ICT-56-2020 "Next Generation Internet of Things"

Grant Agreement number: 957218

IntelliIoT

Deliverable D4.6
5G Network Functionalities (final version)

Deliverable release date	18/01/2024
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Status of the Document	Final
Version	1.0
Dissemination level	Public

Table of Contents

1 INTRODUCTION

This deliverable, being the final output of Task 4.6 ("5G network functionalities"), aims to describe the design and implementation of 5G functionalities required by the third pillar ("efficient, reliable and trustworthy computation & communication infrastructure") of the IntellIoT proposed framework. This pillar aims at addressing two of the 5 IntellIoT identified objectives.

Objective 2: Enable ultra-reliable low-latency communication over heterogeneous networks to enable tactile (real-time) and contextual (adaptive) interaction between IoT devices, humans, and services.

This deliverable describes the state-of-art architecture and standard of 5G network, as well as results obtained to meet this objective. In particular, this deliverable presents the 5G network functions supporting Ultra-Reliable Low-Latency (URLL) communications.

Objective 5: Development of a reference implementation of the IntellIoT framework, demonstrated and evaluated in the three use case areas: agriculture, healthcare and manufacturing.

This deliverable provides the description of the 5G architecture proposed to be developed for the IntellIoT framework, as well as the set of 5G network functions, which have been deployed in the different use cases.

As 3GPP is a constantly evolving set of specification, IntellIoT developed its innovation based mostly on 5G NR rel. 15 and rel.16 for framework development and implementation, while anticipating future 5G NR rel.17 and rel.18 in its research and evaluation. The developments of the 5G network is based on EURECOM's OpenAirInterface and Mosaic5G, where the required functions have been built upon existing NR & MEC/Edge functionalities.

From the Component perspectives, 5G Network Functions consists of the 5 components emphasized on Figure 1 in red First, private 5G Core and RAN has been developed to support private 5G NR radio access for IntellIoT functions, in particular URLL. Second, a 5G low latency MEC has been developed to deploy edge applications close to a 5G edge and therefore reduce the service latency. Finally, O-RAN compatible 5G network monitoring component has been developed to provide 5G statistics and real-time performance to other components, in particular the Edge Orchestrator and the 5G Communication Resource Manager.

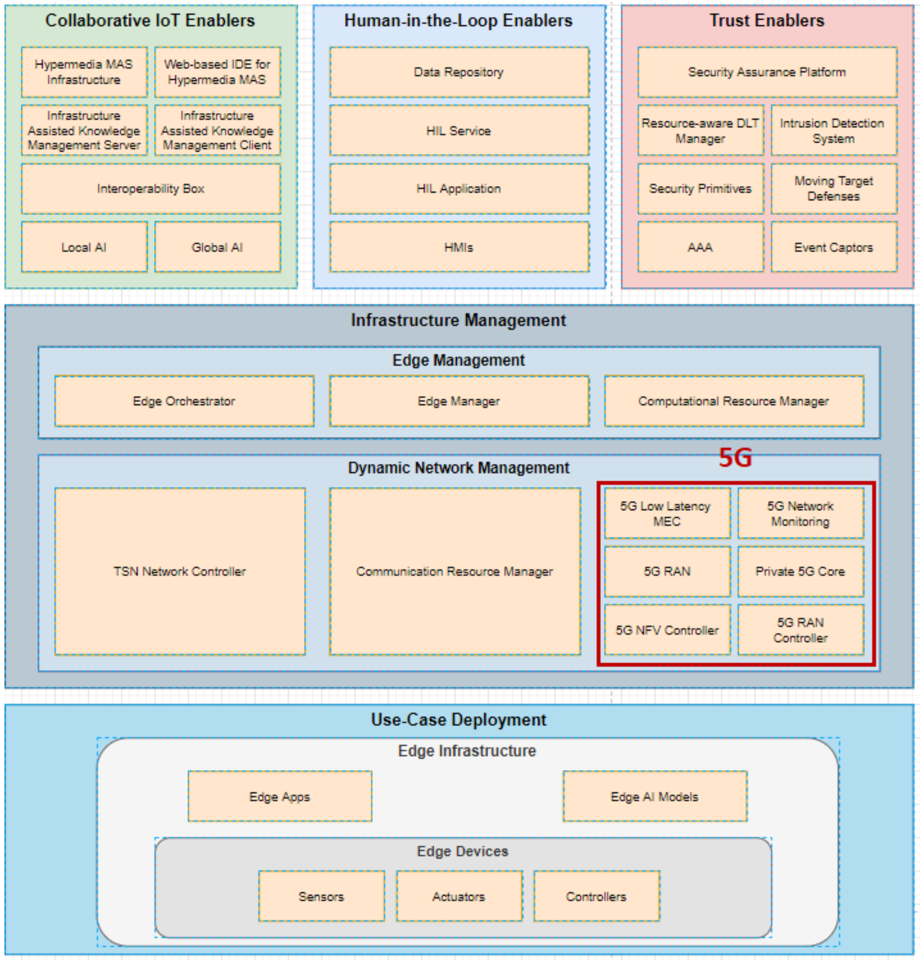


Figure 1 IntellIot Component Architecture, with the 5G part highlighted

As it can be seen on the component architecture of Figure 1, the 5G components have a strong interaction with other components developed in different tasks and WPs. In particular, T4.2 takes input from Task 2.1 ("Use cases specification & Open Call definition "), Task 2.2 ("Technology analysis & requirements specification "), and Task 2.3 ("Architecture specification & interoperability") related to the use case objectives, and required components.

Dedicated 5G Edge/MEC APIs are provided for the MEC/Edge services from T4.5 (" IoT/edge infrastructure management "), and the 5G dynamic management solutions developed in Task 4.7 ("Dynamic network management ") has been integrated into the 5G architecture to meet the 3rd pillar requirements and optimize the use of the wireless resources. Finally, the output of Task 4.8 ("Trustworthy infrastructure by design") has been considered in the design of the 5G network functions.

Finally, the outcome of the IntellIoT 1st Cycle in various WPs has been closely considered to enhance the 5G Network Functionalities developed in the 2nd Cycle. More details of the interplay between Task 4.6 and other tasks or WP are depicted on Figure 2.

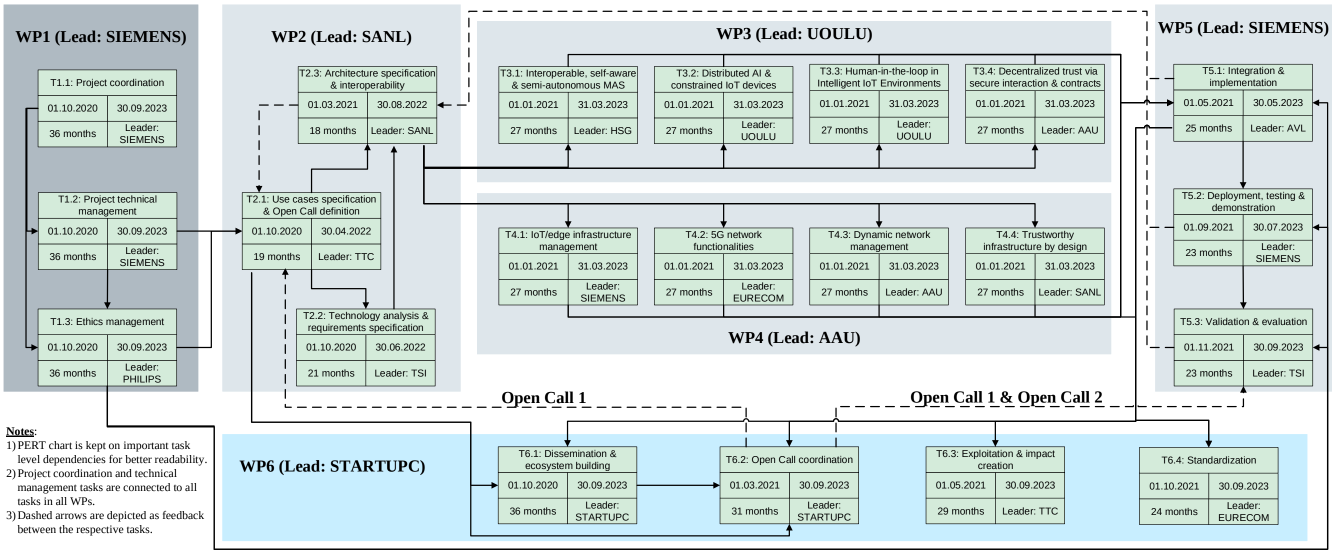


Figure 2 Interplay between IntellIoT tasks and work packages

Task 4.6 follows IntellIoT cycle-based development depicted in Figure 3, which consists of two sequential cycles, coinciding with one Open Call. The Cycle-based prioritized developments of Task 4.6 are described below.

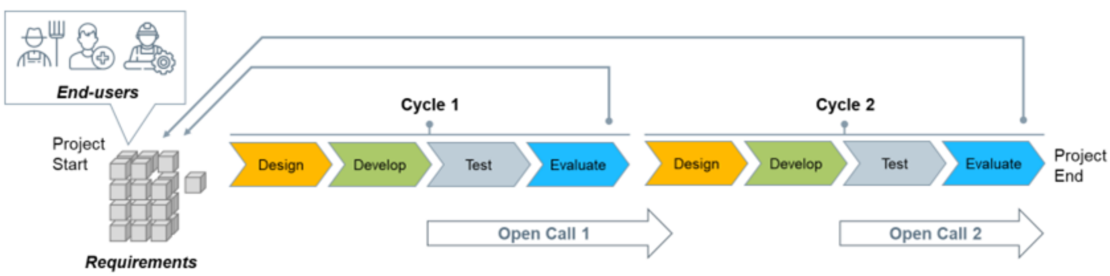


Figure 3 IntellIoT Cycle-based development

Task 4.6 contributed to reaching the following four key performance indicator (KPI).

KPI 2.1: Extending 5G network functionalities supporting URLL & eMBB for the needs of the 3 use cases.

Task 4.6 extended OAI and Mosaic5G to support a standalone 5G NR network for a frequency range < 6Ghz. It has been developed and evaluated in a controlled environment enhanced 5G numerology matching URLL requirements. Task 4.6 also extended the 5G NR network to millimeter wave spectrum (>20Ghz) and validate the new URLL numerology in the target environments at both frequency ranges. TRL 5 has been reached.

KPI 2.2: TSN functions integration in computation & communication infrastructure (combined with 5G)

In Task 4.6, preliminary TSN extensions to 5G network to support an end-to-end TSN link has been considered. A limited TRL level 3 has been met due to the prospective status of the 3GPP standards in that domain.

KPI 2.3: Enabling heterogeneous networking technologies: LTE, 5G NR, Cellular IoT, D2D

Task 4.6 extended OAI 4G architecture to support 5G. Heterogeneous technologies has been reached through the support of two 5G architectures called non-standalone and standalone, where the former has heterogeneous technology limited to the wireless part, while the latter extends the former with heterogeneous technologies on the network side.

KPI 2.4: Enabling wireless TSN-grade D2D scheduler for decentralized computing in IoT context

Task 4.6 evaluated the performance of the state-of-art 5G NR V2X technology, where the D2D links have a prominent role. It also proposed advanced mechanisms to support TSN-grade D2D radio resource management in terms of ultra-reliability and guaranteed low delay.

1.1 Key 5G Innovations for 5G Infrastructures

While the general public considers 5G as providing only higher capacity on Radio Access Network (RAN), the reality is that 5G provides not only high rates but prominent new functionalities in terms of dynamic management and optimization of all 5G functions. We describe them next.

- **5G Private Network** - This corresponds most likely to the biggest innovation of 5G in terms of enabling 5G not only being virtually operated but physically operated by various stakeholders. 5G Private Networks consist of being able to host and operate a 5G network in a particular location, and controlling all aspects of such network. First, 5G spectrum should not be commercial and be available to private 5G operators. For this, private spectra are gradually being defined in various EU countries. Second, it involves operating a 5G network, therefore, hosting a 5G Core at the premises. Finally, it is required to control data flow within the private 5G network, therefore, maintaining a strict privacy and accountability for data gathered by a particular stakeholder.
- **5G URLL** - The target objectives of 5G network are to reach the 1 ms RAN latency as well as >3 Gbps RAN capacity. Reaching a 1 ms RAN latency requires a more flexible radio resource numerology in order to avoid multi-subframe resource allocations. It also requires a larger bandwidth, which could be reached over millimetre wave spectra (a.k.a. FR2). It finally needs to have an optimal data-driven radio resource allocation entity, which could be capable of anticipating/predicting the required resources and reserve the ones providing the most reliable and lowest latency.
- **5G Edge/MEC** - Low latency must not only be guaranteed on the RAN links, but also in the back-end links. Accordingly, 5G applications and services should be deployed closer to the UE point of attachment. 5G edge/MEC architectures are another key 5G innovation, enabling applications to be deployed, managed and optimized at the network edge. 5G Edge refers to 3GPP whereas MEC is a similar concept from ETSI. Accordingly, a harmonization between 3GPP and ETSI is currently being done to propose a harmonized 5G architecture enabling web technology solutions to be fully integrated in 5G networks.
- **5G D2D** – while D2D communications have already been proposed in 4G, its limited functions or limited 4G links did not provide the expected success from such radical innovation. 5G D2D is being developed, with 5G V2X specification already being available, to benefit from the 5G RAN and Core innovations for D2D. For example, 5G D2D is expected to support URLL, slicing as well as decentralized edge applications.
- **5G TSN** – While TSN is critical in industrial networks, its availability in the wireless domain has so far been limited to sensor or WIFI technologies. With the development of Private 5G networks, TSN support becomes necessary to guaranty the successful deployment of private 5G networks in various industrial stakeholders and avoid technology segmentation within their industry. 3GPP proposes various architecture extensions to support TSN for 5G, with the objective at the same time to support TSN protocols within 3GPP networks and

through GTP tunnelling, to support time-controlled scheduling at the radio resource management and finally to keep TSN timing transparent over a 5G network.

