessage (0) ▼ initiatingMessage procedureCode: id-sgNBAdditionPreparation (27) criticality: reject (0) ▼ value ▼ SgNBAdditionRequest ▼ protocolIEs: 6 items ▼ Item 0: id-MeNB-UE-X2AP-ID ▼ ProtocolIE-Field id: id-MeNB-UE-X2AP-ID (111) criticality: reject (0) ▼ value UE-X2AP-ID: 0 ▼ Item 1: id-NRUESecurityCapabilities ▼ ProtocolIE-Field id: id-NRUESecurityCapabilities (248) criticality: reject (0) ▼ value NRUESecurityCapabilities ▶ nRencryptionAlgorithms: e000 [bit length 16, 1110 0000 0000 0000 decimal value 57344] ▶ nRintegrityProtectionAlgorithms: e000 [bit length 16, 1110 0000 0000 0000 decimal value 57344] ▼ Item 2: id-SgNBSecurityKey ▼ ProtocolIE-Field id: id-SgNBSecurityKey (203) criticality: reject (0) ▼ value SgNBSecurityKey: 0fd2d3a0990b90ae8a130b5d2ef75edb592bde8affcc38b6555e09bc3f9ef817 [bit length 256] ▼ Item 3: id-SgNBUEAggregateMaximumBitRate ▼ ProtocolIE-Field id: id-SgNBUEAggregateMaximumBitRate (204) criticality: reject (0) ▼ value UEAggregateMaximumBitRate ▼ Item 4: id-E-RABS-ToBeAdded-SgNBAddReqList ▼ ProtocolIE-Field id: id-E-RABS-ToBeAdded-SgNBAddReqList (205) criticality: reject (0) ▼ value E-RABS-ToBeAdded-SgNBAddReqList: 1 item ▼ Item 5: id-MeNBtoSgNBContainer ▼ ProtocolIE-Field id: id-MeNBtoSgNBContainer (206) criticality: reject (0) ▼ value MeNBtoSgNBContainer: 100080cc225a02380902c180389a00000008000809a1e001901841b107800000820080... ▶ CG-ConfigInfo						

Figure 9 UE addition to the secondary cell (gNB) through the X2 exchanged messages

▼ SgNBtoMeNBContainer: 18040a30440a1ae2078e0190437e30d041e641c8541e2100832ba16e63001a4e47c01349... ▼ CG-Config ▼ criticalExtensions: c1 (0) ▼ c1: cg-Config (0) ▼ cg-Config ▼ scg-CellGroupConfig: 0881435c40f1c032086fc61a083cc8390a83c4201065742dcc600349c8f8026938800000... ▼ RRCReconfiguration rrc-TransactionIdentifier: 0 ▼ criticalExtensions: rrcReconfiguration (0) ▼ rrcReconfiguration ▼ secondaryCellGroup: 5c40f1c032086fc61a083cc8390a83c4201065742dcc600349c8f80269388000004d2c3... ▼ CellGroupConfig cellGroupId: 1 ▼ rlc-BearerToAddModList: 1 item ▼ Item 0 ▶ RLC-BearerConfig ▼ mac-CellGroupConfig ▶ bsr-Config ▶ tag-Config ▶ phr-Config: setup (1) 0 skipUplinkTxDynamic: False ▶ physicalCellGroupConfig ▶ spCellConfig ▼ scg-RB-Config: 140928178fc00c08 ▼ RadioBearerConfig ▼ drb-ToAddModList: 1 item ▼ Item 0 ▼ DRB-ToAddMod ▶ cnAssociation: eps-BearerIdentity (0) drb-Identity: 1 ▶ pdcp-Config ▼ securityConfig ▼ securityAlgorithmConfig cipheringAlgorithm: nea0 (0) keyToUse: secondary (1)						
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	--	--	--	--	--	--

Figure 10 NR RRC Reconfiguration container inside sgNB Addition Request Ack. Message

114	12.277943	192.168.12.196	192.168.12.207	X2AP	106 SgNBReconfigurationComplete
<pre> ▶ Frame 114: 106 bytes on wire (848 bits), 106 bytes captured (848 bits) ▶ Ethernet II, Src: D-Link_b1:4e:df (5c:d9:98:b1:4e:df), Dst: Giga-Byt_9b:ea:5e (e0:d5:5e:9b:ea:5e) ▶ Internet Protocol Version 4, Src: 192.168.12.196, Dst: 192.168.12.207 ▶ Stream Control Transmission Protocol, Src Port: 36422 (36422), Dst Port: 36422 (36422) ▼ EUTRAN X2 Application Protocol (X2AP) ▼ X2AP-PDU: initiatingMessage (0) ▼ initiatingMessage procedureCode: id-sgNBReconfigurationCompletion (28) criticality: ignore (1) ▼ value ▼ SgNBReconfigurationComplete ▼ protocolIEs: 3 items ▼ Item 0: id-MeNB-UE-X2AP-ID ▼ ProtocolIE-Field id: id-MeNB-UE-X2AP-ID (111) criticality: reject (0) ▼ value UE-X2AP-ID: 0 ▼ Item 1: id-SgNB-UE-X2AP-ID ▼ ProtocolIE-Field id: id-SgNB-UE-X2AP-ID (207) criticality: reject (0) ▼ value SgNB-UE-X2AP-ID: 37465 ▼ Item 2: id-ResponseInformationSgNBReconfComp ▼ ProtocolIE-Field id: id-ResponseInformationSgNBReconfComp (214) criticality: ignore (1) ▼ value ▼ ResponseInformationSgNBReconfComp: success-SgNBReconfComp (0) success-SgNBReconfComp </pre>					

Figure 11 X2 sgNB Reconfiguration complete message indicating the success of NR RRC reconfiguration procedure

In Figure 12, the part of the gNB logs corresponding to the *CFRA procedures* of the COTS UE towards the 5G cell is depicted. These procedures take place after the UE has successfully synchronized to the 5G cell. The UE initiates Random Access (RA) by sending Msg1 (RA preamble), the gNB receives it and it replies with Msg2 (RA response) and the process gets completed with the reception of Msg3 at the gNB through PUSCH. After that the UE is 5G connected.

```

[0m][0m][PHY] [gNB 0][RAPROC] Frame 211, slot 19 Initiating RA procedure with preamble 63, energy 47.5 dB, delay 6 start symbol 0 freq index
[0m][0m][MAC] UL info[Frame 212, Slot 0] Calling initiate_ra_proc RACH:SFN/SLOT:211/19
[0m][0m][MAC] [gNB 0][RAPROC] CC_id 0 Frame 211, Slot 19 Initiating RA procedure for preamble index 63
[0m][0m][MAC] nr_initiate_ra_proc() Msg2[02127] SFN/SF:021119
[0m][0m][MAC] [gNB 0][RAPROC] CC_id 0 Frame 211 Activating Msg2 generation in frame 212, slot 7 using RA rnti 10b SSB index 0
[0m][0m][MAC] [gNB 0][RAPROC] CC_id 0 Frame 212, slotP 7: Generating RAR DCI, state 1
[0m][0m][MAC] [RAPROC] Scheduling common search space DCI type 1 dLBWP BW 24
[0m][0m][MAC] [RAPROC] DCI type 1 payload: freq_alloc 120 (0,6,24), time_alloc 3, vrb to prb 0, mcs 0 tb_scaling 0
[0m][0m][MAC] Frame 212: Subframe 7 : Adding common DL DCI for RA RNTI 10b
[0m][0m][MAC] [RAPROC] DCI params: rnti 267, rnti_type 2, dci_format 0 coreset params: FreqDomainResource 7fb985b3e758, start_symbol 0 n_sym
[0m][0m][MAC] [RAPROC] Msg3 slot 17: current slot 7 Msg3 frame 212 k2 7 Msg3 tda_id 2 start symbol index 10
[0m][0m][MAC] Frame 212, Slot 7: Setting Msg3 reception for Frame 212 Slot 17
[0m][0m][MAC] [gNB 0][RAPROC] Frame 212, Subframe 7 : CC_id 0 RA is active, Msg3 in (212,17)
[0m][0m][MAC] [gNB] Generate RAR MAC PDU frame 212 slot 7 preamble index 63 TA command 6
[0m][0m][MAC] [gNB 0][RAPROC] Frame 212, Slot 7: RA state 2
[0m][0m][MAC] [gNB 0] Adding UE with rnti 57b9 (num.UEs 0)
[0m][0m][MAC] UCI: CSI bit len : ssbri 0, rsrp: 7, diff_rsrp: 4
[0m][0m][MAC] gNB 0] Add NR UE_id 0 : rnti 57b9
[0m][0m][NR_MAC] [gNB 0][RAPROC] PUSCH with TC RNTI 57b9 received correctly, adding UE MAC Context UE_id 0/RNTI 57b9

```

Figure 12 OAI gNB logs corresponding to the CFRA procedures for the initial access of the COTS UE to the 5G cell

In parallel, the eNB initiates the procedures for the *data plane path switch* towards the core network, so that the traffic between the COTS UE and the CN gets transferred through the gNB from now on. This is done by sending the *S1AP E-RAB Modification indication* message towards the MME. This message contains information on the IP address of the gNB and the

corresponding gtp-u tunnel that should be used for the Down Link traffic between the SGW and gNB. The MME indicates the successful modification for the E-RAB through the confirmation message (see Figure 13 below).

120	12.327423	192.168.12.196	192.168.12.148	S1AP	106 E-RABModificationIndication
121	12.328840	192.168.12.196	192.168.12.148	PDCP-LTE	125 sn=17 MAC=0xfc3891bd (4 bytes data) [9-bytes] sn=18 MAC=0x...
122	12.328848	192.168.12.196	192.168.12.148	RLC-LTE	66 UEId=1 [DL] [AM] SRB:1 [CONTROL] ACK_SN=17
123	12.329634	192.168.12.148	192.168.12.196	GTP	60 End Marker
124	12.330665	192.168.12.148	192.168.12.196	S1AP	114 E-RABModificationConfirm

```

Frame 120: 106 bytes on wire (848 bits), 106 bytes captured (848 bits)
Ethernet II, Src: D-Link_b1:4e:df (5c:d9:98:b1:4e:df), Dst: ASUSTekC_85:4b:f7 (e0:cb:4e:85:4b:f7)
Internet Protocol Version 4, Src: 192.168.12.196, Dst: 192.168.12.148
Stream Control Transmission Protocol, Src Port: 36412 (36412), Dst Port: 36412 (36412)
S1 Application Protocol
  S1AP-PDU: initiatingMessage (0)
    initiatingMessage (0)
      procedureCode: id-E-RABModificationIndication (50)
      criticality: reject (0)
      value
        E-RABModificationIndication
          protocolIEs: 3 items
            Item 0: id-MME-UE-S1AP-ID
              ProtocolIE-Field
                id: id-MME-UE-S1AP-ID (0)
                criticality: reject (0)
                value
                  MME-UE-S1AP-ID: 553648128
            Item 1: id-eNB-UE-S1AP-ID
              ProtocolIE-Field
                id: id-eNB-UE-S1AP-ID (8)
                criticality: reject (0)
                value
                  eNB-UE-S1AP-ID: 12041263
            Item 2: id-E-RABToBeModifiedListBearerModInd
              ProtocolIE-Field
                id: id-E-RABToBeModifiedListBearerModInd (199)
                criticality: reject (0)
                value
                  E-RABToBeModifiedListBearerModInd: 1 item
                    Item 0: id-E-RABToBeModifiedItemBearerModInd
                      ProtocolIE-SingleContainer
                        id: id-E-RABToBeModifiedItemBearerModInd (200)
                        criticality: reject (0)
                        value
                          E-RABToBeModifiedItemBearerModInd
                            e-RAB-ID: 5
                            transportLayerAddress: c0a80ccf [bit length 32, 1100 0000 1010 1000 0000 1100 1100 1111 decimal value 3232238799]
                            transportLayerAddress(IPv4): 192.168.12.207
                        dL-GTP-TEID: 649bacbf

```

Figure 13 Contents of E-RAB Modification Indication message

After this step, the COTS UE can exchange IP traffic with the CN through the gNB over gtp-u, as shown in the gNB trace below (Figure 14), where 192.172.0.1 corresponds to the SGW interface IP address and 192.172.0.2 corresponds to the COTS UE.

365...	23.135770	192.172.0.1	192.172.0.2	GTP <UDP>	68 33831 → 5001 Len=1470
365...	23.136279	192.168.12.148	192.168.12.207	IPv4	1514 Fragmented IP protocol (proto=UDP 17, off=0, ID=1880) [Reassembled in #36585]
365...	23.136283	192.172.0.1	192.172.0.2	GTP <UDP>	68 33831 → 5001 Len=1470
365...	23.136718	192.168.12.148	192.168.12.207	IPv4	1514 Fragmented IP protocol (proto=UDP 17, off=0, ID=1881) [Reassembled in #36587]
365...	23.136721	192.172.0.1	192.172.0.2	GTP <UDP>	68 33831 → 5001 Len=1470
365...	23.137229	192.168.12.148	192.168.12.207	IPv4	1514 Fragmented IP protocol (proto=UDP 17, off=0, ID=1882) [Reassembled in #36589]
365...	23.137231	192.172.0.1	192.172.0.2	GTP <UDP>	68 33831 → 5001 Len=1470
365...	23.137651	192.168.12.148	192.168.12.207	IPv4	1514 Fragmented IP protocol (proto=UDP 17, off=0, ID=1883) [Reassembled in #36591]
365...	23.137653	192.172.0.1	192.172.0.2	GTP <UDP>	68 33831 → 5001 Len=1470
365...	23.138163	192.168.12.148	192.168.12.207	IPv4	1514 Fragmented IP protocol (proto=UDP 17, off=0, ID=1884) [Reassembled in #36593]

Figure 14 Down Link IP traffic towards the COTS UE through the gNB

In Figure 15Figure 17, some snapshots of the Down Link and Up Link performance throughput and RTT latency of the NSA setup are shown.

