5G-OPERA Deliverable 3.1

Private 5G: State of the Art and Gap Analysis based on country specific conditions

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Executive summary

This report analyses and describes the detailed of state of art and gap analysis based on the country specific conditions for private 5G networks in Germany and France. Particularly the partners of the 5G-Opera project explain which current parts of the state of the Art should be expanded. The report starts with a general introduction in section 1.

Section 2 summarizes the regulatory conditions for private 5G networks in both countries and explains communalities and differences. It explains the spectrum ranges available in Germany and France for private 5G network. FR 1 and FR 2 frequency ranges can be used for private 5G, depending on the local rules. FR 1 covers frequency range from 410 to 7,125 MHz, while FR 2 includes frequency range from 24.25 to 52.6 GHz. Bundesnetzagentur (BNetzA) is the responsible authority from German side to allocate frequencies, whereas Autorité de Régulation des communications électroniques, des postes et de la distribution de la presse (ARCEP) is the responsable authority from French side.

Section 3 gives an overview of the use cases for private 5G network. Three organizations have been working on usage of private 5G: 3GPP, 5G-ACIA and VDMA. These organizations have listed a wide range of use cases of which the most important are named in the section. Particularly, some use cases in the focus of 5G-OPERA can be education, hospitals, entertainment venues, business, and logistic and manufacturing.

Section 4 presents the 5G system both Radio Access Network (RAN) and Core Network (CN) side, describing the general architecture and featuresets aiming, but not limited to, from release 16. Addition to this, it gives a short introduction of 3GPP, Open RAN, private 5G, and time sensitive networking (TSN).

Section 5 summarizes the state of the art of RAN, CN, Service Management and Orchestration (SMO), User Equipment (EU), testbeds available in the 5G-OPERA project partners. Specifically, the available units of RAN have been introduced. Moreover, functionalities and supported features of CNs, SMO have been summarized. The description of testbeds is following the list of UEs. Partners who own a testbed are Eurecom, Alsatis, TU Dresden, Smart Systems Hub, Fraunhofer IIS, and Fraunhofer HHI.

Section 6 analyses the gaps in open RAN to implement private 5G RAN. Particularly, the necessary improvements and difficulties of OAI are explained. Then, the gaps in acceleration are presented. Finally, the limitations and challenges in CNs are summarized.

Section 7 concludes the report and presents the next deliverables, and relation between WPs. Cited references are listed in reference section, which is end of this report.

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1 Introduction

The goal of the main project **5G-OPERA** is to build a Franco-German ecosystem for private 5G networks under the joint leadership of TU Dresden and EURECOM (Sophia Antipolis). The project focuses on the idea of open hardware, software and interfaces so that multiple providers can participate in the technical equipment of private 5G networks and user needs can be flexibly realized. The overall goal of the project is to ensure that the hardware and software of all project partners can work together technically, independently of the respective manufacturer. In addition to setting up reference test environments and demonstrators in Industry 4.0 environments of both countries, **5G-OPERA** is supporting the trials in the three demonstration projects and will advise all additional projects joining the program

This deliverable is the first of the 5G-OPERA project and analyses the country-specific conditions of deploying private 5G networks in Germany and France. It gives an overview of 5G systems with a special focus on private 5G and then open RAN architecture. Then analyses the State of the Art of open RAN software and hardware and presents a Gap Analysis that shows how these existing solutions need to be adapted for real private 5G deployments. Last but not least it provides an overview of all the testbeds used in the 5G-OPERA project and how their particular evolvement is planned over the course of the project.

2 Country-Specific Conditions

In general, 5G uses two frequency ranges (FR), FR 1 includes the frequencies from 410 to 7,125 MHz, whereas FR 2 describes the section between 24.25 and 52.6 GHz. Spectrum in both areas can be used for private 5G networks, depending on the local legislation. There exist European framework conditions to harmonize the usage of the n78 and the n258 frequency band [1, 2]. However, each country can decide on its own how to allocate different sections of these bands to specific use-cases. This results in varying frequency ranges available in France and Germany.

2.1 Germany

The Bundesnetzagentur (BNetzA) is a German federal authority responsible, among other things, for the allocation of radio frequencies. There exist two administrative regulations ("Verwaltungsvorschrift", VV) regarding the spectrum for local private 5G networks: VV Lokales Breitband [3] and VV Lokales Breitband 26 GHz [4]. They describe the available frequency ranges for local private 5G networks and details about the allocation of spectrum. Moreover, they define the allowed utilization of this spectrum regarding e.g., field strengths in adjacent networks or thresholds for e.g., in-block and out-of-band transmissions. Figure 1 shows the block edge mask (BEM), illustrating the different thresholds to ensure the coexistence of wireless transmissions in neighboring frequency blocks. Each VV lists individual limits for frequency-dependent power limits.

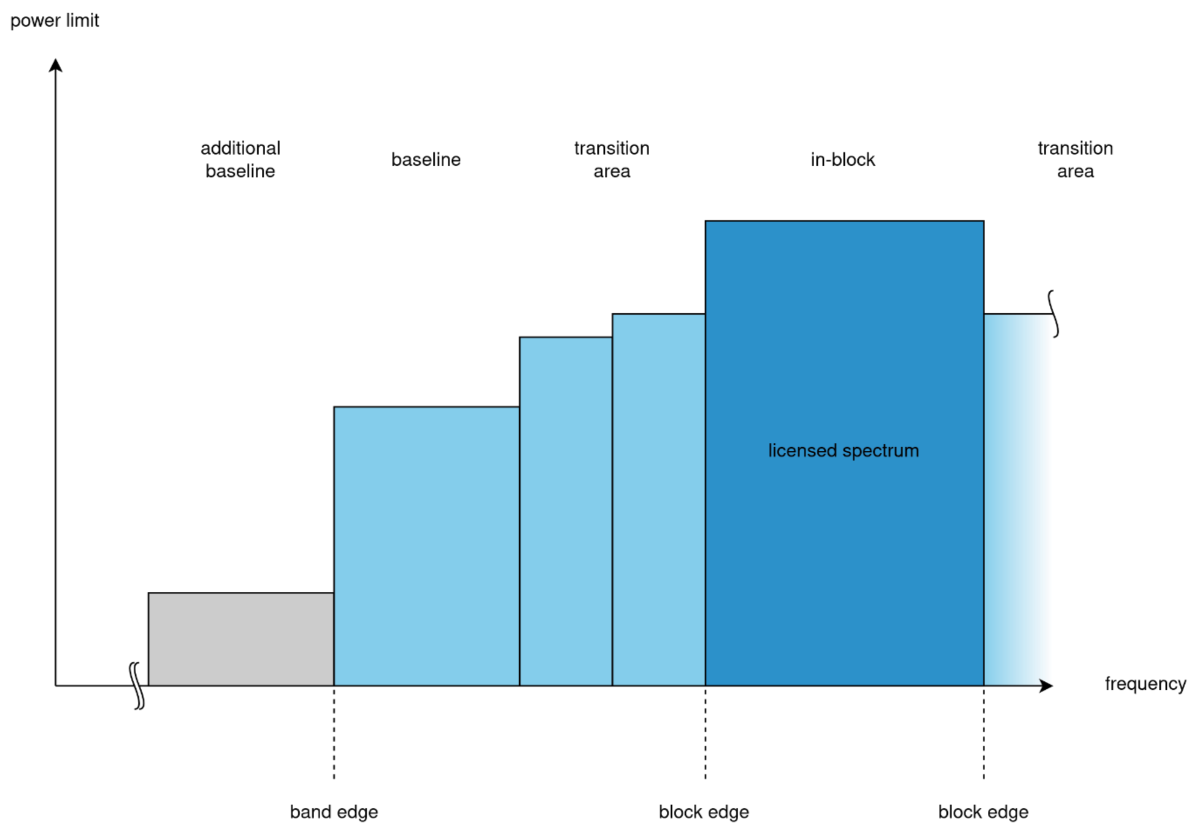


Figure 1: Block Edge Mask for transmission thresholds

The “VV Lokales Breitband” covers the frequency range from 3,700 to 3,800 MHz. Spectrum can be allocated to organizations in blocks of multiples of 10 MHz, that can be used exclusively in TDD mode. There are no guard intervals specified. However, they might be required towards the adjacent publicly used frequencies below 3,700 MHz. A synchronized mode of operation between neighbouring allocation holders is recommended, in order to avoid the necessity of guard intervals in the 3,700 to 3,800 MHz block. In the case of unsynchronized or semi-synchronized networks, necessary guard intervals are at the expense of both of the neighbouring networks.

The local network operator has to ensure an interference-free usage of the allocated frequencies, especially with respect to the neighbouring local networks. The BNetzA does not demand a specific field strength threshold but specifies mandatory negotiations between adjacent network operators. If they cannot achieve a solution ensuring interference-free operation, the BNetzA specifies a limit of $\frac{32\frac{dB\mu V}{m}}{5\,MHz}$ in 3 m height. This threshold is based on recommendation ECC/REC(15)01 [5].

Apart from this limit, thresholds for in-block and out-of-block transmissions of base stations referring to Figure 1 are given. The BNetzA does not define any threshold for in-block transmission, but the transmission power has to be chosen, so that disturbances on neighbouring channels are minimized. In contrast, for out-of-block transmissions, there are specific limits. Moreover, the BNetzA distinguishes between non-active (non-AAS) and active antenna system (AAS). For the first the limit is given as a maximal equivalent isotropically radiated power (EIRP) per antenna, while for the latter the limit is defined as total radiated power (TRP) per cell. In a multi-sector base station, the limit applies for each individual sector. Table 1 shows the different thresholds for synchronized networks. The additional explicit thresholds for the frequency range above 3,800 MHz exist to protect satellite communication ("Fester Funkdienst über Satelliten" FFS). In contrast, for unsynchronized and semi-synchronized networks a limit of -34 dBm / 5 MHz per cell for non-AAS and of -43 dBm / 5 MHz per cell for AAS applies. As a technical condition for TDD end devices (UEs) an in-block transmission limit of 28 dBm TRP is given.

Table 1: Transmission threshold for synchronized base stations in FR1

Frequency range	Maximal EIRP for non-AAS	Maximal TRP for AAS
Baseline **>= 10 MHz distance from block**	Min(P_{max} – 43, 13) dBm / 5 MHz	Min(P_{max} – 43, 1) dBm / 5 MHz
Transition area 1 **0..5 MHz distance from block**	Min(P_{max} – 40, 21) dBm / 5 MHz	Min(P_{max} – 43, 16) dBm / 5 MHz
Transition area 2 **5..10 MHz distance from block**	Min(P_{max} – 43, 15) dBm / 5 MHz	Min(P_{max} – 43, 12) dBm / 5 MHz
3,800..3,805 MHz	Min(P_{max} – 40, 21) dBm / 5 MHz	Min(P_{max} – 43, 16) dBm / 5 MHz
3,805..3,810 MHz	Min(P_{max} – 43, 15) dBm / 5 MHz	Min(P_{max} – 43, 12) dBm / 5 MHz
3,810..3,840 MHz	Min(P_{max} – 43, 13) dBm / 5 MHz	Min(P_{max} – 43, 1 dBm / 5 MHz
> 3,840 MHz	-2 dBm / 5 MHz	-14 dBm / 5 MHz

In addition to these general thresholds, there are multiple locations in Germany that are protected by the BNetzA via frequency alignment. These locations are:

- Geodätischen Observatorium Wettzell (GOW)
- Mess-Erdfunkstelle Leeheim
- bestehende und koordinierte Empfangsfunkanlagen des Festen Funkdienstes über Satelliten
- Funkmessstationen des Prüf- und Messdienstes der Bundesnetzagentur
- Funkstellen im Grenzgebiet

The "VV Lokales Breitband 26 GHz" covers the frequency range from 24.25 to 27.5 GHz. Spectrum can be allocated to organizations in blocks of multiples of 200 MHz, up to a total bandwidth of 800 MHz. Smaller blocks (50, 100, 150 MHz) are also possible to increase the efficient use of the available spectrum. The upper limit of the frequency block is aligned with the upper band limit of 27.5 GHz or a multiple of 200 MHz apart from this. The difference between blocks is always a multiple of 10 MHz, which is especially important in cases requiring a guard interval. A synchronized mode of operation between neighbouring allocation holders is recommended.

The local network operator has to ensure an interference-free usage of the allocated frequencies, especially with respect to the neighbouring local networks. The BNetzA does not demand a specific field strength threshold but specifies mandatory negotiations between adjacent network operators. If they cannot achieve a solution ensuring interference-free operation, the BNetzA specifies a limit of $\frac{65\frac{dB\mu V}{m}}{200\,MHz}$ in 3 m height. Apart from this limit, thresholds for in-block and out-of-block transmissions of base stations referring to Figure 1 are given. The BNetzA does not define any threshold for in-block transmission, but the transmission power has to be chosen, so that disturbances on neighbouring channels are minimized. In contrast, for out-of-block transmissions, there are specific limits. Table 2 shows the different thresholds for synchronized networks. In addition, Table 3 shows the transmission threshold for UEs. The additional baseline conditions exist to prevent interference with satellite communication int the range of 23.6 to 24.0 GHz. Moreover, the main beam and the mechanical alignment of the antennas must be aligned below the horizon in outdoor setups.

Table 2: Transmission threshold for synchronized base stations in FR2

Frequency range	Maximal TRP	Measurement bandwdith
Transition area **≤ 50 MHz distance from block**	12 dBm	50 MHz
Baseline **≥ 50 MHz distance from block**	4 dBm	50 MHz
Additional baseline **23.6 .. 24.0 GHz**	- 33 dBW	200 MHz (starting 24.04.2020)
	- 39 dBW	200 MHz (starting 01.01.2024)

Table 3: Transmission thresholds for UEs

Frequency range	Maximal TRP	Measurement bandwdith
Additional baseline **23.6 .. 24.0 GHz**	- 29 dBW	200 MHz (starting 24.04.2020)
	- 35 dBW	200 MHz (starting 01.01.2024)

In addition to these general thresholds, there are multiple locations in Germany that are protected by the BNetzA via frequency alignment. Table 4 shows these locations alongside the allowed field strength and their coordinates.

Table 4: Overview of locations that are protected via frequency coordination

Location	Allowed field strength in $\frac{\frac{db\mu V}{m}}{MHz}$
Leeheim (08° 23‘ 52“ E 49° 51‘ 12“ N)	24
Neustrelitz (13° 04‘ 09“ E 53° 19‘ 47“ N)	25
Oberpfaffenhofen (11° 16‘ 47“ E 48° 05‘ 10“ N)	53
Weilheim (11° 04‘ 51“ E 47° 52‘ 55“ N)	25
Wettzell (12° 52‘ 39“ E 49° 08‘ 42“ N)	14

In order to obtain a license for a certain frequency block in either FR, a request to the BNetzA is required. At this point (June 2022), a web portal for this process is under construction. Hence the application has to be handed in via the mail address **226.lokalesbreitband@bnetza.de**. The following documents are necessary:

- Application for area allocation and specification of performance parameters of the base stations
- Concept for frequency utilization
- Confirmation of eligibility to apply
- Confirmation of expertise, capability and reliability

- If necessary, agreements with neighboring operators
- If necessary, excerpt from the commercial register

Explanations and some references to templates can be found in the corresponding VV. This includes details about the required content of frequency utilization concept regarding technical details. Moreover, the price for the frequency allocations is presented in these documents. The fee is calculated as follows:

$Fee = 1000 + B \cdot t \cdot f \cdot (6a_1 + a_2)$ where

- 1000 € is the basic charge
- B is the bandwidth in MHz (min. 10 MHz for FR1, min. 50 MHz for FR2)
- t is the contract period in years
- f is the FR factor (5 for FR1, 0.63 for FR2)
- a is the area in km^2 where a_1 describes the settlement and traffic area and a_2 describes other area

2.2 France

ARCEP (Autorité de Régulation des communications électroniques, des postes et de la distribution de la presse) is an Independent administrative authority (IAA). It is responsible for regulating the electronic communications and postal sectors, on behalf of the State, but entirely independently of any political power or economic stakeholder. It was created on 5 January 1997, and originally called the Telecoms Regulatory Authority or ART.

ARCEP is responsible to allocate frequency and numbering resources, through individual decisions, to Prescribe soft laws, such as guidelines or recommendations to provide the sector with clarity on how it performs its duties or to guide stakeholders' behaviour.

It is also in charge to Engage in an ongoing dialogue with the sector's players, to maintain an in-depth knowledge of the markets it regulates, adjust its regulatory decisions and make them widely known. This dialogue takes the form of regular meetings and events (workshops, plenary meetings, conferences, etc.) and requests for feedback to the many public consultations that ARCEP holds.

ARCEP has several priorities, and one of them is to support trials and experimentation into the regulatory framework [6].

Currently, two set of frequencies in FR1 are opened for private network usage in France.

TDD Band N38 covering frequency ranges from 2570 to 2620 MHz for 4G or 5G TDD private mobile networks operations and TDD Band covering frequency ranges from 3800 to 4000 MHz, subset of Band N77 for private network experimentation. This band is opened for request in France until end of 2022 for an experimental usage up to 3 years duration.

For FR2 Band, ARCEP had launch in early 2019 a call for the creation of 5G experimentation platforms in the 26 GHz frequency band (26500 – 27500 MHz), open to third parties for a 3 years period. Objectives were to promote the appropriation by all players of the possibilities offered by this frequency band and to identify the new uses allowed by these frequencies. This call is now closed, however, this frequency range could still be granted temporarily on a per request basis as experimental purpose.

2.2.1 TDD band N38

This band is subject to European Union Commission Implementation Decision as defined in article 2020/636 [7]. This document describes the technical conditions for using the 2500–2690 MHz frequency band.

Block Edge Mask (BEM) are defined to ensure co-existence between neighbouring networks. BEM consists of several elements :

- In-Block : Refers to block assigned for which the BEM is derived
- Baseline : defines the area outside of block assigned for which power limit threshold baseline is given
- Transitional region : applies to 5Mhz spectrum boundaries above the block assigned
- Additional baseline : applies to spectrum between 2690-2700 MHz

These elements are defined for both Active Antenna Systems (AAS) and Non AAS.

In France, ARCEP has defined maximum EIRP per 5 MHz block as follow :

	non AAS	AAS
Maximum EIRP per 5 MHz block	68 dBm	60 dBm

For Band 38 (2570 – 2620 MHz), ARCEP has opened an online reporting portal for frequency request and attribution on this band. Process is defined in two phases :

1st phase with a minimum duration of 2 months is starting once a letter of expression of interest has been submitted and approved by ARCEP. This letter must be contains information on :

- frequency bandwidth requested (block of 5, 10, 15 or 20 MHz)
- The desired authorization zone
- The planned deployment schedule
- The planned TDD Radio Frame on the targeted area
- Characteristics of the deployment project

During this phase, planned deployment will be publicly visible on ARCEP online portal, to allow potential players interested in the allocation of frequencies in the same area to express their needs. Standard request should be up to 20 MHz bandwidth, but requestors may ask for up to 40 Mhz assuming detailed justification are given on the specific need for extra frequencies.