Task 4.6 addresses all five key 5G innovations as a function of the cycle-based development previously described. The OpenAirInterface (OAI) [1] platform has been selected as 5G technology in IntellIoT. OAI is the only open-source software project today delivering implementations of both 5G NSA and SA RAN (eNB, gNB, nrUE). Moreover, it achieves interoperability with OAI 4G and 5G Core networks considering standalone and non-standalone setup respectively as well as with COTS UE devices, spanning the full protocol stack of 3GPP standard and offering an end-to-end, native OAI solution. This is feasible by running the OAI software on top of general purpose x86 processors. Accordingly, IntellIoT 5G network architecture will be built on top of OAI.

KPI 2.1 proposes a 5G Private Network supporting 5G URLL, KPI2.3 covers 5G Edge/MEC heterogeneous managing functions, KPI2.2 provides a TSN-compliant 5G network supporting TSN functions, while KPI2.4 develops TSN-grade 5G D2D schedulers.

1.2 Relation to IntellIoT use cases

The 5G key innovations mentioned above play a central role in Next Generation IoT (NG-IoT), and therefore, in each of the IntellIoT use cases, as explained next.

1.2.1 AGRICULTURE (UC1)

Figure 4 depicts a schema of the NG-IoT services developed by IntellIoT for UC1. It also shows where 5G technologies play a major role. First, the IntellIoT will build a private 5G network supporting a 5G Edge/MEC for low latency service access. Second, the radio link between the tractor and the IntellIoT infrastructure will be based on 5G NR supporting URLL communications mostly in DL in order to support remote controlling from a distant remote operator and transmit video feedback in from the tractor to the operator. In order to further reduce latency, 5G NR in FR2 will be developed to provide increased capacity for URLL traffic. Finally, considering the potential benefit of drones to provide extended perceptions or additional AI/ML management, V2X communication can be used for connecting the tractor and the drone, although, this feature has been considered only at the theoretical level and not in the final demos.

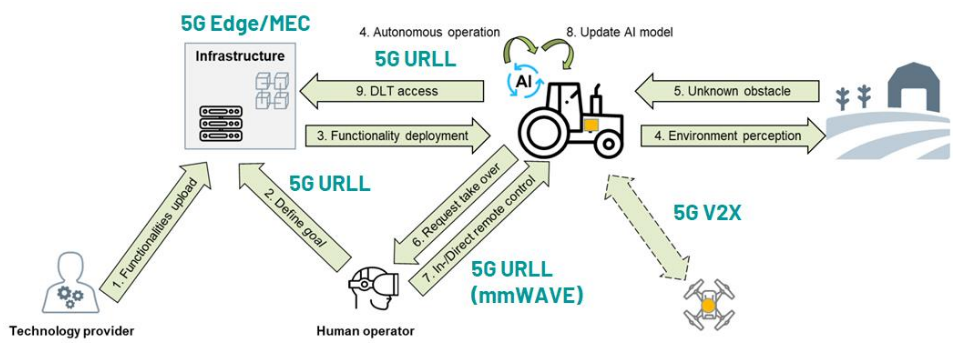


Figure 4 Impact of 5G on the Agriculture Use Case

[1] OpenAirInterface - https://openairinterface.org/

1.2.2 HEALTHCARE (UC2)

Figure 5 depicts a schema of the NG-IoT services developed by IntellIoT for UC2. It also shows where 5G technologies play a major role. Compared to UC1, the 5G challenges here are not low latency or reliable 5G communication, but massive IoT data to be transmitted between personal IoT devices and a 5G Edge/MEC platform. The 5G Edge/MEC platform not only plays a role to manage AI/ML mechanisms towards smart health recommendations, but also to store data in a private space, irrespectively if the 5G network is public or private. Considering the proposal of IntellIoT not to transmit patient data but AI/ML models, such private Edge/MEC is the guarantee by IntellIoT that highly sensitive patient health data remains confidential. Although 5G IoT technologies are currently being drafted by 3GPP, it is anticipated that they have to support massive amount of IoT data transmitted in UL. The current lack of 5G IoT devices or even prototypes, and the 3GPP postponing of 5G IoT to Rel.18 influenced IntellIoT not to fully rely on 5G IoT technologies but rather on improved 5G NR technologies. This should not be considered as a scale down option for two reasons. First, the expected size of AI/ML models are not expected to fit to the current specification of 5G IoT (massive amount of small size). Second, the sensitivity of data transmitted between personal IoT devices and a 5G Edge/MEC are not expected to be massive locally. However, it is expected that massive AI/ML model exchanges between Edge/MEC might be required for cross-domain/cross site AI/ML federation, for which the IntellIoT project has developed a solution.

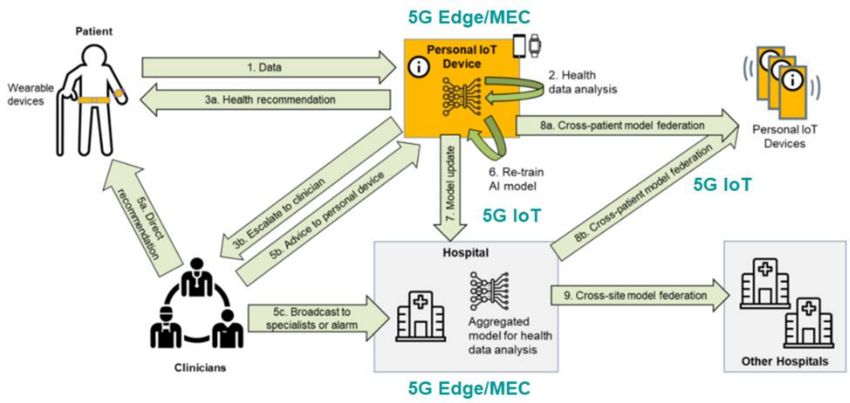


Figure 5 Impact of 5G on the Healthcare Use Case

1.2.3 MANUFACTURING (UC3)

Figure 6 depicts a schema of the NG-IoT services developed by IntellIoT for UC3. The 5G impact on this UC is similar to UC1 with the following major differences. First, unlike UC1, a wired TSN connection is expected between a robot and a 5G Edge/MEC, 5G URLL is provided between the plant operator and the 5G Edge/MEC in AR. Accordingly, 5G URLL in that case is more critical in UL rather than DL. Second, compared to UC1, this UC tests 5G in indoor instead of outdoor scenarios. Indoor vs outdoor scenarios change the 5G capacity, in particular considering FR2. 5G V2X technologies are also envisioned in order first to enable a direct link between the plant operator and the robot when he is next to it, but also a multi-robot direct communication either for AI/ML direct exchange or to synchronize potential movements. The latter has been considered at the theoretical level and it is not part of the final demos.

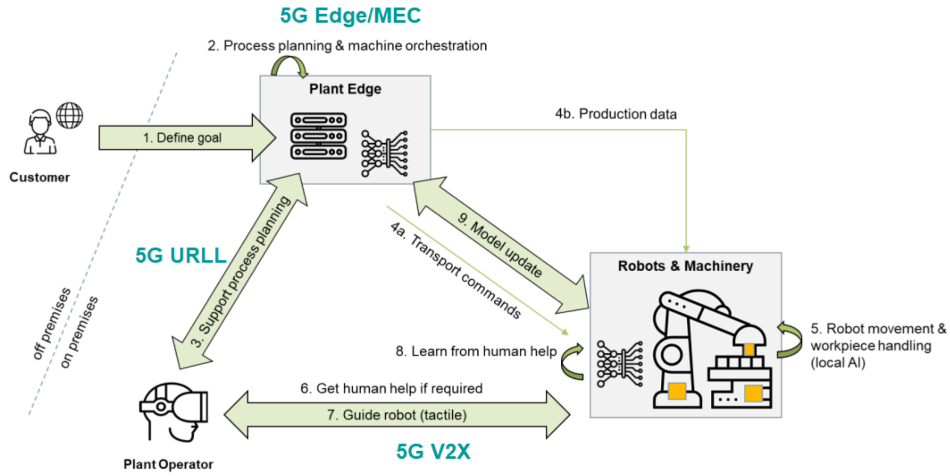


Figure 6 Impact of 5G on the Manufacturing Use Case

1.3 Deliverable Outline

To present the above 5G innovations and their applications to the three IntelIoT use cases, this deliverable is organised as follows:

- Chapter 2 introduces 5G technology concepts as well as the development platform used for IntelIoT. It provides a description of the current standards for 5G networks as well as for Edge computing, both aspects being at the heart of 5G innovations for IntelIoT. Second, it describes the OpenAirInterface platform and its more recent architecture supporting 5G. This chapter finally describes the details of the applications of the described 5G innovations in each of the IntelIoT use cases.
- Chapter 3 provides more details of the technical development on the OAI platform to support the availability of the targeted 5G innovations. In particular, it shows the first tests of 5G connectivity between OAI and a COST UE both in non-standalone and standalone step-ups. It then describes the new components developed on Mosaic5G to support dynamic management of 5G networks.
- Chapter 4 provides details on the 5G D2D innovations, starting with a state-of-art overview of 5G Proximity Services and the differences between D2D and V2X mechanisms. Second, it presents simulation-based performance evaluation results of the capability of current 5G V2X technology as well innovations related to new TSN-grade V2X schedulers.

2 5G NETWORKS AND PLATFORMS

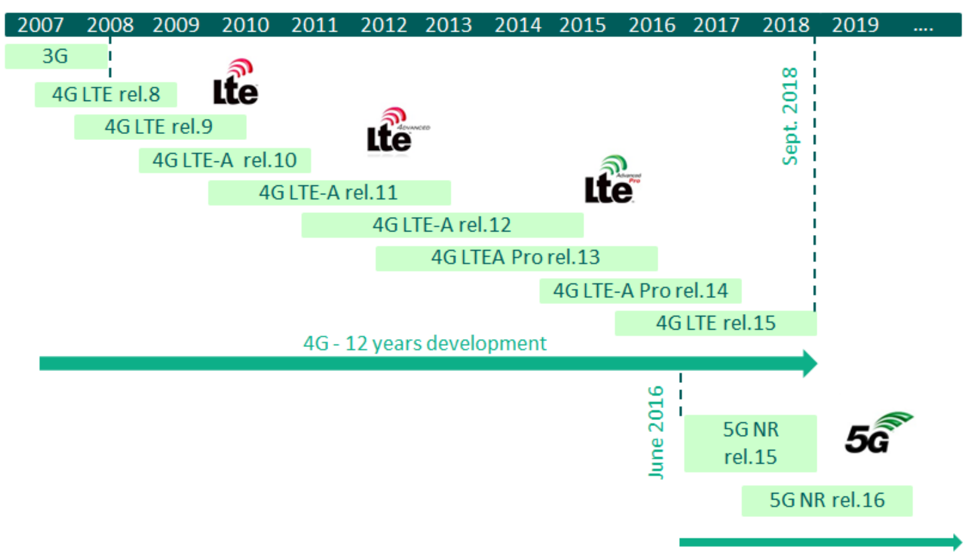
We provide in this section the state-of-art of 5G Networks as well as a description of the OpenAirInterface Open5G platform, which has been used and extended in IntellIoT.

2.1 Brief Introduction to 3GPP Release-based Development

3GPP develops cellular technologies considering three denominations: generations, releases and commercial names.

The *generations* correspond approximatively to 10-12 years of development. For example, as depicted the figure below, LTE appeared in 2008, while 5G appeared in 2018. The underlying specifications consisting to a particular 'generation' are called *releases*. A release (a.k.a. rel.) corresponds to a new *release* of the 3GPP specification including the addition of new functions developed for that *release*. This enables 3GPP to select and prioritize functions and components to be developed first, and leave other components to be included to later releases. For example, if enabling Proximity Services with LTE has been planned almost at the early phases of the 4G cycle (rel. 8), it has been defined only at the 12th release (rel.12), and applications to the automotive industry postponed to rel. 14. A release is said to be 'frozen' when its set of specifications is finalized and could be transferred to industrial stakeholders for production. A release is not bound to a cycle, as required modification for the 3G cycle may be added in a release currently being developed for the 5G cycle. Also, not all releases end up in productions. Accordingly, commercial names correspond to a full or partial compliancy to a particular release, which will be produced by industrial stakeholders. For example, LTE corresponds to full compliancy to the 8th release for LTE, and LTE Advanced Pro to partial compliancy to LTE Rel. 12 functions.

The 5th Generation (5G) cycle development started in 2016 with the first 5G NR rel. 16, but LTE continues to be extended even in rel.16 and rel. 17. The most recent 5G NR frozen release at the time of writing is 5G NR rel. 16, and IntellIoT will be based on 5G Network from rel. 15 to rel. 17.



2.2 5G Core & Radio Access Network

A brief introduction/overview of the key features of a 5G network according to the 16th release is provided in this section.

2.2.1 5GS REFERENCE ARCHITECTURE AND FUNCTIONS

The reference architecture of the 5G System (5GS) is illustrated in Figure 7. While the UE, RAN and to some extend the Data Network (DN) entities are similar to an LTE architecture, the 5G core (5GC) significantly evolved. A brief description of each entity is provided below.

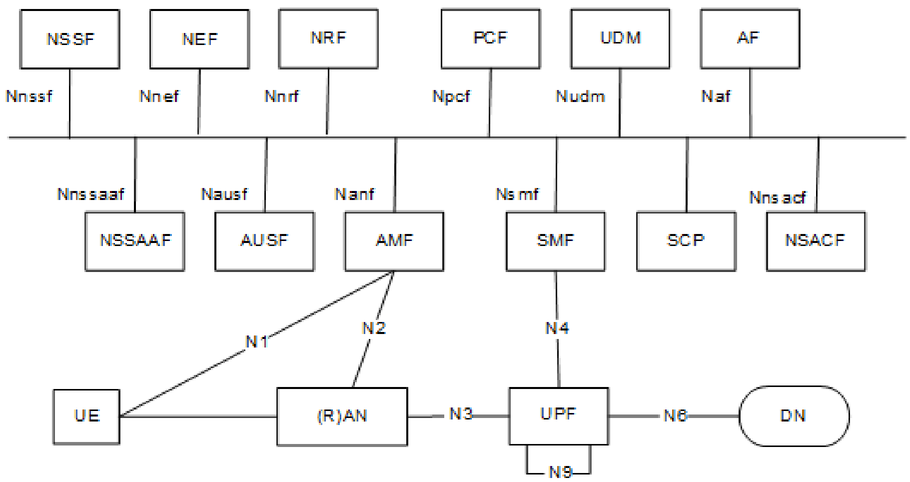


Figure 7 Illustration of the components of the 5G Core

5G NR RAN Functions:

- **UE –** User Equipment, representing a 5G equipment capable of connecting to the 5G RAN.
- **RAN –** Radio Access Network, provides radio access to between a public/private network and UEs via radio links.
- **UPF –** User Plane Functions, support similar functionalities as S-GW and P-GW entities in LTE, enhanced to support network virtualization via Control and User Plane Separation (CUPS). It provides Packet routing & forwarding functions as well as IP address/prefix allocations, as well as the critical User Plane part of policy rule enforcement, e.g., Gating, Redirection or Traffic steering.
- **DN –** Data Network, IP or non-IP based network, outside of the scope of 3GPP, which can either correspond to the Internet or a private data network.