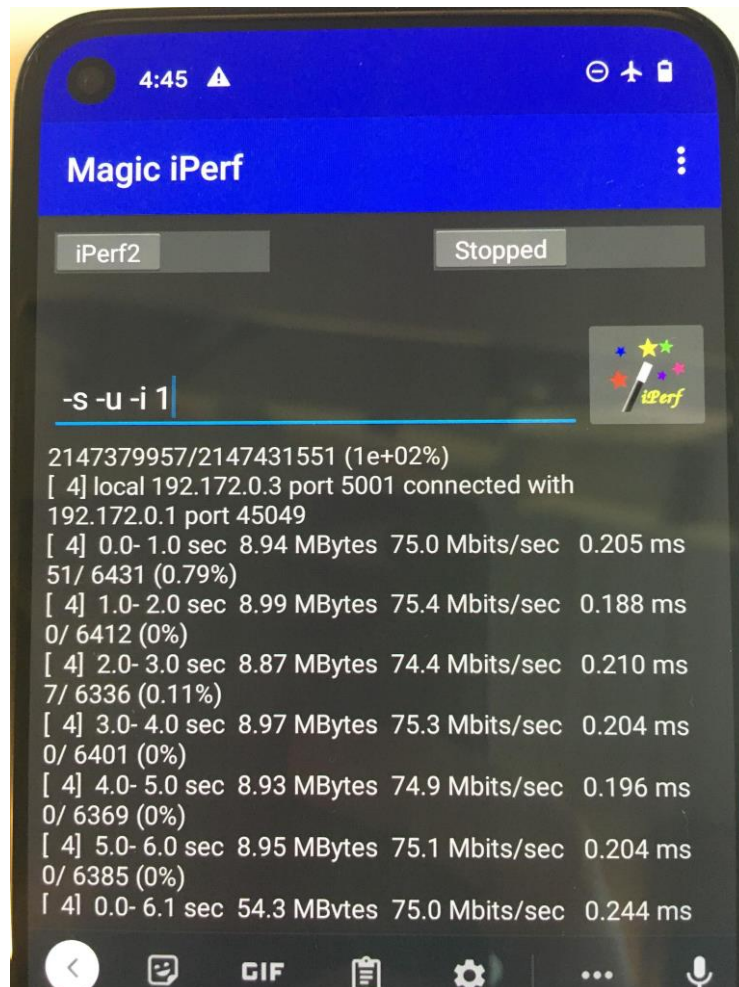


Figure 15 Measured Down Link throughput using iperf at COTS UE

```

hecatonchire@hecatonchire: ~
[ 4] 6.0- 7.0 sec 871 KBytes 7.14 Mbits/sec 3.643 ms 0/ 607 (0%)
[ 4] 7.0- 8.0 sec 871 KBytes 7.14 Mbits/sec 2.109 ms 0/ 607 (0%)
[ 4] 8.0- 9.0 sec 850 KBytes 6.96 Mbits/sec 5.040 ms 0/ 592 (0%)
[ 4] 9.0-10.0 sec 893 KBytes 7.31 Mbits/sec 4.749 ms 0/ 622 (0%)
[ 4] 10.0-11.0 sec 871 KBytes 7.14 Mbits/sec 2.417 ms 0/ 607 (0%)
[ 4] 0.0-11.4 sec 9.67 MBytes 7.14 Mbits/sec 1.880 ms 2147469846/214747674
7 (1e+02%)
read failed: Connection refused
[ 3] local 192.172.0.1 port 5001 connected with 192.172.0.2 port 42320
[ 3] 0.0- 1.0 sec 870 KBytes 7.13 Mbits/sec 1.541 ms 0/ 606 (0%)
[ 3] 1.0- 2.0 sec 871 KBytes 7.14 Mbits/sec 1.316 ms 0/ 607 (0%)
[ 3] 2.0- 3.0 sec 871 KBytes 7.14 Mbits/sec 2.768 ms 0/ 607 (0%)
[ 3] 3.0- 4.0 sec 873 KBytes 7.15 Mbits/sec 3.441 ms 0/ 608 (0%)
[ 3] 4.0- 5.0 sec 871 KBytes 7.14 Mbits/sec 2.677 ms 0/ 607 (0%)
[ 3] 5.0- 6.0 sec 873 KBytes 7.15 Mbits/sec 3.377 ms 0/ 608 (0%)
[ 3] 6.0- 7.0 sec 871 KBytes 7.14 Mbits/sec 5.442 ms 0/ 607 (0%)
[ 3] 7.0- 8.0 sec 871 KBytes 7.14 Mbits/sec 2.377 ms 0/ 607 (0%)
[ 3] 8.0- 9.0 sec 871 KBytes 7.14 Mbits/sec 2.916 ms 0/ 607 (0%)
[ 3] 9.0-10.0 sec 871 KBytes 7.14 Mbits/sec 3.428 ms 0/ 607 (0%)
[ 3] 10.0-11.0 sec 871 KBytes 7.14 Mbits/sec 2.270 ms 0/ 607 (0%)
[ 3] 0.0-11.3 sec 9.63 MBytes 7.14 Mbits/sec 5.288 ms 2147469910/214747677
9 (1e+02%)

```

Figure 16 Measured Up Link throughput using iperf at the core network

```
hecatonchire@hecatonchire: ~  
64 bytes from 192.172.0.2: icmp_seq=83 ttl=64 time=13.6 ms  
64 bytes from 192.172.0.2: icmp_seq=84 ttl=64 time=12.6 ms  
64 bytes from 192.172.0.2: icmp_seq=85 ttl=64 time=11.5 ms  
64 bytes from 192.172.0.2: icmp_seq=86 ttl=64 time=15.6 ms  
64 bytes from 192.172.0.2: icmp_seq=87 ttl=64 time=14.6 ms  
64 bytes from 192.172.0.2: icmp_seq=88 ttl=64 time=13.6 ms  
64 bytes from 192.172.0.2: icmp_seq=89 ttl=64 time=12.6 ms  
64 bytes from 192.172.0.2: icmp_seq=90 ttl=64 time=16.4 ms  
64 bytes from 192.172.0.2: icmp_seq=91 ttl=64 time=15.7 ms  
64 bytes from 192.172.0.2: icmp_seq=92 ttl=64 time=14.6 ms  
64 bytes from 192.172.0.2: icmp_seq=93 ttl=64 time=13.5 ms  
64 bytes from 192.172.0.2: icmp_seq=94 ttl=64 time=12.6 ms  
64 bytes from 192.172.0.2: icmp_seq=95 ttl=64 time=16.6 ms  
64 bytes from 192.172.0.2: icmp_seq=96 ttl=64 time=15.6 ms  
64 bytes from 192.172.0.2: icmp_seq=97 ttl=64 time=14.5 ms  
64 bytes from 192.172.0.2: icmp_seq=98 ttl=64 time=13.6 ms  
64 bytes from 192.172.0.2: icmp_seq=99 ttl=64 time=12.6 ms  
64 bytes from 192.172.0.2: icmp_seq=100 ttl=64 time=11.5 ms  
64 bytes from 192.172.0.2: icmp_seq=101 ttl=64 time=15.6 ms  
^C  
--- 192.172.0.2 ping statistics ---  
101 packets transmitted, 101 received, 0% packet loss, time 20092ms  
rtt min/avg/max/mdev = 10.631/13.608/16.622/1.525 ms  
hecatonchire@hecatonchire:~$
```

Figure 17 Measured RTT latency between the CN and the COTS UE using ping

3.3. Deployment and Installation

A detailed deployment and installation guide for the NSA setup, according to the configuration parameters described in section 3.2.3 is provided in [12].

4. OAI BASED E2E 5G SA NETWORK

4.1. Background

After the completion of the procedures required for the E2E NSA setup in OAI, Eurecom started working on the required developments to support the end-to-end SA setup during the first quarter of the 3rd year of 5GENESIS project. The target is to deliver an OAI gNB, able to support an end-to-end SA setup based on a 5G CN (OAI or other) and SA capable COTS UE devices. As there are many developments taking place in parallel and capturing the whole RAN stack, intermediate validation steps have been taking place using first the OAI UE (which is also developed in parallel to support SA deployments) in simulation and RF mode, and then the COTS UE devices.

In the following, the implemented software architecture to support SA in OAI is provided as well as the end-to-end integrated procedures which have already been validated using COTS UEs as per 3GPP Rel.15-16.

4.2. Architecture, Implementation, Integration and Testing

4.2.1 Supported SA architecture and implemented extensions in OAI

The 5G Standalone access mode does not depend on legacy 4G LTE but requires a new 5G core network (5GC). This new 5GC uses a cloud-aligned Service-Based Architecture (SBA) that supports control-plane function interaction, re-usability, flexible connections, and service discovery that spans all functions. The main 5GC functions are AMF, SMF, NRF and UPF (SPGW-U-tiny), all of which have been implemented in OAI and can easily be deployed using docker-compose [13].

Compared to NSA, in SA the gNB needs to also implement the complete RRC layer [9] and handling of all the associated messages as well as the NGAP [14] to interface with AMF (N2 interface) and UPF (N3 interface), as shown in Figure 18. Moreover the gNB needs to support multiple bandwidth parts as the initial access happens only on the initial bandwidth part, which has a smaller bandwidth than the full cell bandwidth. Further support for contention based random access is needed, as well as support for common and dedicated control channels. Only after the initial connection and authentication with the AMF, the full bandwidth part is configured and used for user-plane traffic.

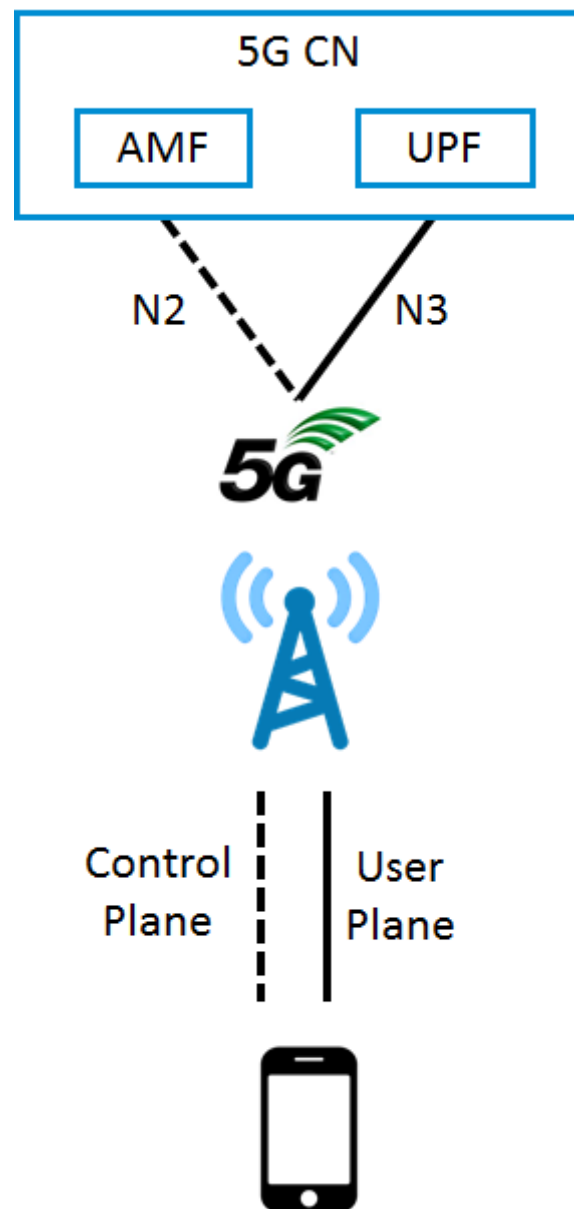


Figure 18 SA architecture deployed in OAI

From a deployment perspective, two options are provided for OAI gNB: the *monolithic* and the *CU/DU functional split* mode. The former option corresponds to a single gNB program on a single host running the whole 5G NR RAN stack. In the latter option, the OAI gNB portion is divided into two blocks: the *Central Unit (CU)* that contains the implementation of RRC and PDCP layers and the *Distributed Unit (DU)* that contains the implementation of RLC, MAC and PHY layers. The two units communicate with each other over the *F1-C* interface for the control plane and configuration exchanges based on F1AP protocol [15]. The Down Link and Up Link user plane data transfer is made through the *F1-U* interface over gtp-u protocol. The CU and DU portions can thus run as separate programs in different hosts, offering significant flexibility for the deployment of the OAI 5G SA setup and the interoperability of OAI blocks with other commercial CUs or DUs.

Figure 19 depicts the 5G RAN protocol architecture of the OAI gNB according to the CU/DU functional split deployment. The layers that had to be extended to support end-to-end SA functionality are highlighted in yellow.

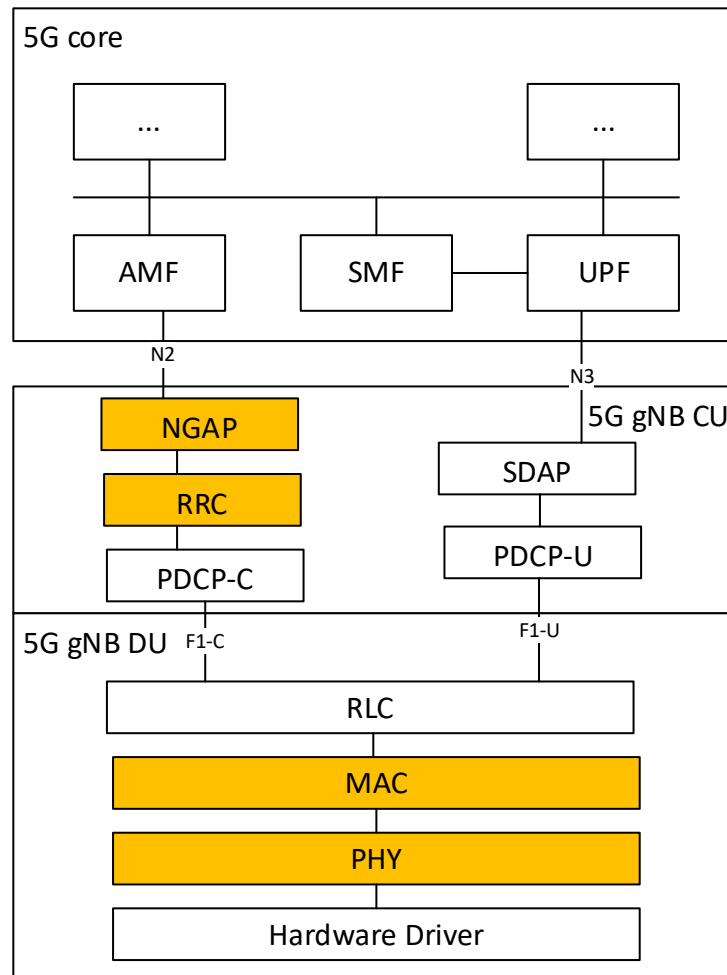


Figure 19 OAI gNB protocol architecture supporting 5G SA with CU/DU split

4.2.3 Hardware architecture

The hardware requirements for the OAI gNB on the SA deployment scenario are the same as the ones described in section 3.2.4 and Table for the NSA deployment.

4.2.2 Testing and validation

At the time of writing this document, interoperability tests of the OAI gNB with different 5G CNs and UE components from different vendors are ongoing. Specifically, interoperability with the OAI CN and Nokia SA Box has been fully validated. With respect to the UE components, interoperability has been fully validated with the Quectel RM500Q-GL module[16], Huawei mate 30 pro smartphone and OAI UE and partially validated with SIMCOM SIM8200EA[17] module.

In the following, some checkpoints for the validation of the end-to-end SA setup are provided, to highlight the establishment of the 5G radio connection, the UE registration to the 5G CN, the PDU session establishment for the exchange of user plane traffic and some basic traffic test. The underlined tests were performed using the Quectel RM500Q-GL module.