2nd phase is starting if no other conflicting request was received leading to more than 40 Mhz on the same area for the sum of each request.

For this phase, requestor has one month to provide a formal request on frequency attribution, as well as additional technical details such as:

- Technical aspect of the deployment project: general description of the radio access network, detailed site planning, planned covered area, planned service activation, etc.
- Financial aspects of the project: planned annual investments, funding capacity, etc.

Frequency band usage on this spectrum is subject to annual fee payment and is calculated as follow:

Annual Fee [€] = **k6** [€] . **l** [MHz] . **bf** . **c** . **a**

- **K6** is reference value in Euro = <u>34 000 €</u>
- **l** is the frequency bandwidth in MHz
- **bf** is a coefficient dependent of the frequency band in use: <u>8.7</u> for band 38
- **c** is a coefficient linked to surface area: <u>0.006</u> for area below 100 km^2
- **a** isa coefficient linked to service type: <u>2</u> for independent mobile service usage

From October 2022, new conditions are in preparation and a draft decree is in public consultation. Current application only allows one level of royalties including areas from 0 to 100 km^2. This surface is much larger than the vast majority of industrial installations and the price for this first level is prohibitive for most manufacturers who wish to carry out experiments today.

This decree aims to modify coefficient ‘c’ in above calculation in order to provide smaller granularity down to 0.3 km^2. New table for ‘c’ coefficient is proposed as below

Size of surface area	**Value of ‘c’ coefficient**
Between 20 and 100 km^2	0.006
Between 5 to 20 km^2	0.0015
Between 1 and 5 km^2	0.0005
Between 0.3 and 1 km^2	0.00013
Between 0 and 0.3 km km^2	0.00005

2.2.2 TDD Band 3800-4000 MHz

ARCEP has opened beginning of 2022 possibility for industrial companies to build and experiment 5G platforms in the 3.8 - 4.0 GHz band. This is aimed to experiment with new use cases for 5G: industrial players or logisticians, "vertical" players in the energy, health, or even smart city sectors. Close to the 5G "core" band, the chosen frequency band will allow these players to quickly access a varied and mature ecosystem of radio equipment and terminals.

Applicants may request the provision of a maximum of 100 MHz of spectrum between 3800 and 4000 MHz, in the form of a local authorization for the use of frequencies for experimental purposes, for a period of three years. Last application requests are due until December 31, 2022.

3 Use-Cases for private 5G networks

Use cases for private networks are described manifold in literature. Main sources from our point of view are the standardization organization **3GPP, the global 5G Alliance for Connected Industries and Automation (5G-ACIA)** and the **German Verband der Maschinen- und Anlagenbauer (VDMA).**

In the following, the use cases for 5G connectivity especially with private networks are summarized.

3.1 3GPP

The results of the 3GPP feasibility study on “Communication for Automation in Vertical domains (FS_CAV)” are summarized in the public report TR 22.804 [8]

The use cases cover different types of use case groups, covering private networks as well as using 5G networks for vertical use cases, with different requirements with respect to data throughput, latency, service availability, service area and number of users, which means that the use cases span the complete 5G triangle of mMTC, URLLC and eMBB.

It would exceed the scope of this document to describe all the use cases and corresponding requirements, which are in detail available in the 3GPP report already. Only those use cases from 3GPP are listed, which are of interest for 5G-OPERA (Private: Educational (schools), Hospitals, medical campuses, Public safety, Smart cities, Entertainment venues (e.g. Football, Concert); Business: Enterprises/campuses/warehouses, Industry 4.0: logistics and manufacturing, Mining, Agriculture):

- Rail-bound mass transmit
  - Communication services in rail-bound transit
  - Coexistence of MTTC service (Mass Transit Train Control) and CCTV (Real-time video surveillance)
  - Coexistence of MTTC service and a high data rate service with low priority
  - Set-up of emergency call
  - Emergency call during a sudden rise of CCTV data rate
  - CCTV offload / transfer of CCTV archives from commuter train to ground
  - Wireless communication between mechanically coupled train seg-ments
  - Wireless communication between virtually coupled trains
  - Anticipatory train control
- Building automation
  - Environmental monitoring
  - Fire detection
  - Feedback control
- Factories of the future
  - Motion control

- Motion control – transmission of non-real-time data
- Motion control – seamless integration with Industrial Ethernet
- Control-to-control communication (motion subsystems)
- Mobile control panels with safety functions
- Mobile robots
- Massive wireless sensor networks
- Remote access and maintenance
- Augmented reality
- Process automation – closed-loop control
- Process automation – process monitoring
- Process monitoring – plant asset management

1. Connectivity for the factory floor
2. Inbound logistics for manufacturing
3. Wide-area connectivity for fleet management
4. Variable message reliability
5. Flexible, modular assembly area
6. Plug and produce for field devices
7. Type-A network PLMN interaction
8. Communication monitoring, diagnosis and error analysis

- Smart Living – Health Care
    1. Telecare data traffic between home and remote monitoring centre
- Smart city
    1. Remote CCTV analysis
- Electric power distribution
    1. Primary Frequency Control
    2. Distributed Voltage Control with up to 100% RES
    3. Power distribution grid fault and outage management: distributed au-tomated switching for isolation and service restoration for overhead lines
    4. Smart Grid: synchronicity between the entities
    5. Application of differential protection in distribution Network of Smart Grid
    6. Smart Grid : Millisecond-level precise load control
- Centralised power generation
    1. Run-time access to operational data and control information
    2. Data acquisition for non-real-time plant monitoring
    3. Remote support for plant maintenance
    4. Customised access of stakeholders to wind power plant network
- Programme Making and Special Event (PMSE)
    1. Low-latency audio streaming for live production
    2. Low-latency audio streaming for local conference system
    3. High data rate video streaming / professional video production
    4. Please note that a separate study item was carried out in 3GPP especially on PMSE in Release 17. The study report including multiple use case descriptions and corresponding requirements is found in 3GPP TR 22.827 [9]
- Smart Farming
    1. Smart farming – automated irrigation
    2. Smart farming – 5G system that enables protection against poaching

3.2 5G-ACIA

The 5G-ACIA is an industrial alliance for the operational technology's players and companies from the ICT domain, together with research institutes like Fraunhofer. Main interest is the usage of 5G for industrial purposes and with a focus on private networks. There are several publications available [10], among others two whitepapers on 5G for automation in industry [11] and key 5G use cases from the automation domain [12].

As 5G-ACIA is working close to 3GPP and monitors its results, the publications reference the 3GPP report TR 22.804 as well (see previous subchapter).

The white paper on 5G key use cases states … *"In order to identify a list of key use cases and requirements, a variety of relevant use cases, mainly drawn from TR 22.804* [8] *, were discussed, reviewed, and evaluated within 5G-ACIA.*

This process resulted in the following use case categories:

1. *Connectivity for the factory floor*
2. *Seamless integration of wired and wireless components for motion control*
3. *Local control-to-control communication*
4. *Remote control-to-control communication*
5. *Mobile robots and automated guided vehicles (AGVs)*
6. *Closed-loop control for process automation*
7. *Remote monitoring for process automation "*

These use case categories from the 5G-ACIA whitepaper can be seen as a consolidated and prioritized subset of the broader variety of 3GPP on the category "factories of the future" from the perspective of 5G-ACIA, representing the automation industry.

3.3 VDMA

The *VDMA Leitfaden* [13] is an introduction to 5G in automation industry and additionally, VDMA provided an associated set of 35 use cases for 5G by the German industry [14], which are of course overlapping with the use cases of 3GPP and 5G-ACIA, but additionally take into account requirements for 5G positioning, which is not covered by 3GPP in TR 22.804.

Use Case Familie	**Use Case Variationen**
Echtzeitfähigen Datenstrecken in verschleißbehafteten Anwendungen (LAPP, Fraunhofer IIS)	Use Case 1: Kommunikation von Greifer
	Use Case 2: Lokalisierung von Greifer
Mobile Bedienterminals mit Nothalt (SICK, Fraunhofer IIS)	Use Case 3: Bedienterminal mit bidirektionaler, zyklischer Datenkommunikation (Montageroboter)
	Use Case 4: Bedienerterminal mit nicht zyklischer, bidirektionaler Datenkommunikation (Video)
	Use Case 5: Bedienterminal mit bidirektionaler, zyklischer Datenkommunikation (Mobil-/Festportalkräne)
	Use Case 6: Indoor-Ortungsdienst für Bedienterminal (Werksgefahrenzonen) (Lokalisierung)
	Use Case 7: Indoor-Ortungsdienst für Bedienterminal (Fabrikhalle) (Lokalisierung)
Ortung und Kommunikation in der Logistik (KION GROUP/STILL, SEW-EURODRIVE, Frauhofer IIS)	Use Case 8: Blocklager (Lokalisierung)
	Use Case 9: Sicherheit (Lokalisierung)
	Use Case 10: Leitstelle (Lokalisierung)
Predictive Maintenance (RITTAL, Fraunhofer IIS)	Use Case 11: Speicherung und Analyse auf dem Campus (intern)
	Use Case 12: Speicherung und Analyse auf der Cloud (extern)
Retrofit (KION GROUP/STILL, SICK, Fraunhofer IIS)	Use Case 13: Retrofit für datentechnische Anbindung an Flottenmanagementsysteme
	Use Case 14: Retrofit für datentechnische Anbindung an Maintenance Systeme

Figure 2: VDMA use cases 1-14 for factory of the future (from VDMA, Fraunhofer IIS, "Technologieabgleich aller Use Cases")

Use Case Familie	Use Case Variationen
Retrofit (KION GROUP/STILL, SICK, Fraunhofer IIS)	Use Case 15: Zyklische Datenkommunikation
	Use Case 16: Nicht-zyklische Datenkommunikation
M2M-Anwendungen (WEIDMÜLLER Gruppe, LAPP, Fraunhofer IIS)	Use Case 17: Profinet IRT
	Use Case 18: Profinet TSN
	Use Case 19: ModbusTCP
	Use Case 20: Ethernet/IP für IO Systeme
	Use Case 21: Ethernet/IP CIPsync für Servoantriebe
	Use Case 22: CC Link IE TSN
	Use Case 23: Ethernet TCP/IP
	Use Case 24: EtherCat
HMI – Human Machine Interface (HAHN GROUP, SEW-EURODRIVE, Fraunhofer IIS)	Use Case 25: Einrichtung der Maschine via wireless handheld (z. B. Tablet)
	Use Case 26: Überwachung der Prozessparameter via wireless handheld (z. B. Tablet)
	Use Case 27: Einrichtung der Maschine via AR
	Use Case 28: Überwachung der Prozessparameter via AR
Mobile Messsysteme in Produktionsumgebungen (ZEISS Gruppe, Fraunhofer IIS)	Use Case 29: Drahtlose Übertragung von Bilddaten von statischem Sensorsystem zur Auswerteeinheit
	Use Case 30: Zusammenarbeit statischer optischer Sensorsysteme und eines von Hand bewegten optischen Sensorsystems sowie drahtlose Datenübertragung mit hochgenauem Zeitstempel
	Use Case 31: Verwendung der selben drahtlosen Übertragungstechnik für Zeitsynchronisation und Übertragung nicht komprimierter Bilddaten
	Use Case 32: Zeitsynchronisation zwischen optischen Sensorsystemen und Antriebseinheiten sowie kabellose Übertragung großer Datenmengen zu einer externen Auswerteeinheit
	Use Case 33: Synchronisierung der Daten mit Antriebssystem eines Werkstücktransportsystems und/oder mit geographischen Koordinaten
	Use Case 34: Messvorgang mit synchronisiert bewegten Messmaschinen/Messrobotern
Remoteanwendungen (AGCO-Fendt, SEW-EURODRIVE, MASCHINENBAU KITZ, Fraunhofer IIS)	Use Case 35: Remote

Figure 3: VDMA use cases 15-35 for factory of the future (from VDMA, Fraunhofer IIS, "Technologieabgleich aller Use Cases")

3.4 Public

Use case	Existing use case on 3GPP, 5G-ACIA, VDMA
Hospitals, medical campuses	**3GPP (TR 22.804):** Smart Living – Health Care (Chap. 5.4) • **Telecare data traffic between home and remote monitoring centre (Chap. 5.4.2)**
Public safety	**3GPP (TR 22.804):** Building automation (Chap. 5.2) • **Environment monitoring (Chap. 5.2.2)** • **Fire detection (Chap. 5.2.3)** • **Feedback control (Chap. 5.2.4)**
Smart cities	**3GPP (TR 22.804):** Smart city (Chap. 5.5) • **Remote CCTV analysis (Chap. 5.5.2)**
Entertainment venues (e.g. Football, Concert)	**3GPP (TR 22.804):** Programme Making and Special Event (PMSE) (Chap. 5.8) • **Low-latency audio streaming for live production (Chap. 5.8.2)** • **Low-latency audio streaming for local conference system (Chap. 5.8.3)** • **High data rate video streaming / professional video production (Chap. 5.8.4)**

3.5 Business

Use case	Existing use case on 3GPP, 5G-ACIA, VDMA
Enterprises/ campuses/ warehouses	**3GPP (TR 22.804):** Factories of the future (Chap. 5.3) • **Motion control (Chap. 5.3.2)** • Motion control – transmission of non-real-time data • **Motion control – seamless integration with Industrial Ethernet (Chap. 5.3.4)** • Control-to-control communication (motion subsystems) • Mobile control panels with safety functions • Wide-area connectivity for fleet management • Variable message reliability • Flexible, modular assembly area • Plug and produce for field devices • Type-A network PLMN interaction • Communication monitoring, diagnosis and error analysis
Industry 4.0: logistics and manufacturing	**3GPP (TR 22.804):** Factories of the future (Chap 5.3) • **Mobile robots (Chap. 5.3.7)**

	• **Massive wireless sensor networks (Chap. 5.3.8)** • **Remote access and maintenance (Chap 5.3.9)** • Augmented reality • Connectivity for the factory floor • Inbound logistics for manufacturing
Agriculture	**3GPP (TR 22.804):** Smart Farming (Chap. 5.9) • **Smart farming – automated irrigation (Chap 5.9.2)** • **Smart farming – 5G system that enables protection against poaching (Chap 5.9.3)**

4 5G system overview

5G-Overview Rel. 16 – 3GPP Based reference architecture

See 5G-SystemOverview drawio

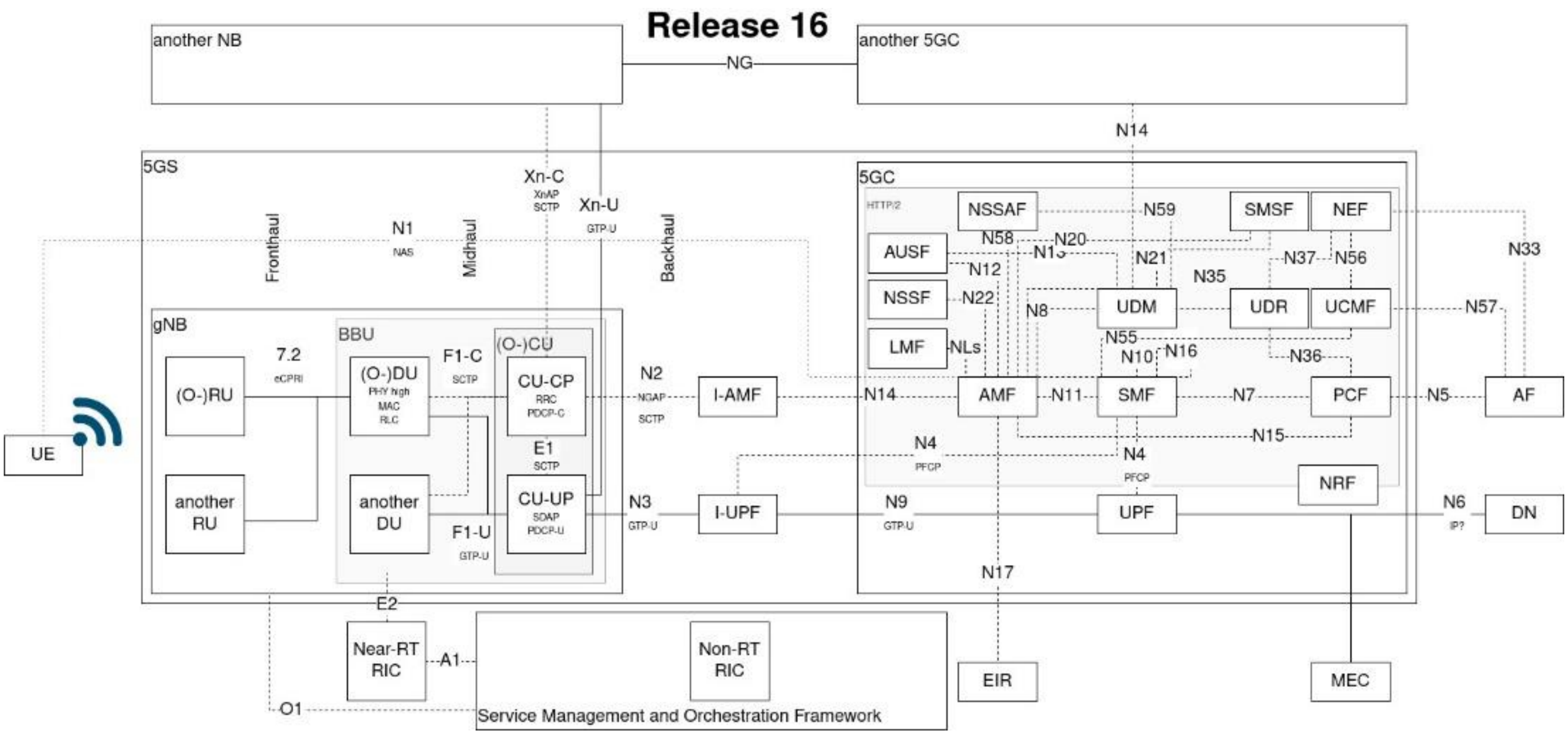


Figure 4: Overview of 5G based on 3GPP release 16

Abbreviation	Explanation
UE	User Equipment
gNB	gNodeB
RU	Radio Unit
DU	Distributed Unit
CU	Centralized Unit
BBU	BaseBand Unit
RT RIC	Real Time RAN Intelligent Controller
5GC	5GCore
5GS	5GSystem

More Info	List
X2/Xn	[15]
DU-CU-Splits	[16]
O-RAN	[17] [18]
Core Overview	[19]

Abbreviation	Explanation	Standard 23.501
(I-)UPF	(Intermediate-) User Plane Function	29244
(I-)AMF	(Intermediate-) Access and Mobility Management Function	29.518
SMF	Session Management Function	29.502
PCF	Policy Control Function	23.503
UDM	Unified Data Management	29.503
AUSF	Authentication Server Function	29509
NSSF	Network Slice Selection Function	29.531
NSSAF	Network Slice Specific Authentication and Authorization Function	29526
UCMF	UE radio Capability Management Function	29.673
NEF	Network Exposure Function	29.522, 29.541, 29.591
EIR	Equipment Identity Register	29511
LMF	Location Management Function	29.572
NRF	NF Repository Function	29.510
MEC	Multi-Access Edge Cloud	23558
UDR	Unified Data Repository	29.504
AF	Application Function	29517
DN	Data Network	29561

Abbreviation	Explanation	Standard
NAS	Non-Access Stratum	24.501
NGAP	NG Application Protocol	38.413
GTP-U	(GPRS) Tunneling Protocol User Plane	29.281

eCPRI	Enhanced Common Public Radio Interface	V2.0[1]
SCTP	Stream Control Transmission Protocol	38.412
PFCP	Packet Forwarding Control Protocol	29.244

Reference Point	Standard
N3	38.414
F1-C	38.472
F1-U	38.474

4.1 3GPP

The 5G system is specified by 3GPP starting with Release 15. This release includes a brand-new core network, called the 5G core (5GC) and radio interface, called 5G New Radio (5G-NR). The network has been designed from ground up to support enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), as well as Massive Machine Type Communications (mMTC) enabling new use cases for a large variety of industries. This has been achieved by a large number of new features compared to 4G LTE, such as flexible subcarrier spacing and slot lengths (also called numerology), increased bandwidth (up to 400MHz), flexible slot structure (including mini-slots and slot aggregation). 5G-NR also includes new channel codes: polar codes for control and Low-Density Parity Check (LDPC) for data. A good overview of all new features is given in [20, 21].