5G Core Functions:

- **AMF –** Access and Mobility Function, first entity connected to UE and RAN (gNB), which role is to provide various management tasks (registration, connection, reachability, mobility, access authentication and authorization). AMF is connected to the RAN and UE via the N2 and N1 reference point respectively.
- **SMF –** Session Management Function, provides session management (establishment, release, modification of sessions, tunnelling between a UE and UPF), IP address allocation, DHCP or ARP functions. The SMF is connected to the UPF via the N4 reference point.
- **PCF** – Policy Control Function, provides policy rules to Control Plane function(s) to enforce them.

- **NEF –** Network Exposure Function are critical to 5GS, as it enables to expose network functions to external entities without giving them access to the 5GS. Typical network functions exposed are network capabilities, secured provisioning of data from external networks, or translation between internal-external information.
- **NRF** - Network Repository Function maintains an up-to-date repository of network functions available in the 5G core. Network functions are key innovations of 5G and includes the previously described functions as well as MEC or D2D functions for instance.
- **UDM** – Unified Data Management handles several functions as generating AAA security credentials, access authorization, lawful interceptions etc...
- **AUSF** – Authentication Server Function deals with authentication mechanisms for 3GPP and untrusted non 3GPP entities.
- **AF** – Application Function interacts with other 5G core functions to support 3GPP services such as application influence over routing, time synchronization services. ProSe or V2X Application servers or TSN are typical illustration of AF.
- **NSSF** – Network Slide Selection Function, as its name indicates, deals with managing and selecting the appropriate network slice serving a UE and selecting the most appropriate AMF dealing with that slice.

Additional functions, such as NSSAAF, NSACF, further complete the multi-function 5G Core.

2.2.2 5G USER PLANE PROTOCOL STACK

Figure 8 depicts the 3GPP protocol stack for the User Plane for a PDU session. Independently to the end-to-end Application sessions (or even IP sessions), a PDU session must be initiated between a UE and its UPF function in the 5GC architecture. The PDU layer corresponds to the PDU carried between the UE and the DN over the PDU Session, as IPv4, IPv6 or Ethernet. GTP-U is a useful 'fossil' from the GPRS time, which is designed to tunnel data packets between the 5G RAN and the corresponding UPF (i.e., tunnelling non 3GPP PDU within a 3GPP network). As it can also be seen, a key role of the 5G (R)AN is also to map the RAN-specific protocol stack (3GPP or non-3GPP) to the more traditional L1, L2 and IP stack.

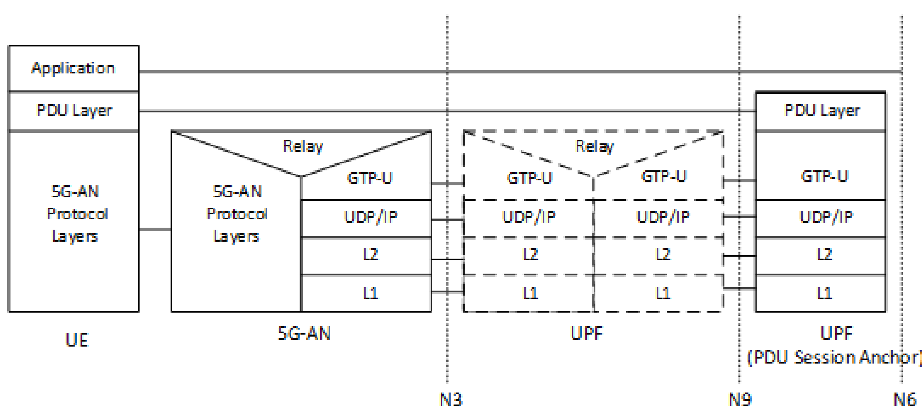


Figure 8 3GPP protocol stack for the User Plane

2.2.3 5G QOS FLOW MANAGEMENT

A 5GS QoS model is based on 5G QoS Flows, which are defined by a QoS Flow ID (QFI) and a QoS Flow Profile (QFP), the latter depending mostly on two parameters:

- **5QI** – 5G QoS Indicator which is defined by a set of parameters, such as the resource type (GBR or non-GBR), the priority level, the packet delay budget or the target packet error rate.
- **ARP** – Allocation and Retention Priority, which defines the global priority level of the QFP in particular when flows need to either being dropped or pre-empted by more important flows in case of traffic congestions.

2.2.4 5G STANDALONE AND NON-STANDALONE SETUPS

The development potential product availabilities of 5G RAN and 5GC did not progress simultaneously, and in order not to delay 5G NR deployment, two 5G setups have been proposed:

- 5G non-standalone (NSA) - It represents the situation where a 5GC is not available and 5G RAN needs to work with a 4G EPC. In that case, only 4G services may be provided, but benefiting from the increased capacity of 5G NR.
- 5G standalone (SA) - in that configuration, a 5GC and 5G RAN are available and may operate without 4G. 5G services are provided, benefiting from the 5G NR increased capacity.

2.3 5G Edge

2.3.1 EDGE COMPUTING ARCHITECTURE FOR 5GS

While Multi-access Edge Computing (MEC), also known as Mobile Edge Computing, has been defined by ETSI and is popular to enable innovative services close to the consumer, 3GPP also proposed an Edge architecture in its rel. 17 specification. The generic edge architecture in 5GS for non-roaming case is depicted in Figure 9.

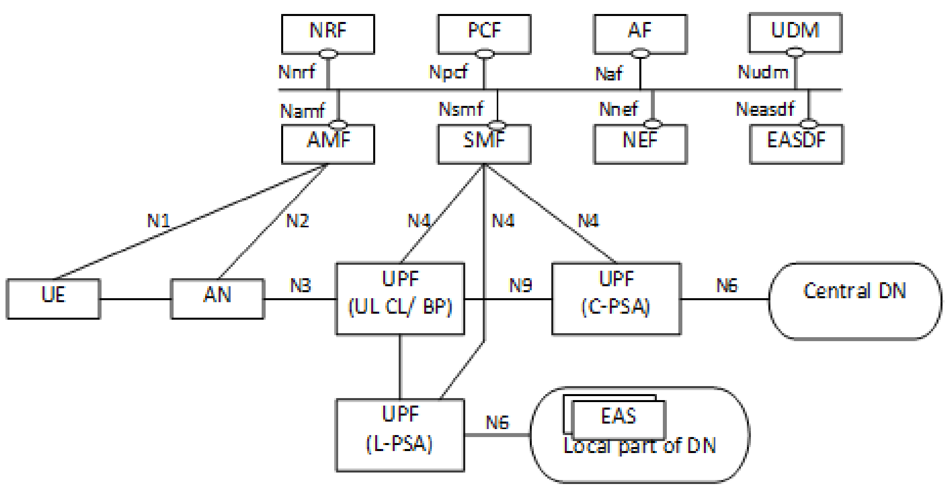


Figure 9 3GPP Edge architecture for a 5GS in non-roaming case

While the central DN can be considered as the home location of global services, a local part of DN is hosted also close to the AN. The local part of DN hosts one or more Edge Application Servers (EAS), which can be reached by a session breakout triggered by the UPF. In other words, according to a 5G QFP or other 5G-specific configurable parameters, a 5G Flow can be re-routed to a local DN rather than a central DN.

As illustrated on Figure 9, considering the C-PSA UPF being the central session anchor point for the service hosted in the central DN, a second 'intermediate' UPF function creates a breakout point according to an UL classifier (UL CL) and re-direct the selected flows to a third UPF, hosting the local session anchor point for the service hosted in the local DN. From a 3GPP perspective, an EAS is hosted on a DN, so its specification is out of the scope of 3GPP, but 3GPP provides edge functions and flow classifiers (UL CL) to re-direct traffic transparently to an EAS. As it can also be seen on Figure 9, UPF being user plane functions, the SMF hosts the control plane functions determining the re-routing parameters and triggering the local breakout according to various authorization, security and billing options.

3GPP defines three types of connectivity models for Edge Computing as depicted on Figure 10:

- **Distributed Anchor point** – a distance service supports distributed databases and processing, which are located at the edge. Accordingly, the UPF represents a distributed PDU session anchor point and connects the UE to the EAS hosted in the local DN.
- **Session Breakout** – according to 5G QFP and a UL classifier controlled by a 5G Core SMF, selected traffic can be re-directed to an EAS located on a local DN. Accordingly, a local UPF in in charge of the breakout point and act as a local anchor point.
- **Multiple PDU sessions** – in that configuration, different PDU sessions are created to either reach the central DN or the local DN.

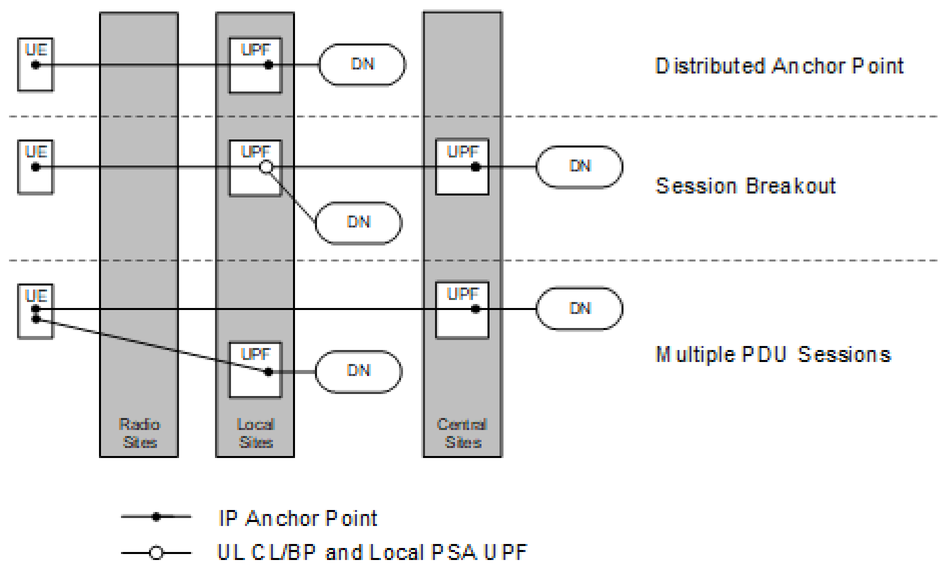


Figure 10 3GPP Edge Computing Connectivity Models

2.3.2 EDGE COMPUTING DISCOVERY PROCEDURE

Edge Computing enables operator and 3rd party services to be hosted in EAS close to the UE's point of attachment. The traffic to EAS can be routed based on the UE position and EAS availability "near to" that position.

3GPP defines 4 procedures to enable and manage edge computing on a 5GS. The most important one is the EAS discovery/re-discovery procedure, enabling a UE to discover the existence of an EAS close to its point of attachment.

EAS Discovery is the procedure by which a UE discovers the IP address(es) of a suitable Edge Application Server(s) using Domain Name System (DNS). EAS Re-discovery is the EAS Discovery procedure that takes place when the previously discovered Edge Application Server cannot be used or may have become non-optimal (e.g., at edge relocation). Accordingly, DNS service should be available to a 5GS both in local (L-DNS) and global (G-DNS) configuration. The L-DNS service can be reached through anycast addressing, and will resolve the current IP address of the local EAS.

2.4 OpenAirInterface 5G Platform

OpenAirInterface (OAI) is an Open5G Software Defined Radio (SDR) platform gathering a community of developers from around the world, who work together to build wireless cellular Radio Access Network (RAN) and Core Network (CN) technologies. Initially developed by EURECOM as a platform for SDR research on cellular technologies since 2.5G, OAI evolved to a major community-based software alliance led by EURECOM to enable open research and development of 5G wireless technologies. OAI is composed of three main projects.

2.4.1 OAI 5G RAN

The scope of the OAI 5G RAN project is to develop and deliver a 5G software stack under the OAI Public Licence V1.1. Figure 11 depicts the general architecture targeted by the OAI 5G RAN for both non-standalone and standalone modes.

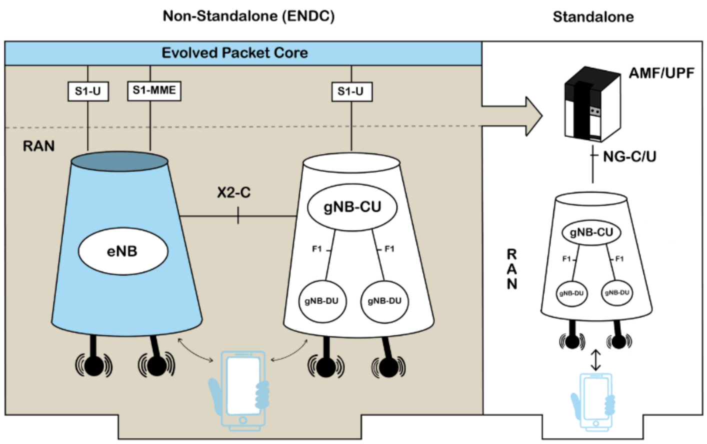


Figure 11 OAI 5G RAN NSA and SA architecture

2.4.1.1 OAI RAN SOFTWARE ARCHITECTURE

The OAI 5G NR software is depicted on Figure 12, both for the gNB and NR-UE case. The NGAP function connects to the 5GC AMF, whereas the N3 function connects to the 5GC UPF. The SDAP layer is an addition to the 5GS stack compared to the LTE stack. The SDAP (Service Data Adaptation Protocol) handles the QoS mapping and adaptation to radio resources and radio bearers.