After the UE synchronizes to the 5G cell and receives the System Information messages from the gNB, it initiates the *contention based random access procedure (CBRA)* in order to connect to the 5G cell. The procedure is finalized through the reception of Msg4 (*RRCSetup*) acknowledgment from the gNB (Figure 20). Then the UE replies with the *RRCSetupComplete* message which encapsulates the *NAS registration request* message towards the AMF. Upon reception of RRC Setup Complete, the UE state at the gNB becomes RRC Connected.

```

1170 [0m][0m[MR MAC] (ue 0, rnti 0x70bd) Received Ack of RA-Msg4. CBRA procedure succeeded!
1171 [0m][0m[MR MAC] [34m[RLC] RB found! (channel ID 1)
1172 [0m][0m[RLC] /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:452:deliver_sdu: delivering SDU (rnti 28861 is_
1 rb id 1) size 92
1173 [0m][0m[MR RRC] Received message NR_RRC_DCCH_DATA_IND
1174 [0m][0m[MR RRC] Decoding DCCH : ue 28861, inst 0, ctxt 0x7f2ba7f7eeb0, size 86
1175 [0m]12 c0 00 20 00 04 f7 e0 17 b6 ce d3 60 47 e0 04 14 90 00 bf 20 5f 51 00 10 00 00 00 00 02 [0m[MR MAC] 884. 4 RNTI 70bd: 3 bytes from DC
(ndata 3, remaining size 14)
1176 [0m][0m[MR MAC] 884. 4 RNTI 70bd: 0 bytes from DCCH 1 (ndata 3, remaining size 8)
1177 [0m]2 e0 2f 07 07 10 03 07 e0 04 14 90 00 bf 20 5f 51 00 10 00 00 00 00 02 b1 00 10 02 e0 2f 07 02 f0 50 40 1d 14 3a 55 20 5f 51 00 00 00 11 8c
17 40 00 09 05 30 10 10
1178 [0m[MR RRC] [FRAME 00000][gNB][MOD 00][RNTI 70bd] [RAPPROC] Logical Channel UL-DCCH, processing NR_RRCSetupComplete from UE (SRB1 Active)
1179 [0m][0m[NGAP] [gNB 0] Build NGAP_NAS_FIRST_REQ adding in s_TMSI: GUAMI amf_set_id 0 amf_region_id 1 ue 70bd
1180 [0m][0m[MR RRC] [FRAME 00000][gNB][MOD 00][RNTI 70bd] UE State = NR_RRC_CONNECTED

```

Figure 20 Successful CBRA procedure and reception of RRC Setup Complete message at the gNB

This NAS message is conveyed transparently from the gNB to the AMF through the NGAP *InitialUEMessage* (Figure 21). A sequence of NGAP/NAS messages are exchanged afterwards between the gNB, the UE and the AMF to perform the authentication and security procedures leading to the successful Registration of the UE to the AMF (*Registration Accept* and *Registration Complete* NAS messages).

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	192.168.18.203	192.168.18.131	NGAP	134	NgSetupRequest
2	0.003745	192.168.18.131	192.168.18.203	NGAP	614	NgSetupResponse
3	0.077278	192.168.18.203	192.168.18.131	NGAP/NAS-5GS	146	InitialUEMessage, Registration request
4	0.094364	192.168.18.131	192.168.18.203	NGAP/NAS-5GS	630	DownlinkNASTransport, Authentication request
5	0.123432	192.168.18.203	192.168.18.131	NGAP/NAS-5GS	146	UplinkNASTransport, Authentication response
6	0.126800	192.168.18.131	192.168.18.203	NGAP/NAS-5GS	462	DownlinkNASTransport, Security mode command
7	0.135349	192.168.18.203	192.168.18.131	NGAP/NAS-5GS/NAS...	174	UplinkNASTransport, Security mode complete, Registration request
8	0.140345	192.168.18.131	192.168.18.203	NGAP/NAS-5GS	1302	InitialContextSetupRequest, Registration accept
9	0.257311	192.168.18.203	192.168.18.131	NGAP	122	UERadioCapabilityInfoIndication
10	0.459484	192.168.18.203	192.168.18.131	NGAP	86	InitialContextSetupResponse
11	0.330930	192.168.18.203	192.168.18.131	NGAP/NAS-5GS	118	UplinkNASTransport, Registration complete
12	0.341520	192.168.18.131	192.168.18.203	NGAP/NAS-5GS	710	DownlinkNASTransport, Configuration update command
13	0.341561	192.168.18.203	192.168.18.131	NGAP/NAS-5GS	162	UplinkNASTransport, UL NAS transport, PDU session establishment request
14	0.355758	192.168.18.131	192.168.18.203	NGAP/NAS-5GS	266	PDUSessionResourceSetupRequest, DL NAS transport, PDU session establishment accept
15	0.356056	192.168.18.203	192.168.18.131	NGAP	214	PDUSessionResourceSetupResponse

Figure 21 NGAP/NAS exchanges with the Core Network for UE Registration and PDU Session establishment

The UE then initiates the PDU Session Establishment which is validated through the *PDU Session Establishment Accept* NAS message coming from the CN. This message contains the IP address of the UE provided from the SMF. In Figure 22 the configured IP address is shown through the Quectel connection manager software.


```

[06-01 11:01:51:500] Quectel_QConnectManager_Linux_V1.6.0.16
[06-01 11:01:51:500] Find /sys/bus/usb/devices/1-1.3 idVendor=0x2c7c idProduct=0x800, bus=0x001, dev=0x014
[06-01 11:01:51:501] Auto find qmichannel = /dev/cdc-wdm0
[06-01 11:01:51:501] Auto find usbnet_adapter = wwan0
[06-01 11:01:51:501] netcard driver = qmi_wwan, driver version = 22-Aug-2005
[06-01 11:01:51:501] ioctl(0x89f3, qmap_settings) failed: Operation not supported, rc=-1
[06-01 11:01:51:501] Modem works in QMI mode
[06-01 11:01:51:508] cdc_wdm_fd = 7
[06-01 11:01:51:594] Get_clientWDS = 15
[06-01 11:01:51:625] Get_clientDMS = 1
[06-01 11:01:51:658] Get_clientNAS = 4
[06-01 11:01:51:690] Get_clientUIM = 1
[06-01 11:01:51:722] Get_clientWDA = 1
[06-01 11:01:51:754] requestBaseBandVersion RM500QGLABR11A02M4G
[06-01 11:01:51:882] requestGetSIMStatus SIMStatus: SIM_ABSENT
[06-01 11:01:51:914] requestGetProfile[1] oai.ipv4///0
[06-01 11:01:51:946] requestRegistrationState2 MCC: 0, MNC: 0, PS: Detached, DataCap: UNKNOWN
[06-01 11:01:51:977] requestQueryDataCall IPv4ConnectionStatus: DISCONNECTED
[06-01 11:01:51:977] ifconfig wwan0 0.0.0.0
[06-01 11:01:51:979] ifconfig wwan0 down
[06-01 11:03:22:967] requestRegistrationState2 MCC: 505, MNC: 1, PS: Detached, DataCap: UNKNOWN
[06-01 11:03:22:999] requestRegistrationState2 MCC: 505, MNC: 1, PS: Detached, DataCap: UNKNOWN
[06-01 11:03:23:031] requestRegistrationState2 MCC: 505, MNC: 1, PS: Detached, DataCap: UNKNOWN
[06-01 11:03:41:088] requestRegistrationState2 MCC: 505, MNC: 1, PS: Detached, DataCap: UNKNOWN
[06-01 11:03:41:729] requestRegistrationState2 MCC: 505, MNC: 1, PS: Attached, DataCap: 5G_SA
[06-01 11:03:41:985] requestSetupDataCall WdsConnectionIPv4Handle: 0x3b50c6b0
[06-01 11:03:42:113] ifconfig wwan0 up
[06-01 11:03:42:114] busybox udhccp -f -n -q -t 5 -i wwan0
udhccp: started, v1.30.1
udhccp: sending discover
udhccp: sending select for 192.198.0.2
udhccp: lease of 192.198.0.2 obtained, lease time 7200
[06-01 11:03:42:190] ./netup wwan0 192.198.0.2

```

Figure 22 Quectel module connection manager

At the same time, the gNB also sends a *dedicated RRCReconfiguration* message to the UE containing the configuration of the DRB that should be established at the UE to enable the user plane traffic flow at the RAN stack (PDCP, RLC, MAC layers). The UE replies with an *RRCReconfigurationComplete* message to signal the successful reconfiguration. Upon reception of the Reconfiguration Complete message, the gNB performs its own DRB configuration for the lower layers (Figure 23). In parallel, the gNB establishes a gtp-u tunnel with the UPF to enable the user-plane traffic flow over the N3 interface (Figure 19).

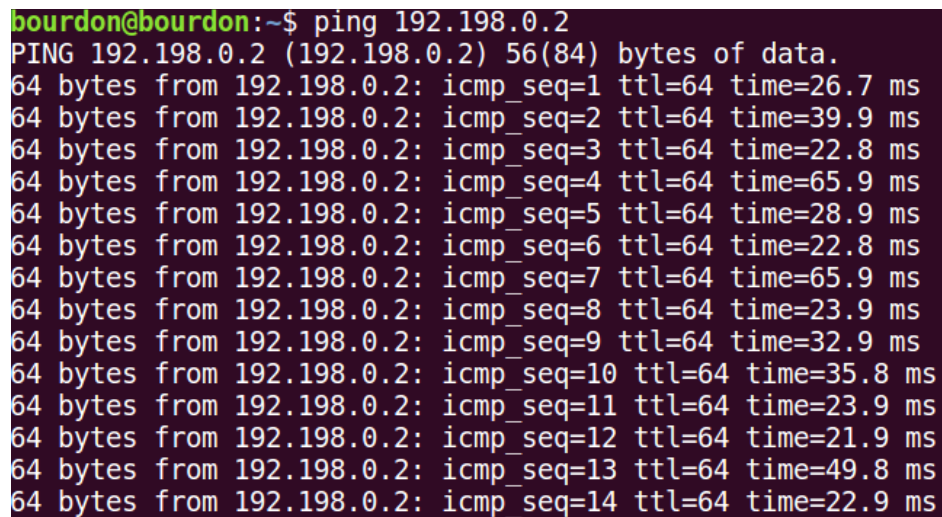
```

[0m][NR_RRC] Receive RRC Reconfiguration Complete message UE 70bd
[0m][NR_RRC] Configuring PDCP DRBs/SRBs for UE 70bd
[0m][PDCP] /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_pdcpc/nr_pdcpc_oai_api.c:add_drb:878: added DRB for UE RNTI 70bd
[0m][NR_MAC] Modified UE id 0/70bd with CellGroup
[0m][NR_MAC] Adding SchedulingRequestconfig
[0m][NR_MAC] Adding BSR config
[0m][NR_MAC] Adding TAG config
[0m][NR_MAC] Adding PHR config
[0m][NR_MAC] Adding LCID 1 (SRB 1)
[0m][NR_MAC] Adding LCID 2 (SRB 2)
[0m][NR_MAC] Adding LCID 4 (DRB 4)
[0m][NR_RRC] Configuring RLC DRBs/SRBs for UE 70bd
[0m][RLC] Trying to add SRB 2
[0m][RLC] /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:710:add_rlc_srb: added srb 2 to UE with RNTI
[0m][RLC] /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:792:add_drb_am: added drb 1 to UE with
0x70bd
[0m][RLC] /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:add_drb:879: added DRB to UE with RNTI 0x70bd
[0m][NR_RRC] [gNB 0] Frame 0 CC 0 : SRB2 is now active
[0m][NR_RRC] [gNB 0] Frame 0 : Logical Channel UL-DCCH, Received NR_RRCReconfigurationComplete from UE rnti 70bd, reconfiguring DRB 1

```

Figure 23 DRB establishment at the gNB upon reception of RRC Reconfiguration Complete message

After these steps, the UE can exchange IP traffic through the CN. In Figure 24, a snapshot from a ping test initiated from the CN towards the UE is shown.



```
bourdon@bourdon:~$ ping 192.198.0.2
PING 192.198.0.2 (192.198.0.2) 56(84) bytes of data.
64 bytes from 192.198.0.2: icmp_seq=1 ttl=64 time=26.7 ms
64 bytes from 192.198.0.2: icmp_seq=2 ttl=64 time=39.9 ms
64 bytes from 192.198.0.2: icmp_seq=3 ttl=64 time=22.8 ms
64 bytes from 192.198.0.2: icmp_seq=4 ttl=64 time=65.9 ms
64 bytes from 192.198.0.2: icmp_seq=5 ttl=64 time=28.9 ms
64 bytes from 192.198.0.2: icmp_seq=6 ttl=64 time=22.8 ms
64 bytes from 192.198.0.2: icmp_seq=7 ttl=64 time=65.9 ms
64 bytes from 192.198.0.2: icmp_seq=8 ttl=64 time=23.9 ms
64 bytes from 192.198.0.2: icmp_seq=9 ttl=64 time=32.9 ms
64 bytes from 192.198.0.2: icmp_seq=10 ttl=64 time=35.8 ms
64 bytes from 192.198.0.2: icmp_seq=11 ttl=64 time=23.9 ms
64 bytes from 192.198.0.2: icmp_seq=12 ttl=64 time=21.9 ms
64 bytes from 192.198.0.2: icmp_seq=13 ttl=64 time=49.8 ms
64 bytes from 192.198.0.2: icmp_seq=14 ttl=64 time=22.9 ms
```

Figure 24 ping test for user plane traffic with the OAI SA setup

At the time of writing this document, further validation and performance improvements of the SA setup with user-plane traffic are ongoing.

4.3. Deployment, installation and execution instructions

The deployment, installation and execution instructions are described in Annex-2 at the end of this document.

4.4. Innovation

OpenAirInterface is the only open-source software project today delivering implementations of both 5G NSA and SA RAN (eNB, gNB, nrUE). Moreover, it achieves interoperability with OAI 4G EPC (MME, S+PGW, HSS) and 5G CN (AMF, UPF, SMF etc.) for the NSA and SA setup respectively as well as with COTS UE devices, spanning the full protocol stack of 3GPP standard and offering an end-to-end, native OpenAirInterface solution. This is feasible by running the OAI software on top of general purpose x86 processors.

A wide range of deployment options are provided for 5G experimentation, ranging from emulation to real-time RF solutions with different SDR components (e.g., USRP B210, USRP N3xx), depending on the experimentation and performance targets as described in section 3.2.4. Moreover, OAI software supports different functional splits (e.g., CU/DU based on 3GPP F1 interface[15], MAC/PHY based on FAPI interface [5]), targeting flexible RAN component deployments and interoperability with third-party equipment.

5. TERRESTRIAL BACKHAUL SYSTEM

5.1. Background

5GENESIS deliverable D3.11 [1] addressed the mmWave transport (backhaul) solution that is providing high data rate wireless connectivity between the edge data center in Berlin and the nomadic 5G deployment. A real-world example of this implementation was captured in the Berlin Platform deliverable D4.14 [2], using the mmWave link connecting the Humboldt University building with the nomadic, remote island at the courtyard of the Humboldt University.

In 5GENESIS, IHP is providing its 60 GHz solution for providing wireless transport links within the Berlin platform. This deliverable presents the latest design considerations, developments and result stemming from the assessment of this solution.

5.2. Architecture, Implementation, Integration and Testing

In deliverable D3.11 [1], the basic components of IHP's 60 GHz prototype were introduced and explained, and an image of the final, integrated solution was provided. By the time D3.11 was released, the work on the integrated prototype was ongoing; hence, it was not yet fully functional for performance evaluation.

To recall it, the prototype consists of a proprietary FPGA-based hardware platform (i.e. motherboard called digibackBoard [24] with software-defined radio (SDR) capability and an adapter board that has been designed to be attached to the motherboard in order to host the commercial-of-the-shelf (COTS) 60 GHz transceiver module with phased array from SiversIMA (now Sivers Semiconductors). The integrated solution is then mounted on an active cooler with a Peltier pump, as shown in Figure 25.