Initial deployments of 5G-NR use the architecture option 3 of 3GPP, also called Evolved Universal Terrestrial Radio Access (EUTRA-NR) Dual Connectivity (EN-DC). In this option the 5G cell is connected to a 4G evolved packet core network and is operating under the control of a 4G cell, which serves as an anchor to the system and carries all Control Plane (CP) traffic. User Equipment (UE)s first need to connect to the 4G network and will receive all the necessary configuration to connect to a 5G cell through Radio Resource Control (RRC) signalling on the 4G link. This setup will allow a smooth migration from 4G to 5G. This scenario is the one that is currently deployed by the operators but does not yet unlock all the new features of 5G, especially the ones needed for private 5G campus networks.

3GPP has also defined a new 5G Core (5GC) architecture that supports service delivery over wireless, fixed or converged networks. This new core network allows for so called standalone operation of 5G NR, i.e. it does not rely anymore on a 4G network.

The new 5G system architecture relies on the SBA in which the system functionality is achieved by a set of Network Functions (NFs), providing services to other authorized NFs to access their services [22]. In this architecture, the 5GC components have been simplified with most of them being software based so that they could be adapted according to the need. Also, the CP functions are separated from the UP in order to make them scale independently allowing operators to use these components for dimensioning, deploying and adapting the network to their needs easily.

Figure 4 depicts the reference architecture for 5GC [23]. This figure illustrates the 5G system architecture which consists of different components. At the bottom, the UP components are sketched. The communication between R(AN) and UP Function (UPF) will be done directly and from there, to the Data Network (DN). The CP components include among others:

- Authentication Server Function (AUSF) is to support authentication for 3GPP access and untrusted non-3GPP access;

[1] http://www.cpri.info/downloads/eCPRI_v_2.0_2019_05_10c.pdf

- Access and Mobility Management Function (AMF) is responsible for managing access control and mobility;
- Network Exposure Function (NEF) provides a mechanism to expose services and features of the 5G NFs to external entities;
- NF Repository Function (NRF) is to provide NF service registration and discovery;
- Network Slice Selection Function (NSSF) is to assist in the selection of suitable network slice instances for users;
- Policy Control Function (PCF) is responsible for handling policies and rules in 5G system for network slicing, roaming and mobility management;
- Session Management Function (SMF) is to set up and manages sessions according to network policy; and
- Unified Data Management (UDM) generates the Authentication and Key Agreement (AKA) credentials and stores subscriber data and profiles.

4.2 Open RAN

The open RAN architecture builds on top of the 3GPP 5G architecture and defined additional interfaces with the purpose to provide a disagregated and configurable RAN. In an open RAN design, interfaces such as fronthaul and midhaul but also management and operation are open and defined by the O-RAN alliance as depicted in Figure 4. The most important elements are the radio unit (O-RU), the distributed unit (O-DU), and the centralized unit (O-CU), which make up the main elements of a traditional base station (gNB). The O-RU and the O-DU are connected over the fronthaul (FH) interface, which is also called the O-RAN 7.2 interface while O-DU and O-CU are connected over the F1 interface. O-RU and O-DU also have an E2 interface which allows the near-real time RAN intelligent controller (RIC) to get feedback from the RAN (e.g., channel measurements, load, etc.) and control certain elements in the RAN (e.g., scheduling decisions, handover decisions etc.). This design allows the RIC to run artificial intelligence algorithms that can control certain elements in the RAN. O-RAN also specified an O1 interface which allows for management and orchestration of the RAN entities.

4.3 Private 5G [

Private 5G network is a non-public local area network based on 5G New Radio (NR) technology. A dedicated wireless connectivity in a particular region is required. Private 5G is beneficial when necessary, requirements such as coverage, security, speed, and positioning are beyond those offered by Wi-Fi and other network technologies. Unlike public 5G networks, private 5G network provides operators greater control to prioritize certain network activities, namely customize the services. In private 5G network, it is also possible to isolate UEs from public networks.

Private 5G networks can be deployed in different ways [24]. One way is stand-alone deployment in which the network is completely separated from public network. All network functions and flow of the data happen inside the premises, e.g., a factory or warehouse. A firewall can connect private network to the public network. Another way of deployment is based on integration of public network [25] in which RAN and control plane can be shared. There can be numerous use cases for private 5G. Some of them are industrial automation, industrial remote operations (e.g., mines and building contractions), universities and hospitals.

There are some challenges in design aspect of the private network [25]. One aspect is providing network slicing into 5G private network. Network slicing is creating multiple logical networks over the common physical network for specific requirements of applications. Another aspect is integration of time-sensitive-networking (TSN) detail of which is explained in next section. Last aspect is to provide an open architecture for private 5G network. However, the interfaces should be standardized for interoperability.

4.4 Time Sensitive Networking

Industrial Ethernet protocols are not well suited to Industry 4.0. At the same time, standard IT-oriented Ethernet does not deliver the real-time performance that control systems demand.

The IEEE, in 2004, formed a group to establish standards for audio/video streaming for consumer applications, later extending its efforts to meet professional standards. This group developed audio/video bridging (AVB) standards for synchronizing devices on a network to the same time base (borrowing from IEEE 1588), traffic shaping, and admission controls. Although not ideally suited to industrial applications, these standards provided a framework for more precise management of Ethernet traffic. Recognizing the potential to adapt AVB for industrial use, the IEEE group changed its name to Time Sensitive Networking (TSN). In addition, it began revising the 802 standards family to address the needs of industrial and automotive applications and improve features for professional audio/video use.

New standards define time-aware traffic shaping and policing to enable the scheduling of critical traffic. To facilitate scheduling, new standards specified the pre-emption of non-critical frames. New standards for redundant network paths improved network reliability. Industrial companies can now deploy a single IEEE-standard Ethernet network that carries both the time-critical control traffic of OT systems and the regular best-effort traffic of IT systems. Now that pivotal networking technologies for the industrial IoT are defined, these companies can focus on the strategic benefits of OT-IT convergence and Industry 4.0. Some of the new specifications that are a part of TSN and have industrial use cases include; 802.1AS-Rev Timing and Synchronization, 802.1Qav Forwarding and Queuing Enhancements, 802.1Qbv Enhancements for Scheduled Traffic, 802.1Qca Path Control and Reservation, 802.1Qat Stream Reservation Protocol, 802.1Qcc Enhanced Stream Reservation Protocol, 802.1Qci Per-Stream Filtering and Policing, 802.1CB Frame Replication and Elimination for Reliability, 802.1Qbu Frame Pre-emption, 802.1Qch Cyclic Queuing and Forwarding.

However, the above was true for wired communication; like it was challenging to bring real-time performance over Ethernet, it was even more challenging to specify over wireless, specifically on 5G.

3GPP Release 16 included TSN as enabler along with specifications 3GPP 24.519 & 24.535. 3GPP Release specified for time-sensitive communication (TSC), a 5G System (5GS) can be integrated as a bridge in a time-sensitive networking (TSN) network (i.e. a TSN bridge). UE-side edge can integrate with a TSN Network using 3GPP specified device-side TSN Translator (DS-TT) and the network-side TSN translator (NW-TT) at the network edge. The TSN application function (TSN-AF) is deployed to exchange TSN bridge information with the central network controller (CNC). The TSN bridge information includes port management information which is related to Ethernet ports located in DS-TT and TSN-AF.

4.5 5G Localization Architecture

The 5G positioning architecture in the Release 16 follows the LTE positioning model by introducing new entities in the 5G Next Generation Radio Access Network (5G-RAN) and the 5G Core Network (5GC) depicted in Figure 5.

This architecture supports several different localization methods. We can distinguish between UE-based localization and network based localizations.

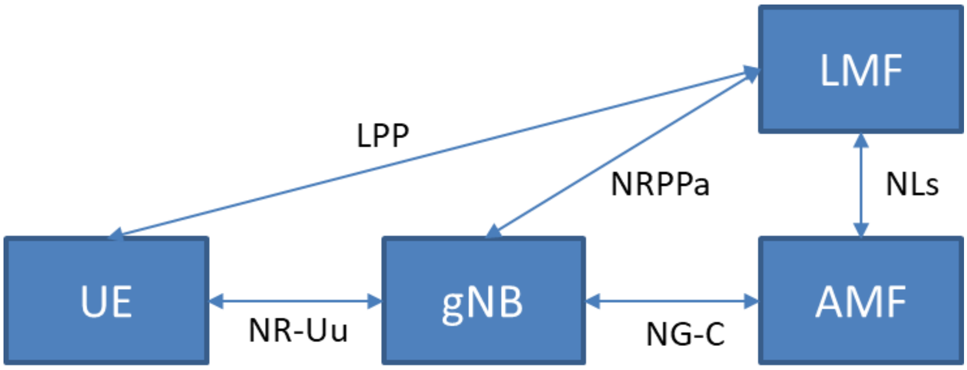


Figure 5: 5G localization architecture

In UE based localization, the LTE Positioning Protocol (LPP) is used as a communication protocol between the UE and the Location Management Function (LMF) via Access Mobility Function (AMF) in the 5GC. Moreover, signaling between gNB and LMF is obtained over New Generation Positioning Protocol A (NRPPa).

UE based localization uses DL positioning reference signals (PRS). By performing a Reference Signal Time Difference (RSTD) estimation on determined beams with the highest power from multiple gNBs, UE measures DL-TDoA of DL-PRS resources.

Multiple antennas on gNBs and the availability of mm-Wave in 5G NR, enable the measurement of Downlink Angle of Departure (DL-AoD) as supporting information for UE to localize itself. This is a new on-demand System Information (SI) procedure, a UE can request positioning System Information Blocks (posSIBs) including the coordinate of the transmitting antennas as well as the beam angle information. The gNB provides this information to LMF over NRPPa.

Based on PRS DL-TDoA, DL-AoD, and the geographical coordinates of the gNBs shared by LMF, UE can estimate its position.

In network based localization the gNBs perform RTSD estimation based on the sounding reference signals sent by the UEs. This information is then sent over the NRPPa protocol to the LMF, which performs UL-TDoA localization procedure.

5 State of the Art

5.1 Radio Access Network

5.1.1 OpenAirInterface

OpenAirInterface (OAI) is an open source initiative that today provides a 3GPP and O-RAN compliant reference implementations of key elements of 4G and 5G Radio Access Network (RAN) and core network that run on general purpose computing platforms (x86) together with Off-The-Shelf (COTS) Software Defined Radio (SDR) cards like the ETTUS Universal Software Radio Peripheral (USRP) in [26] as well as commercial radio heads, like the ones from AW2S in [27]. It allows users to set up a compliant 4G, 5G non-standalone, as well as 5G standalone network and inter-operate with commercial equipment.

In the following we will only describe the 5G standalone features of OAI.

5.1.1.1 OAI RAN

The OAI RAN provides all the functionality of a 3GPP gNB and can be deployed either in a monolithic mode or a disaggregated mode. The Figure 5 shows a disaggregated view of the gNB with all its interfaces

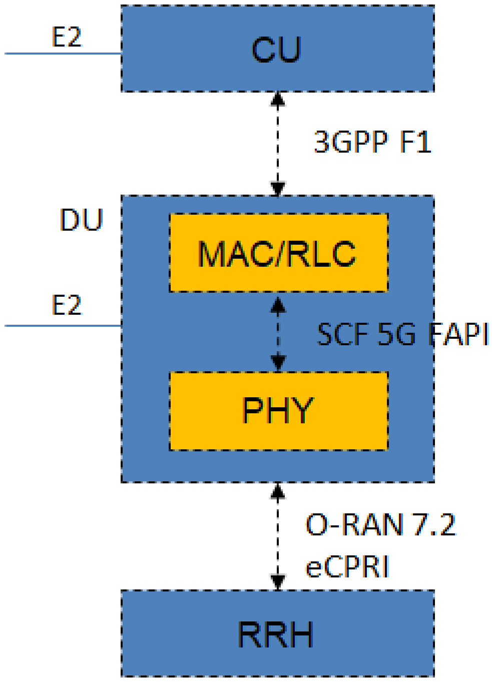


Figure 5: Disaggregation of gNB with interfaces

Both CU and DU contain an E2 interface that allows to connect them to the FlexRIC of the Mosaic 5G project [28]

The F1 interface between the CU and DU contains a control plane (F1-C) and user plane (F1-U). The first version of this interface that allows to connect 1 CU with 1 DU is available in OAI and has been tested with a 3rd party CU from Acceleran. Support for multiple DU is planned for end of 2022 and the E1 split (C-U separation within the CU) is also planned for the end of 2022.

OAI uses the SCF 5G FAPI interface internally between the PHY and the MAC layer. Interoperability testing with a third party PHY is currently ongoing. OAI also supports the 5G nFAPI interface, which allows a further disagregation split between the PHY and the MAC

The fronthaul connects the DU with the RU. Currently OAI supports eCPRI (with AW2S RUs) and O-RAN 7.2 U-plane (with Benetel). Integration of xRAN fronthaul library (O-RAN 7.2 CUS-plane) is currently ongoing in order to support a wide range of commercially available RRUs (Mavenir, Foxconn, STL, AW2S).

A full list of features of each of these elements is given in [29]:

The OAI RAN has been validated with the following core networks

- OAI 5GC and
- Nokia Sabox
- Free 5GC

And has been tested with the following UEs

- Simcom SIMCOM8200EA
- Quectel RM500Q-GL
- OnePlus 8 (with PLMN 00101)
- Huawei P40 and P40 Pro
- Google Pixel 5G
- OAI UE

5.1.1.2 OAI Core

The OAI 5GC currently contains the following network elements:

- Access and Mobility Management Function (**AMF**)
- Authentication Server Management Function (**AUSF**)
- Network Repository Function (**NRF**)
- Session Management Function (**SMF**)
- Unified Data Management (**UDM**)
- Unified Data Repository (**UDR**)
- User Plane Function (**UPF**) with 2 variants:
  - Simple Implementation based on our 4G CUPS component (**SPGWU-TINY**)
  - VPP-Based Implementation (**UPF-VPP**)
- Network Slicing Selection Function (**NSSF**)
- Network Data Analytics Function (**NWDAF**)
- Unstructured Data Storage Function (**UDSF**)

All of these functions are also available as docker images and can be easily deployed using docker-compose. See [30] for details.

5.1.1.3 OAI License

OAI distinguishes itself from other similar projects through its unique open source license, the OAI public license v1.1, which was created by the OAI Software Alliance (OSA, [31]) in 2017. This license is a modified version of Apache v2.0 License, with an additional clause that allows contributing parties to make patent licenses available to third parties under FRAND terms similar to 3GPP for commercial exploitation. The usage of OAI code is free for non-commercial/academic research purposes. The main reason for this modification is to allow companies/individuals which own significant portfolio of patents to be able to contribute to the OAI source code and still be able to keep their patent rights. Such a license allows contributions from 3GPP member companies while at the same allowing commercial exploitation of the code, which is not at all possible with other open-source projects.

5.1.2 SRS RAN

SRS RAN [32] provides an open-source implementation of a gNB that also works with the USRP SDRs. Compared to OAI, it uses a GNU Affero General Public License (AGPL) version 3 and commercial licenses which allow the copyright holder, Software Radio Systems, to also commercially exploit the code in their products. SRS RAN also provides a 4G eNB and a 4G UE.

5.1.3 NXP Distributed Unit

5.1.3.1 Layerscape Architecture

Layerscape architecture aims to “expose” each chip’s performance in a way that programmers find very accessible. The architecture extends the current trend toward multicore chip design (both homogenous and heterogeneous) to achieve maximum performance, while also abstracting away enough of the complex hardware to make software development efficient, maintainable, neat, fast and relatively simple.

The Layerscape device family consists of a scalable range of SoCs targeting networking and related markets. Layerscape SoCs all have a common architecture on both HW and SW sides but are scalable in performance, power and cost. Hardware differentiation is provided by programmable (packet) acceleration and offloaded security. On the software side, NXP provides solution level packages for specific application including wireless, cloud, security and virtualization. Figure 6 shows the LX2160, a flagship device from the Layerscape family.

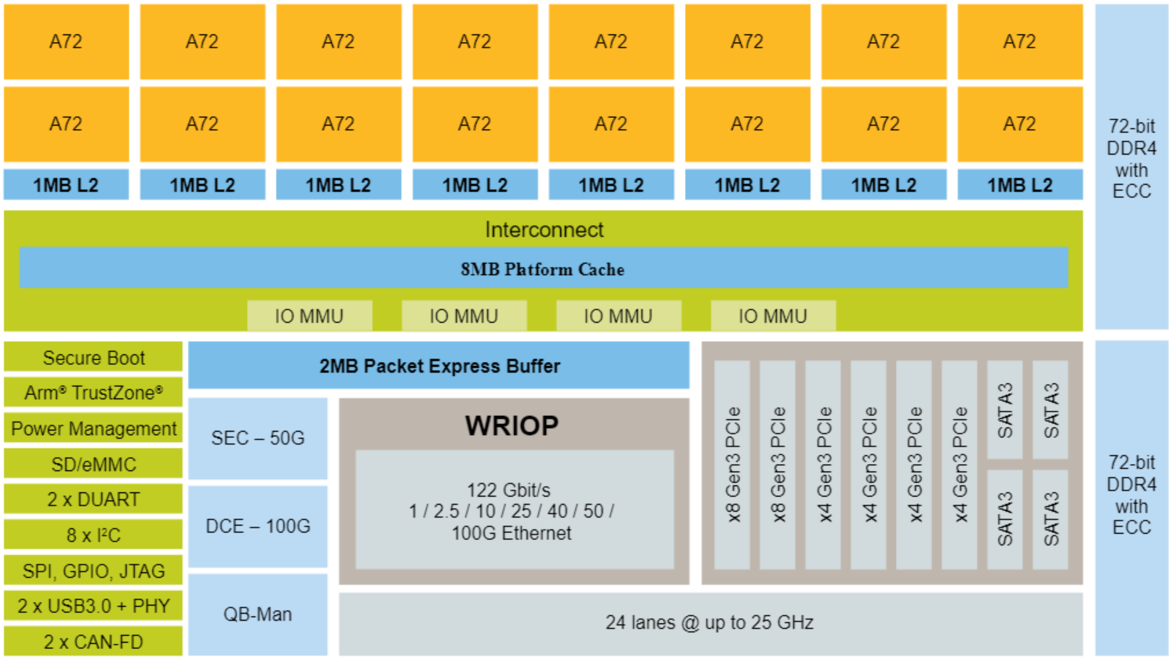


Figure 6. Layerscape LX2160 processor block diagram.