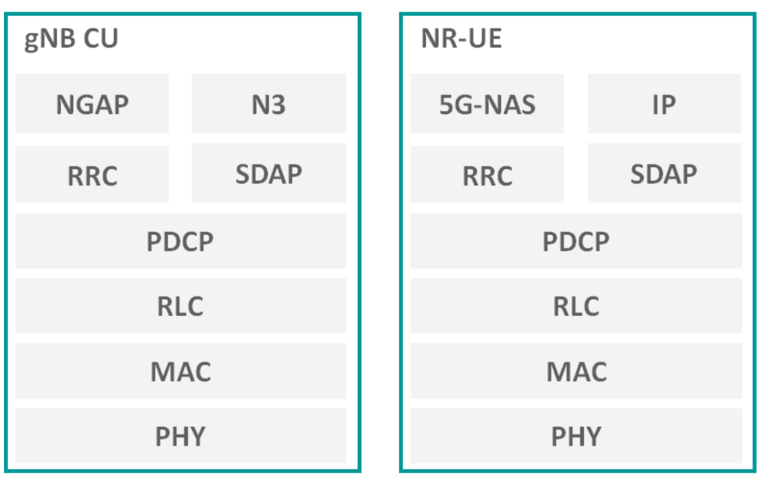


Figure 12 OAI NR RAN software architecture

The roadmap for the OAI 5G RAN is to test and prove components from Figure 13 , in particular adding SDAP functionalities and provide support for FR2.

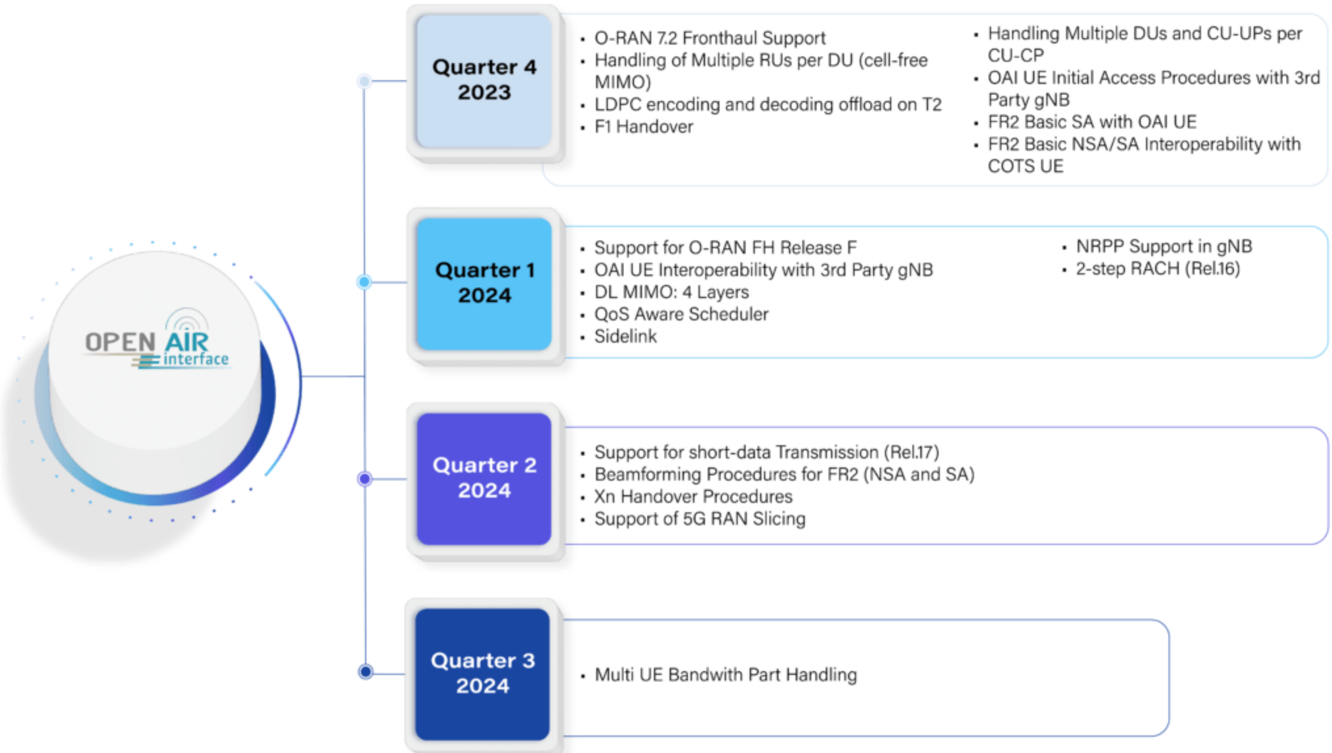


Figure 13 OpenAirInterface 5G RAN Roadmap

2.4.2 OAI 5G CORE

The OAI 5G Core architecture is depicted on Figure 14 . It shows the evolution of OAI 4G EPC towards 5GC, where old EPC functions are in white and new 5GC functions are in orange. This figure also allows to better understand the architectural difference between a 4G EPC and a 5GC.

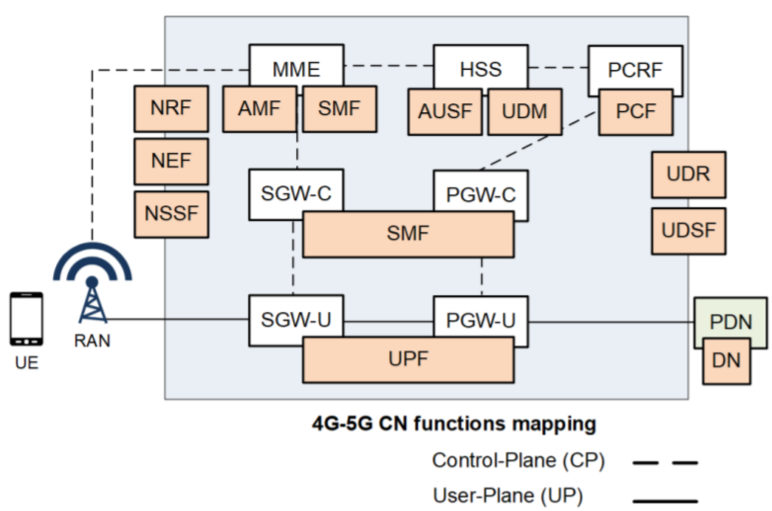


Figure 15 OAI 5GC architecture

OAI is actively working to develop a fully functional 5GC. The development roadmap is depicted on Figure 16.

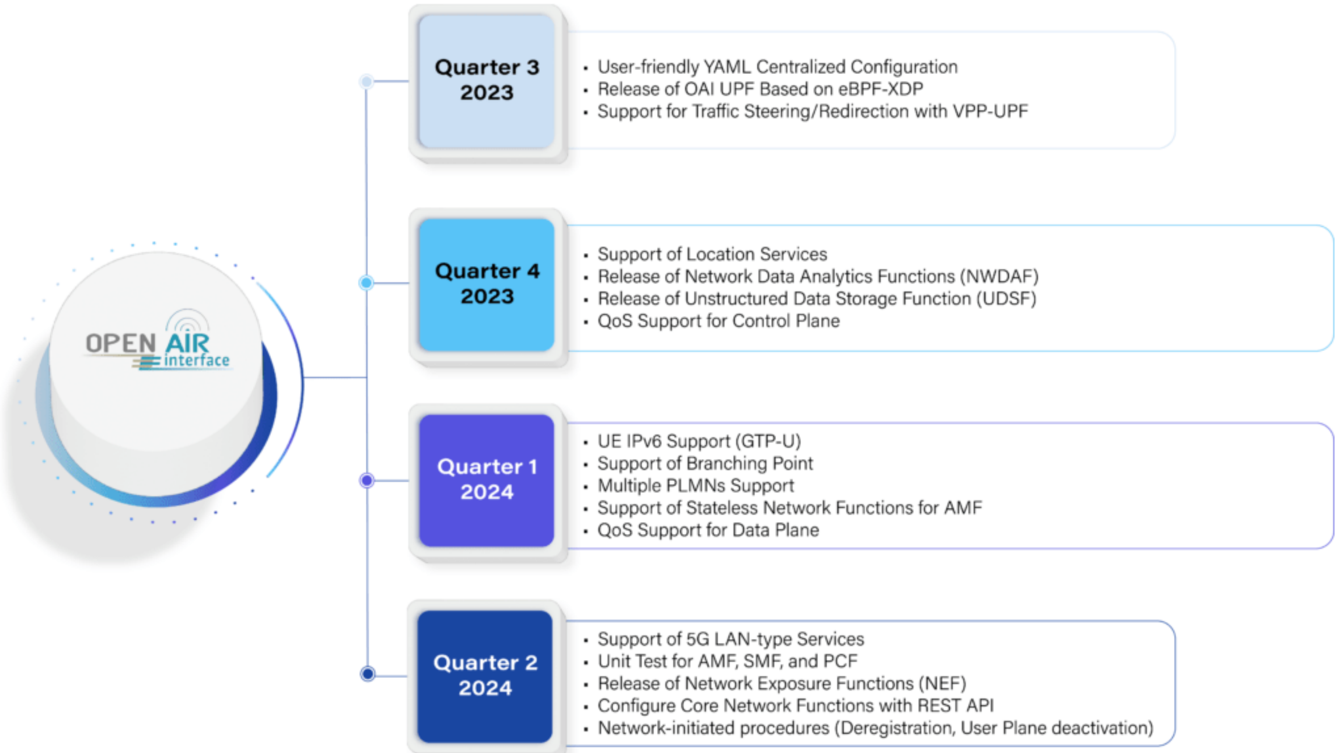


Figure 16 OAI 5GC roadmap

2.4.3 MOSAIC5G

Mosaic5G represents the architecture of the various flexible management functions of a 5GS. As depicted on Figure 17, Mosaic5G is built on top of OAI 5G-RAN and 5GC and has two main layers:

- **FlexRIC** – Flexible RAN Intelligent Control (RIC) providing dynamic control over RAN parameters (e.g., radio bearer configuration, QoS handling, slice parameters).
- **FlexCN** - Flexible Core Network (CN) mechanisms to support edge application servers (EAS) as well as dynamic low latency edge services, such as PDU local breakout points, as well as API supporting ETSI MEC functions.
- **Trirematics** - This layer represents the orchestration and management of the underlying layers. It provides components for controlling and monitoring resources, handling AI as well as storage of ready-to-use optimisation functions.

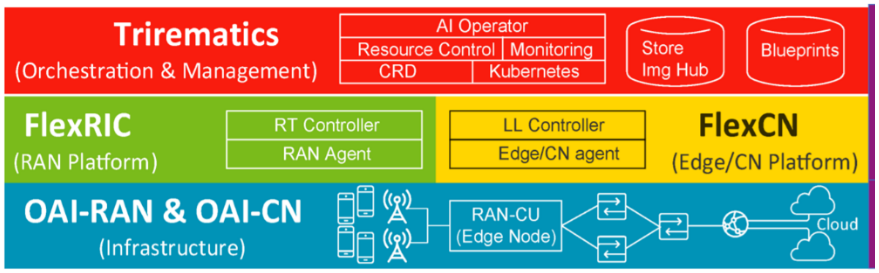


Figure 17 Mosaic5G Architecture

Mosaic5G 5G architecture is currently being developed as replacement of the 4G architecture according to the current roadmap depicted in Figure 18.

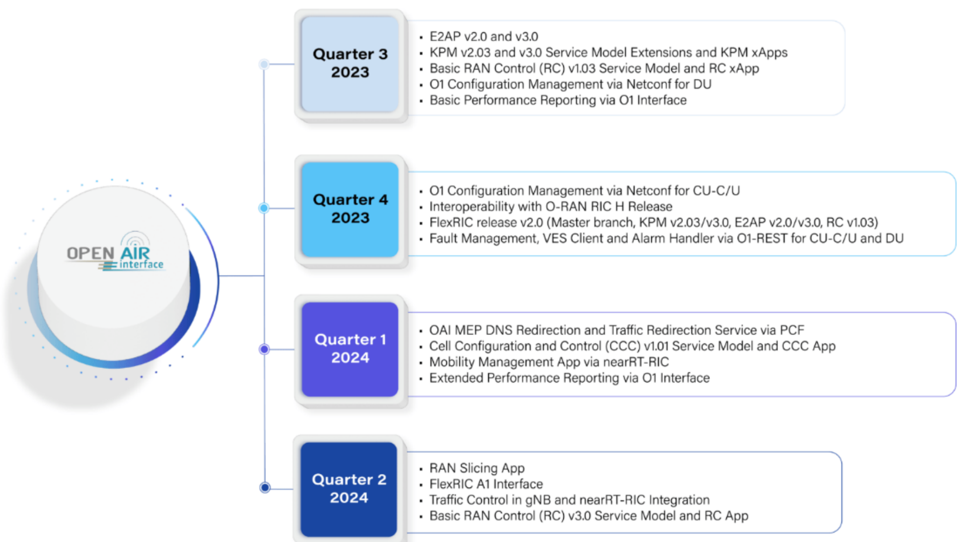


Figure 18 Mosaic5G roadmap

2.5 5G Architecture in IntellIoT use cases

5G functions have been deployed in all three IntellIoT use cases. We describe below the proposed 5G architecture for each use case.

2.5.1 Use Case 1

The 5G architecture proposed for the agriculture use case is depicted on Figure 19. As it may be observed, the main 5G functions previously described are deployed. First, the tractor will be connected over a 5G NR radio link to a 5G gNB. The link is expected to support URLL in order to enable remote control of the tractor from a distant operator. A 5G Core entity will also be deployed next to the 5G gNB and the 5G Edge/MEC entities for control and monitoring.

An Edge architecture is also described, which can be split in two parts:

- **Radio edge** – a Mosaic5G based FlexRIC and Flex CN entities will be deployed, which objectives are to configure and control 5G slices and perform PDU session breakout for tractor edge apps to reach the 5G edge apps rather than the central apps.

- **Application edge** – an Edge controller will deploy required edge apps from a local database when required. These Edge Apps will support ETSI MEC API to interact with the CN & RIC controllers.

Together, the 5G gNB, 5G Core and the 5G Edge/MEC entities are locally hosted at the tractor operator premise, providing a fully functional Private 5G architecture.