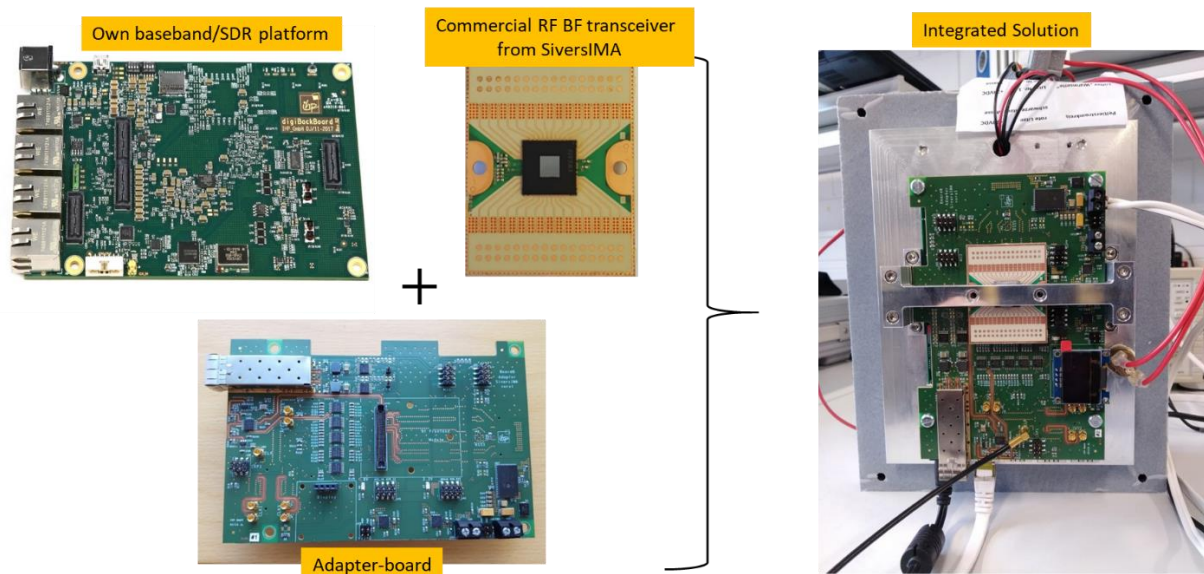


Figure 25 The key building blocks of the 60 GHz prototype and the integrated solution

After deliverable D3.11 release and prior to deliverable D6.2 [25], the prototype was finalised and made operational. The initial performance was reported in D6.2, where a short, indoor link, based on the above mentioned device, has been established in a laboratory, demonstrating the data rate of approx. 900 Mb/s and the mean RTT latency of unloaded link of 0.4 - 0.6 ms. The subsequent plan was to perform the outdoor link measurements. However, the COVID-19 pandemic made the access to the infrastructures and the set-up of the equipment not feasible, leading to a delay in carrying out these activities.

For the outdoor link deployment and performance evaluation, the 60 GHz device from Figure 25 is mounted into a special housing. Some details on the housing have already been shared in deliverable D4.14 [2]. Here, we provide more information on the final solution for outdoor use.

Figure 26 shows the outdoor unit including the housing, which consists of two plastic, waterproof boxes that are mounted on a stand. The overall size of the boxes is 65 cm x 25 cm x 12 cm. The stand is equipped with a metallic rod with a foot. The total height of the outdoor unit, when mounted on the rod, is around 1.6 metres. The mmWave hardware (i.e. the integrated solution from Figure 25) is installed in the top box. The Peltier pump-based cooler is located at the backside.

Two Ethernet cables for data communication and management are routed from the bottom box, and cables providing power supply to the motherboard and 60 GHz module (both require 12 V DC). The bottom box comprises an AC-DC converter, providing 24 V DC link for the active cooler, additional 12 V DC link for power supplying the motherboard and RF module, a manageable Ethernet switch, a power switch (relay) for powering down/up the device, and a Wi-Fi Access Point (AP) for accessing the mmWave device (if not possible via cable) for debugging and management purposes.

The used peripherals in the bottom box are listed as follows:

- Microsens MS440219PMXH-48G6 Industrial Switch,
- ETH002 Power Switch (Relay),
- GL-MT300N Wi-Fi Management Client,
- MW Switching Regulator DRP-240-24,
- MW Switching Regulator DR-75-12.

In addition, a Netgear GS108Ev3 External Switch is used outside of the box (any other network switch that supports VLAN tagging configuration could have been used). The logical connection of peripherals and their configuration is shown in Figure 27. To distinguish between all devices in the setup, their IDs are unique and indexed with n for the IHP box, where n = 1...6. E.g., MS1 refers to the industrial switch mounted in Box 1. The IDs are also marked with stickers on each peripheral device. Port 6 of the MSn switch (connected to the long LAN cable out of the box) is used as a Trunk interface to an external switch, i.e., it cannot be directly accessed by a VLAN untagged device. Port 2 is the data and the remaining ports are control. For internal testing and management, connection is made via the external switch using Ports 1-3. Ports 4-6 of the ES are used for data traffic. Another management option would be a Wi-Fi connection via the yellow Wi-Fi access point.

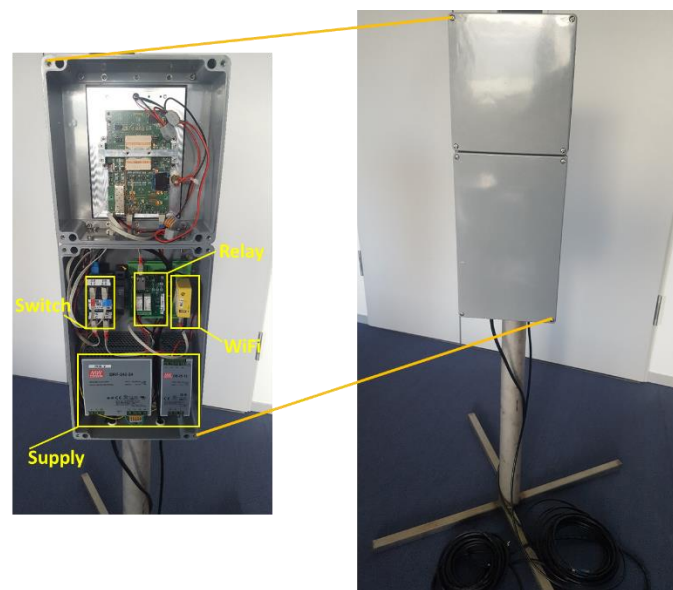


Figure 26 The 60 GHz solution for outdoor deployment

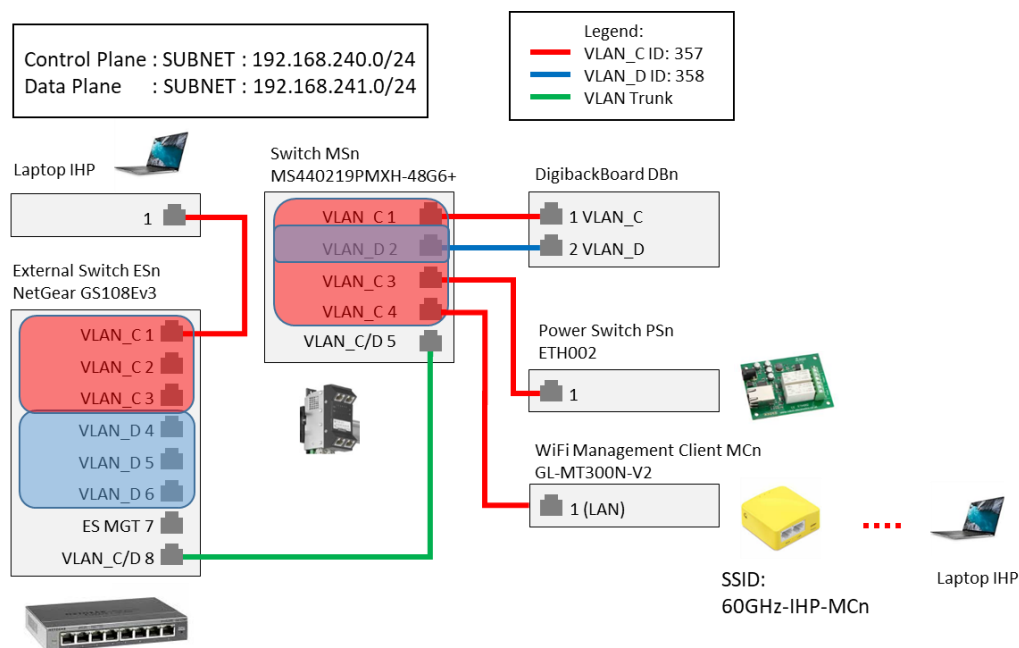


Figure 27 Logical connection/configuration of peripherals and 60 GHz device

Before installing the outdoor deployment, a wireless point-to-point link comprising two of the abovementioned devices was established indoors, in a hallway of IHP. The two devices were installed on the bridges to two different conference rooms on the second floor, as shown in Figure 28 and Figure 29. This way, the potential ground reflection is avoided as there is no floor between the two bridges. The link distance is around 20 metres. Standard laptops with Ubuntu 18.04 LTS OS were connected at each end of the link to perform measurements. We performed the throughput and latency tests to evaluate the link performance.



Figure 28 The slave device at the bridge to conference room A/B-2



Figure 29 The master device at the bridge to conference room E/A-2

The results of the throughput and latency tests are depicted in Figure 30. In Figure 31 and Figure 32, some snapshots of the throughput and RTT latency performances for the above setup are shown. It can be noted that the average throughput is around 935 Mb/s and the mean latency is around 0.55 ms. These results are in alignment with those reported in deliverable D6.2 [25].

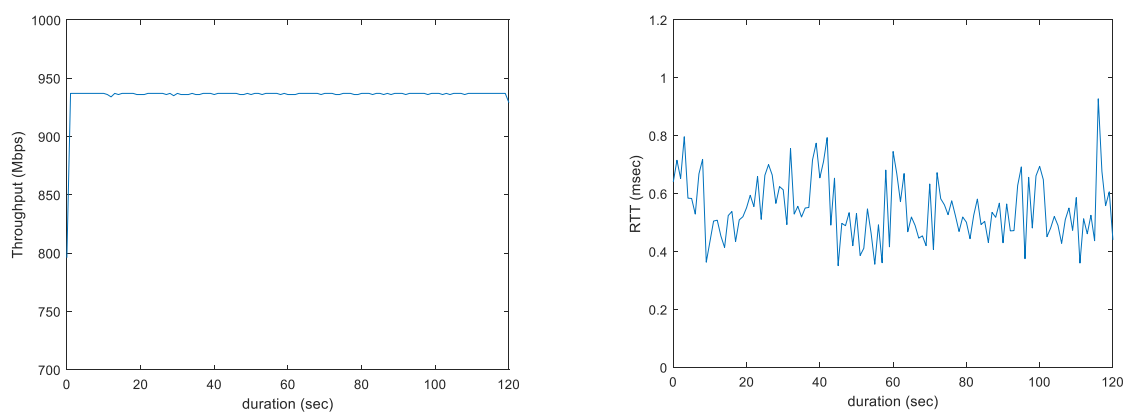


Figure 30 The results of 2-min throughput test and of RTT latency test (of an unloaded link) using iPerf and ping, respectively

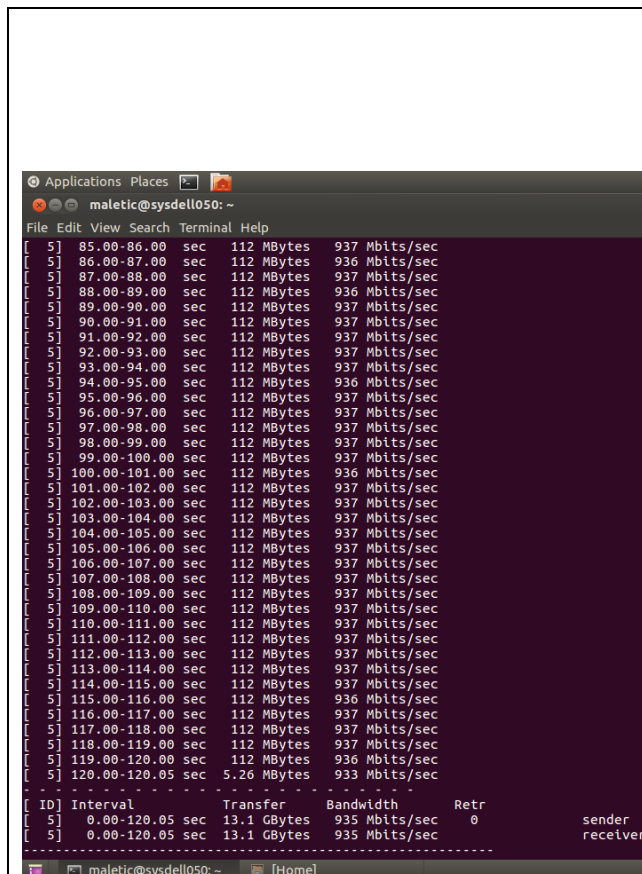


Figure 31 A snapshot of the measured throughput using iPerf (TCP/IP)

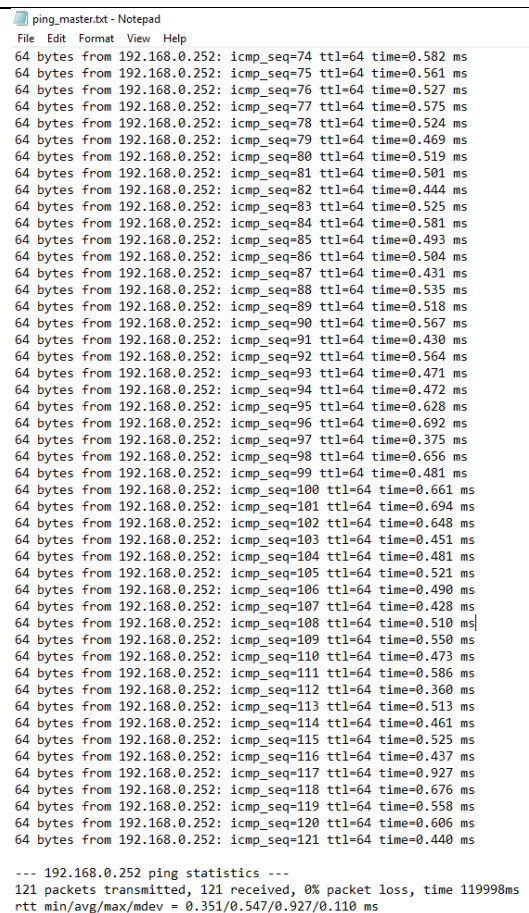


Figure 32 A txt dump of the measured RTT latency of unloaded link between the master and the slave using ping

5.3. Deployment and Installation

Finally, as the last step of evaluation of IHP's 60 GHz prototype in the 5GENESIS project, two outdoor units are deployed at the rooftop of IHP, i.e. at the rooftops of wings A and B. The respective locations are labelled in an aerial photo shown in Figure 33.

The 60-GHz master device installed at the rooftop of the A wing is shown in

Figure 34 a. Similarly, the 60-GHz slave device is deployed at the rooftop of the B wing, and the photo is shown in

Figure 34 b.