Some key features of the LX2160 include:

- Core and memory subsystem. The LX2160 supports 16 ARM 64bit A72 cores at up to 2.2GHz. The cores support ARMv8 NEON SIMD instructions and are connected to the memory subsystem through a coherent interconnect. The memory subsystem supports dual 64bit+ECC memory controllers at ≤3.2GTPS
- Datapath Acceleration (DPAA2) networking hardware infrastructure. This includes hardware Buffer Management (BMan), Frame Queue Management (QMan) and Parse-Classify-Distribute support. Combined, DPAA supports efficient packet (type) classification and delivery to cores, accelerators and I/O. The DPAA infrastructure includes a 130Gbps integrated Ethernet switch (WRIOP), terminating or switching a combination of 1, 2.5, 10, 25, 40, 50 and 100Gbps Ethernet ports.
- Egress hierarchical QoS/packet shaping supporting dual rate traffic sharing – for example per operator and Class of Service
    - Flexible/configurable combination of strict and weighted fair scheduling
    - Dual rate token bucket shaping at port level and channel level
- PCIgen4 connectivity using up to 6 controllers, sharing ≤24 SerDes lanes that can run at a combination of frequencies up to 28GHz. The SerDes lanes are shared with Ethernet and SATA
- Security Engine. This is a protocol-aware hardware engine that offloads several security algorithms.

Layerscape architecture incorporate data-plane / packet processing acceleration through the Data Plane Acceleration Architecture (DPAA) IP. Various functions such as packet routing, IPSec, QoS and others can be implemented as a software function on the CPU core or in hardware acceleration, depending on the specific chip implementation. Either way, the function is transparent to programmers, making it straightforward to switch from one chip implementation to another without altering any code. Structured programming interfaces encapsulate the compression, so that neither the code that calls it, nor is called by it, need know how the compression is actually implemented. Abstraction of functionality preserves software efficiency and performance.

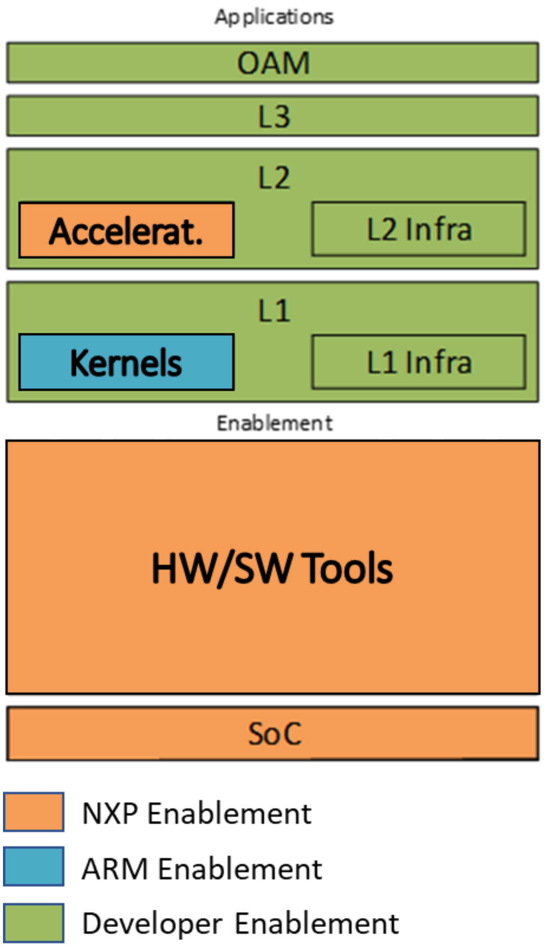
5.1.3.2 NXP O-RAN DU

In the supported deployment model, the lower PHY is implemented at the RRH, and transport/PDCP is implemented in a centralized/cloudified style. Thus, the partitioning takes both RAN split option 2 and 7.

In such partitioning, the Distributed Unit (DU) implements MAC/RLC as well as "upper PHY" functionality. The lower PHY ((i)FFT, RACH, DFE) is offloaded to the RRH, which removes the bulk of the math intensive functionality from the DU.

The remainder functions (channel coding, bit manipulation, channel estimation/equalization and MIMO processing) can be mapped to Digital Signal Processors and hardware accelerators (traditional approach) or also be implemented as software functions running on a multi/many-core ARM processor such as the NXP LX2160.

The architecture for O-DU implementation in a Layerscape processor is summarized in the following components.



Layer 3

- Layer 3 application, targeting 5G NR/RRC etc.
- Virtualization / Container-based edge infrastructure

Layer 2

- HW specific acceleration, for example ciphering acceleration.
- Layer 2 infrastructure, such as task scheduling framework or FAPI.
- Layer 2 application, targeting 5G NR/MAC, RLC or PDCP.

Layer 1

- ISA specific Signal Processing kernels (ARM)
- Layer 1 infrastructure, such as task scheduling framework, IQ I/O, etc.
- Layer 1 application or targeting 5G NR/(HI-)PHY.

Enablement and Silicon support

- Linux based. Support for IEEE1588, DPDK, Preemptable + Realtime, etc.

5.1.3.3 NXP Acceleration Support for DU

Figure 7 depicts a common architecture to implement acceleration for computing-intensive DU functions using the Layerscape® device family as a multicore host and Layerscape Access accelerator processors. Layerscape Access chips include both VSPA DSP cores and hardware accelerators for LDPC/Polar, among other functions. Exemplary functions that can be accelerated with the presented architecture include 5G DCI/UCI (Polar) encoder-decoder and 5G Shared Channel (LDPC) encoder-decoder. Programmer can choose whether to offload (near-)complete physical layer to Layerscape Access (full performance) or only offload LDPC/Polar (more SW flexibility).

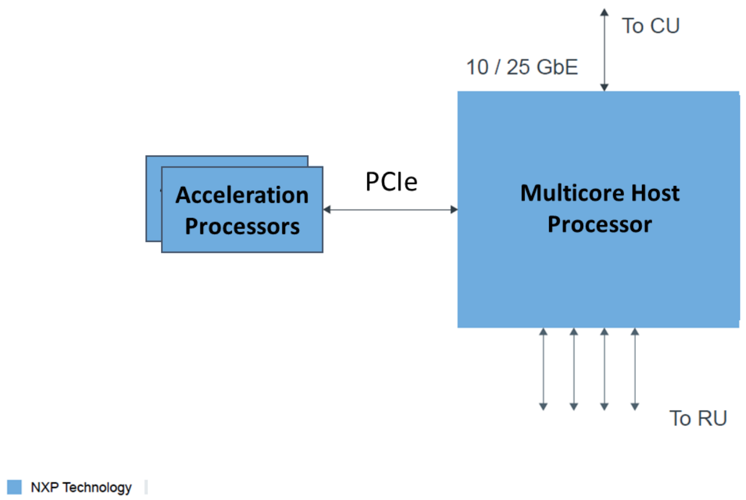


Figure 7. Exemplary DU acceleration support by Layerscape® processors.

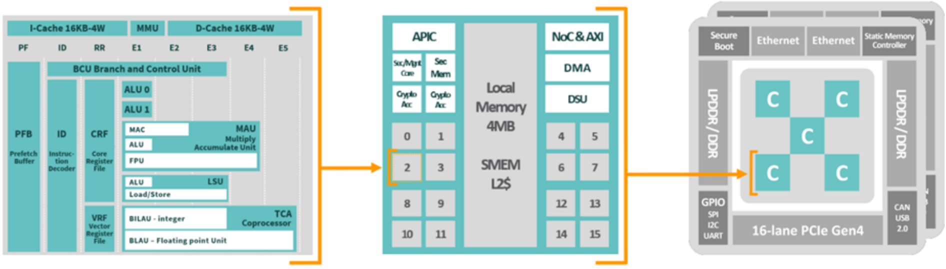
The previously introduced VSPA is typically used as a math-coprocessor or as a data-plane accelerator on a chip, combined with a standard general-purpose host processor. VSPA is a vector signal processing platform optimized for vectorized compute applications. The platform uses a single-instruction multiple-data (SIMD) architecture with a very long instruction word (VLIW) control path, together with a sophisticated 7-stage vector data path. It supports mixed precision fixed (16b) and floating (16b, 32b, 64b) point IEEE754 operation with zero-overhead inline type conversion.

The vector data path is scalable and is suitable for a broad range of applications, from low complexity short range modems to highly complex macro-cellular base stations and convolutional neural networks.

5.1.4 Kalray DU Architecture

5.1.4.1 MPPA Digital Processor Unit

The High performance, manycore, real time data processing is built to be suitable for 5G RAN



From bottom to top,

At core level, the 3RD GENERATION KALRAY CORE is based on

- VLIW 64-bit core
- 6-issue VLIW architecture
- MMU + I&D cache (16KB+16KB)
- 16-bit/32-bit/64-bit IEEE 754-2008 FPU
- Vision/CNN Co-processor (TCA)

At cluster level, the architecture contains

- 16 cores,
- 1 safety/security dedicated core, 1GHz
- L1 cache coherency (configurable)
- 8MB configurable memory (L2 cache)
- 256 bits / bandwidth up to 614GB/s

At chip level, the core are groups into:

- 5 Clusters for a total of 80 cores + 80 co-processors
- With Load Balancer / Packet Parser
- 2x100Gbps Ethernet
- PCIe Gen4
- DDR4 – 3200
- DMA-based highly efficient data connection

Last, each chip is boosted with a 5G FEC Hardware Acceleration IP (Encoder, Decoder, HARQ, Rate Matching) to handle almost the entire bit level processing of 5G Hi PHY layer

5.1.4.2 MPPA Digital Processor Unit

The following table summarized the MPPA value to match the 5G NR latency constraints:

- Hard Real Time capability
- High level of parallelization
- 5G specific HW acceleration

	WHAT	HOW
MPPA architecture value	Hard Real time application • Isolate • Determinism	• 5 clusters • DMA based (DDR ↔ SMEM) • Light RTOS
	Parallelization efficiency • Granularity • Easy programming & efficiency parallelization	• 80 PE • OpenMP
MPPA extension	HW accelerators - Matrix computing - 5G specific	• TCA • LDCP codec IP

TCA means “Titly Coupled Accelerator” targeted for “tensor” computing

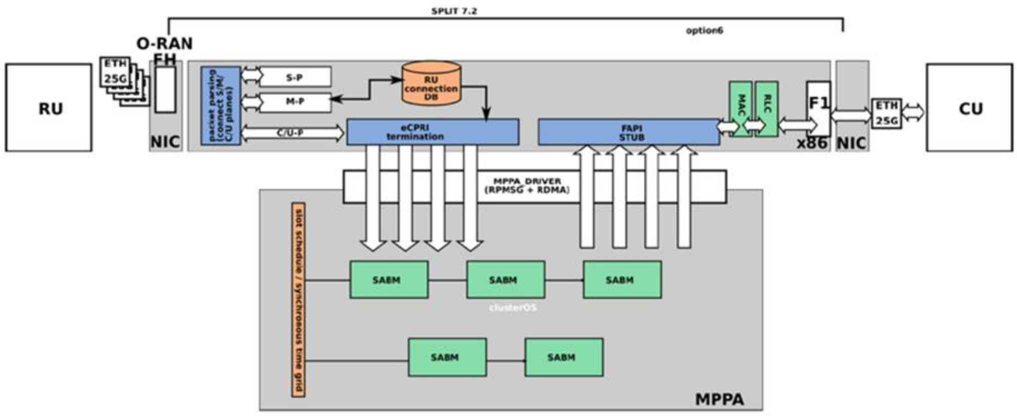
5.1.4.3 DU configuration

Thanks to MPPA I/O capability, two configurations will be supported, both supporting the ORAN split 7.2.

5.1.4.3.1 ‘In line’ architecture

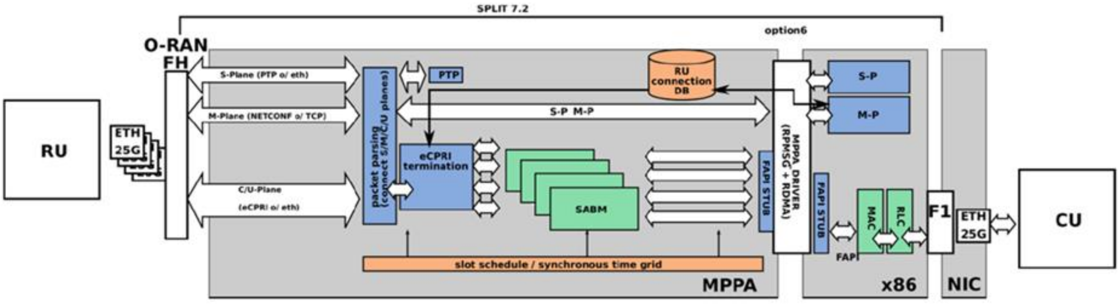
With “In line” architecture, one cluster is dedicated to ethernet & protocol processing running on a Linux 16 cores to carry FAPI and eCPRI processing. The other 4 clusters act as local accelerators of LINUX in charge of data processing of the high part of the 5G L1 layer.

Option 1A: Lookaside: PCIe card, eCPRI termination on x86



5.1.4.3.2 'Look A Side' architecture

In Look A Side configuration, the ethernet protocol is managed by host processor, and data stream pass thought the 16 lanes PCI Gen 4. The configuration is suitable to accelerate the overall L1 high PHY processing or only the critical algorithms like LDPC encoder/decoder or signal processing of channel estimation, equalization and demodulation that carry in MIMO 2x2 configuration up to 50% of the overall processing.



5.1.5 Xelera's acceleration approach

Intel FlexRAN is the most widely used solution for L1 baseband processing today and the most technically rich solution. It integrates into DPDK via DPDK's Wireless Baseband Device Library (BBDEV) and is thus capable of integration with other software components. There are a total of four BBDEV drivers officially integrated into DPDK. All four come exclusively from Intel for use in conjunction with FlexRAN. FlexRAN runs exclusively on Intel hardware: Intel Xeon (CPU software), Intel PAC (FPGA accelerator for L1 FEC) and Intel ACC100 (ASIC for L1 FEC). The hardware platforms of other manufacturers are not supported.

Xelera has set up an Intel FlexRAN test bench to use it as reference and to gradually replace the proprietary software with components from open source OpenAirInterface and the accelerator hardware with solutions from the consortium such as NXP and Kalray. The baseline for this activity is the Xelera Suite, a latency- and throughput-optimized software stack that integrates hardware accelerators from various vendors with virtualization frameworks and Docker/Kubernetes environments, among others. The Xelera suite is deployable in multiple public clouds as well as data center and edge cloud deployments and supports DPDK. The Suite already largely meets the requirements for an O-RAN Accelerator Abstraction Layer (AAL) similar to DPDK's BBDEV and can be used to add new BBDEV drivers.

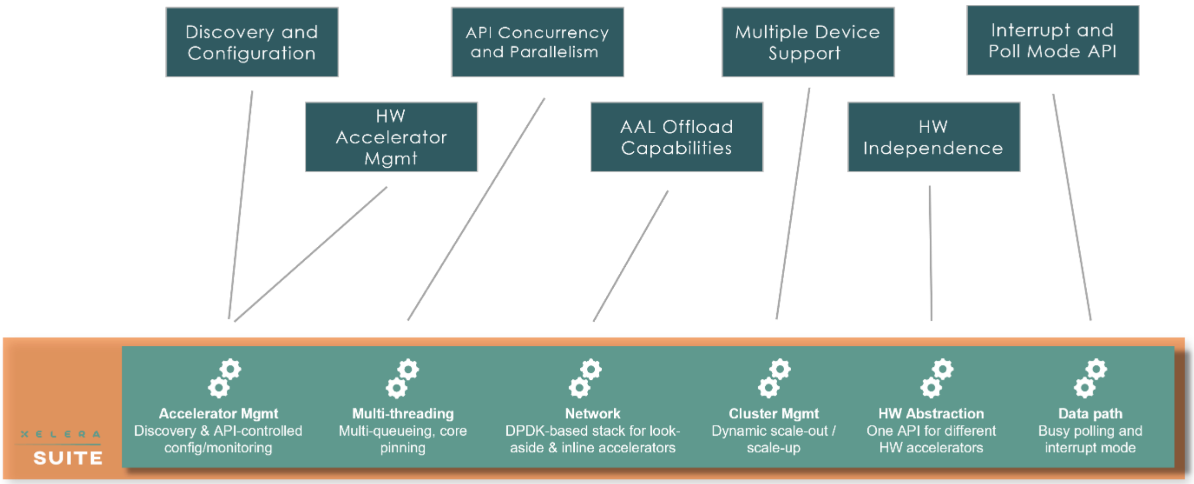


Figure 8 - O-RAN Alliance AAL requirements that are covered by Xelera Suite

5.1.6 Radio Unit

5.1.6.1 NXP Software Defined Radio

Layerscape Access provides all hardware and most of the core software building blocks to enable high-performance integration of communication devices, ranging from relatively low-end and low DC power consumption solutions up to multi-carrier high-end wireless infrastructure systems. Layerscape Access refers to devices that support Vector Signal Processing Accelerator (VSPA) architecture which is a highly performance efficient Digital Signal Processor (DSP) IP that balances efficiency and programmability, supporting Software Defined Radio modem implementations. Seemingly contradicting requirements for cost and programmability are supported through increased integration. In the case of Layerscape Access, integration of state-of-the-art ADC/DAC technology, VSPA and management MPU cores.