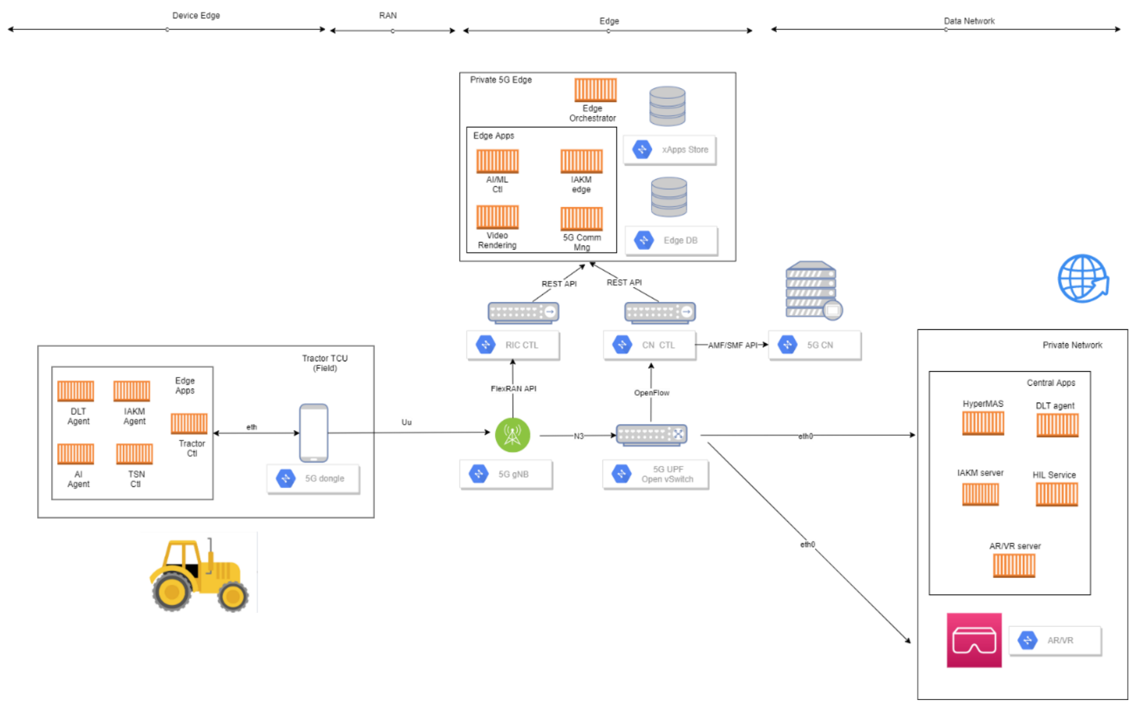


Figure 19 5G Architecture for the agriculture use case

2.5.2 Use Case 2

The 5G architecture proposed for the Smart Health use case is depicted on Figure 20. Considering that it is not possible to deploy a non-commercial 5G network at the UC2 demonstration site, a commercial 5G operator will be used for 5G RAN and Core functionalities. It is yet not a major issue, as the main 5G functions to be tested in the Smart Health use cases are the cooperative IoT/Trustworthy mechanisms, for which a commercial/existing 5G RAN may already be sufficient in terms of delay and throughput (no remote control or AR/VR requirements). Critical to this use case is to maintain data privacy, which will be provided by an Edge platform, responsible to host and manage the edge applications as if they were located on a private 5G network. Edge applications and central applications will both be able to interface with the edge applications, and data transfer between patient, edge and central entities will be encrypted to maintain privacy. The Edge platform architecture has been built to respect as much as possible 3GPP and ETSI APIs in order to facilities their integration in a non-commercial Private 5G network outside of the scope of the demonstrator.

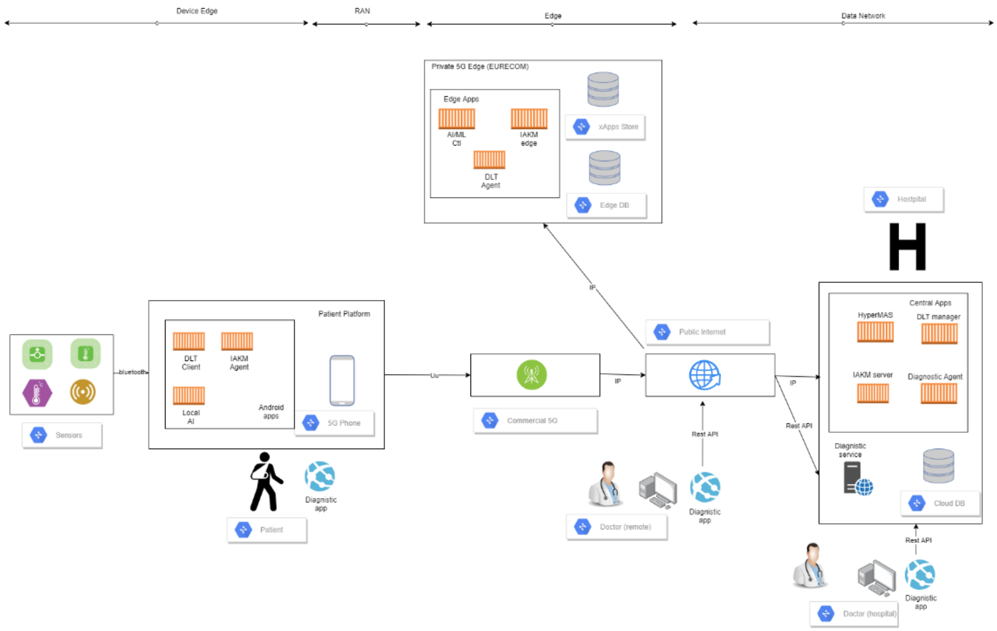


Figure 20 5G Architecture for Smart Health

2.5.3 Use Case 3

The 5G architecture proposed for the Smart Factory use case is depicted on Figure 21. The architecture is similar to the 5G architecture for UC1, with the main difference being that the required 5G NR radio link is required between the AR control analogous to the VR control used by the tractor in UC3.

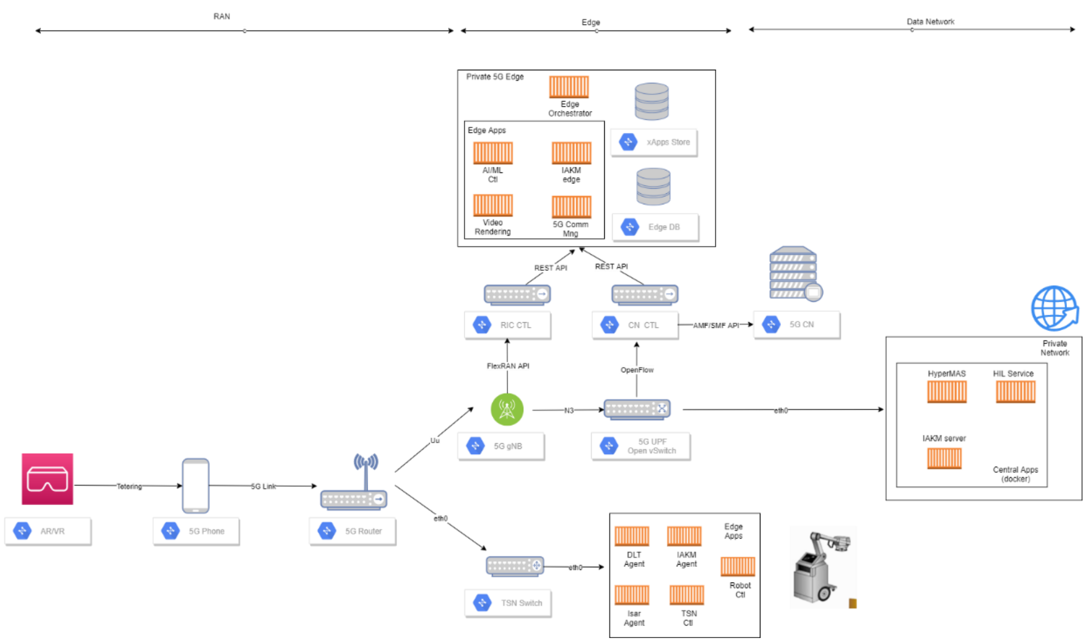


Figure 21 5G architecture for the manufacturing use case

3 IMPLEMENTATION OF OAI COMPONENTS FOR 5G NETWORKING

This section provides a technical description of the 5G-related components described before. It also describes the initial performance and validation tests done prior to the final integration and evaluations within WP5.

3.1 OAI Based E2E 5G NSA Network

We provide here the extension of OAI for NSA developments.

3.1.1 BACKGROUND

For the 1st Cycle of IntellIoT, an NSA setup based on OAI EPC, gNB and UE components was completed. In a first development round, there is no Core Network and eNB, and all required configurations that would normally take place over the LTE links to establish a 5G connection are preconfigured, so that data plane IP traffic over the 5G NR stack could be demonstrated.

On a second Development round, an E2E version of the NSA setup based on OAI RAN and COTS UEs, interoperable with OAI EPC and other commercial Core Networks has also been developed. Significant enhancements with respect to the stability of the setup, supported radio configurations, resources scheduling and performance improvements have been integrated during the 2nd Cycle of IntellIoT.

3.1.2 ARCHITECTURE, IMPLEMENTATION, INTEGRATION AND TESTING

3.1.2.1 SUPPORTED NSA ARCHITECTURE

OAI supports NSA architecture option 3a as described in 3GPP TS 37.340 rel.15. As depicted in Figure 22, according to this deployment, all the control plane traffic is exchanged with the UE through the eNB. In order to successfully add the COTS UE to the NR cell (gNB), the eNB acts as the intermediary node that communicates with the gNB over X2-C interface to convey all required NR configuration to and from the UE. S1-C interface is responsible for the exchanges between the eNB and the 4G EPC (MME component) for the successful attachment of the UE. Once the UE is attached to the CN and connected to the 5G cell, the end-to-end user-plane traffic is delivered to the UE and the core network (S1-U interface to the SGW) exclusively through the gNB. It is noted that as per this architecture option, there is no delivery of user-plane traffic through the X2 interface (i.e., no split bearer option).

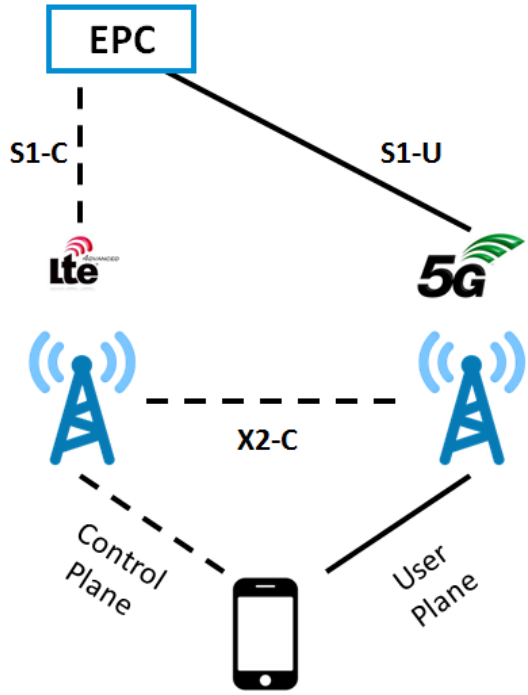


Figure 22 OAI 5G NSA architecture

3.1.2.2 IMPLEMENTATION AND SOFTWARE ARCHITECTURE

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

- **MAC/PHY:**
  - Integration of 5G NR Contention Free Random Access (CFRA) procedures to enable successful 5G connection of the UE to the 5G cell according to 3GPP TS 38.213 and 3GPP TS 38.321.
  - Complete integration of SCF 5G FAPI interface between MAC and PHY layer according to SCF FAPI 222.10.02[2].
  - Integration of dynamic scheduling and capability to support multiple users.
  - Integration of HARQ procedures on top of downlink and uplink physical channels to provide support for data acknowledging and retransmissions according to 3GPP TS 38.321.
- **PDCP/RLC:** Complete implementation of NR PDCP and RLC AM (Acknowledged Mode) and UM (Unacknowledged Mode) according to 3GPP TS 38.322 and 3GPP TS 38.323, in order to support data plane traffic over 5G established DRBs.
- **RRC** extensions according to 3GPP TS 36.331 and 3GPP TS 38.331:
  - Integration of the LTE eNB procedures triggering the UE addition/release request to the 5G cell and the data path switch procedures towards the 5G cell,
  - Extensions of LTE RRC messages with NR message containers originating from the gNB

[2] Small Cell Forum (SCF) - https://www.smallcellforum.org/work-items/fapi/

  - Integration of all the gNB NSA configuration procedures for a UE added to the NR cell and construction of the corresponding NR message containers conveyed to the UE through the eNB.
- **X2AP** extensions according to 3GPP TS 36.423: Integration of the required X2AP messages and interfacing with RRC to support the establishment, maintenance and release of an ENDC X2 connection between the eNB and gNB and the addition/release of a UE to the 5G cell.
- **S1AP** extensions according to 3GPP TS 36.413: Integration of the E-RAB Modification procedures initiated from the LTE cell (eNB) to trigger the data path switch towards the NR cell (gNB) at the core network.

3.1.2.3 SUPPORTED FEATURES AND PERFORMANCE

Based on the OAI NSA setup, the main focus is on the spectrum below 6 GHz (a.k.a. FR1). More specifically, TDD configuration is used at the gNB side with 30 KHz subcarrier spacing and 106 PRBs. At the end of the 1st Cycle, the most stable performance at the gNB is achieved for 40 MHz channel bandwidth, reaching up to 75 Mbps downlink and 7 Mbps uplink throughput.

At the end of the 2nd Cycle we achieved a 100Mbps downlink, 30Mbps uplink stable performance for 50MHz channel bandwidths, due to the new 1/2 TDD configuration.

3.1.2.4 HARDWARE ARCHITECTURE

The hardware platform required for the OAI NSA setup consists of two sets of PCS and USRP for the eNB and gNB components. Depending on the configuration used at the gNB side and the associated performance, the required hardware equipment and consequently the deployment cost can differ. Specifically, as shown in the following table, to achieve higher NR performance for 80 or 100 MHz channel bandwidths, a USRP N3xx series has to be used, together with a powerful server (>8 CPU cores). For a limited performance setup (40 MHz channel bandwidth), the cheaper USRP B210 board can be used. More information about the hardware and operating system requirements can be found here[3].