Figure 33 A bird-view of IHP with the roof locations where the devices are installed for outdoor 60 GHz link testing



Figure 34 a The master device at the roof of the A wing, 34 b the slave device at the roof of the B wing

Once the 60 GHz devices are installed and powered up, the initial tests were performed. First, the network connectivity to each component, such as Ethernet switch, power relay, and Wi-Fi client, has been tested. Then, testing the serial terminal output of the digibackboard (i.e., 60 GHz motherboard) has been performed via Putty. This interface is used for performing initial tests, debugging purposes, and reading the Medium Access (MAC) output/statistics once the 60 GHz link is up and running.

root@MT300N-V2: ~ (as superuser)

root@MT300N-V2: ~ (as superuser)

```
X_FIFO_RDF0=0
UMRP: CFG0=0X0508A910 PLO_RXCNT=00001271 SYNTH=[PLCP|PHY|HMAC|FSE|ETH]
UMRP: CFG0=0X0C35D1DC ROUTE=Host2PLCP STRM=[I|STRM_EVT|COPY_SF]
PLCP: BB_TX_VLD_CNT=001 BB_RX_VLD_CNT=001 SH_FFT=1 CFG0=00000A03 IER=00000000EFF
PLCP: BB_DBG=00000000 STAT=00000015 TEST_MODE=IDL TX/RX=0,0/0,00 Mbps
PLCP: ISR=00000000 TX_IDLE=1 RX_ENBL=1 DBG=100 BBRFF=0 USR_PLCP_bb_rx_reg_VLD
=0
PHY: CS_HI: 00FFFC0 00000000 CS_LO: 00002100 00000821 FS_State=1>idle2 FS
TX_IDLE=1 FSC_WRRPLY=0 SF_IDLE_State=0>idle
PHY: FS_ID_VLD_CNT=4448 PHY_RX_VLD_CNT=1856 RX_PVLD=0 RX_PVLD_CNT=008 SF_PVLD_C
NT=008 SF_VLD_EVT=008
*****
*** SYSTEM_INIT SUCCESSFUL ***
*** USER_INIT SUCCESSFUL ***
*****
# 0 status          5 init_dacs
# 1 set_debug(1)    6 set_IMC_ADC_SRC(BB->SDR/BB->SDR)
# 2 test_mode(>RX)  7 set_SDR_IDC
# 3 send_test_frame 8 adc_cal_line_clk ( adc_cal_line_data
# 4 set_rx_enable(0) 9 adc_samples2bram
# M start/stop MAC[1] r BB reset
# p print_RADDATA    n/p print (slow/fast) MAC stat
*****
SYS : STAT=000000EFF Uptime= 134m ZYNC=27.2C LH86=31.0C EZV=45.0C P51=34C PLO=34C
SYS : LTH4676: VIN=11.88V IIN=0.958A T2=58.38C CH0(1.00V 5.09A 5.09u 43.12C) CH1(4.00V 0.05A 0.2
1u 45.44C)
adcval: 056F
temperature: 58 deg C

Master

X_FIFO_RDF0=0
UMRP: CFG0=0X0508A910 PLO_RXCNT=00001501 SYNTH=[PLCP|PHY|HMAC|FSE|ETH]
UMRP: CFG0=0X0C35D1DC ROUTE=Host2PLCP STRM=[I|STRM_EVT|COPY_SF]
PLCP: BB_TX_VLD_CNT=001 BB_RX_VLD_CNT=001 SH_FFT=1 CFG0=00000A03 IER=00000000EFF
PLCP: BB_DBG=00000000 STAT=00000015 TEST_MODE=IDL TX/RX=0,0/0,00 Mbps
PLCP: ISR=00000000 TX_IDLE=1 RX_ENBL=1 DBG=100 BBRFF=0 USR_PLCP_bb_rx_reg_VLD
=0
PHY: CS_HI: 00FFFC0 00000000 CS_LO: 00002E00 0000B21 FS_State=1>idle2 FS
TX_IDLE=1 FSC_WRRPLY=0 SF_IDLE_State=0>idle
PHY: FS_ID_VLD_CNT=11904 PHY_RX_VLD_CNT=2624 RX_PVLD=0 RX_PVLD_CNT=011 SF_PVLD_C
NT=011 SF_VLD_EVT=011
*****
*** SYSTEM_INIT SUCCESSFUL ***
*** USER_INIT SUCCESSFUL ***
*****
# 0 status          5 init_dacs
# 1 set_debug(1)    6 set_IMC_ADC_SRC(BB->SDR/BB->SDR)
# 2 test_mode(>RX)  7 set_SDR_IDC
# 3 send_test_frame 8 adc_cal_line_clk ( adc_cal_line_data
# 4 set_rx_enable(0) 9 adc_samples2bram
# M start/stop MAC[1] r BB reset
# p print_RADDATA    n/p print (slow/fast) MAC stat
*****
SYS : STAT=000000EFF Uptime= 152m ZYNC=28.0C LH86=30.0C EZV=44.0C P51=41C PLO=34C
SYS : LTH4676: VIN=11.84V IIN=0.57A T2=57.56C CH0(1.00V 5.12A 5.12u 43.00C) CH1(4.00V 0.08A 0.33u 45.19C)
adcval: 060B
temperature: 65 deg C

Slave
```

Figure 35 The outputs of serial terminals of 60 GHz devices

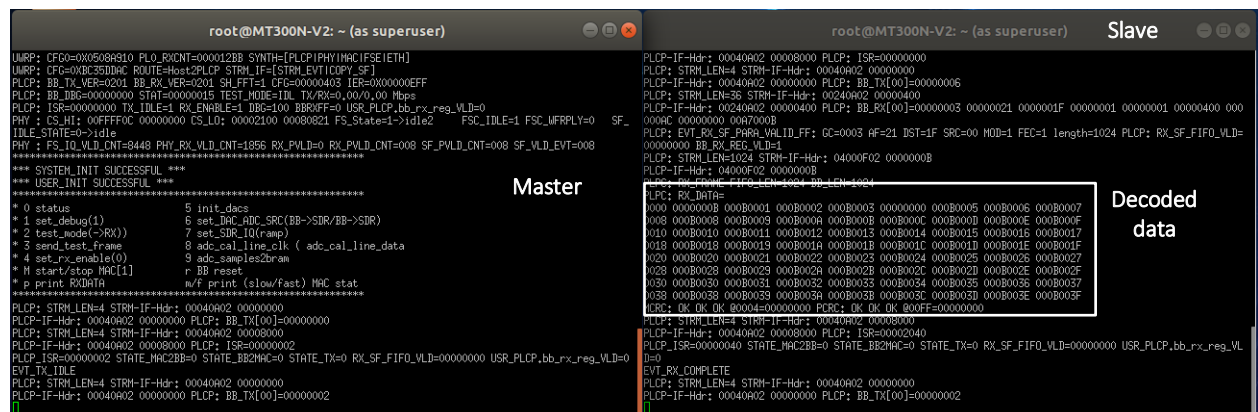
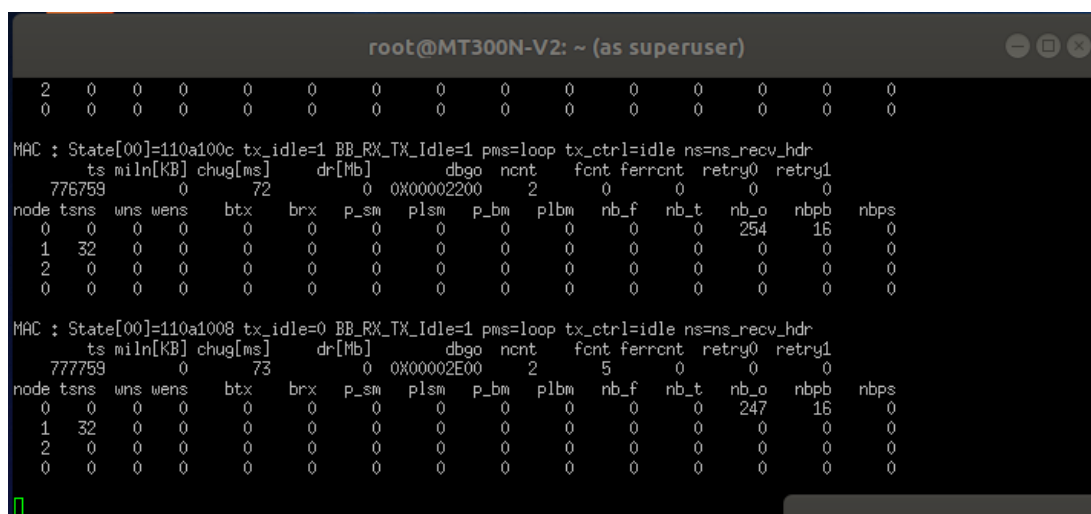


Figure 36 The output of serial terminals when a test frame is sent from the master, received and successfully decoded by the slave

The outputs of serial terminals of 60 GHz devices when the link is active (i.e., MAC is activated at both devices) is shown in Figure 37.



```

root@MT300N-V2: ~ (as superuser)

MAC : State[00]=110a1008 tx_idle=0 BB_RX_TX_Idle=1 pms=loop tx_ctrl=idle ns=ns_rcv_hdr
ts miln[KB] chug[ms] dr[Mb] dbgo ncnt fcnt ferrcnt retry0 retry1
778714 0 41 0 0X00002200 2 0 0 0 0 0
node tsns wns wens btx brx p_sm plsm p_bm plbm nb_f nb_t nb_o nbpb nbps
0 31 0 0 0 0 0 0 0 0 0 0 0 0 0
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

MAC : State[00]=110a1008 tx_idle=0 BB_RX_TX_Idle=1 pms=loop tx_ctrl=idle ns=ns_rcv_hdr
ts miln[KB] chug[ms] dr[Mb] dbgo ncnt fcnt ferrcnt retry0 retry1
779714 0 46 0 0X00002E00 2 0 0 0 0 0
node tsns wns wens btx brx p_sm plsm p_bm plbm nb_f nb_t nb_o nbpb nbps
0 31 0 0 0 0 0 0 0 0 0 0 254 16 0
1 0 0 0 0 0 0 0 0 0 0 0 0 0 0
2 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

SYS : STAT=00000EFF Uptime= 14m ZYNC=27.0C LM86=29.0C E2V=43.0C PS1=36C PL0=31C
SYS : LTM4676: VIN=11.83V IIN=0.58A T2=55.38C CH0(1.00V 5.16A 5.17W 40.06C) CH1(4.00V 0.08A 0.32W 43.19C)
adc_val: 0605
temperature: 63 deg C

```

Figure 37 The outputs of serial terminals of 60 GHz devices when the link is active (i.e., MAC is activated at both devices)

Next, the latency test of the unloaded 60 GHz link using ping have been performed. The result is depicted in Figure 38, showing the mean RTT between the master and the slave of 0.25 ms. The evolution of RTT over time is illustrated in Figure 39.

```

Applications  Places  Terminal  Mon 09:33
genesis03@genesis03:~

File Edit View Search Terminal Help

64 bytes from 192.168.241.252: icmp_seq=189 ttl=64 time=0.244 ms
64 bytes from 192.168.241.252: icmp_seq=190 ttl=64 time=0.239 ms
64 bytes from 192.168.241.252: icmp_seq=191 ttl=64 time=0.233 ms
64 bytes from 192.168.241.252: icmp_seq=192 ttl=64 time=0.232 ms
64 bytes from 192.168.241.252: icmp_seq=193 ttl=64 time=0.243 ms
64 bytes from 192.168.241.252: icmp_seq=194 ttl=64 time=0.234 ms
64 bytes from 192.168.241.252: icmp_seq=195 ttl=64 time=0.258 ms
64 bytes from 192.168.241.252: icmp_seq=196 ttl=64 time=0.247 ms
64 bytes from 192.168.241.252: icmp_seq=197 ttl=64 time=0.234 ms
64 bytes from 192.168.241.252: icmp_seq=198 ttl=64 time=0.253 ms
64 bytes from 192.168.241.252: icmp_seq=199 ttl=64 time=0.248 ms
64 bytes from 192.168.241.252: icmp_seq=200 ttl=64 time=0.257 ms
64 bytes from 192.168.241.252: icmp_seq=201 ttl=64 time=0.231 ms
64 bytes from 192.168.241.252: icmp_seq=202 ttl=64 time=0.259 ms
64 bytes from 192.168.241.252: icmp_seq=203 ttl=64 time=0.256 ms
64 bytes from 192.168.241.252: icmp_seq=204 ttl=64 time=0.239 ms
64 bytes from 192.168.241.252: icmp_seq=205 ttl=64 time=0.238 ms
64 bytes from 192.168.241.252: icmp_seq=206 ttl=64 time=0.255 ms
64 bytes from 192.168.241.252: icmp_seq=207 ttl=64 time=0.251 ms
64 bytes from 192.168.241.252: icmp_seq=208 ttl=64 time=0.257 ms
64 bytes from 192.168.241.252: icmp_seq=209 ttl=64 time=0.257 ms
64 bytes from 192.168.241.252: icmp_seq=210 ttl=64 time=0.247 ms
64 bytes from 192.168.241.252: icmp_seq=211 ttl=64 time=0.251 ms
64 bytes from 192.168.241.252: icmp_seq=212 ttl=64 time=0.246 ms
64 bytes from 192.168.241.252: icmp_seq=213 ttl=64 time=0.233 ms
64 bytes from 192.168.241.252: icmp_seq=214 ttl=64 time=0.232 ms
64 bytes from 192.168.241.252: icmp_seq=215 ttl=64 time=0.445 ms
64 bytes from 192.168.241.252: icmp_seq=216 ttl=64 time=0.237 ms
64 bytes from 192.168.241.252: icmp_seq=217 ttl=64 time=0.247 ms
64 bytes from 192.168.241.252: icmp_seq=218 ttl=64 time=0.229 ms
64 bytes from 192.168.241.252: icmp_seq=219 ttl=64 time=0.360 ms
64 bytes from 192.168.241.252: icmp_seq=220 ttl=64 time=0.236 ms
64 bytes from 192.168.241.252: icmp_seq=221 ttl=64 time=0.257 ms
64 bytes from 192.168.241.252: icmp_seq=222 ttl=64 time=0.254 ms
64 bytes from 192.168.241.252: icmp_seq=223 ttl=64 time=0.276 ms
64 bytes from 192.168.241.252: icmp_seq=224 ttl=64 time=0.228 ms
64 bytes from 192.168.241.252: icmp_seq=225 ttl=64 time=0.238 ms
64 bytes from 192.168.241.252: icmp_seq=226 ttl=64 time=0.255 ms
64 bytes from 192.168.241.252: icmp_seq=227 ttl=64 time=0.227 ms
64 bytes from 192.168.241.252: icmp_seq=228 ttl=64 time=0.247 ms
64 bytes from 192.168.241.252: icmp_seq=229 ttl=64 time=0.244 ms
64 bytes from 192.168.241.252: icmp_seq=230 ttl=64 time=0.231 ms
64 bytes from 192.168.241.252: icmp_seq=231 ttl=64 time=0.254 ms
64 bytes from 192.168.241.252: icmp_seq=232 ttl=64 time=0.253 ms
64 bytes from 192.168.241.252: icmp_seq=233 ttl=64 time=0.231 ms
^C
--- 192.168.241.252 ping statistics ---
233 packets transmitted, 233 received, 0% packet loss, time 232365ms
rtt min/avg/max/mdev = 0.195/0.248/0.600/0.045 ms
genesis03@genesis03:~$