The LayerScape Access single hardware/software modem architecture supports multiple modem implementations through firmware loads. Key components of the architecture are:

- PHY: Single physical layer architecture and implementation across converging wireless and wired standards, providing programmability and flexibility without sacrificing efficiency
- SoC: Integrated solution leveraging the key technologies – programmable PHY and MAC, Packet Engines, ARM64b Cores and associated memory, interconnect and high-speed I/O

Similarly, the Layerscape device family complements above's SDR functionality with components like:

- MAC: Tight integration with an optimized packet processing engine that is scalable to support the required multi-Gbps MAC layer throughput
- Packet processing (Networking) Engine: Seamless integration with networking and control IP designed to support complex packet routing applications, network services, as well as support for remote provisioning and virtualized networks

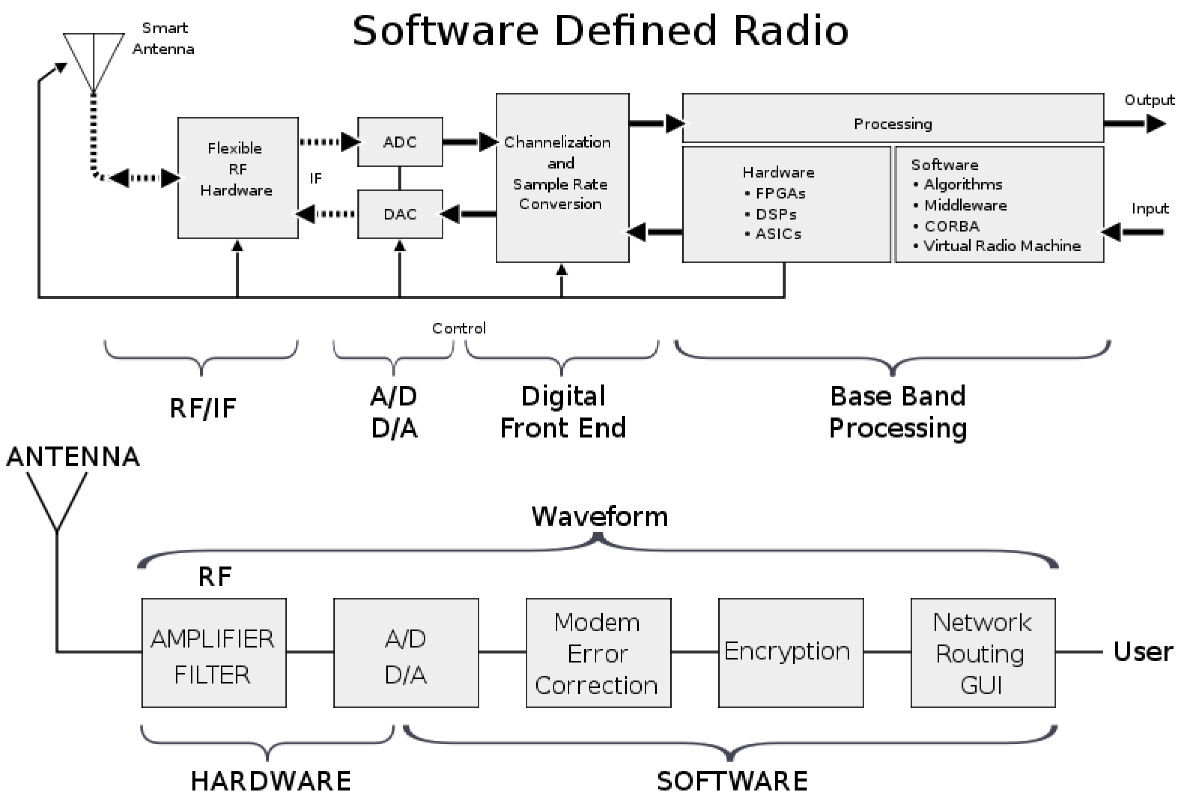


Figure 9: Source: By SDR_et_WF.JPG: Topi Tuukkanen derivative work: McSush (talk) - SDR_et_WF.JPG, Copyrighted free use [33]

5.1.6.2 AW2S RU

O-RAN specification will be used for AW2S approach in order to have a reference guideline in this project. With O-RAN alliance, trials are in progress around the world with 4x4 RU and Massive MIMO active antennas. Since the beginning, AW2S proposes RU "opened" based on "Open Radio Interface" and AW2S provides since more than 5 years Radio based on eCPRI in split 8, hardware already integrated with OAI partners. This project allows to AW2S to accelerate the development of 4x4 RU O-RAN compliant. The O-RAN VIAVI DU testbed acquired by AW2S will serve as reference to interface our RU to DU provided by other members/customers. In Q1 2023, first integration with a third-party CU/DU partner is planned. This opportunity will help for 5G OPERA CU/DU integration as well. As a next step, AW2S plans to integrate this kind of support in any of its products such as FR1 RU digital beamforming active antennas and FR2 analog beamforming for mmWave active antennas.

Thanks to other funding projects, developments are done in parallel and the next gen 4x4 platform will be focused for Vertical markets and available in the following frequency bands: n78, n77, n38 giving access to the partners to deploy testbeds but also commercial projects.

5.1.7 Near-RT RIC

5.1.7.1 SD-RAN µONOS RIC

The SD-RAN is an open-source project by the Open Networking Foundation (ONF) for the development and implementation of O-RAN near-RT RIC [34, 35]. The project facilitates the development of xApps to manage RAN components and offers a Software Development Kit (SDK) to expedite the development of new xApps. The project makes use of the custom (or pre-standard) service models created by the SD-RAN community in addition to the standard-complaint E2 Service Models (E2SMs). The Open Networking Operating System (ONOS) controller serves as the foundation for the microservices of this SD-RAN RIC. These microservices consist of distributed data storage services, network- and user-based information services, and xApp subscription services.

SD-RAN near-RT RIC platform also uses gRPC APIs for inter-process communication. The RIC provides the network information base (NIB) database to store the information on the E2 nodes (RAN-NIB) and also information related to the UEs (UE-NIB). The ONOS-exporter collects the KPIs from multiple onos SD-RAN components via gRPC interfaces and exports these metrics to a back-end database. The project also consists of ONF's O-RAN-compliant RAN simulator for testing the xApps using the SD-RAN RIC platform. A list of the open-source xApps to run over the SD-RAN RIC includes KPIMON xApp (onos-kpimon) to get metrics from an E2 node for monitoring of key performance indicators(KPIs), physical cell identity (PCI) conflict resolution xApp (onos-pci) to detect the PCI conflicts and resolves them based on an algorithm using neighboring cell information, mobility load balancing xApp (onos-mlb) to balance the load among neighboring cells, mobility handover xApp (onos-mho) to trigger handovers based on the UE mobility information and RAN slice management xApp (onos-rsm).

5.1.7.2 ORAN-SC RIC

The O-RAN Software Community (OSC), a collaboration between the O-RAN Alliance and Linux Foundation, provides a reference implementation of a near-RT RIC [36, 37, 38] . The OSC near RT-RIC is based on multiple components running as microservices on a Kubernetes cluster. The near RT RIC platform provides an infrastructure for the xApps to control the distributed RAN components (via the O-RAN alliance's E2 protocol) and it provides support for the northbound interfaces (i.e., O1 and A1)

The OSC near-RT-RIC platform enables modular, open, and efficient services for the xApps development for monitoring, configuring and managing the network components. The key components of the OSC RIC include the E2Manager (E2M) that controls E2 connection establishment and provides REST APIs to manage these connections, the E2Termination (E2T) to establish the SCTP connection as requested by E2M, the Routing Manager for generating and distributing routing policies to xApps, and the Subscription Manager to manage the subscription of the E2Node.

An InfluxDB supports the storage of the KPIs and network information for the OSC-RIC. The OSC RIC uses a custom library called RIC Message Router (RMR) for the internal messaging between xApps, services and interface terminations within RIC. The management, onboarding, termination, tracing, and logging for xApps are done through wrappers on the Kubernetes infrastructure. The project also consists of open source xApps to run over the OSC RIC platform including KPI monitoring xApp (KPIMON), quality of experience (QoE) predictor xApp (QP), traffic steering xApp for UE handovers or cell reselection decisions based on the KPI values, and anomaly detection xApp to detect the anomalous UEs present in the network. The end-to-end signaling procedure for the KPIMON xApp provided by the OSC is shown in Figure 10

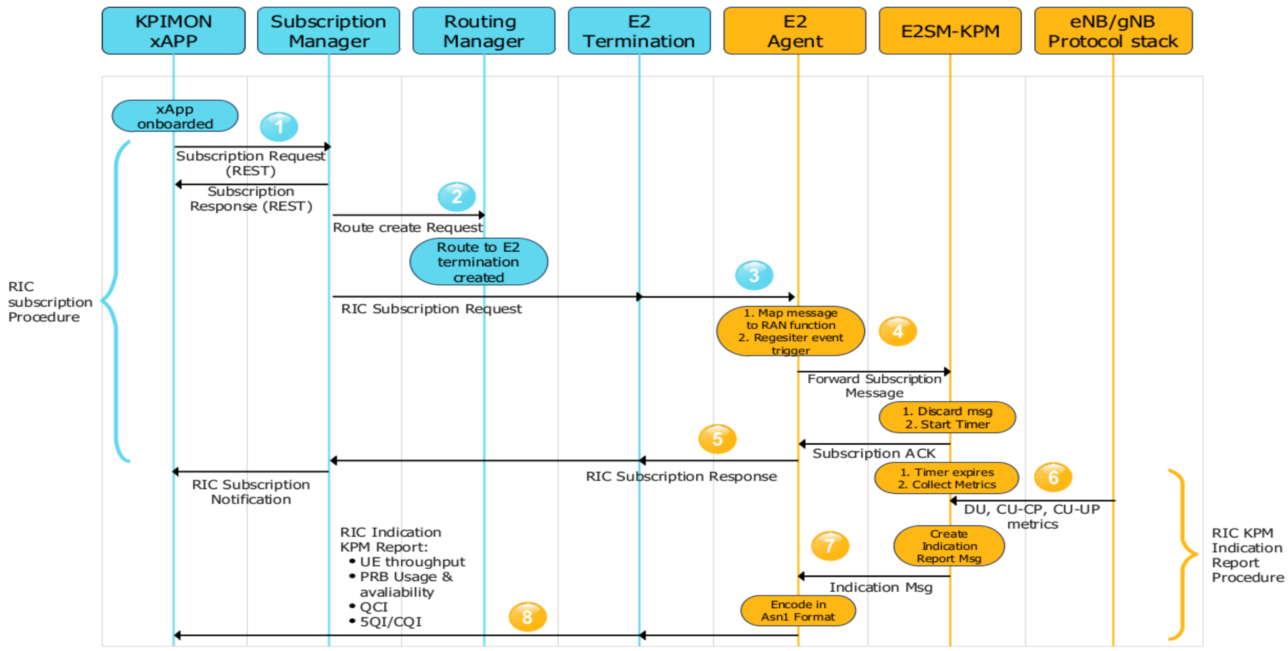


Figure 10: End-to-end workflow and signaling procedure for the KPIMON xApp [39]

5.1.7.3 FlexRIC

FlexRIC is a software development kit (SDK), that is part of the Mosaic5G project, which is now part of the OpenAirInterface Software Alliance [28] and that is available as open source in [40].

FlexRIC consists of a server library and an agent library with two optional extensions: controller-internal applications (iApps) and communication interfaces. The objective of the SDK is to facilitate the realization of specialized SD-RAN controllers to target specific use cases, while being simple to use. In its simplest form, the SDK can be used to implement an SD-RAN controller using an E2-compatible protocol, as it is shown in Figure 11.

The agent library is the basis to extend a base station with the agent functionalities. It provides an API to implement custom RAN functions, i.e., RAN functionality that can be monitored and/or controlled by applications, and comes with a bundle of pre-defined RAN functions that implement a set of SMs that can be included. A controller is built through the server library, iApps, and optionally a communication interface. The server library manages agent connections, and multiplexes messages between iApps and the agents. Through the iApps, it is possible to modularly build specialized controllers: based on the considered use-case, iApps can implement SMs themselves, or expose information to external applications (xApps) via a northbound communication interface. In the latter case, xApps can control the RAN while being functionally isolated from the controller, which is the favored method of the reference SD-RAN controller implemented by O-RAN, but bears a certain overhead.

The FlexRIC SDK provides an abstraction of the E2 interface via an internal representation of E2 messages, and users of the SDK do not have to be concerned with the actual encoding and transport of the messages. It is therefore straight-forward to integrate FlexRIC with pre-existing E2-compliant SD-RAN infrastructure. However, the standard mandates an encapsulation of ASN.1-encoded data inside of ASN.1 and its transport over the SCTP protocol, which may be inefficient in certain cases, for instance when the message size becomes large (case for monitoring information). Therefore, the SDK also supports to change both the encoding scheme and transport protocol allowing the integration of vendor-specific possibly more efficient E2 protocol for low-overhead, real-time control between a controller and an agent.

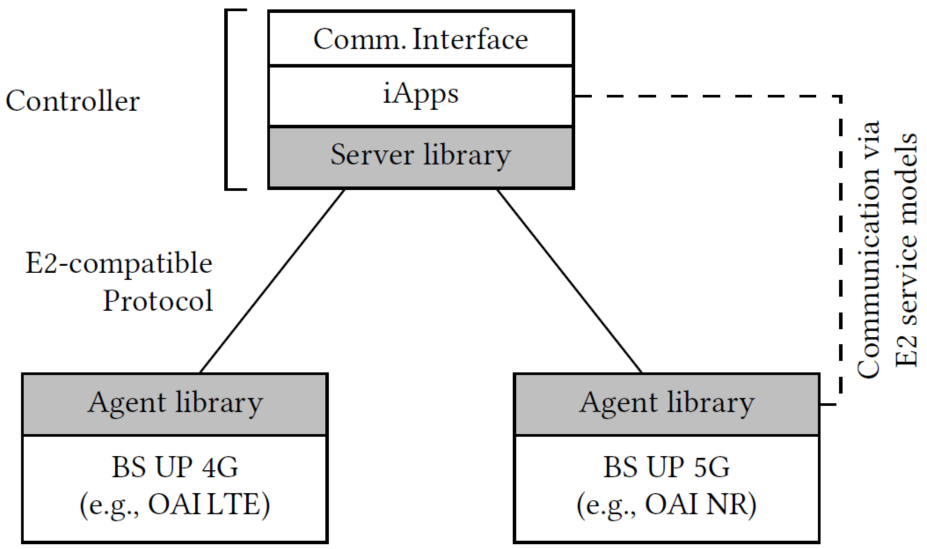


Figure 11: Communication via E2 service models

5.2 Core Network

5.2.1 Available Core Networks in the Project and General Overview

Project partners have installed a large variety of core networks from different sources. There are various open source 5G-Core implementations such as OAI and Open5GS. These open source cores can be deployed with various RAN vendors into private 5G networks. However, this usually requires a lot of integration and installation effort. With these open solutions researchers can implement, deploy, test and evaluate innovations. These 5G-Cores require no internet connection to function, which allows operators to have control over the network. The contribution to these projects is usually more difficult. The functionalities of the 5G-Cores are publicly available and will be described later. In addition to open source 5G-Cores, some project partners also operate private 5G-networks with commercial 5G cores from different vendors such as: Amarisoft 5G, Halys 4G/5G, Druid 5G SA, NG4T, Athonnet, GeniusCore, PolarisCore, Nokia and Ericsson. Most of these 5G-Cores are interoperable with different RAN vendors. However, the Ericsson limits access to their hard- and software and is therefore not interoperable.

5.2.2 Available Functionalities and Supported Features of Core Networks

The Core networks will be described in their current status depending on: implemented 5G-Core functions, deployment scenarios and special features.

5.2.2.1 OpenAirInterface Core Network

OpenAirInterface (OAI) core network (CN) designed to provide flexibility of diverse 5G use cases. Current OAI 5G CN can be deployed currently in two different modes:

- Minimalist 5G CN supports AMF, SMF, NRF, and UPF network functions.
- Basic 5G CN works with AMF, SMF, NRF, UPF, UDM, AUSF, and UDR network functions.

There are three different deployment scenarios:

- Deployment on bare metal or on a virtual machine.
- Docker-Compose can be used to automate deployment of network functions in Docker containers.
- Cloud native deployment using Helm Chart on OpenShift or Kubernetes cluster is possible.

Basic procedure for connection, registration and session management are supported by OAI 5G CN currently. Multiple UEs and PDU sessions, and mobility can also be supported by OAI CN.

The OAI CN has been validated with different SWs and HWs:

- It has been tested with open source RAN simulators. These are gNBSim, UERANSIM, my5G-RANTester
- It has been tested with OAI RAN + (OAI UE or COTS UE)
- Commercial gNBs such as Amarisoft and Baicell together with COTS UEs

Currently, the NEF, LMF and PCF network functions are under development. Moreover, supporting IPv6, mobility, and transmission of redundancy for URLLC are also in the roadmap.

5.2.2.2 Open5GS Core Network

Open5GC CN is an implementation of CN in C language for new radio according to the release 16. Some features that supported by Open5GS core network are supporting IPv6, multiple PDU sessions, handover, and voice over NR. The known limitations are roaming, multicast broadcast services, emergency call, and interworking with EPC.

The current Open5GC supports the network functions

- AMF, SMF, UPF, AUSF, NRF, UDM, PCF, NSSF, BSF
- These functions can also be used separately

There are two different deployment scenarios:

- Deployment on bare metal or on a virtual machine.
- The Open5GS can be deployed in a Docker container.

5.2.2.3 Amarisoft Core Network

Amarisoft CN is compatible with NR release 16 and network stacks are integrated on Linux. It has AMF, AUSF, SMF, UPF, and UDM network functions together with 5G-Equipment Identity Register (EIR). Amarisoft CN supports several gNBs with standard NG interface according to the NGAP and GTP-U protocols. Provided UE procedures are registration, deregistration, authentication, security configuration, service access, paging, and radio bearer establishment. Some other features provided by this CN are supporting network slicing, and broadcast and multicast PDU session options. More supported features are listed in [41].

5.2.2.4 RaemisTM 5G Core Network

Raemis is a 5G Core plattform developed by Druid Software and includes a 4G and 5G Core. It is a commercial 5G-Core which focuses on private 5G-network deployments. The 5G-core is scalable to the network size and the requirements of the customer.

- Focus of Druid Raemis 5G CN is private 5G networks.
- Scaling the performance up and down is possible.

The current verions supports the network functions

- AMF, SMF, UPF, AUSF, NRF, UDM, PCF, NSSF, IMS, SMSF

The Reamis 5G-Core can be deployed in various scenarios with Docker containers of on a linux distribution.

5.2.2.5 Athonet 5G Core Network

- Focus is private networks.
- It can run in a fully virtualized platform, data center, or on standard COTs servers.
- Some supported features are mobility, network slicing, roaming, edge computing, and voice over NR.

5.2.2.6 PolarisCore

PolarisCore is developed by PolarisNetworks and distributed by MECsWare for private 5G networks and offers a solution on virtual machines to run 5G core and 4G core (LTE EPC). Both 5G and 4G networks can run parallel.

- 5G core is based on 3GPP release 15.
- Supported network functions are AMF, AUSF, UMD, UDR, SMF, PCF, UPF, NRF, NSSF, SEPP.
- MEC software can run on COTS server from multiple vendors.

5.2.2.7 GeniusCore

The GeniusCore is a 5G-Core supporting SA mode from release 16 onwards. It is developed by CampusGenius, a spin-off of TU Dresden. The focus is the private 5G-network market and it is a commercial 5G-Core

The GeniusCore currently supports the following functions:

- AMF, AUSF, UDM, SMF, PCF, NRF, AUSF, UPF as well as the required interfaces

It can be deployed without an Internet connection or in Cloud environments, Deployments can be on a linux distribution or in a docker container.