Table 1 OAI 5G Hardware Architecture

	eNB	gNB/40MHz bandwidth	gNB/50-80 MHz bandwidth
PC/Server	≥4 cores processor (e.g., Intel® Core™ i5-6600K CPU @ 3.50GHz × 4)	≥4 cores processor (e.g., Intel® Core™ i5-6600K CPU @ 3.50GHz × 4)	≥10 cores processor and 2x10Gbit Ethernet (e.g., Intel(R) Xeon(R) Gold 6154 CPU @ 3.00GHz with 18 cores)
Radio Head	B210	B210, N310, N300, AW2S	N310, N300, AW2S

3.1.2.5 TESTING AND VALIDATION

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

During the initial attachment of the UE to the LTE cell and the core network, the UE reveals its capabilities for NR connectivity and the eNB provides information to the UE on how to perform 5G NR cell specific measurements on the NR frequencies. Based on this information, after its attachment to the core network, the UE sends RRC measurement

[3] 5G NR development and setup" [Online] https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/5g-nr-development-and-setup, 05/2021.

reports including measurements from the NR cell (gNB). Upon reception of the NR measurement report, the eNB triggers the addition of the UE to the secondary node (sgNB) by sending the X2 sgNB Addition Request message. This message includes RRC and radio bearer configuration, as well as security information elements and other information per layer regarding additional UE capabilities (Figure 23).

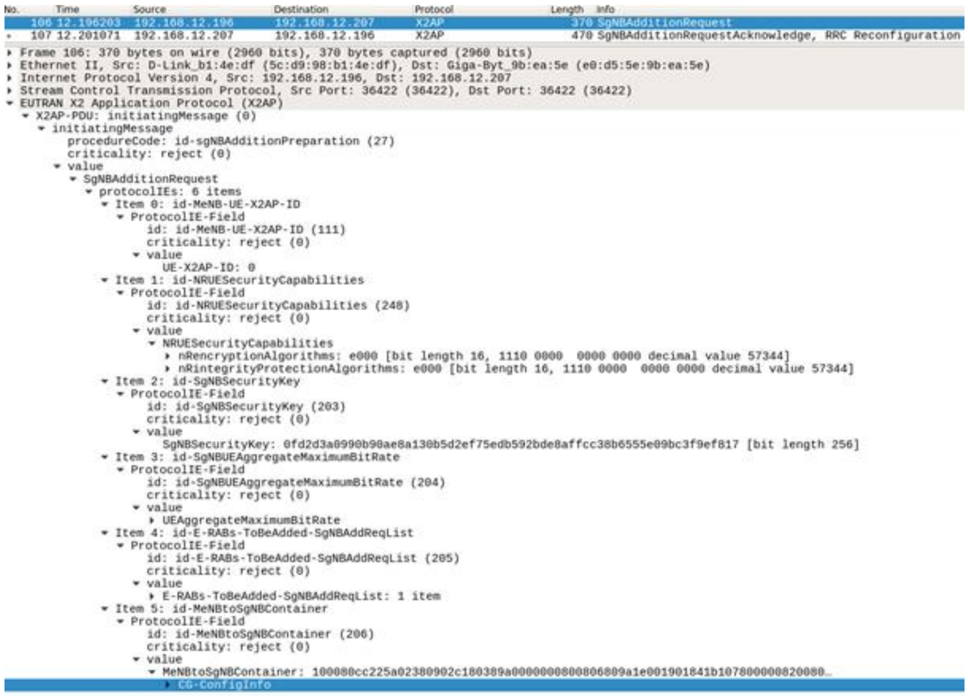


Figure 23 UE addition to the secondary cell (gNB) through the X2 exchanged messages

After performing the required configuration procedures for the addition of the UE, the gNB replies with the X2 sgNB Addition Request Acknowledge message. This message includes the NR RRC Reconfiguration container which provides the configuration information that the UE needs to know to successfully get connected with the gNB (Figure 24). The eNB then includes the NR RRC Reconfiguration container in the LTE RRC Connection Reconfiguration message sent to the UE. The UE replies with the NR RRC Reconfiguration Complete container (encapsulated in LTE RRC Connection Reconfiguration Complete message) indicating the successful outcome of the RRC Reconfiguration procedure. The eNB then forwards this information to the gNB through the X2 sgNB Reconfiguration Complete message (Figure 25).

Figure 24 NR RRC Reconfiguration container inside sgNB Addition Request Ack. Message

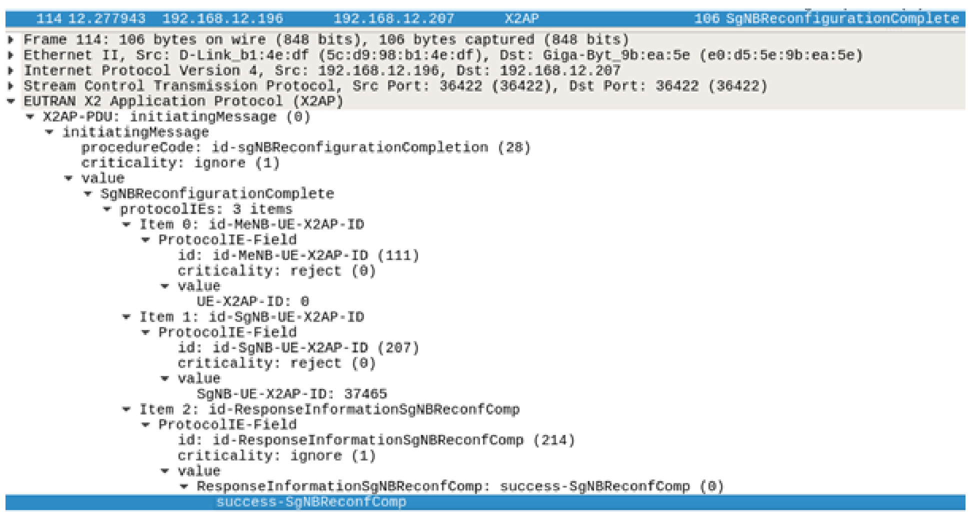


Figure 25 X2 sgNB reconfiguration complete message indicating the success of NR RRC reconfiguration procedure

In Figure 26, the part of the gNB logs corresponding to the CFRA procedures of the COTS UE towards the 5G cell is depicted. These procedures take place after the UE has successfully synchronized to the 5G cell. The UE initiates RA by sending Msg1 (RA preamble), the gNB receives it and it replies with Msg2 (RA response) and the process gets completed with the reception of Msg3 at the gNB through PUSCH. After that the UE is 5g connected.

```
[0m[0m[PHY]   [gNB 0][RAPROC] Frame 211, slot 19 Initiating RA procedure with preamble 63, energy 47.5 dB, delay 6 start symbol 0 freq index
[0m[0m[MAC]   UL_info[Frame 212, Slot 0] Calling initiate_ra_proc RACH:SFN/SLOT:211/19
[0m[0m[MAC]   [gNB 0][RAPROC] CC_id 0 Frame 211, Slot 19  Initiating RA procedure for preamble index 63
[0m[0m[MAC]   nr_initiate_ra_proc() Msg2[02127] SFN/SF:021119
[0m[0m[MAC]   [gNB 0][RAPROC] CC_id 0 Frame 211 Activating Msg2 generation in frame 212, slot 7 using RA rnti 10b SSB index 0
[0m[0m[MAC]   [gNB 0] [RAPROC] CC_id 0 Frame 212, slotP 7: Generating RAR DCI, state 1
[0m[0m[MAC]   [RAPROC] Scheduling common search space DCI type 1 dlBWP BW 24
[0m[0m[MAC]   [RAPROC] DCI type 1 payload: freq_alloc 120 (0,6,24), time_alloc 3, vrb to prb 0, mcs 0 tb_scaling 0
[0m[0m[MAC]   Frame 212: Subframe 7 : Adding common DL DCI for RA_RNTI 10b
[0m[0m[MAC]   [RAPROC] DCI params: rnti 267, rnti_type 2, dci_format 0 coreset params: FreqDomainResource 7fb985b3e758, start_symbol 0  n_sym
[0m[0m[MAC]   [RAPROC] Msg3 slot 17: current slot 7 Msg3 frame 212 k2 7 Msg3_tda_id 2 start symbol index 10
[0m[0m[MAC]   Frame 212, Slot 7: Setting Msg3 reception for Frame 212 Slot 17
[0m[0m[MAC]   [gNB 0][RAPROC] Frame 212, Subframe 7 : CC_id 0 RA is active, Msg3 in (212,17)
[0m[0m[MAC]   [gNB] Generate RAR MAC PDU frame 212 slot 7 preamble index 63 TA command 6
[0m[0m[MAC]   [gNB 0][RAPROC] Frame 212, Slot 7: RA state 2
[0m[0m[MAC]   [gNB 0] Adding UE with rnti 57b9 (num_UEs 0)
[0m[0m[MAC]   UCI: CSI_bit len : ssbri 0, rsrp: 7, diff_rsrp: 4
[0m[0m[MAC]   gNB 0] Add NR UE_id 0 : rnti 57b9
[0m[0m[NR_MAC]   [gNB 0][RAPROC] PUSCH with TC_RNTI 57b9 received correctly, adding UE MAC Context UE_id 0/RNTI 57b9
```

Figure 26 OAI gNB logs corresponding to the CFRA procedures for the initial access of the COTS UE to the 5g cell

In parallel, the eNB initiates the procedures for the data plane path switch towards the core network, so that the traffic between the COTS UE and the CN gets transferred through the gNB from now on. This is done by sending the S1AP E-RAB Modification indication message towards the MME. This message contains information on the IP address of the gNB and the corresponding gtp-u tunnel that should be used for the downlink traffic between the SGW and gNB. The MME indicates the successful modification for the E-RAB through the confirmation message.

```
120 12.327423  192.168.12.196   192.168.12.148   S1AP       106 E-RABModificationIndication
121 12.328840  192.168.12.196   192.168.12.148   PDCP-LTE   125  sn=17  MAC=0xfc3891bd (4 bytes data)  [9-bytes]  |  sn=18  MAC=0x
122 12.328848  192.168.12.196   192.168.12.148   RLC-LTE     66 UEId=1      [DL] [AM] SRB:1  [CONTROL]  ACK_SN=17
123 12.329634  192.168.12.148   192.168.12.196   GTP         60 End Marker
124 12.330665  192.168.12.148   192.168.12.196   S1AP       114 E-RABModificationConfirm
▸ Frame 120: 106 bytes on wire (848 bits), 106 bytes captured (848 bits)
▸ Ethernet II, Src: D-Link_b1:4e:df (5c:d9:98:b1:4e:df), Dst: ASUSTekC_85:4b:f7 (e0:cb:4e:85:4b:f7)
▸ Internet Protocol Version 4, Src: 192.168.12.196, Dst: 192.168.12.148
▸ Stream Control Transmission Protocol, Src Port: 36412 (36412), Dst Port: 36412 (36412)
▾ S1 Application Protocol
  ▾ S1AP-PDU: initiatingMessage (0)
    ▾ initiatingMessage
        procedureCode: id-E-RABModificationIndication (50)
        criticality: reject (0)
      ▾ value
        ▾ E-RABModificationIndication
          ▾ protocolIEs: 3 items
            ▾ Item 0: id-MME-UE-S1AP-ID
              ▾ ProtocolIE-Field
                  id: id-MME-UE-S1AP-ID (0)
                  criticality: reject (0)
                ▾ value
                    MME-UE-S1AP-ID: 553648128
            ▾ Item 1: id-eNB-UE-S1AP-ID
              ▾ ProtocolIE-Field
                  id: id-eNB-UE-S1AP-ID (8)
                  criticality: reject (0)
                ▾ value
                    ENB-UE-S1AP-ID: 12041263
            ▾ Item 2: id-E-RABToBeModifiedListBearerModInd
              ▾ ProtocolIE-Field
                  id: id-E-RABToBeModifiedListBearerModInd (199)
                  criticality: reject (0)
                ▾ value
                  ▾ E-RABToBeModifiedListBearerModInd: 1 item
                    ▾ Item 0: id-E-RABToBeModifiedItemBearerModInd
                      ▾ ProtocolIE-SingleContainer
                          id: id-E-RABToBeModifiedItemBearerModInd (200)
                          criticality: reject (0)
                        ▾ value
                          ▾ E-RABToBeModifiedItemBearerModInd
                              e-RAB-ID: 5
                            ▾ transportLayerAddress: c0a80ccf [bit length 32, 1100 0000  1010 1000  0000 1100  1100 1111 decimal value 3232238799]
                                transportLayerAddress(IPv4): 192.168.12.207
                              dL-GTP-TEID: 649bacbf
```

Figure 27 Contents of E-RAB Modification Indication message

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

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

Figure 28 Downlink IP traffic towards the COTS UE through the gNB

In Figure 29, Figure 30 and Figure 31, some snapshots of the downlink and uplink performance throughput and RTT latency of the NSA setup are shown.