```

Figure 38 A screenshot of latency testing of unloaded 60 GHz link using ping

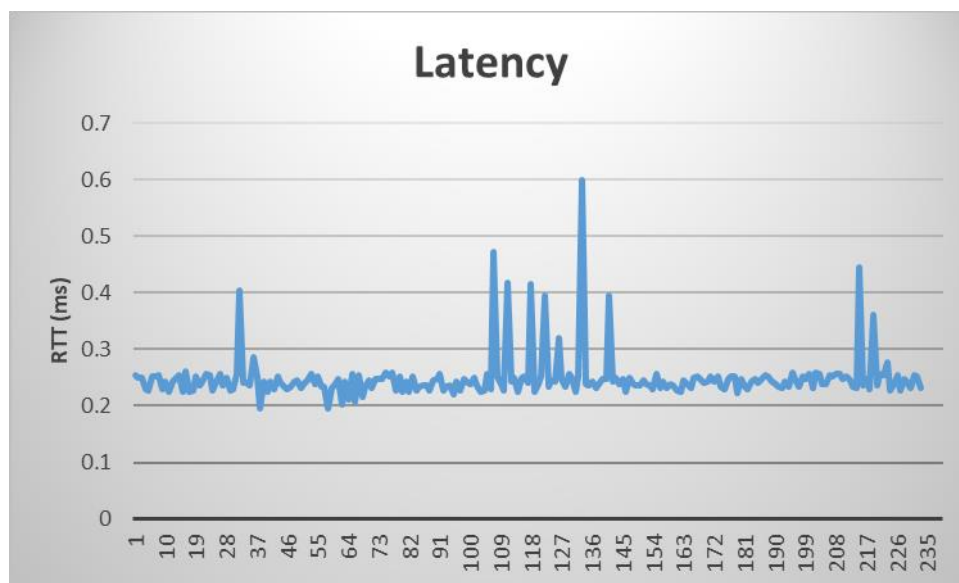


Figure 39 RTT of the unloaded 60 GHz link

Finally, the throughput of the 60 GHz link using iPerf (TCP/IP) was performed. An average data rate of 936 Mb/s is measured from the master to the slave, as shown in Figure 40. The 2-min evolution is depicted in Figure 41. In the opposite direction, 873 Mb/s is measured on average, according to Figure 42. It can be noted that most of the time the data rate is around 900 Mbps, with several link drops appearing. These are currently under investigation.

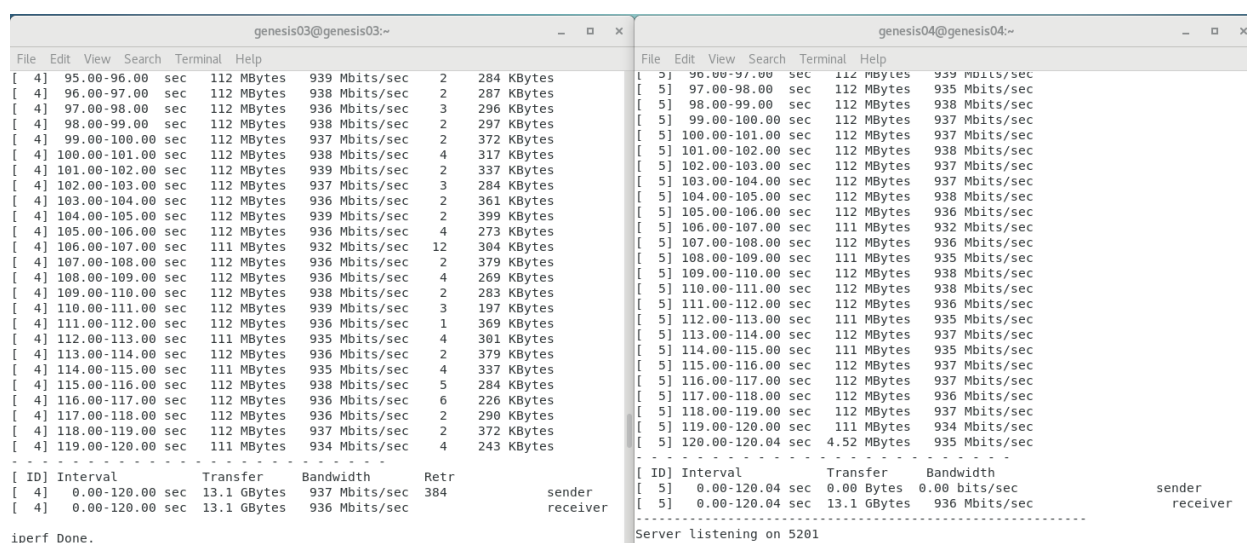


Figure 40 A screenshot of the 60 GHz link throughput testing using iPerf TCP/IP

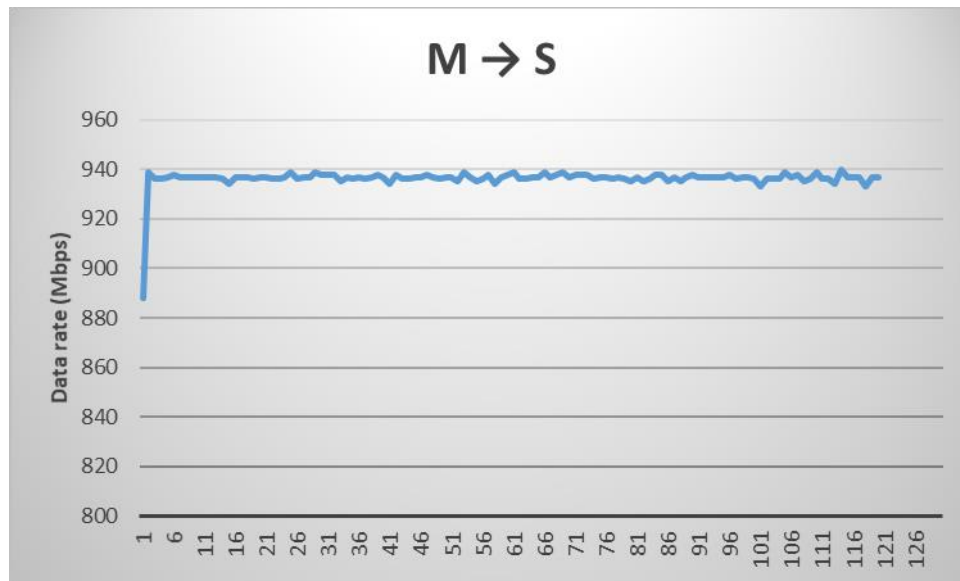


Figure 41 2-min iPerf TCP/IP test of the 60 GHz link from master to slave

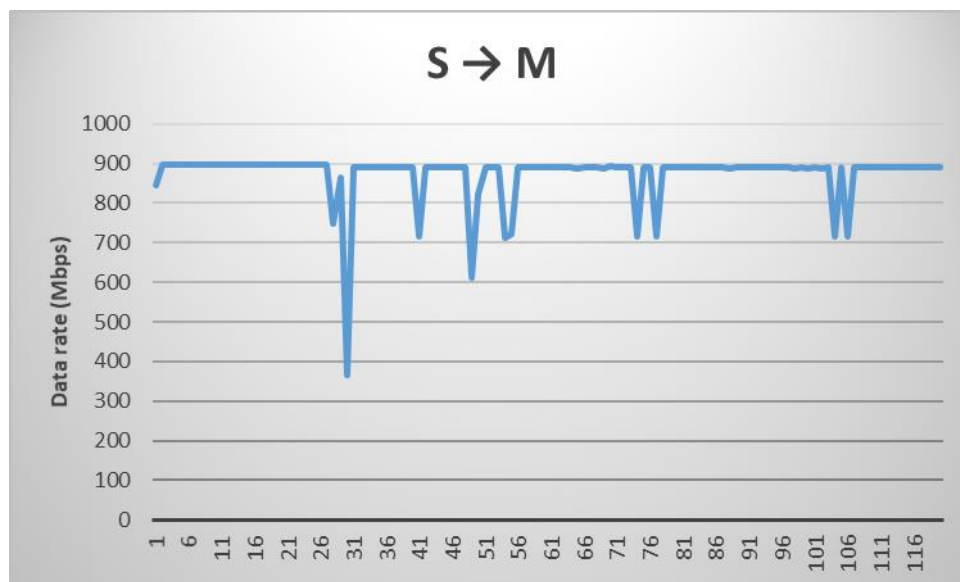


Figure 42 2-min iPerf TCP/IP test of the 60 GHz link from slave to master

Further measurements of the outdoor 60 GHz link will be carried out remotely by Fraunhofer FOKUS for KPIs' evaluation using their automatic monitoring and analytics capabilities developed in 5GENESIS. The detailed results will be reported in deliverable D6.3.

5.4. Innovation

The mmWave prototype built by IHP targets rapid prototyping and flexibility in the micro- and mmWave frequency region, which eases the interconnection of the BB platform with COTS front ends [24]. The prototype can accommodate electrical or optical signal transmission and allows real-time and SDR working modes.

Some key benefits of IHP's mmWave solution are summarised below:

- Proprietary FPGA hardware platform for high-speed data communication (data converters with up to 2.5 GSps) with Software Defined Radio (SDR) capability
- SDR allows evaluation of signal processing algorithms in hardware-in-the-loop manner prior to their Hardware Description Language (HDL) implementation on the same hardware platform
- An adapter-board (with SFP+ cage for 10G connection and debugging pins) as an interface between the baseband platform and different mmWave RF modules (proprietary or COTS)
- Time-stamping capability (potential ranging and localisation add-on feature to the basic data communication)
- Possible upgrade to the next generation of wireless transport links at e.g. D-Band (140 GHz) by attaching appropriate RF module.

6. SPECTRUM MANAGEMENT IN 5G MOBILE NETWORKS

6.1. Motivation

5GENESIS envisions that efficient spectrum management will be key asset in 5G mobile networks and beyond, since they will need more spectrum than previous mobile generations, especially when the roll-out of 5G networks reaches a mature level. This belief is based on the fact that 5G:

- provides higher peak bit rates,
- allows to offer new services to new costumers (i.e. several vertical industries such as automotive, manufacturing, entertainment, e-health, energy, etc.),
- allows the disaggregation of the gNB base station in three units (i.e. central unit (CU), distributed unit (DU) and radio unit (RU)), which results in the backhaul network having higher probability to rely in wireless links than before.

In addition to the need for additional spectrum, spectrum needs in 5G and beyond will also vary in time and space more than in previous mobile generations [19]. This is primarily due to the fact that the combinations of offered services in each time instant at each location can be variable. Figure 43 illustrates the traffic demand in a real mobile network in a metropolitan area. As one can see from this figure, the traffic peaks in the downtown area and as we go to the suburb area, the traffic drops significantly.

If nothing is done, i.e., if we continue to rely on fixed allocation of spectrum for 5G networks considering busy-hour requirements in busy cells of the network, large amounts of spectrum, which could otherwise be used by other mobile or non-mobile networks, will be ‘wasted’. From 5G onwards, mobile network deployments will heavily rely on softwarization, giving the networks the flexibility to adapt quickly to variable traffic requirements and radio conditions, by shrinking and expanding the network capacity on demand. So, 5GENESIS proposes to analyse the opportunity to abandon the fixed allocation of spectrum and put forward an aggressive and dynamic allocation of spectrum both in time and space, according to the traffic demand.

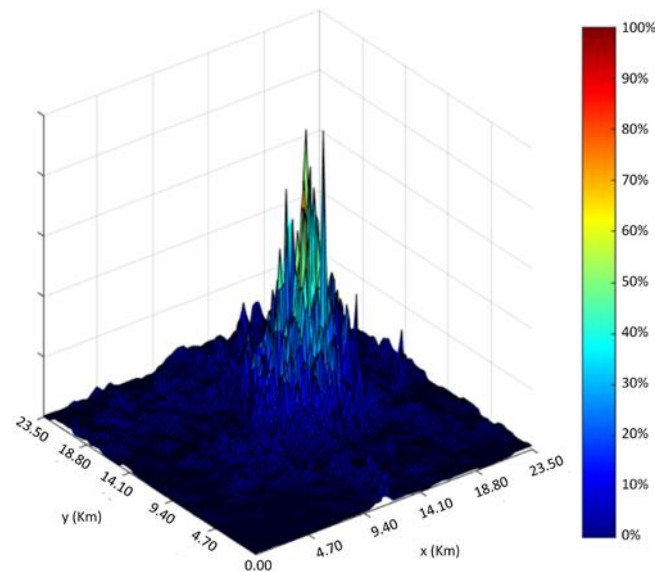


Figure 43 – Traffic demand in a real network [19]

The dynamic allocation of radio resources in 5G will not be trivial especially due to the high number of service combinations, radio parameters and deployment options, which makes dynamic spectrum allocation, by traditional rule-based techniques, inefficient or difficult to implement in 5G. Hence, we propose to use Machine Learning (ML) techniques for spectrum management in 5G, where learning algorithms continuously adapt to every change in network conditions.

6.2. State-of-the-art on spectrum sharing schemes

Dynamic allocation of radio resources for spectrum sharing purposes has already been advocated in the literature.

The first widely known sharing of spectrum occurred in the ISM (industrial, scientific and medical) bands, which were opened for use by low-powered unlicensed devices for the first time in the U.S. in around 1985. In these bands, devices rely on a spectrum etiquette (reduced duty cycle, dynamic frequency selection, listen before talk, carrier sense multiple access, etc.) defined by the regulator, to reduce the probability of interfering among them. Although this solution works, as can be proved by the huge success of Wi-Fi networks operating in these bands after 1997, the interference increases with the number of devices and networks using the band, eventually reaching a level that renders communication impossible.

A second widely known sharing scheme – TV white spaces (TVWS) – was proposed in the U.S. in 2004. It was essentially driven by the imminent migration of TV broadcasts from analogue to digital technology, which reduced the amount of spectrum needed to transmit the same number of TV signals. Hence, in areas where a given TV frequency was not used, enabling technologies like software-defined-radio (SDR) and cognitive radio (CR) would allow low-powered unlicensed devices to use that frequency in a secondary basis without interfering with the TV signals transmitted by surrounding TV stations and without claiming interference protection from primary users or other secondary users. Although in a first phase it was proposed to use spectrum sensing to detect the TV signals to protect, this was later abandoned

in favor of the use of spectrum databases that store information about which frequencies are protected in each place.

Another sharing scheme was proposed by mobile equipment vendors in 2011 in Europe, called Authorized Shared Access (ASA). The main idea was that mobile networks can get additional spectrum by using bands already allocated to other services (e.g., radars, fixed links, broadcasting ...) under pre-defined circumstances without having to remove the incumbents from that band. Around the same time, European regulators proposed a very similar scheme, called Licensed Shared Access (LSA), whose main difference from ASA is that LSA does not require that the new users of a band are mobile operators. Unlike previous sharing schemes, ASA/LSA tried to ensure that both the incumbents and the new users of the band (i.e., the mobile networks) can benefit from a given quality of service (QoS). In ASA/LSA the QoS is ensured by i) selecting bands with reduced utilization by the incumbents in significant portions of the territory or for significant portions of time, ii) granting sharing licenses only to a limited number of new users/networks, and iii) requiring that mobile networks consult a spectrum database to know which frequencies they may use in a given time and place before starting to use them.