5.3 Service, Management and Orchestration (SMO) (non RT RIC)

5.3.1 Overall Definition

According to the O-RAN Alliance specifications, SMO is responsible for the management domain, i.e., automation and orchestration to monitor and control the Open RAN components. SMO consist of Non-Real-Time Radio Intelligent Controller (Non-RT RIC) and a set of interfaces. These interfaces are for interaction between different RAN components. Moreover, interfaces also support data collection to monitor network and control by ML/AI. Addition to these, another key capability of SMO is O-Cloud management, orchestration and workflow management. Figure 12 illustrates architecture of SMO.

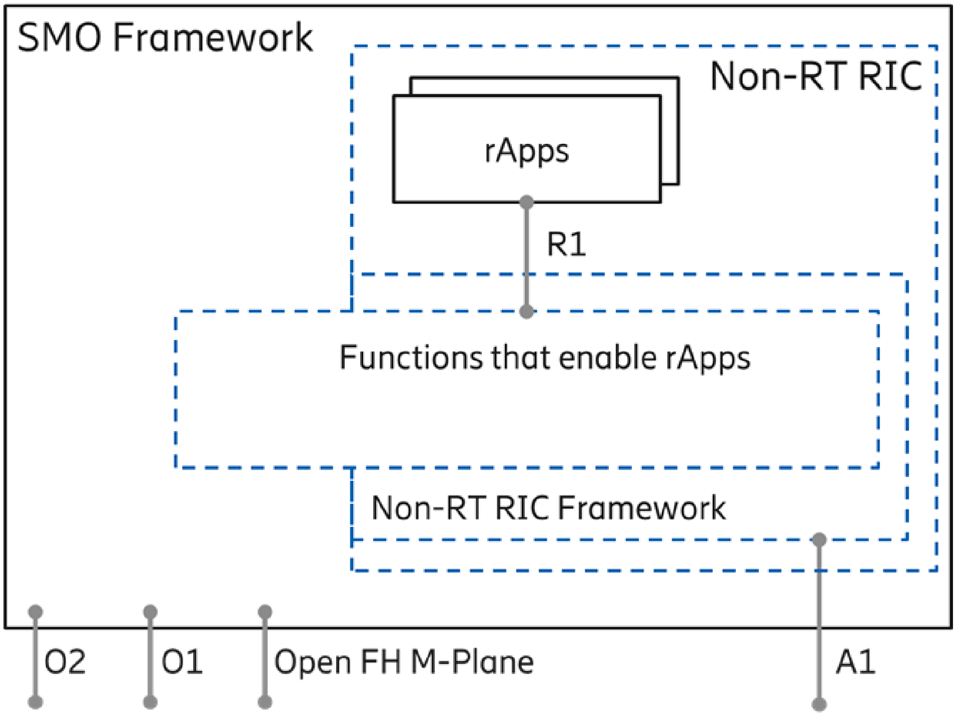


Figure 12: Exposure of SMO and Non-RT RIC Framework Services [42]

5.3.2 Non-RT RIC

The Non-real-time RIC (Non-RT RIC) controls and optimizes the RAN elements and resources in a non-real time interval (i.e, greater than 1 second). As shown in Figure 12, the Non-RT RIC is composed of two sub-functions: Non-RT RIC framework and Non-RT RIC Applications (rApps). Non-RT RIC Framework is responsible to expose all required functionalities to the rApps. rApps are modular applications that perform RAN optimization and operations including policy guidance, configuration management, and data analytics [43]. R1 interface enables rApps to have information and take actions via the A1, O1, O2, and Open FH M-Plane interfaces. Any third party can develop and deliver these rApps since aApps are based on the open interfaces and they can run on any vendor's Non-RT RIC.

5.3.3 Interfaces in SMO

O1 interface connects Near-RT RIC, O-CU, and O-DU with SMO and Non-RT RIC. Thus, O1 is an open interface. Some supported functionalities are performance management, configuration management, fault management, file management, trace, communication surveillance, etc.

O2 interface connects SMO to the O-Cloud to provide platform resources and workload management.

A1 interface connects the Non-RT RIC and Near-RT RIC. The main function of this interface is that it enables non-RT RIC to provide policy-based guidance, and ML/AI model management to the Near-RT RIC to optimize a certain RAN function. Additionally, A1 is also provide feedback from Near-RT RIC to allow the Non-RT RIC to use policies [44]. These three essential services are provided by A1: Policy management service, ML model management service, and enrichment information service.

The Open FH M-plane interface is to support Fault, Configuration, Accounting, Performance, Security (FCAPS) to the O-RU. Some FCAPS function that supported by the Open FH M-plane interface are 'start-up installation', and SW, configuration, performance, fault and file managements.

5.4 User Equipment

Device Type	UE	SoC/Module	Chipset
Smartphone/Tablet	Huawei P40	HiSilicon Kirin 990 5G	Balong 5000
	Huawei P40 Pro	HiSilicon Kirin 990 5G	Balong 5000
	Samsung Galaxy Tab S7 FE 5G	Qualcomm SM7225 Snapdragon 750G 5G	Qualcomm X52
	Google Pixel 5	Qualcomm SM7250 Snapdragon 765G 5G	Qualcomm X52
	Nokie 8.3 5G	Qualcomm SM7250 Snapdragon 765G 5G	Qualcomm X52
	Google Pixel 4a 5G	Qualcomm SM7250 Snapdragon 765G 5G	Qualcomm X52
	OnePlus 8	Qualcomm SM8250 Snapdragon 865 5G	Qualcomm X55
	ASUS ZenFone 8	Qualcomm SM8350 Snapdragon 888 5G	Qualcomm X60
	OnePlus 9	Qualcomm SM8350 Snapdragon 888 5G	Qualcomm X60
	Samsung S21+ 5G	Exynos 2100 (International) **or** Qualcomm SM8350 Snapdragon 888 5G (USA/China)	Samsung Exynos 2100 **or** Qualcomm X60
	Samsung A52s 5G	Qualcomm SM7325 Snapdragon 778G 5G	Qualcomm X62
	Samsung Galaxy Tab S8+ 5G	Qualcomm SM8450 Snapdragon 8 Gen 1	Qualcomm X65
	Xiaomi 12	Qualcomm SM8450 Snapdragon 8 Gen 1	Qualcomm X65
	Motorola Edge 30 Pro	Qualcomm SM8450 Snapdragon 8 Gen 1	Qualcomm X65
Router/CPE	Cradlepoint W1850-5GB	Sierra Wireless EM9190	Qualcomm X50
	Cradlepoint R1900-5GB	Sierra Wireless EM9190	Qualcomm X50
	Mikrotik Chateau 5G	Quectel RM500Q-GL **or** RM502Q-GL **or** RM500Q-AE **or** RM502Q-AE **or** RG500Q-EA **or** RG502Q-EA	Qualcomm X55
	Greenpacket 5G NR Outdoor O5A	-	Qualcomm X55
	AirSpan CPE AirSpot 9621 (My-ES5-SW-MB-W-16-EU)	Fibocom FM150-AE	Qualcomm X55
	Fritzbox 6850 5G	Quectel RM500Q-AE-VA	Qualcomm X55
	Netgear MR5200	?	Qualcomm X55
	Robustel R5020	Quectel RM500Q-AE	Qualcomm X55

	Wistron NeWeb (WNC) SKM-5xE	?	Qualcomm X55
	Siemens SCALANCE MUM856-1	Simcom SIM8202G-M2	Qualcomm X55
	Hongdiang X2	?	Qualcomm X55
Embedded Module	Quectel RG500L-EU	-	MediaTek 750
	SIMCom 8200 Series	-	Qualcomm X55
	Quectel RM50xQ Series	-	Qualcomm X55
	Telit FN980/FN980M	-	Qualcomm X55
	Fibocom FM160 EAU	-	Qualcomm X62
	Quectel RG520N-GL	-	Qualcomm X62

5.5 5G-OPERA testbeds

5.5.1 Eurecom open 5G lab

5.5.1.1 General testbed description

Open5GLab at EURECOM is one of the experimental 5G sites in France developed in the context of the 5G-EVE ICT-17 project. Construction began in July 2018 and 5G experimentation is now available. The site is interconnected with similar sites in Europe in the 5G-EVE network. It is also one of the test sites for the OPNFV VCO 3.0 (Virtual Central Office) project and as such is interconnected with sites in North Carolina, USA and Montreal, Canada. It is currently being used in the ICT-19 5G!DRONES and 5G-VICTORI projects, the ICT-42 5G-RECORDS and AFFORDABLE-5G projects and the ICT-56 IntellIoT project.

Open5gLab provides experimental 5G services including so-called Enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency (URLLC) and massive machine-type communications and is based on fully open source tools and open-architecture design. It is the main experimental playground for OpenAirInterface (OAI) and Mosaic-5g (M5G) software packages.

5.5.1.1.1 Available Frequency Licenses

The current platform focuses primarily on 5G SA and NSA deployments in bands n38 and n78. In the future we will also use bands n77 and n258. Outdoor communications are limited to the immediate proximity of EURECOM's premises.

- Band n38: 40MHz (2575 - 2615 MHz)
- Band n78: 10MHz (3,42 - 3,43 GHz)
- Band n77: 100MHz (under negotiations)
- Band n258: experimental license available on demand (request to be made once OAI FR2 functionality has been validated)

5.5.1.1.2 Remote access

Remote access to Eurecom's infrastructure is available for project partners and other affiliates of Eurecom through a simple ssh connection (requests can be made by email to Florian Kaltenberger).

5.5.1.2 Infrastucture

The site's cluster computing resource makes use of RedHat's OpenShift 4.9 Kubernetes container platform and benefits from technical support from RedHat. The main cluster is used for radio-access, core network and mobile-edge functions shown at a high-level in Figure 13. The cluster's switching fabric currently make use of three Edgecore 7312-54XS Data Center switches running CumulusOS. These will be upgraded to Cisco Nexus 9k-based switching fabric including PTP support in mid-2022. Three additional P4-programmable switches (Edgecore Wedge) used as Edge Fabric and particularly for the 5G UPF function are under integration.

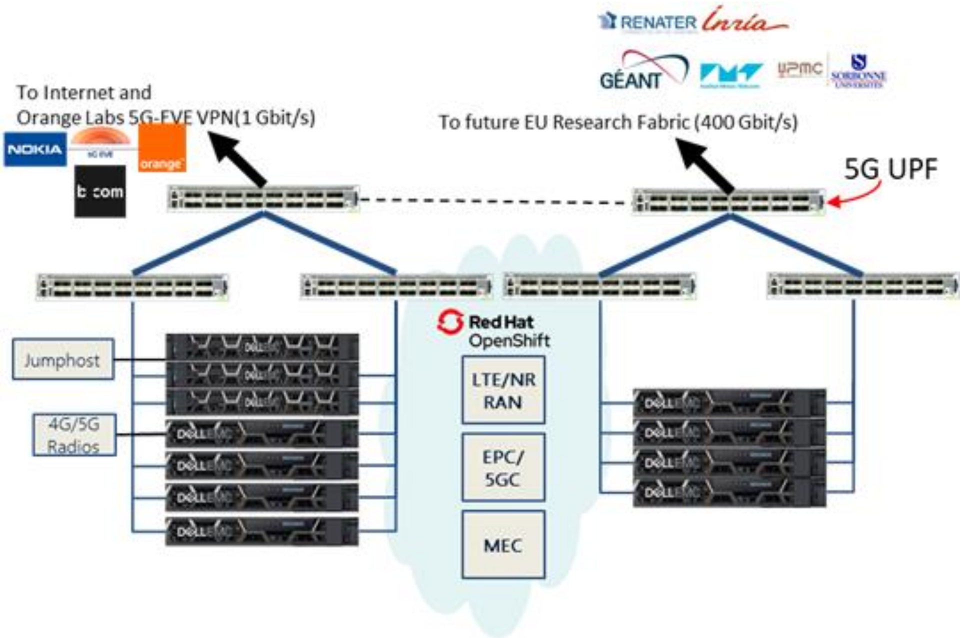


Figure 13: : Open5GLab computing and switching elements

For timing-aware radio equipment (e.g. ORAN O-RU, AW2S) an additional Fibrolan Falcon-RX is used to interconnect the main cloud-fabric with these devices. A PTP grandmaster is also used on the fabric for synchronization.

The main cluster is comprised of 3 2x18-core Xeon Gold 6154 and 3 2x18-core Xeon Gold 6254 x86 servers (Dell R640). All nodes are connected 2x25Gbit/s to the switching fabric. One computing node has extra fronthaul networking interfaces for direct interconnections with O-RAN radio equipment. A second single-node OpenShift cluster built on a 2x64-core AMD Epyq server (Dell R7525) is available for sandbox testing and as a dedicated 3GPP-DU cluster. It is equipped with 4x25Gbit/s Ethernet connected to both the main switching fabric and for direct interconnection with O-RAN radio equipment.

Two interconnections with external networks are available. Firstly a 1 Gbit/s VPN tunnel with Orange Chatillon is used to interconnect with Orange computing resources, in particular the experimental ONAP cluster and to allow for disaggregated deployments of 3GPP network functions. A second 400 Gbit/s interconnection with INRIA Sophia Antipolis and the new national RENATER infrastructure developed in the context of the SLICES Research Infrastructure. This will allow for pan-EU next-generation networking experimentation in the coming years.

Some bare-metal nodes with in-lab 5G-capable radio devices (FR1 and FR2) are available as a sandbox that can be used by experimenters and developers and are interconnected with the two Kubernetes clusters described above. External access for onboarding software, collecting measurement data and developing basic software for the site is available for partners using secure-shell access. Interfaces for an external orchestrator (ONAP) have been validated in the context of 5G-EVE between Orange Labs Chatillon and Open5GLab. The nodes of the site are also used by OpenAirInterface Jenkins-based continuous integration / continuous delivery (CI/CD) framework.

Open5GLab's radio infrastructure includes indoor and high-power outdoor radio-units operating in several 4G and 5G bands in the immediate vicinity of the test site, specifically Band n38 (2.6 GHz TDD), Band n78 (3.5 GHz TDD) and Band n258 (25 GHz TDD). The outdoor units are interconnected with the switching fabric using 300m fiber (10/25 Gbit/s). The units are a combination of in-house designs and commercial remote radio-units. The outdoor installation is shown in Figure 14.

Figure 14: Open5GLab outdoor radio equipment

5.5.1.2.1 RAN and CORE

The deployment framework for openair5gLab is full open source and distributed on the openair-k8s github in [45]. openair-k8s allows building high-quality OCI-compliant container images for the OpenAirInterface 4G/5G radio access (eNB/gNB) and core networks (EPC) and deploying these components on OpenShift or other enterprise-grade Kubernetes distributions. More recently some OAI partners have provided support for vanilla kubernetes on freely available CentOS and Ubuntu distributions. The RAN and Core network networking configuration provided by openair-k8s is shown for 5G NR Non-Standalone (NSA) mode in Figure 15. Networking functions are split between hard real-time functions and soft real-time functions and execute on specific worker nodes in cluster configured accordingly. The workers themselves are Kubernetes Pods and make use of the Multus container network interface (CNI) plugin for Kubernetes. This allows for all types of networking interconnections control/user plane separation as well as fronthaul and midhaul for the hard-real-time components.

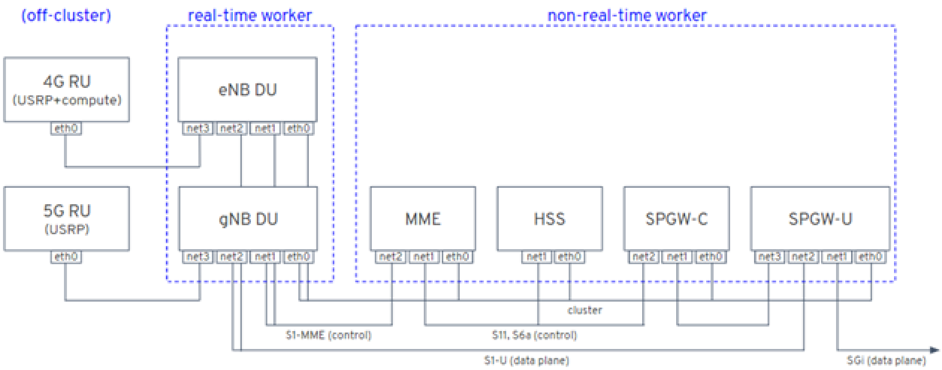


Figure 15: RAN/Core k8s Pods (5G NSA)

Open5glab can provide third-party RAN and Core software software testing services. Examples include Nokia SABOX/LTEBOX and Accelleran's gNB CU micro-services.

RAN/CORE Disaggregation

The RAN and Core component of open5glab can be disaggregated using the 3GPP F1 and N4 interfaces. Support for full disaggregation in the RAN via the E1 interface will be added in Q2 2022. This allows for geographically-distributed deployment of 3GPP RAN and Core functions in Engage5G.

O-RAN Controllers and xAPPS

Support for integration of O-RAN based controllers and xAPPS via the E2 interface is available. Deployment of such controllers makes use of the FlexRIC E2 framekwork provided by Mosaic5g and can be built using the Edge application deployment framework described in the following section.

5.5.1.2.2 Cloud Edge

The edge computing component shares the open5glab fabric with the deployed RAN and Core functions. For integration of vertical service software directly on open5glab fabric EURECOM provides a service creation and deployment framework with a web-based portal developed in the context of the ICT-19 5G!DRONES project. This portal is accessible from the outside of open5glab and allows for either deploying container images on either OpenShift or vanilla Kubernetes. In addition, for OpenShift deployments it can make use of the automatic building of the application on the cluster at EURECOM. KPI and other monitoring services can be accessed via the portal.

Deployment of specific Edge computing hardware can also be carried out by EURECOM staff as is the case in the ICT-42 5G-RECORDS project where dedicated audio processing hardware was added for a particular vertical application. EURECOM can make this hardware remotely accessible by project partners.

5.5.1.2.3 User Equipment

Open5GLab provides remotely-controllable 4G and 5G user-equipment, including both off-the-shelf 5G NR SA smartphones (Huawei P40, Oneplus 8/9) and cellular IoT modules (Quectel RM500Q, SIMCOM 8200). This allows experimenters to control and extract measurements from the user-equipment in a running experiment. Two drones are also equipped with 5G user-equipment developed in the context of the 5G!DRONES project With the help of EURECOM, software can be on-boarded into the user-equipment devices.

The OAI 5G NR UE is available for testing purposes via the OAI CI/CD pipelines.

An Amarisoft UE Emulator (4G/5G, 64 UEs) is available for experimenters to scale up testing in of 4G/5G RAN services in a controlled lab setting.

5.5.1.3 Evolutions

Q3 2022

open5glab will integrate O-RAN 7.2 compliant radio nodes from Mavenir which are currently under test. These will be available only for indoor testing because of their operating band which overlaps with commercial n78 channels. In addition, through a partnership with NVIDIA, EURECOM is integration RAN equipment using the NVIDIA Aerial GPU-based platform and an RRU from FOXCONN. Aerial will also be used for Egde computing experiments.

Requests to ARCEP for new bands and extended bandwidth in n38 will be made

Q4 2022

The open5glab switching fabric will be upgraded in Q2 2022.