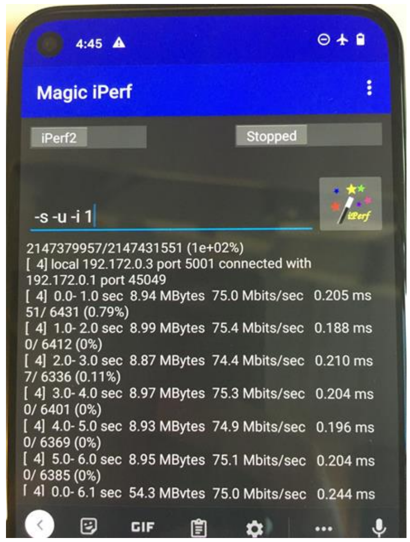


Figure 29 Measured downlink throughput using iperf at COTS UE

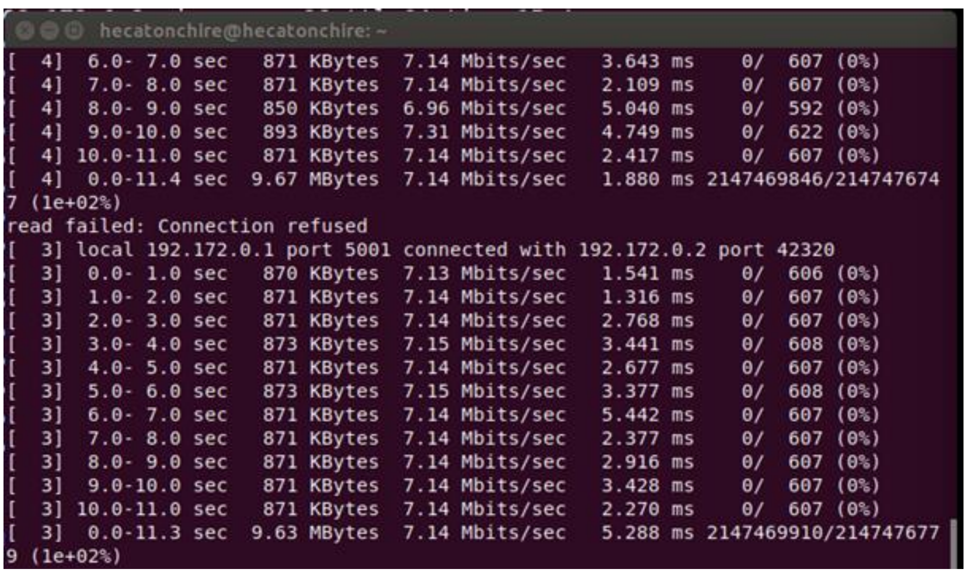


Figure 30 Measured uplink throughput using iperf at the core network

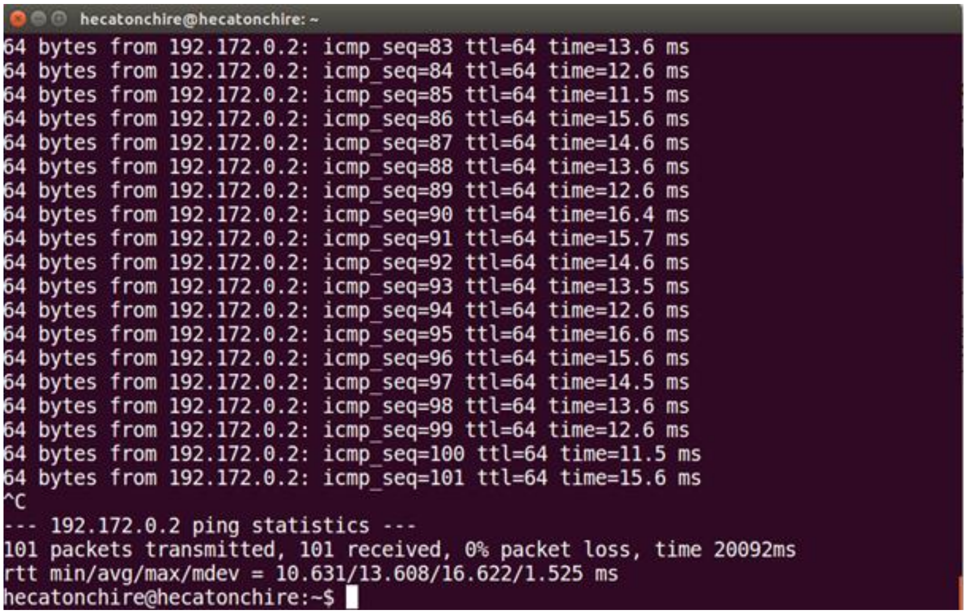


Figure 31 Measured RTT latency between the CN and the COTS UE using ping

As it can be seen, an UL RAN latency larger than 1 ms is reached on NSA, which is mostly due to the NSA architecture. A lower latency is expected for SA. The RTT, however, is significantly longer than the UL latency, due to the backend management, which would need to be reduced both on the SA as well as with an edge/MEC architecture.

3.1.2.6 DEPLOYMENT AND INSTALLATION

A detailed deployment and installation guide for the NSA setup, according to the configuration parameters is provided here[4] in section 3.2.3.

3.2 OAI Based E2E 5G SA Network

We provide here the extension of OAI for SA developments.

3.2.1 BACKGROUND

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

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

---

[4] Testing gNB with COTS UE" [Online] https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc/TESTING_GNB_W_COTS_UE.md, 12/2023

3.2.2 ARCHITECTURE, IMPLEMENTATION, INTEGRATION AND TESTING

3.2.2.1 SUPPORTED NSA ARCHITECTURE

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

Compared to NSA, in SA the gNB needs to also implement the complete RRC layer from 3GPP TS 38.331 and handling of all the associated messages as well as the NGAP from 3GPP TS 38.413 to interface with AMF (N2 interface) and UPF (N3 interface), as shown in Figure 32. Moreover, the gNB needs to support multiple bandwidth parts as the initial access happens only on the initial bandwidth part, which has a smaller bandwidth than the full cell bandwidth. Further support for contention based random access is needed, as well as support for common and dedicated control channels. Only after the initial connection and authentication with the AMF, the full bandwidth part is configured and used for user-plane traffic.

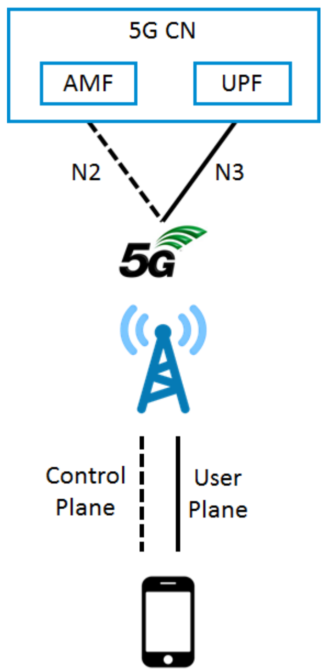


Figure 33 SA architecture deployed in OAI

From a deployment perspective, two options are provided for OAI gNB: the monolithic and the CU/DU functional split mode. The former option corresponds to a single gNB program on a single host running the whole 5G NR RAN stack. In the latter option, the OAI gNB portion is divided into two blocks: the Central Unit (CU) that contains the implementation of RRC and PDCP layers and the Distributed Unit (DU) that contains the implementation of RLC, MAC and PHY layers. The two units communicate with each other over the F1-C interface for the control plane and configuration exchanges based on F1AP protocol from 3GPP TS 38.473. The Downlink and Uplink user plane data transfer is made through the F1-U interface over GTP-U protocol. The CU and DU portions can thus run as separate programs in different hosts, offering significant flexibility for the deployment of the OAI 5G SA setup and the interoperability of OAI blocks with other commercial CUs or DUs.

Figure 34 depicts the 5G RAN protocol architecture of the OAI gNB according to the CU/DU functional split deployment. The layers that had to be extended in order to support end-to-end SA functionality are highlighted in yellow.

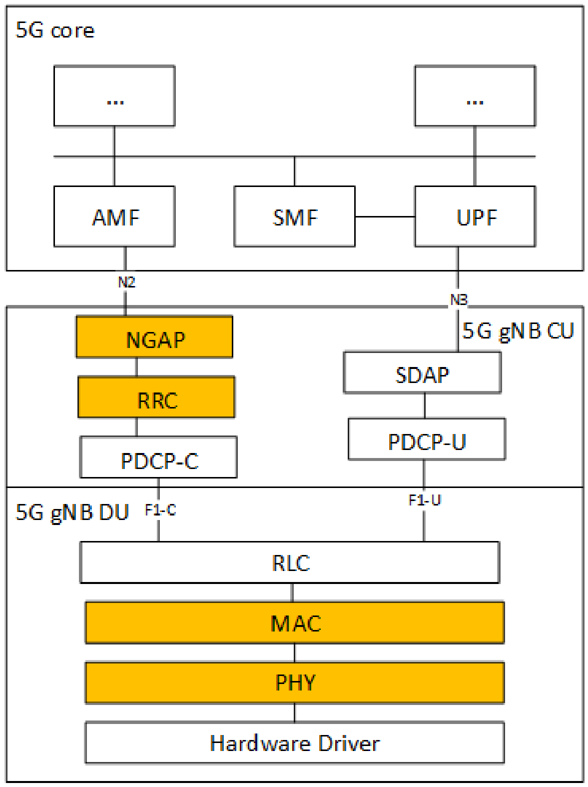


Figure 34 OAI gNB protocol architecture supporting 5G SA with CU/DU split

3.2.2.2 HARDWARE ARCHITECTURE

The hardware requirements for the OAI gNB on the SA deployment scenario are the same as the ones described in Section 3.1.2.4 and Table 1 for the NSA deployment.

3.2.2.3 TESTING AND VALIDATION

Several interoperability tests of the OAI gNB with different 5GC and UE components from different vendors have been performed and more are still ongoing. Specifically, interoperability with the OAI CN and Nokia SA Box has been fully validated. With respect to the UE components, interoperability has been fully validated with the Quectel RM500Q-GL module[5], Huawei mate 30 pro smartphone and OAI UE and partially validated with SIMCOM SIM8200EA[6] module.

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

[5] Quectel RM500Q-GL module" [Online] https://www.quectel.com/product/5g-rm500q-gl/, 05/2021
[6] "SIMCOM SIM8200EA module" [Online] https://www.simcom.com/product/SIM8200EA_M2.html, 05/2021

After the UE synchronizes to the 5G cell and receives the System Information messages from the gNB, it initiates the *contention based random access procedure (CBRA)* in order to connect to the 5G cell. The procedure is finalized through the reception of Msg4 (*RRCSetup*) acknowledgment from the gNB (Figure 35). Then the UE replies with the *RRCSetupComplete* message which encapsulates the *NAS registration request* message towards the AMF. Upon reception of RRC Setup Complete, the UE state at the gNB becomes RRC Connected.

```
1170 [0m [0m[NR_MAC]   (ue 0, rnti 0x70bd) Received Ack of RA-Msg4. CBRA procedure succeeded!
1171 [0m [0m [34m[RLC]   RB found! (channel ID 1)
1172 [0m [0m[RLC]   /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:452:deliver_sdu: delivering SDU (rnti 28861 is_
     1 rb_id 1) size 92
1173 [0m [0m[NR_RRC]   Received message NR_RRC_DCCH_DATA_IND
1174 [0m [0m[NR_RRC]   Decoding DCCH : ue 28861, inst 0, ctxt 0x7f2ba7ffeeb0, size 86
1175 [0m12 c0 00 20 00 04 f7 e0 17 b6 ce d3 60 47 e0 04 14 90 00 bf 20 5f 51 00 10 00 00 00 00 02 [0m[NR_MAC]   884. 4 RNTI 70bd: 3 bytes from DC
     (ndata 3, remaining size 14)
1176 [0m [0m[NR_MAC]   884. 4 RNTI 70bd: 0 bytes from DCCH 1 (ndata 3, remaining size 8)
1177 [0mb2 e0 2f 07 07 10 03 07 e0 04 14 90 00 bf 20 5f 51 00 10 00 00 00 00 02 b1 00 10 02 e0 2f 07 02 f0 50 40 1d 14 3a 55 20 5f 51 00 00 00 11 80
     17 40 00 09 05 30 10 10
1178 [0m[NR_RRC]   [FRAME 00000][gNB][MOD 00][RNTI 70bd] [RAPROC] Logical Channel UL-DCCH, processing NR_RRCSetupComplete from UE (SRB1 Active)
1179 [0m [0m[NGAP]   [gNB 0] Build NGAP_NAS_FIRST_REQ adding in s_TMSI: GUAMI amf_set_id 0 amf_region_id 1 ue 70bd
1180 [0m [0m[NR_RRC]   [FRAME 00000][gNB][MOD 00][RNTI 70bd] UE State = NR_RRC_CONNECTED
```

Figure 35 Successful CBRA procedure and reception of RRC Setup Complete message at the gNB

This NAS message is conveyed transparently from the gNB to the AMF through the NGAP *InitialUEMessage* (Figure 36). A sequence of NGAP/NAS messages are exchanged afterwards between the gNB, the UE and the AMF to perform the authentication and security procedures leading to the successful Registration of the UE to the AMF (Registration Accept and Registration Complete NAS messages).

No.	Time	Source	Destination	Protocol	Length	Info
1	0.000000	192.168.18.203	192.168.69.131	NGAP	134	NGSetupRequest
2	0.003745	192.168.69.131	192.168.18.203	NGAP	614	NGSetupResponse
3	8.077278	192.168.18.203	192.168.69.131	NGAP/NAS-5GS	146	InitialUEMessage, Registration request
4	8.094364	192.168.69.131	192.168.18.203	NGAP/NAS-5GS	630	DownlinkNASTransport, Authentication request
5	8.123432	192.168.18.203	192.168.69.131	NGAP/NAS-5GS	146	UplinkNASTransport, Authentication response
6	8.126800	192.168.69.131	192.168.18.203	NGAP/NAS-5GS	462	DownlinkNASTransport, Security mode command
7	8.135349	192.168.18.203	192.168.69.131	NGAP/NAS-5GS/NAS-…	174	UplinkNASTransport, Security mode complete, Registration request
8	8.140345	192.168.69.131	192.168.18.203	NGAP/NAS-5GS	1302	InitialContextSetupRequest, Registration accept
9	8.257311	192.168.18.203	192.168.69.131	NGAP	122	UERadioCapabilityInfoIndication
10	8.459484	192.168.18.203	192.168.69.131	NGAP	86	InitialContextSetupResponse
11	9.338930	192.168.18.203	192.168.69.131	NGAP/NAS-5GS	118	UplinkNASTransport, Registration complete
12	9.341520	192.168.69.131	192.168.18.203	NGAP/NAS-5GS	710	DownlinkNASTransport, Configuration update command
13	9.341561	192.168.18.203	192.168.69.131	NGAP/NAS-5GS	162	UplinkNASTransport, UL NAS transport, PDU session establishment request
14	9.355758	192.168.69.131	192.168.18.203	NGAP/NAS-5GS	266	PDUSessionResourceSetupRequest, DL NAS transport, PDU session establishment accept
15	9.356056	192.168.18.203	192.168.69.131	NGAP	214	PDUSessionResourceSetupResponse

Figure 36 NGAP/NAS exchanges with the Core Network for UE Registration and PDU Session establishment

The UE then initiates the PDU Session Establishment, which is validated through the PDU Session Establishment Accept NAS message coming from the CN. This message contains the IP address of the UE provided from the SMF. In Figure 37 the configured IP address is shown through the Quectel connection manager software.