In 2012 the U.S. regulator proposed a new sharing scheme called Spectrum Access System (SAS) to be used to deliver broadband services using bands already allocated to the military agencies. The service delivered through the SAS was called Citizens Broadband Radio Service (CBRS). CBRS considers a three-tiered spectrum access scheme:

- In the top tier are the military services, which have highest priority to use the spectrum and are protected against interference from all other users.
- In the second tier are the new Priority Access Licenses (PAL), which may use the spectrum when and where the military services are not using it. PALs are protected against interference from other spectrum users in the same tier or in the lower tier.
- In the third tier are the General Authorized Access (GAA) users, which are unlicensed networks or devices which may use the spectrum when the other tiers are not using it, and cannot claim any protection from interference.

Although CBRS is defined since around 2012, the rules to assign PALs have been under discussion for a long time, with auctions finalized just in July 2020.

From 2018 to 2021, evolved LSA (eLSA) standard was specified by European Telecommunications Standards Institute (ETSI). eLSA improved the ASA/LSA concept by considering that mobile networks, particularly 5G networks, can be used by multiple tenants to deploy local area networks to operate over short or long time periods. eLSA standard introduces enhanced time and space dynamicity to spectrum allocation when compared with ASA/LSA standard (which assumed pre-defined channel allocations among the licensees). However, it has to be stressed that eLSA focuses on private local area networks only, and it considers only two types of spectrum users: the incumbents and the licensees. That is, only two priority levels can exist, and they are fixed.

6.3. 5GENESIS Spectrum sharing scheme

Existing spectrum sharing schemes allow to define only up to three different priorities to access the unused spectrum, and three corresponding protection levels against interference. Moreover, once defined, these priorities and protection levels remain constant, and they cannot change over time or space.

5GENESIS goes beyond the state-of-the-art on spectrum sharing, by proposing a generic spectrum sharing scheme that allows to define any number of priorities to access unused spectrum and any type of protection against interference. To this end, 5GENESIS's slice template is augmented to include the following items:

Priority level: # Preemption level (vulnerability, capability): #, # Interference protected? Y/N Protection level: metric=#, threshold=#.#, units=# Protection zone: list of pixels Protection time: start=#, end=# Permissible radio configurations: {...} Current radio configuration: {...}

Figure 44 – Extension of the 5GENESIS slice template for spectrum management purposes

In Figure 44, the priority level is a positive integer that defines the priority of the network slice to get their request for spectrum processed when there are several network slices requesting for spectrum. The lower numeric value the higher the priority.

If there are enough free spectrum available, the new slices will use it. Otherwise, some of active network slices may have to leave the spectrum they are currently using. To decide which network slice has to leave the spectrum, we have to resort to the information about preemption capability and preemption vulnerability. Both of these fields are positive integers. To decide if a network slice X can make another slice Y leave the spectrum, we compare the preemption capability of slice X with preemption vulnerability of slice Y. If the preemption capability of slice X is higher than the preemption vulnerability of slice Y, then the slice Y has to leave the spectrum.

Having decided which network slices will have the right to use the spectrum, we may need to define the maximum amount of interference that can be caused on their receivers. To do this, we should set the interference protection flag and define the interference protection level. As different radio services may define the maximum amount of interference they can cope with using different metrics, the definition of protection level involves the selection of a given interference metric (e.g., maximum electric field of the interference signals, C/I, I/N, C/(I+N), SINAD¹, THD², etc.; In these expressions C indicates the desired signal power, I is used for the total interference power and N is the noise power) followed by the indication of a floating point value and the selection of the unit (i.e., V/m, dBuV/m, linear units, dB, dBm). We must then

¹ By definition, signal-to-noise and distortion (SINAD) ratio is given by $SINAD = (C + N + I) / (N + I) = C / (N + I) + 1$. In this expression C indicates the desired signal power, I is the total interference power, and N is the noise power.

² Total harmonic distortion (THD), given by $THD = \sqrt{I/C}$, where C is the power of the desired signal and I is the total interference power.

indicate the list of pixels where the slice is protected against excessive interference and define the time period during which this protection is going to be enforced.

Having defined the priority to access to the spectrum, the preemption characteristics, and the interference protection level, each slice should also contain a list of radio parameters (i.e., bands, bandwidths, radio technologies, channel ranks, carrier aggregation capabilities, dual/multi-connectivity capabilities, transmission power levels, etc.) that the hardware supports and the slice is allowed to use.

With this information, the spectrum management algorithms described below would allocate in an optimized way the radio resources (i.e., bands, bandwidths, radio technologies, channel ranks, carrier aggregation capabilities, dual/multi-connectivity capabilities, transmission power levels, etc.) to be used by each slice.

It should be stressed that the sharing scheme depicted in Figure 44 allows to go beyond the current state-of-the-art in spectrum sharing in the following senses:

- it allows to define any number of priority levels that may change over time and/or space.
- it allows to configure specific interference protection levels for each network.
- it can be used to coordinate several subnetworks of the same network, e.g., it can be used to coordinate the access and backhaul domains of the same network.
- it can be used to coordinate any type of networks, i.e., either network slices or independent public and/or private networks.
- it can be applied to terrestrial or satellite radio services
- it can be configured to apply to any band and regulatory domain (i.e., applied in any country).
- it can be used to coordinate networks located in the same place at different time instances (time-sharing only) or located in different places at the same time (spatial sharing only), or networks that appear and disappear anywhere anytime (time and spatial sharing). Thus, it avoids the need to reserve different bands for country-wide public mobile operators or for local private networks.
- It allows to use current sharing schemes (unlicensed operation, white spaces operation, ASA/LSA/eLSA, and CBRS) as well as potential future sharing schemes.

6.4. Ideal regulatory framework for 5GENESIS sharing scheme

The spectrum efficiency gains introduced by the spectrum sharing scheme proposed by 5GENESIS can be maximized introducing a few changes in the current spectrum licensing methodology. Taking into account the maximization of spectrum efficiency only, we propose the introduction of the following changes:

- a) To analyse the opportunity to abandon the practice of licensing spectrum to all operators at the same time, for the same large-areas and for the same long-term periods. Instead, allow each operator to apply to a license when and where it needs, i.e., in the area it needs and for the time it needs, provided that it demonstrates it has the technical resources to use the spectrum within that time and space windows.

- b) Produce complete and accurate radio maps to characterize the performance of 5G networks. Besides the indication of signal strength and throughput, include in those maps also other metrics (e.g., latency, SINR, dropped packets, reliability, ...). Instead of producing those maps once or twice a year as it is commonplace today, update this information frequently so both averaged and instantaneous maps are available for spectrum management purposes. The maps can be built using the measurements already performed by 5G UEs. Additional measurements could be requested to UEs that are having lower utilization and have battery above a given threshold or produced by dedicated sensing networks. The maps could be produced and stored by the telecom operators which may also use them for network optimization purposes. The operators should allow anonymized versions of these maps to be visualized (e.g., providing links, or software applications) by the regulator, verticals and the end-users. The reliability of the maps should be evaluated by the regulator through sporadic measurement campaigns. The regulator, or a third-party on behalf of the regulator, could then use these maps as input to ML algorithms to automatically determine the carrier frequency to be allocated to each network, regardless of the combination of the networks that are sharing a band.

Except for some initiatives in the U.S., using TV white spaces and CBRS, spectrum sharing has not seen wide commercial adoption so far. To incentivize telecom operators to start sharing the spectrum, we suggest that the regulators identify one band to be shared by a limited number of network providers and assign licenses to those companies for free for a reasonable amount of time. Another measure that we suggest increasing the adoption of spectrum sharing is that regulators promote the deployment of national testbeds where the sharing scheme is implemented and improved. This helps convince network providers that spectrum sharing is technically feasible and has not negative impact on their business models.

6.5. 5GENESIS spectrum management architecture

As mentioned in previous sections, the base station can be divided into three different units – Central Unit (CU), distributed unit (DU) and radio unit (RU) – eventually not being deployed in the same physical location. We take advantage of this feature to devise a spectrum management architecture, built on top of the 3GPP 5G network management system, which is able to continuously perform optimization of radio resource parameters in different places of the network in an autonomous fashion. The proposed spectrum management architecture is illustrated in Figure 45. It is worth mentioning that 5G management system uses a service-based-architecture; therefore, each management function when authorized, can communicate with any other management function.

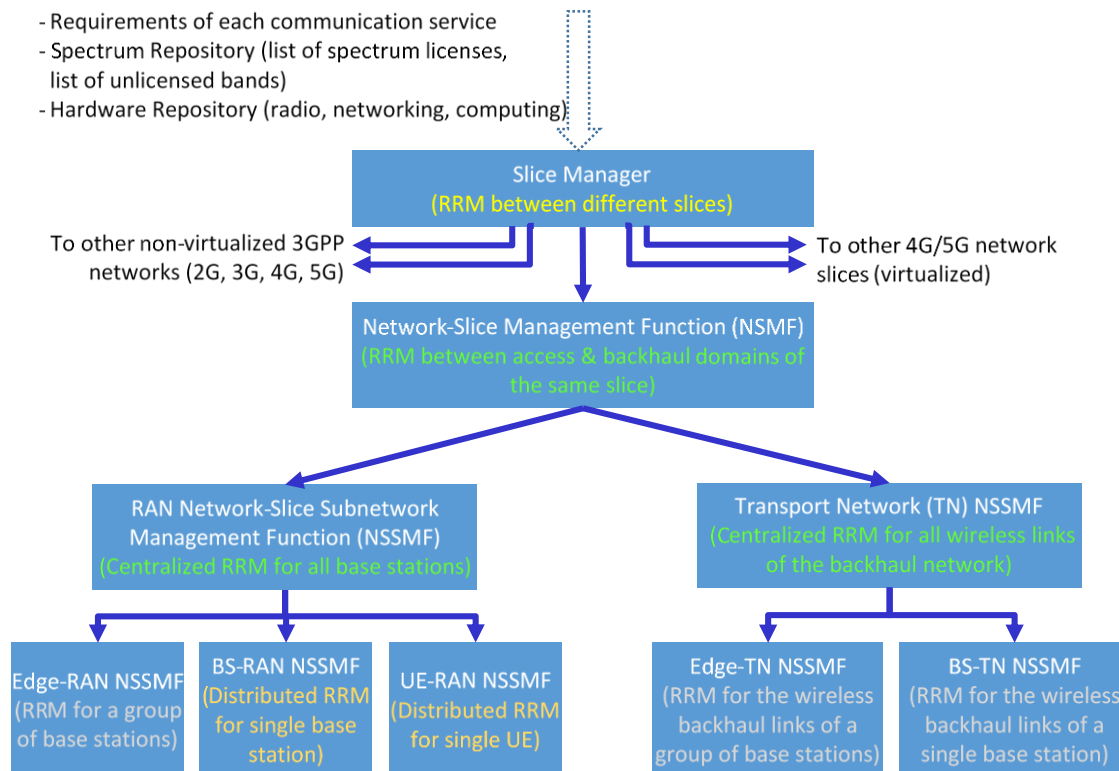


Figure 45 – 5GENESIS spectrum management architecture

To coordinate spectrum management between different radio networks, the proposed spectrum management architecture is capable to select the radio technology, number of component carriers, bandwidth and carrier frequency for each network (or network slice). To do that, it considers the surrounding networks that use the same band and require to be protected against excessive interference. We stress the fact that when selecting the radio technology, the spectrum management architecture has to take into account not only the spectrum issues but also the RAN hardware that is available for selection. This task is under the responsibility of the Slice Manager.

Having decided which radio resources are assigned to each network, the proposed architecture, more specifically the Network-Slice Management Function (NSMF) controlling each mobile network, will decide how to divide those resources among the radio domain and the backhaul domain of the same mobile network. After this decision, for each mobile network, each domain (RAN and wireless backhaul) will know which spectrum they have to use.

In the RAN domain of each network, optimization of radio parameters can occur at four different levels:

- Centralized RAN optimization algorithms running in the central cloud (e.g., same cloud as the one used for the core network) that will coordinate radio parameters for all base stations.
- RAN optimization algorithms running in the edge to coordinate radio parameters for a group of base stations.
- RAN optimization algorithms running in each base station to coordinate the radio parameters of each cell.

- RAN optimization algorithms running in each UE to assist the network in the optimization of the radio link used by each UE. Most 5G UEs will have multi-radio capabilities supporting at least 5G, 4G and WiFi. Thus, the UE can assist the network to steer, switch, or split the traffic among these technologies, which are typically deployed in different bands.

Although the management of the transport network is outside of the 3GPP scope, we propose to use Slice Manager, Network-Slice Management Function (NSMF) and Network-Slice Subnet Management Functions (NSSMF) to run non-real-time spectrum management algorithms for the wireless backhaul links and communicate their decisions to the SDN controllers. For real-time spectrum management algorithms for wireless backhaul links, it is better to run the algorithms directly in the SDN controllers. In this case, the NSSMFs will act just as proxies for the spectrum management architecture and the managers (or controllers) of the backhaul network. In either way, we consider different optimization levels:

- Centralized Transport Network NSSMF that will interact with one or more SDN controllers for spectrum management purposes related to all wireless backhaul links of a mobile network (e.g., defining the initial topology of the entire backhaul network, selecting which backhaul links to activate or deactivate, configuring the bandwidth of all backhaul links, etc.).
- Edge transport network NSSMF that will interact with one SDN controller to configure the backhaul network of a group of base stations (e.g., dynamically updating the topology and bandwidth of the backhaul network associated with a group of base stations).
- Base station transport network NSSMF that interacts with one SDN controller to configure the backhaul network of one base station.

In summary, in the proposed spectrum management architecture, the slice manager constitutes the fundamental part of the architecture in charge of implementing the spectrum sharing scheme proposed by 5GENESIS to coordinate spectrum allocation among different networks, while the NSMF/NSSMF are responsible to optimize radio configuration and network topology within a single network.

6.6. 5GENESIS machine learning pipeline for spectrum management purposes

As mentioned before, the number of different 5G service combinations, and the high number of 5G radio parameters that can be configured, make it extremely difficult to implement dynamic radio resource allocation and optimization using traditional rule-based techniques.

For this reason, 5GENESIS proposes to use ML algorithms to perform this task, assuming that time is discretized into time steps (step size depends on the specific use case under consideration) and space is discretized into square-shaped (2D) or cubic-shaped (3D) pixels.

The ML algorithms run continuously to adapt the network to the radio conditions whatever are the requested service combinations.