Vehicular nodes will be added in Q2 2022.

Outdoor testing will be extended to other parts of Sophia Antipolis through collaboration with INRIA Sophia Antipolis. Outdoor mmwave (n258) experimentation will be available in Q2 2022.

Support for some Rel16 extensions is expected, in particular enhancements for URLLC and NR Sidelink.

5.5.2 Alsatis

5.5.2.1 General testbed description

Alsatis lab is located in France, in Toulouse main offices and consist of End to End 5G SA network with flexible options in term of component providers combination for RAN and Core network elements.

Currently, only OTA (Over The Air) indoor testing is applicable to Alsatis lab test environment.

Test facilities, initially contained in one dedicated room is now under extension over the whole Alsatis building with several 'distributed access points' having Fiber and energy connectivity to the main lab Network elements location (centralized gNB, Core Network Elements).

Integrated RU and RRH are under deployment with objective to provide full coverage over the whole building (2 floors). Target is to provide flexibility and ease of evolution in term of connected RUs and antennas, to evaluate and test uses cases in real 5G indoor conditions.

Alsatis has the authorization to use 100 Mhz bandwidth on band n77 (3900-4000 MHz) until July 2025 as part of 5G platform experimentation, and is under final process authorization to operate 10 MHz bandwidth on band N38.

Alsatis owns and operates a national and secure WAN network and this architecture could be used to provide transport and connectivity between different 5G distributed components such as Core Network, gNB or Network Management Elements on different partner testbeds.

On current lab installation, testbed is interconnected with French Full MVNO 'Airmob' using Alsatis WAN transport

5.5.2.2 Currently deployed infrastructure

For the Radio Access Network part, current indoor deployment consist of :

- One gNB from Amarisoft running on DELL XR12 server, with up to 3 N77 4X4 MIMO RRH from AW2S
- One gNB from Airspan with vCU and vDU Elements running on DELL XR11 server, with 3 Airvelocity 2700 4TRX Radio Unit. These Elements are advertised as O-RAN compliant

For the Core part, available 5G cores are :

- Amarisoft 5G Core
- Halys 4G/5G Core
- Druid 5G SA Core (under installation)

List of UEs and 5G modules available and tested :

- Mikrotik Chateau 5G

- Greenpacket 5G NR Outdoor gateway O5A series
- SIMCom: SIM8202X-M2, SIM8200EA-M2
- Fibocom FM160 EAU

Tools available :

- EXFO FTB-1 pro for E2E connectivity testing (Throughput, Latency, Jitter)

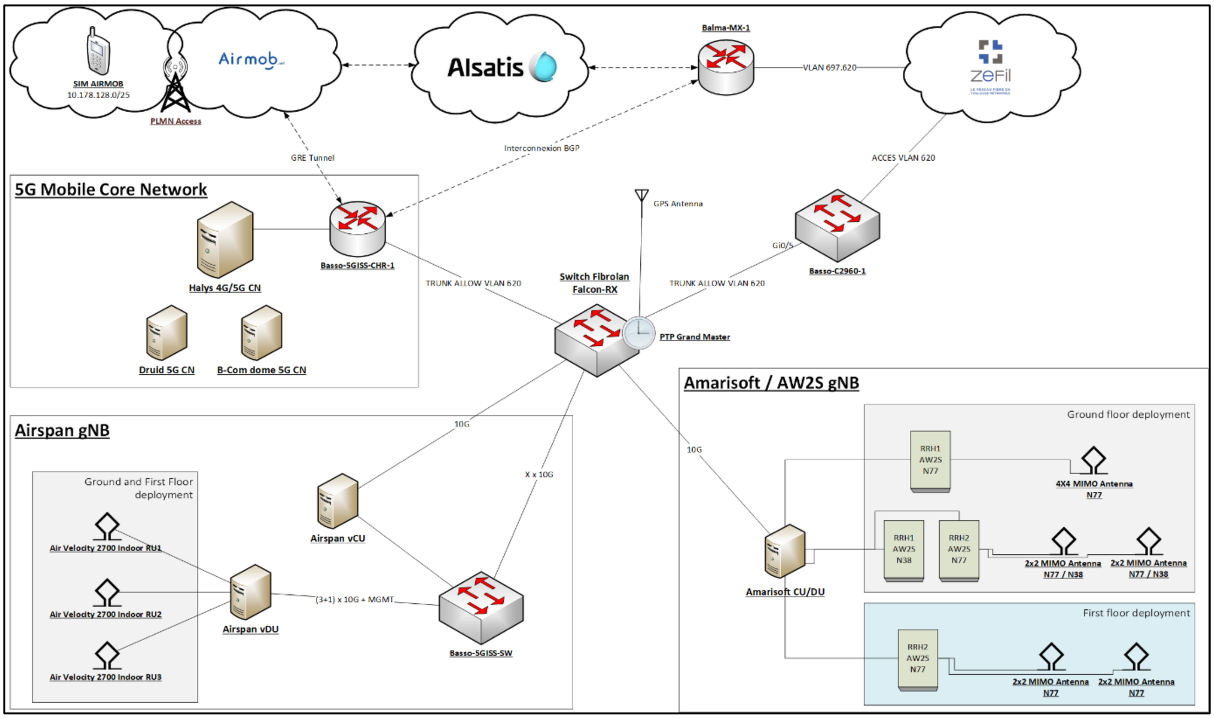


Figure 16 : Alsatis Testbed - High level Architecture view

5.5.2.3 Planned extension and activities in 5G Opera

First planned activity is to deploy and integrate an Open Air Interface gNB connected to one of the existing 5G Core Network. Once a baseline architecture is defined, proposed plan is to work on FR1 O-RU integration and test from AW2S.

In addition, Items from WP5 related to 5G-NR positioning is planned for integration and evaluation in indoor environment.

5.5.3 TU Dresden

5.5.3.1 General testbed description

5.5.3.1.1 General testbed environment

Testbeds available in Technical University Dresden (TU Dresden) in Dresden, Germany are 5G SA testbeds and available for testing Open RAN. Testbed components (software and hardware) are from different vendors such as OpenAirInterface, Airspan, Node-H, Nokia, Huawei, and Ericsson. Open source core networks can be used to complete 5G for almost all testbeds except testbed from Ericsson since it is closed to the 3rd parties. All testbeds can be connected to UEs listed in Table 5. All testbeds comprise indoor deployments, while testbed from Nokia is also for outdoor deployment. Indoor deployments are settled in the TU Dresden buildings in approximately 20 square meters large rooms and they are Pico cell deployments. Only testbed from Nokia is also for outdoor deployment and the outdoor deployment is macro cell.

5.5.3.1.2 Available frequency licences

Band n40: 100 MHZ (2.3 - 2.4 GHz)

Band n78: 100 MHz (3.7 - 3.8 GHz)

Band n258 400 MHz (24.25 - 27.5 GHz)

5.5.3.1.3 Access opportunity

We are in the process of providing access to the project partners.

5.5.3.2 Current Deployed infrastructure

The summary of the available hardware and software are provided in Table 5 as well as available core networks and UEs.

Table 5: Testbed Components

Vendor	CN	RAN components	UEs
Airspan	5GS or OAI	2xRUs (AirVelocity 2700), vCU and vDU	OAI, Nokia 8.3, 40xTelit FN980, Quectel RM500QCM
Node-H		5x(Node-H T&W 5G Enterprise Small Cell)	
Nokia		Nokia ASIK+ABIL+ Nokia ASiR 5G-pRRH AWHQB RU	
Huawei		Huawei BBU 5900	
OpenAirInterface	OAI CN	OAI RAN	
Ericsson	Ericsson CN	Ericsson Baseband 6630	

Airspan Testbed: The RAN part of this testbed is from Airspan. The RAN can be completed by an open source CN. The UEs from Table 5 can be connected. Testbed supports O-RAN 7.2x split for deployment. RUs have 10GbE for fiber and copper Ethernet ports. Virtual CU (vCU) and virtual DU (vDU) runs on Intel COTs server with Kubernetes. A switch from FibroLAN connects vDU, vCU and RUs.

Node-H Testbed: There are 5 Node-H T&W 5G Enterprise Small Cell. The software supports CU and DU, and splits both units clearly into Control-Plane (CP) and User-Plane (UP). These small cells operate in the n78 frequency band. They follow the standards from 3GGP, O-RAN and Small Cells Forum defined architectures in order to support interoperability with different vendors [46].

OpenAirInterface Testbed: This testbed is based on OpenAirInterface (OAI) software built on two regular computers with Xeon microprocessors and two N310 series of Universal Software Defined Radio (USRP) devices. Testbed works within the range of 2.3 and 2.4 GHz frequency.

Nokia, Huawei, and Ericsson Testbeds: The testbed components from these vendors are summarized in Table 5. Testbed from Nokia is for both indoor and outdoor deployments. The radio of the Nokia transmits in the n78 band with the range of 3.7 GHz to 3.8 GHz.

Theoretically, for Open RAN interoperability tests, there is possibility to mix components of Airspan with OAI. There is a QualiPoc Android which is a smartphone based RF optimization and service quality assessment tool.

5.5.3.3 Planned extensions and activities in 5G Opera

WP5 and WP6 are the most relevant work packages for testbeds to evaluate end-to-end security, time sensitive networking, positioning, and network management and test of core network solutions. The coverage of the Nokia testbed for outdoor is planned to be extended in TU Dresden campus for moving small vehicles. The plan is to finish the set-up until begging of next year. The testbed from Huawei and Ericsson is also planned to be extended for outdoor coverage in TU Dresden campus for medical use cases. The extension plan for Nokia and Ericsson will be clear soon. The planned scenarios to run on the testbeds are interoperability test of different RAN system and 5G core, and benchmarking between traditional vendors and new vendors. Some targeted KPIs are latency, stability, and throughput.

5.5.4 Smart Systems Hub

5.5.4.1 General testbed description

The 5G-Testbed at the Smart Systems Hub in Dresden is a semi open 5G-testbed aiming at application development and testing. The Smart Systems Hub provides industrial and research institutions free access to the network, to evaluate, develop and verify 5G use cases. The testbed covers the IoT-Lab of the project partner. Currently 1 demonstrator in the area of robot automation via edge control is deployed and running in the hub.

5.5.4.2 Currently Deployed Infrastructure / Integrated and Tested Hardware

Due to its size and nature the Smart Systems Hub has a very small testbed. It consists of an O-RAN compliant All-in-One Small cell from T&W with Software from the Munich based company Node-H. This small cell is connected to a server via an ethernet connection. On this server runs the commercial GeniusCore and connects the network to the internal company network of the Smart Systems Hub. The demonstrator is connected to the 5G-FritzBox 6850.

5.5.5 5G Bavaria

5.5.5.1 General testbed description

The following description are partly taken form the paper "Planning, Challenges, and Deployment of an OpenRAN based 5G Testbed" written by Ralph Dümmler and Thomas Heyn from Fraunhofer Institute for Integrated Circuits IIS Erlangen, Germany. And from the webpage in [47].

This extended abstract describes the OpenRAN based 5G standalone testbed, which is currently deployed by Fraunhofer IIS in Nuremberg and Erlangen, Germany. The OpenRAN testbed is distributed over two sites and supports both 5G frequency ranges FR1 and FR2 (planned).

The 5G Testbed Industry 4.0 covers locations of **Fraunhofer IIS at Nordostpark 84 in 90411 Nuremberg**.

Site Nuremberg

- Office building (partial)
- Industrial indoor area (L.I.N.K. hall), accessible with heavy trucks
- Outdoor area

Site Erlangen (Germany/Bavaria)

- Transmitter room, entrance area, some labs
- Antenna mast (for outdoor coverage)
- Parking garage (planned)

Feature Overview

- Multiple RAN and Core vendors
- Stand-alone (SA) only 5G NR RAN with 15 radio units and mobility support
- Support for FR1 (sub-6 GHz) band and campus license available on n78 (includes 3.7 GHz to 3.8 GHz) with up to 100 MHz carrier bandwidth
- Virtualized RAN architecture on COTS hardware (five DU, two CU servers), deployed in Docker containers
- Open RAN interfaces & APIs enabling real time processing of data, functional split options 7.2x (O-RAN) and 6 (Small Cell Forum)
- Precise timing synchronization for high accuracy RTLS applications
- Prepared for URLLC and IIoT applications
- Vision:
  - Support for FR2 (mmWave) band n257 (26.5 GHz to 29.5 GHz) with up to 400 MHz carrier bandwidth (Industrial Indoor area only)

A unique technical feature is the combination of 5G communication on FR1 and FR2 as well as the advanced localization possibilities. We have highly advanced positioning reference system available. The OpenRAN Approach enables us to get deep insight information from the network and also extract trace and debug from the network.

5.5.5.1.1 Available frequency bands

- Local frequency allocation for a 5G campus network at 3.7 to 3.8 GHz (FR 1)
- Experimental radio licence for the mm-wave bands n258 at 26 GHz and n257 at 28 GHz (FR 2)

5.5.5.1.2 Availability / access opportunities for collaboration with project partners

As an independent research unit, Fraunhofer IIS intended to build an own testbed to supporting customers, mainly smaller and mid-sized companies, to get access to the 5G technology. The focus should not be just communication but also localization, which are the two main competences of Fraunhofer IIS.

The industrial alliance 5G-ACIA identified different architectures for so called non-public networks [48]. Based on a Bavaria funded research project, “5G Bavaria”, a cutting-edge private Campus network installation is built-up and operated [47]. Great interest from government and industry finally motivated the implementation of a state-of-the-art OpenRAN based 5G testbed supporting a wide variety of potential users and use cases, which are identified in [12] and [8].

5.5.5.2 Currently Deployed Infrastructure / Integrated and Tested Hardware

Infrastructure and equipment

- Industrial hall with truck ramps and hall passage.
- Indoor: 8 panel/MIMO antennas (at different heights)
- Office building: multi-floor building with offices and laboratories, equipped with 5G Small Cells infrastructure and 6 omni/panel antennas for FR1 on one floor

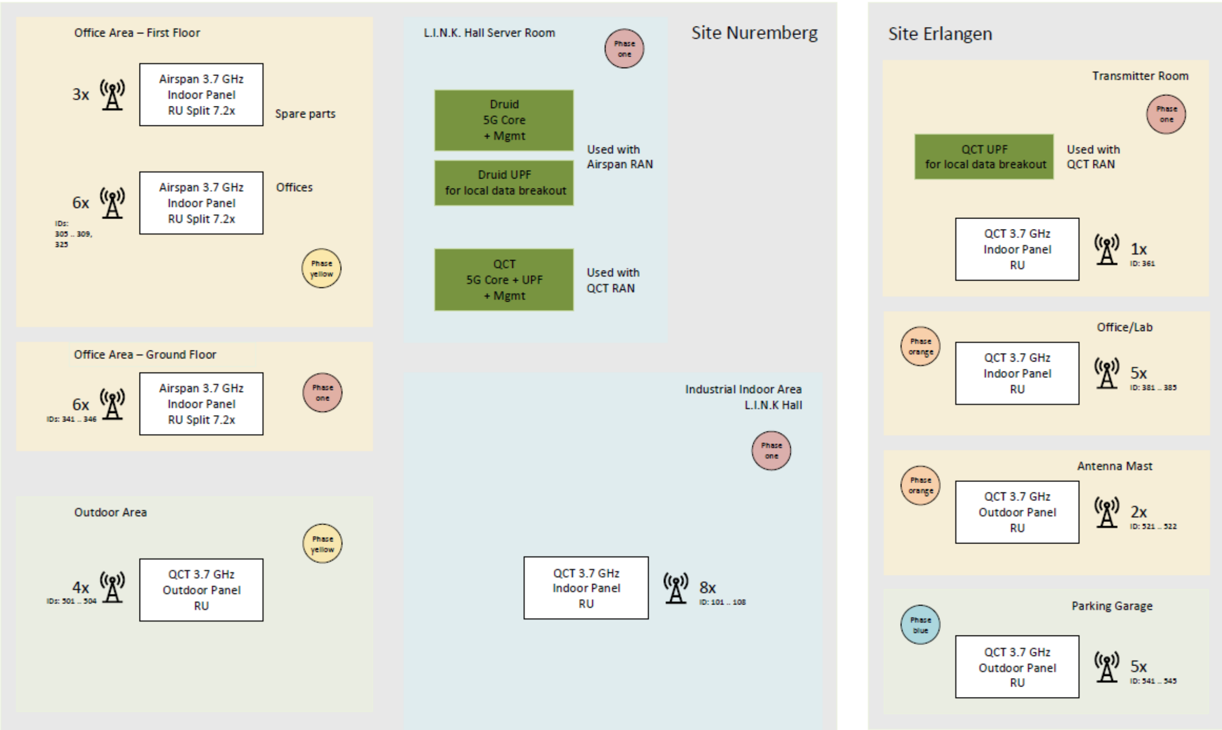


Figure 17: A snapshot of the I4.0 testbed from Q3/2022 for two vendors

RAN – Radio Access Network

- Campus network (5G NR SA) with more than 15 radio units
- Up to 100 MHz carrier bandwidth in the local frequency range 3.7-3.8 GHz
- Up to 400 MHz carrier bandwidth in the mm-wave spectrum at 26 GHz and 28 GHz indoors
- Virtualized open RAN architecture with open interfaces or APIs
- Support for URLLC, IIoT and real-time localization applications (RTLS)

Core Network

- Autonomous 5G core network (cloud-native)
- Service-based architecture
- Integrated cloud and edge computing
- 3GPP compliant network slicing (plan Q1/2023)
- Open interfaces and APIs for raw data extraction and post-processing
- Support for own SIM cards and eSIM support

List of test equipment in the I4.0 Testbed

The Testbed is equipped with several test & measurement solutions to support research and development, UE and network testing, maintenance and troubleshooting with and for our partners and customers.

- **5G Protocol Analyzer (Keysight/Sanjole WaveJudge 5000 with mmWJudge extension)** This is a wireless protocol analyzer, capturing the full over-the-air conversation of upper-layer messages, but also including RF signal characteristics. This analyzer is used for tests in the middle and not only at the endpoints. So it does not change anything of the very behavior of the communication devices in use. It is used for troubleshooting in the Testbed, especially in interoperability testing (IOT).