One of the major concerns related with ML algorithms is their complexity and the energy they require to run. To reduce the computational burden imposed by the ML algorithms, particularly the algorithms that perform spectrum management for an entire network (i.e., algorithms running in the slice manager, NSMF, RAN-NSSMF and TN-NSSMF), we propose an ML pipeline that divides the overall algorithms in three different stages as illustrated by Figure 466:

1. **Forecasting:** to have more time to execute the spectrum allocation algorithms and thus use less powerful CPU/GPU, we use time-series forecasting algorithms (e.g. LSTM) which allow to predict traffic demand, spectrum occupation, etc., in the next time steps in every pixel. This means that the spectrum allocation algorithms can run some time in advance.
2. **Clustering:** Instead of running the spectrum allocation algorithm for every pixel of the network, we use clustering algorithms (e.g., K-Means, or Expectation Maximization) to identify pixels with similar requirements and constraints. This means we need to run spectrum allocation algorithms for each cluster of pixels and not for every pixel, thus reducing the number of spectrum allocation algorithm instances that have to be run.
3. **Spectrum allocation:** the allocation of radio resources for each cluster of pixels for each network is performed using a Reinforcement Learning (RL) algorithm, so we can have efficient allocation decisions regardless of the combinations of the 5G services. The RL algorithm explores the best allocation of the available carrier frequencies to the clusters of pixels, in a given network, through experiments. It adopts a policy that maximizes the reward that is a function of 1) the amount of contiguous spectrum left; and 2) the interference that caused to other networks. This is done because a large number of non-contiguous unused spectrum blocks with short-bandwidth could only be valuable for narrowband networks, while a smaller number of unused spectrum blocks with larger-bandwidth can be useful both for narrowband and wideband networks. The net result is that the amount of spectrum that remains unused is reduced, thus improving the overall spectral efficiency when all networks are considered.

For more details, see [20]. Figure 46 depicts the ML pipeline proposed by 5GENESIS for spectrum management purposes.

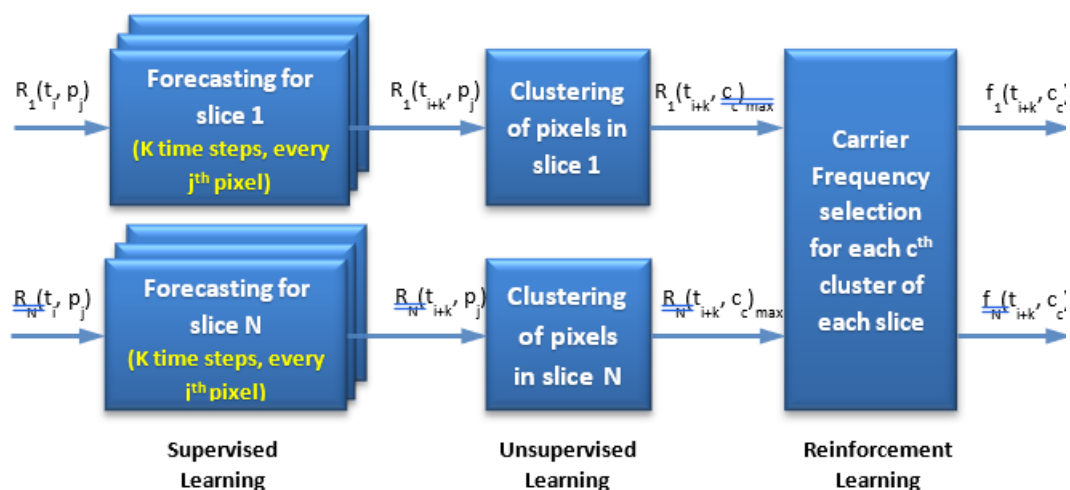


Figure 46 – 5GENESIS Machine Learning pipeline for spectrum management purposes

7. RELEASE B SUMMARY AND FUTURE PLANS

This deliverable summarised the progress in the area of 5G LAN Network Architecture implementation and testing; The implementation of 5G End-to-End NSA and SA networks using Open Air Interface and commercial 5G User Equipment; Wireless terrestrial backhaul design, implementation and testing and a novel concept for spectrum management and sharing for 5G networks using Artificial Intelligence. In this phase, the focus has been on the implementation and testing in the 5GENESIS testbeds:

- Completion of the 5G LAN setup in UMA 5G Platform and testing of an outstanding latency of 0.75 milliseconds latency (RunEL and UMA).
- Implementation and Testing of an E2E Open Air Interface based NSA and SA 5G networks with commercial UE (EURECOM and UMA).
- A 60 GHz backhaul solution for providing wireless transport links within the Berlin platform was presented including the latest design considerations, developments, and result stemming from the assessment of this solution (IHP and FHG).
- A new concept for spectrum management and sharing for 5G Networks was proposed to pursue an aggressive and dynamic allocation of spectrum both in time and space (IT-PT).

The future planned activities for the work reported in this document in the 5GENESIS work frame.

- Further measurements of the 5G LAN network including automated measurements at the UMA testbed (RunEL and UMA).
- Further testing, including automated measurements, of an E2E Open Air Interface based NSA and SA 5G networks with commercial UE (EURECOM and UMA).
- IHP will pursue the rapid prototyping of complete mm-Wave systems, by adding novel features to the existing platform (IHP and FHG).
- Further progress in the AI based implementation of the Spectrum sharing and management system will be reported. (IT-PT)

The results of the further work described above will be reported in the final WP-4 deliverables.

8. CONCLUSIONS

The main conclusion of this report is the successful completion of the implementation, installation and testing of major components of the 5G testbeds in UMA and Berlin platforms including 5G LAN, NSA and SA Open Air Interface E-2-E networks and a 60GHz Backhaul system.

Some remarkable achievements are reported such as URLLC latencies below the millisecond barrier, first time implementation of OAI based E-2-E networks, 60GHz backhaul system with low latency and high throughput as well as a novel design for AI based Spectrum management and sharing.

9. REFERENCES

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ANNEX 1- INSTRUCTIONS FOR 5G-LAN LOOPBACK TEST

The following are the step-by-step instructions provided by RunEL team to UMA 5G testbed team to perform the 5G- LAN Uplink upgrade and the round-trip latency test.

1. Open & Read DRAN_RRH_Advance_Configuration_V1_5.pdf [4]

2. Please read Section 3.5 Update Firmware [4]

Connect 1gb Ethernet cable from RRH to your local network.

From RRH UART Putty terminal, type:

Ifconfig

check unit IP (DHCP from your local network)

From UART Putty terminal (after login to root), type:

mount /dev/mmcblk0p1 /mnt

With FileZilla connect to the unit IP.

In FilZila Please “check” timestamp like in the following picture:

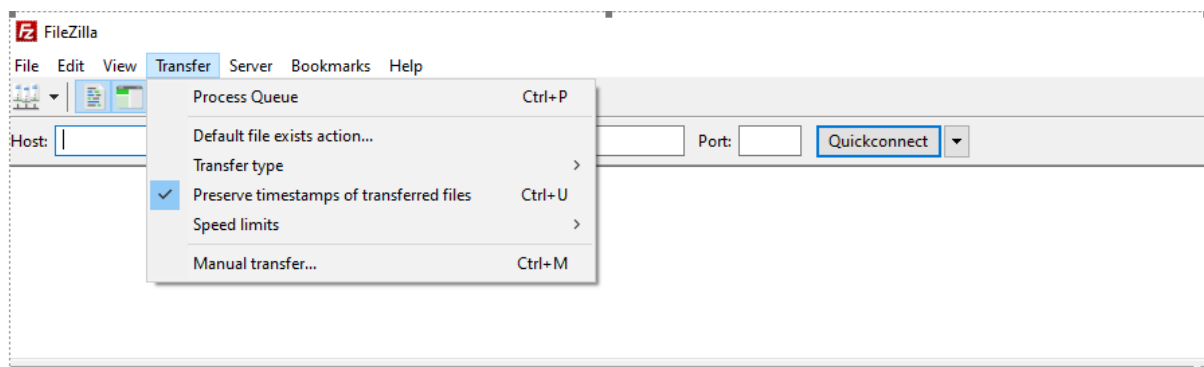


Figure 47 Time Stamp Check

3. Back Up first:

It's important to backup before update the firmware

3.1 Backup /mnt folder

You should mount /mnt as describe above before connect with FileZila, otherwise you should disconnect FileZila and connect again)

The file Zila arrives to /root folder, double click on”..” twice to see mnt folder

From RRH /mnt dir download the files to your PC:

BOOT.BIN

Image

system.dtb

system.dts

3.2 Backup /root/rrh_sw files:

With fileZila select /home/root/rrh_sw

Download the files to your PC:

run_script.sh

board.cfg

4. Edit scrip files:

4.1 Edit run_script.sh

With the USB terminal after login to root type"

cd rrh_sw

vi run_script.sh

Go to the end of the file and press "i" (to insert mode)

Add the lines :

#For RRH RX:

devmem 0xB0050020 32 0x104

devmem 0xB0060020 32 0x104

#

To save the changes: type:

"esc" and ":wq!"

After edit and after out from "vi" type:

sync

(and enter)

4.2 Edit board.cfg

In this file you need to check or change the lines:

pl_dest_ip_addr1=10.0.0.103

pl_dest_ip_addr2=10.0.0.103

pl_dest_port1=1236

pl_dest_port2=1236

If the address are not as above, please change with vi board.cfg

Please note that 10.0.0.103 is your MAC PC that sends the "download",

It means this IP will receive the DATA as well (in port 1236)

If you have other IP for MAC PC, please update the file according to your MAC PC

After edit and after out from "vi" type:

sync

(and enter)

5. Upload files:

5.1 In your PC open the ZIP file and with FileZila upload to /mnt the files:

BOOT.BIN

Image

system.dtb

system.dts

5.2 after that upload files to /home/root/rrh_sw

1sym272rb_end.sh

1sym272rb_start.sh

env.source

hw_rrh_ue_rx.exe

mnt.sh

print_alloc.sh

rst_rrh_ue.sh

5.3 upload the folder "input_rrh_ue " to /home/root/rrh_sw

5.4 from terminal type:

chmod +x * (and enter)

5.5 from terminal type:

sync (and enter)

5.6 Shut down FileZila

6. Up Link test - Run RX script:

6.1 Shut down system DRAN +RRH (Power OFF)

6.2 Power ON again....

6.3 Connect RF to RX

The changes in 6.4(Use RunEL program instead)::

Transmit RF to RX:

On Ubuntu MAC L2 Server run (from the attached Zip file) :

`./mac_shared` (or other mac program name)

(if permission denied please use : `chmod + x mac_shared`)

On Ubuntu MAC L2 Server open VLC

Media >> stream

Add (add any 5Mbit Movie you have)

Stream

Destination UDP (ADD)

Address: 127.0.0.1

Port: 2333

Next

Uncheck Without Transcoding (we don't need transcoding) Next Check with all elementary streams Stream

6.5 Log to RRH (With uart or via 1g Ethernet After login type:

cd rrh_sw

./1sym272rb_end.sh (or ./1sym272rb_start.sh)

Note: it's important to Transmit RF to RX (Up Link) before running "1sym272rb_end.sh" or "1sym272rb_start.sh"

6.6 Check on Host (10.0.0.103) if you receive Data.

While using Ubuntu, you can check the traffic with "bmon".

Sometimes due Ethernet problems, type again:

./1sym272rb_end.sh

If it doesn't help, repeat steps 6.1 - 6.5 The changes in 6.7 (Use RunEL program instead):

On Ubuntu MAC L2 Server run (from the attached Zip file):

`./ue_sc_uncrc`

(if permission denied please use : `chmod + x use_sc_uncrc`)

On Ubuntu MAC L2 Server open VLC

Media >> open network stream

`udp://@1237` or `udp://@127.0.0.1:1237` 6.7 The "ue_sc_uncrc" remove header and tail from the receiving Data.

If you want to build yourself program, you have to remove the header and tail and send the Data to other port (on same machine).

With VLC you can play the Video (if Data is Video) in the new port you sent.

Header to Remove:

Remove first and second word (64b each word).

Second word contain “**Message bytes length – [47:37] – 11 bits**” please also remove the tail after this length

*

Channel Type	message_Bytes length	Seed Descrambler	RRH Number	CRC OK
--------------	----------------------	------------------	------------	--------

CRC [0] – Success 1'b1, Fail 1'b0

RRH Number [5:1] – 5 bits

31bits Seed Init to Polar/LDPC Descrambler – [36:6] – 31 bits

Message bytes length – [47:37] – 11 bits

Channel Type– [63:59] – 5 bits (PUCCH 5'd1, PUSCH 5'd2)

Figure 48 Last Length before tail removal

ANNEX 2- STANDALONE (SA) DEPLOYMENT, INSTALLATION AND EXECUTION INSTRUCTIONS

A deployment and installation guide for the OAI 5G Core Network based on a container environment is provided in [13].

In the following, we provide the instructions for the installation and configuration of the OAI gNB to support the SA setup with COTS UEs in coordination with OAI or other 5G CN. The operating system and hardware requirements for OAI 5G RAN were highlighted in section 3.2.4 and more details can be found in [18].

1. Installation of OAI gNB

To get and build the OAI code for the gNB component, execute the following from a new directory:

```
git clone https://gitlab.eurecom.fr/oai/openairinterface5g.git
git checkout develop
cd openairinterface5g/cmake_targets
./build_oai -I -w USRP #Only for first time installation
./build_oai --gNB -w USRP
```

2. Configuration of OAI gNB

The OAI gNB configuration is based on parsing a configuration file containing a set of different RAN parameters, as well as configuration for the interoperability with the 5G CN and the RF device connected with the gNB server. There are two reference configuration files for the gNB to support SA in band 78 and band 41. Those files are located in: *targets/PROJECTS/GENERIC-NR-5GC/CONF/gnb.sa.band41.fr1.106PRB.usrpb210.conf* and *targets/PROJECTS/GENERIC-NR-5GC/CONF/gnb.sa.band78.fr1.106PRB.usrpb210.conf*, respectively. In the following, we highlight the fields of the file that have to be configured according to the configuration and interfaces of the Core Network. First, the PLMN section has to be filled with the proper values that match the configuration of the AMF and the UE USIM.

```
// Tracking area code, 0x0000 and 0xfffe are reserved values
tracking_area_code = 1;
plmn_list = ({
    mcc = 208;
    mnc = 99;
    mnc_length = 2;
    snssaiList = (
        {
```

```

        sst = 1;
        sd = 0x1; // 0 false, else true
    },
    {
        sst = 1;
        sd = 0x112233; // 0 false, else true
    }
);

});

```

Then, the source and destination IP interfaces for the communication with the Core Network also need to be set as shown below.

```

////////// MME parameters:
    amf_ip_address      = ( { ipv4      = "192.168.70.132";
                             ipv6      = "192:168:30::17";
                             active    = "yes";
                             preference = "ipv4";
                             }
    );

    NETWORK_INTERFACES :
    {
        GNB_INTERFACE_NAME_FOR_NG_AMF      = "demo-oai";
        GNB_IPV4_ADDRESS_FOR_NG_AMF        = "192.168.70.129/24";
        GNB_INTERFACE_NAME_FOR_NGU         = "demo-oai";
        GNB_IPV4_ADDRESS_FOR_NGU           = "192.168.70.129/24";
        GNB_PORT_FOR_S1U                   = 2152; # Spec 2152
    };

```

In the first part (*amf_ip_address*) we specify the IP of the AMF whereas in the second part (*NETWORK_INTERFACES*) we specify the gNB local interface with AMF (N2 interface) and the UPF (N3 interface).

3. Execution of SA scenario

After having configured the gNB, we can start the individual components in the following sequence:

- Launch Core Network
- Launch OAI gNB
- Launch COTS UE (disable airplane mode)

The execution command to start the gNB is the following:

```
cd cmake_targets/ran_build/cuuld  
sudo ./nr-softmodem -O ../../../../targets/PROJECTS/GENERIC-NR-  
5GC/CONF/gnb.sa.band78.fr1.106PRB.usrpb210.conf --sa -E
```

After the successful UE registration and PDU Session establishment with the 5G Core Network, IP traffic tests can be performed as described in section 4.2.2.