- **5G Network Testing Solution (Rohde & Schwarz 5G Site Testing Solution with TSMA6, ROMES4 & Qualipoc incl. Interactivity Test)**
  A mobile and portable solution for all area network testing and monitoring to ensure the maximum functional performance (e.g. latency, data rates) and coverage of the Testbed's and customer's campus networks. The solution uses a scanner, smartphones and industrial embedded modules for measuring.
- **5G Field Test Analyzer (Anritsu MS2090A)**
  A high performance, portable RF real time spectrum analyzer capable to not only capture transmissions below 6 GHz, but also in the mmWave range, to detect interference and guarantee performance and regulatory compliance, including EMF and safety. The device can cope with TDD specific challenges, active antenna systems, beamforming and dynamic physical layer attributes.
- **Transport Network Field Tester (Viavi MTS-5800-100G)**
  Tester for front-, mid-, backhaul-network installation and maintenance. For 5G gNB interface eCPRI throughput and delay measurements as well as high-accuracy time synchronization tests, i.e. SyncE (Synchronous Ethernet) and IEEE 1588 v2 functions.
- **There is more equipment available for use in the Testbed, examples are:**
  - Rohde & Schwarz FSW26 and FSW85 signal and spectrum analyzers
  - Rohde & Schwarz SMW200A vector signal generator with 5G NR options
  - Various antennas, amplifiers, filters and other RF-accessories
- **Keysight F64 Channel Emulato**r
  PROPSIM Channel Emulation Solutions enable realistic realtime performance testing of wireless devices and base stations. The following scenarios are supported according 3GPP
  - Dynamic multipath propagation
  - Range pathloss and blocking effects
  - Doppler from mobility and multipaths
  - Noise and synchronous programmable interference
  -
- **Keysight UXM 5G mobile network tester**

  The Keysight UXM 5G wireless test solution is a highly-integrated signaling test platform with multiformat stack support, rich processing power, and abundant RF resources

  - 5G NR 8CC DL, 4 CC UL 2x2, with LTE 2CC
  - Wide bandwidth in each RF port
  - Multiple angle of arrival (AoA) test
  - Internal fading for 5G NR and LTE formats
  - Frequency extensions to high IF and millimeter-wave with the use of a common interface unit and remote radio heads (RRH)

List of supported UEs tested based on SW version from Airspan and Metaswitch

"Supported" means: Registration to the network is possible, a PDU session can be established, Ping is possible.

Class	UE Model		Module	Chipset / Modem	Airspan SR19.00UR6.2 Metaswitch V4.9.3
Industrial Router	**Robustel R5020** Quectel RM500Q-AE Revision: RM500QAEAAR11A01M4G RM500QAEAAR11A01M4G_01.002.01.002		Quectel RM500Q-AE	Qualcomm Snapdragon X55	**Yes**
Smartphone/Tablet	**Samsung S21+ 5G** - (SM-G996B/DS) Samsung Exynos based, with dedicated Rohde & Schwarz Qualipoc Firmware		N/A	Samsung Exynos 2100	**No**
Smartphone/Tablet	**Samsung Galaxy Tab S7 FE 5G** - (SM-T736B) Qualcomm Snapdragon based, with dedicated Rohde & Schwarz Qualipoc Firmware		N/A	Qualcomm Snapdragon X52	
Smartphone/Tablet	**ASUS ZenFone 8** (ZS590KS) (rooted) Select 5G NR SA in service menu *#*#4636#*#*		N/A	Qualcomm Snapdragon 888 with integrated Snapdragon X60 modem	**Yes**
Small/Home Office Router	**Airspan CPE** Product model My-ES5-SW-MB-W-16-EU Running software version SQXR60_V1.0.1 Module version 89603.1000.00.04.01.04		Fibocom FM150-AE	Qualcomm Snapdragon X55	**?**
Smartphone/Tablet	**Huawei P40 Pro**		N/A	HiSilicon/Huawei Kirin 990 5G	**No**
Industrial Router	**Wistron NeWeb (WNC) SKM-5xE** Software ver.: v00.13.00.02_01232021022914_perf Modem ver.: UMC-A15QE_v13.03 Hardware ver.: v07.07		?	Qualcomm Snapdragon X55	**?**
Embedded Module	**Quectel RM500Q-GL** - on evaluation board Revision: RM500QGLABR11A06M4G RM500QGLABR11A06M4G_01.001.01.001		Quectel RM500Q-GL	Qualcomm Snapdragon X55	**?**
Embedded Module	**Quectel RG500L-EU** (RG500LEUAB-M28_UGASA) - on evaluation board Revision:RG500LEUACR02A04M8G_OCPU MOLY.NR15.R3.MD700.MP.V25.P11, 2022/02/09 13:18		Quectel RG500L-EU	MediaTek 750	**?**
Embedded Module	**Quectel RM520N-GL** (RM520NGLAA-M20-SGASA) - on evaluation board Revision: RM520NGLAAR01A05M4G		Quectel RG520N-GL	Qualcomm Snapdragon X62	**?**

Industrial Router	**Siemens SCALANCE MUM856-1** MUM800 Firmware V07.00.01 Module Version B01V14_201207		Simcom SIM8202G-M2	Qualcomm Snapdragon X55	**No (not registered)**
Industrial Router	**Robustel R5020-5G-A09GL-B** FW: 3.1.7 (Rev 5083) Quectel RM500Q-AE Revision: M500QAEAAR11A02M4G		Quectel RM500Q-AE	Qualcomm Snapdragon X55	**Yes**
Smartphone/Tablet	**Google Pixel 4a 5G** Tested versions of Android OS: 11 and 12		N/A	Qualcomm Snapdragon 765G with integrated Snapdragon X52 modem	**No**
Small/Home Office Router	**Cradlepoint W1850-5GB** SW: 7.22.60 (started to work since SW: 7.22.40)		Sierra Wireless EM9191 (tbc)	Qualcomm Snapdragon X55	**Yes**
Industrial Router	**Cradlepoint R1900-5GB** SW: 7.22.60 (started to work since SW: 7.22.40)		Sierra Wireless EM9191 (tbc)	Qualcomm Snapdragon X55	**Yes**
Small/Home Office Router	**Fritzbox 6850 5G**		Quectel RM500Q-AE (tbc)	Qualcomm Snapdragon X55	**Yes (only ping)**
Small/Home Office Router	**Netgear MR5200**		?	Qualcomm Snapdragon X55	**?**
Smartphone/Tablet	**Samsung Galaxy Tab S8+ 5G** (Software-Update necessary)		N/A	Qualcomm Snapdragon 8 Gen 1 with integrated Snapdragon X65 modem	**No**
Smartphone/Tablet	**Samsung A52s 5G**		N/A	Qualcomm Snapdragon 778G with integrated Snapdragon X53 modem	**No**
Smartphone/Tablet	**Motorola Edge 30 Pro 256GB** - (XT2201-1)		N/A	Qualcomm Snapdragon 8 Gen 1 with integrated Snapdragon X65 modem	**?**
Smartphone/Tablet	**Xiaomi 12 256GB/8GB** - (2201123)		N/A	Qualcomm Snapdragon 8 Gen 1 with integrated	**?**

				Snapdragon X65 modem	
Embedded Module	**Quectel RM520N-GL** (RM520NGLAA-M20-SGASA) - on evaluation board Revision: RM520NGLAAR01A02M4G		Quectel RG520N-GL	Qualcomm Snapdragon X62	**?**

5.5.5.3 Planned extensions and activities in 5G OPERA

t.b.d.

ACKNOWLEDGMENT

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https://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/DE/

5.5.6 Berlin 5G

5.5.6.1 General Testbed Description

The Fraunhofer HHI testbed, including the 5G Berlin Testbed is a 5G SA Network with several mobile and stationary RAN technologies. It is available for E2E Testing with the 5G Opera project.

It operates at 3750 MHz (band n78), where 100 MHz of bandwidth are available. The service area comprises both outdoor and indoor deployments. System vendor for outdoor coverage area is Nokia. Indoor systems are based on Airspan (O-RAN), Nokia, Amarisoft and OpenAirInterface.

All RANs are operated by Fraunhofer HHI and all RANs are covered by a Campus Network License.

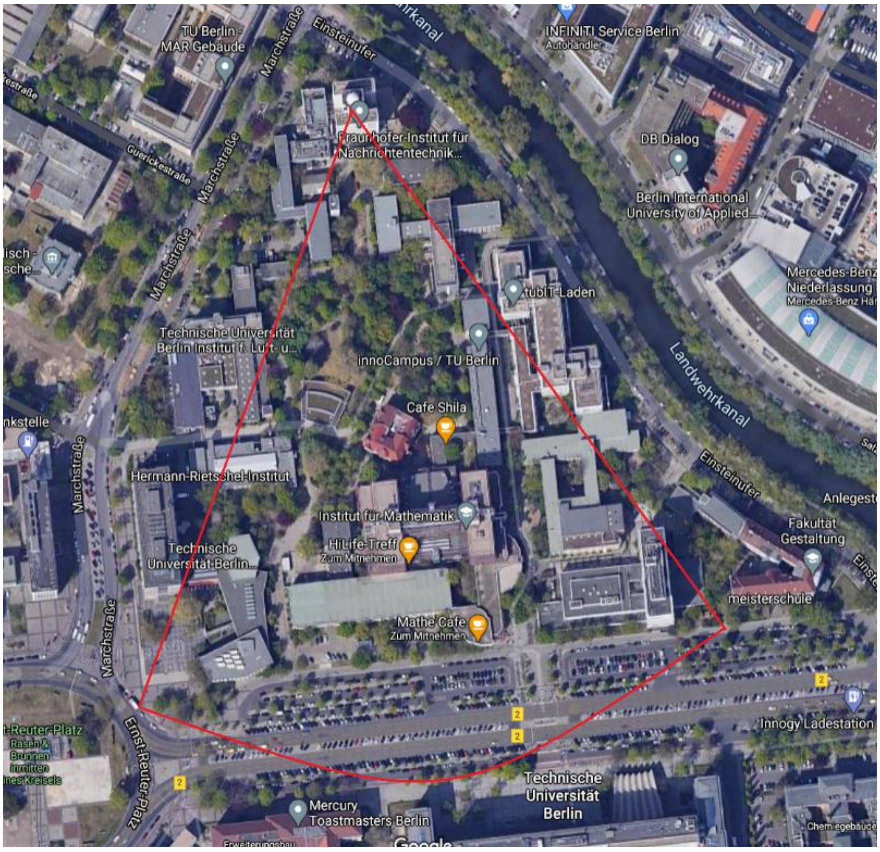

Figure 18: Coverage area of outdoor macro cell deployment (TUB-campus)

5.5.6.2 Current Deployment Infrastructure

The following hard- and software components are available at the time of writing the deliverable.

- Outdoor components:
    - 2x Radio Head (Nokia AEQE, 64TRx) + 2x gNB (Nokia Airscale), coverage area: Fraunhofer HHI/TUB campus.
        - Extension of coverage area to lanolin plant (north of TUB campus) planned for Q3/2023.
- Indoor components:
    - O-RAN system: 4x RU (AirVelocity) + 2x DU, CU (Airspan O-RAN, Dell).
    - Mobile 5G SA system: 2x RRH (Nokia Airscale) + 1x gNB (Nokia, network digital automation cloud)
    - OpenAirInterface deployments based on USRPs (several B210, X310, N320)
- Available 5G Cores:
    - NG4T, Athonet, MECSware, Open5GS, OpenAirInterface, Nokia (for indoor pico cell)

The following UEs have been tested so far in the testbed*:*

- *Modems: Telit FN980 / FN980M, Quectel RM500, Robustel R5020, Hongdiang X2,*
- *Smartphones: Google Pixel 5, Huawei P40 Pro*

The following network test equipment is available:

- *VIAVI CellAdvisor 5G, 5G-Analyzer*
- R&S®TSMA6, R&S®ROMES, QualiPoc

The overall testbed architecture of the testbed (SDR-based part of the testbed not included) is shown in the figure.

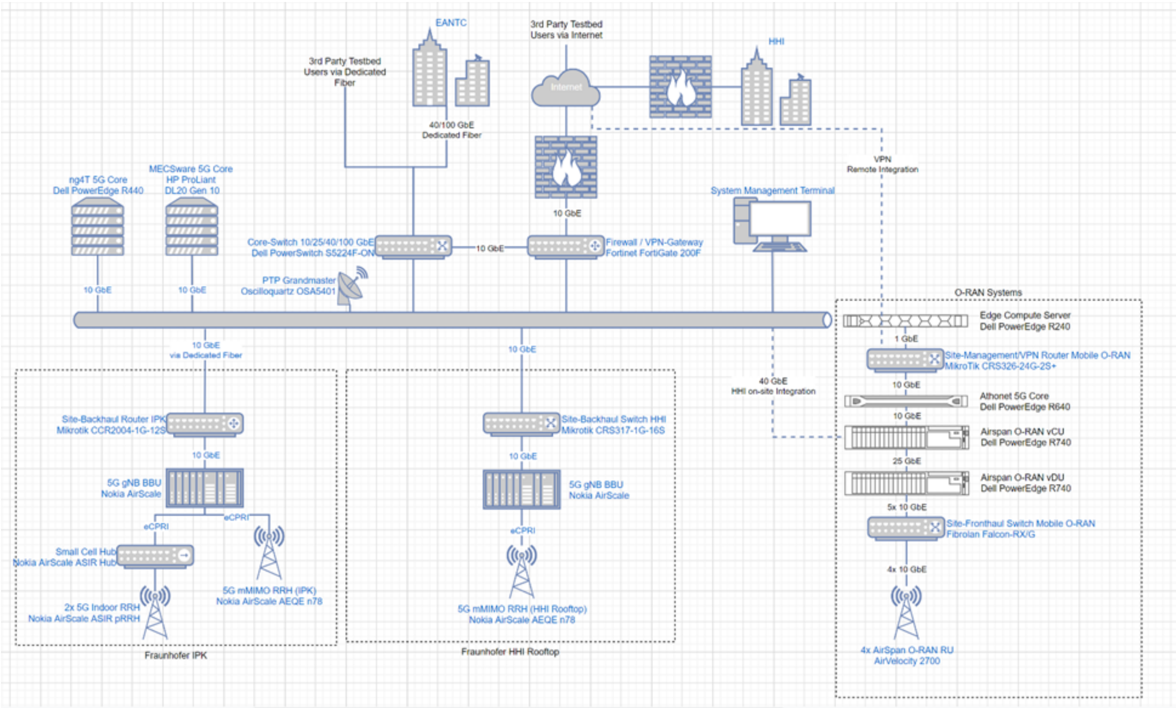

Figure 19: Current testbed architecture of outdoor and indoor testbed at HHI (SDR-based part of the testbed not included)

5.5.6.3 Planned Extensions and Activities in 5G Opera

The testbed is intended and open for the integration and test of WP4/WP5 components. Currently, it is mainly planned to be used for the test of QoS and network slicing related functionalities (with focus in use cases in the area of industry 4.0). Moreover, selected components from WP5 shall be tested, in particular, AI-based network optimization functions (x/r-Apps).

In the following month the testbed will be extended with a second outdoor location, which is also located close to the TU-Berlin campus.

The testbed is open in principle for the integration of all project developments (provided there are enough resources for integration). Already planned is to integrate the 5G Opera work on OpenAirInterface (DU/CU) into the testbed both in indoor and outdoor small cell deployments together with a suitable RU. For the testing of x-Apps/r-Apps suitable RAN intelligent controller components need to be deployed (it is not yet decided, which platform will be used).

In addition, a close cooperation with TU-Berlin w.r.t. RU developments in 5G Opera is planned.

Connectivity to the testbed can potentially be provided by static VPN tunnel or VPN login.

6 Gap Analysis

In general, open RAN solutions are still in their infancy. Even commercial products available today have sometimes issues to interoperate with other vendors as the experiences from the testbeds show. In this section we focus on the software and hardware used in the 5G-OPERA project and what gaps there are in order to implement private 5G networks.

6.1 OpenAirInterface

The current OAI distribution is providing a great open source solution for 5G CORE and RAN. It implements a large set of features and serves as a research and interoperability platform for a wide audience.

The recent feedback from the community shows that deploying OAI in a commercial product is feasible but still requires too much effort. This includes ad-hoc development of non-functional features, as well some significant efforts for stability and performance improvements.

Users are often also commenting on the difficulty of getting a system working quickly. A specific attention should be paid to the documentation, packaging and any aspect that makes the software usable from the get go.

6.1.1 Documentation, Specification and Tools

- Standard Compliance Matrix
- Better documentation of features
- Better documentation of performance and computing requirements
- Better documentation of parameters and usage

6.1.2 Non-functional development

- Better log management
- Better error handling and recovery
- Configuration management
- Fault management

6.1.3 Performance improvements

- Improve channel coding offloading performance
- PDCP (de-)ciphering
- RoHC

6.1.4 3GPP RAN features

- Support for Multi cells per DU
- Support for Multi DRB per UE
- Extend Handover support for intra-gNB via F1 and inter-gNB via Xn interface.
- Multiple QoS flows and network slicing (scheduler)

6.1.5 O-RAN features

- complete support of O-RAN 7.2 fronthaul (CUSM-plane) & interoperability with commercial RUs
- O1 interface
- E2 interface interoperability with 3rd party RICs and xAPPs.

-

6.1.6 Testing

- Increase coverage of tests
    - Different traffic (UDP, TCP, etc)
    - More UEs
    - Different channel conditions
    - long term testing

6.2 Acceleration

The current Xelera Suite is providing all features required for an O-RAN standard Accelerator Abstraction Layer (AAL). However, it is still lacking any kind of integration for accelerators used within this project, such as NXP and Kalray. Furthermore, there are no integrations for required interfaces, such as FAPI and FHI, yet.

6.3 Open 5G-Cores

Most of the available 5G core networks are commercial which means that integration and installation effort are less than the open source core networks. However, interoperability of these core networks with RANs from different vendors still have implementation challenges. The core networks not only need to be interoperable with RANs from different vendors, but also need to fulfil the requirements in the specifications. Moreover, different interpretation of specifications is possible which increase the complexity of the integration process.

Furthermore, the available core networks do not provide all network functions in the standard, I.e., release 16 and further. For instance, Location Management Function (LMF) function is in scope of this project to be developed and not provided in available core networks. Another challenge is that core network and TSN need to be integrated for industrial use cases.

Finally, many tests such as performance, stability, coverage and load tests and work need to be done to make core networks work with RANs from various vendors. Most advanced core network is based on release 16 although the 3GPP has introduced new network functions in release 17 [49]. For instance, MB-SMF, MB-UPF, MBSF, and MBSTF core network functions which support Multicast Broadcast Services (MBS) that can be necessary for private 5G. Some interfaces should be implemented to make core network interoperable. These interfaces are N1 (between the UE and AMF), N2 (between the RAN and the AMF), N3 (between the RAN and the UPF), and N4 (between SMF and the UPF).

7 Conclusions and Outlook

This deliverable presented the regulatory conditions applicable to private 5G networks in Germany and France as well as the main uses cases of private 5G. We then give an overview of the 5G system with a special focus on open RAN deployments, which is going to be the prevailing technology for deploying private 5G networks. These deployments allow for use-case and site-specific optimizations using the RAN intelligent controller (RIC). We then give a state-of-the-art overview of all the different components available today to build such networks. It can be seen that many products are already available on the market, but most of them are not yet mature enough for real deployments or that they are not yet interoperable with other vendors. The report concludes with a gap analysis of what would need to be done to make these products ready for deployment.

This deliverable is the first in a series that will define the work that we will carry out in the 5G-OPERA project. D3.2 will define the reference architecture that we will use in the project, while D3.3 and

D3.4 will define the requirements of both open RAN and open Core solutions. All these deliverables will serve as an input to WP4 and WP5 where the development work will be carried out. Finally, WP6 will demonstrate our developments on real testbeds.

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