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

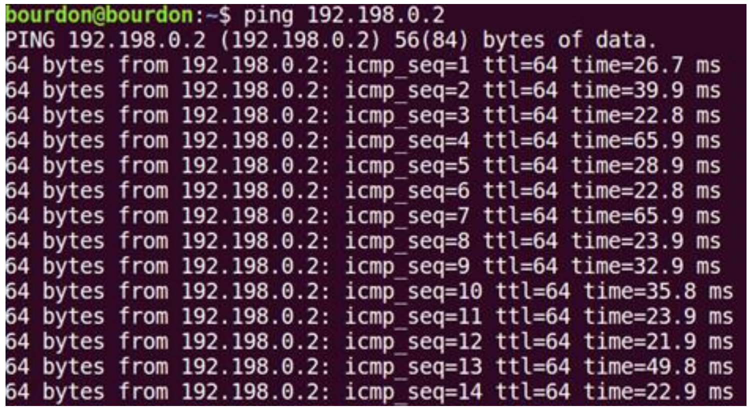
Figure 37 Quectel module connection manager

At the same time, the gNB also sends a dedicated *RRCReconfiguration* message to the UE containing the configuration of the DRB that should be established at the UE to enable the user plane traffic flow at the RAN stack (PDCP, RLC, MAC layers). The UE replies with an *RRCReconfigurationComplete* message to signal the successful reconfiguration. Upon reception of the Reconfiguration Complete message, the gNB performs its own DRB configuration for the lower layers (Figure 38). In parallel, the gNB establishes a gtp-u tunnel with the UPF to enable the user-plane traffic flow over the N3 interface (Figure 34).

```
[0m[NR_RRC]   Receive RRC Reconfiguration Complete message UE 70bd
[0m[0m[NR_RRC]   Configuring PDCP DRBs/SRBs for UE 70bd
[0m[0m[PDCP]   /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_pdcp/nr_pdcp_oai_api.c:add_drb:878: added DRB for UE RNTI 70bd
[0m[0m[NR_MAC]   Modified UE_id 0/70bd with CellGroup
[0m[0m[NR_MAC]   Adding SchedulingRequestconfig
[0m[0m[NR_MAC]   Adding BSR config
[0m[0m[NR_MAC]   Adding TAG config
[0m[0m[NR_MAC]   Adding PHR config
[0m[0m[NR_MAC]   Adding LCID 1 (SRB 1)
[0m[0m[NR_MAC]   Adding LCID 2 (SRB 2)
[0m[0m[NR_MAC]   Adding LCID 4 (DRB 4)
[0m[0m[NR_RRC]   Configuring RLC DRBs/SRBs for UE 70bd
[0m[0m[RLC]   Trying to add SRB 2
[0m[0m[RLC]   /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:710:add_rlc_srb: added srb 2 to UE with RNTI
[0m[0m[34m[RLC]   /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:792:add_drb_am: added drb 1 to UE with
0x70bd
[0m[0m[RLC]   /home/timarque/panos/openairinterface5g/openair2/LAYER2/nr_rlc/nr_rlc_oai_api.c:add_drb:879: added DRB to UE with RNTI 0x70bc
[0m[0m[NR_RRC]   [gNB 0] Frame      0 CC 0 : SRB2 is now active
[0m[0m[NR_RRC]   [gNB 0] Frame  0 : Logical Channel UL-DCCH, Received NR_RRCReconfigurationComplete from UE rnti 70bd, reconfiguring DRB 1
```

Figure 38 DRB establishment at the gNB upon reception of RRC Reconfiguration Complete message

After these steps, the UE can exchange IP traffic through the CN. In Figure 39, a snapshot from a ping test initiated from the CN towards the UE is shown.



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

Figure 39 ping test for user plane traffic with the OAI SA setup

3.3 5G FlexRIC Controller

The 5G FlexRIC controller is an extension of the previously available FlexRAN controller available on Mosaic5G. FlexRAN was based on client-server architecture, where FlexRAN clients, embedded on top of OAI 4G/5G protocol stack and capable of direct control of various 4G/5G RRC parameters, interact with a FlexRAN server developed as a Web Technology entity. Accordingly, FlexRAN controllers enable 4G/5G controls through standardized Web technology APIs and message formats, such as REST and JSON, instead of 3GPP-specific ASN.1 standards.

The general principles of RICs are similar to FlexRAN controllers, but an O-RAN[7] E2 interface has been adopted for enhanced interoperability between various RAN and RIC implementations. The O-RAN E2 interface is used by RICs to control the underlying RAN elements. A E2 interface provides 4 basic operations:

- Report – asks the RAN to report a specific information
- Insert – the RIC asks the underlying RAN to activate a particular user-plane function
- Control – the RIC asks the underlying RAN to activate a particular control-plane function
- Policy – the RIC sets a particular policy function on an activated function.

For example, a RIC may ask over the E2 interface to obtain RAN parameters, activate a particular slice or even provide policies for a scheduler.

Accordingly, various enhancements had to be conducted to extend Mosaic5G components to support this new architecture. Accordingly, OAI RAN (gNB stack) has been extended by a E2agent communicating with the FlexRIC controller over the E2 interface.

[7] Operator Defined and Open RAN (O-RAN) Alliance - https://www.o-ran.org/

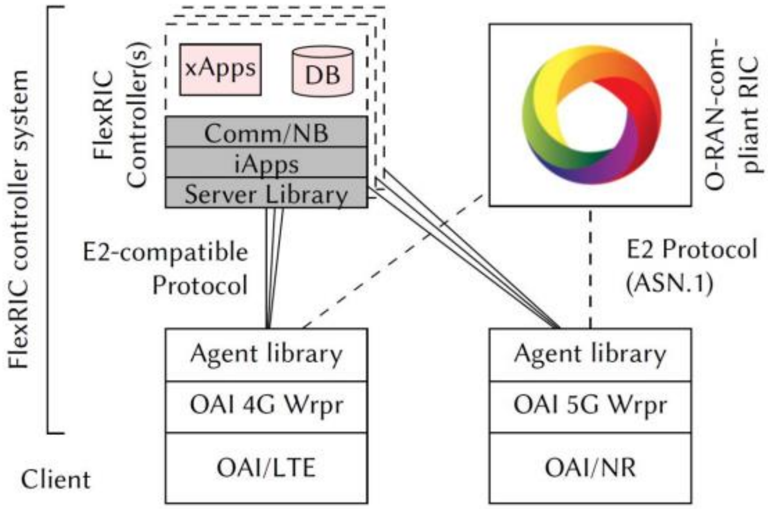


Figure 40 FlexRIC architecture

On top of OAI, Mosaic5G extended the FlexRAN controller server to support RIC specifications, in particular real-time functions. FlexRIC has a built-in Service Model (SM) for monitoring and slicing, that can be easily customized and extended to fulfil the diverse 5G use cases. FlexRIC's Application Protocol (AP) and Service Models (SM) are encoding and decoding agnostic. It also supports the creation of new SMs "à la carte" to satisfy specific, yet not standardized, use cases. Lastly, FlexRIC is expected to act as a booster for the type and quality of Machine Learning algorithms deployed in 5G as it easily enables their validation in real 5G deployments as shown here with the OAI 5G stack.

The Mosaic5G FlexRIC controller provides standardized APIs for third party xApps developments. In IntellIoT nomenclature, FlexRIC xApps are Edge Apps and their deployments are controlled by the Edge orchestrator. The Most important xApp/edge app is the 5G Communication Resource Manager described in Section 3.5.

3.3.1 5G FLEXRIC RESOURCE SLICING SERVICE MODEL

One important SM developed and available by FlexRIC is a 5G resource slicing SM, which is defined to operate as a 2-level process:

- Inter-resource – schedules resources of entire slices.
- Intra-resource – schedules UEs on assigned resources.

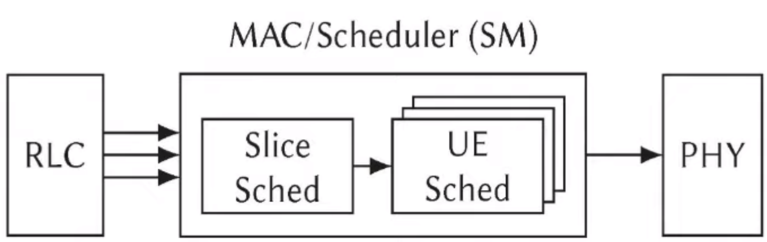


Figure 41 Mosaic5G FlexRIC 2-level scheduling SM

A standardized API has been provided to control the OAI 5G RAN RRC, and various schedulers are available (Inter-resource – Static, NVS, EDF; Intra-resources – RR, PF, RT). The Mosaic5G FlexRIC flexible and open scheduling SM enables fast scheduler enhancement as well as rapid adaptation of scheduling policies within or between slices.

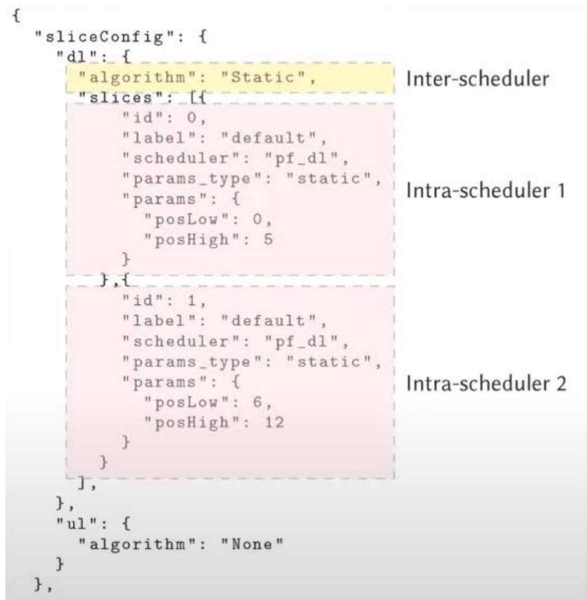


Figure 42 FlexRIC scheduling SM API

In IntelIIoT, the FlexRIC will provide a 5G slice control SM as well as a 5G scheduler policy SM. The 5G slice control SM allows the creation, the constant monitoring and the destruction of 5G slices, whereas the 5G scheduler policy SM provides scheduling parameters to the 5G RAN, potentially dynamically changing the scheduler as function of the 5G RAN conditions. These two SMs will be used by the 5G Communication Resource Manager Edge App to provide and adjust the required 5G performance required by the other IntelIIot components.

3.4 5G FlexCN Controller

The Flexible CN controller (FlexCN) is an extension of the previously available LL-MEC controller available on Mosaic5G. LL-MEC had been initially developed to provide basic CN optimization to support 3GPP edge/ETSI MEC computing functions. The LL-MEC supported ETSI MEC APIs, as well as FlexRAN APIs and could provide basic RAN services such as Radio Network Information Service (RNIS), DNS redirection and traffic shaping.

However, with the creation of FlexRIC as well as to support additional 5GC functionalities, a new FlexCN controller has been also developed. It bears similar objectives as the former LL-MEC but benefit from a full FlexRIC support and direct access to 5GC through Network Exposure Functions and services.

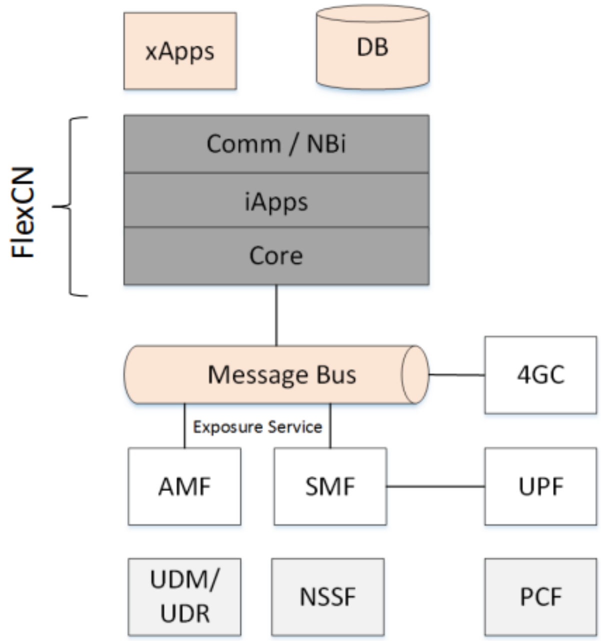


Figure 43 Mosaic5G FlexCN architecture

The 5G FlexCN has been developed to provide open APIs to enable third party xApps developments and even to enable xApps to connect to both the FlexRIC and FlexCN controllers. During the 1st cycle development, only connection to AMF, SMF and UPF are available, enabling 5G FlexCN with similar MEC/Edge-like functions as the LL-MEC controller. At the end of the 2nd Cycle, connections to the other functions (UDM/UDR, NSSF, PCF), as well as a more robust UPF have been developed.

3.5 5G Communication Resource Manager

The 5G Communication Resource Manager is an IntelIoT component aiming at controlling the communication resources allocated by the 5G network. Following the architecture description of the Mosaic5G FlexRIC and FlexCN, the 5G Communication Resource Manager is considered to be an xApp and will control the FlexRIC slicing and scheduling SMs in order to enable dynamic 5G slice creation, resource optimization as well as dynamic adaptation. It is deployed by the Edge Orchestrator component on each 5G RAN entity[8] as function of the FlexCN RNIS function.

The Communication Resource Manager's primary functionality is to distribute the communication related resources to the different devices depending on the specific requirements of application to be run in a suitable manner. The considered performance requirements are latency and bandwidth. Depending on the requested resources the Communication Resource Manager will allocate resources to meet the request. A more in-depth description of the Communication Resource Manager can be found in deliverable D4.7 (" Dynamic network management ").

3.6 5G NR FR1 URLL Architecture

TBC

[8] In the course of IntelIoT Cycle 1 and 2, only one 5G RAN entity will be considered.

3.7 5G NR FR2 Architecture

TBC

4 5G NR DEVICE-TO-DEVICE

5G D2D Communication is considered by IntellIoT in two use cases: UC1 and UC3. Considering that 5G NR ProSe (D2D) is not completed yet, IntellIoT will build its D2D functions on 5G NR V2X rel.16. IntellIoT aims at extending the 5G NR V2X specification to support URLL V2X communications. Considering the lack of currently available 5G NR V2X rel.16 devices, IntellIoT D2D developments will be evaluated via simulations.

Known as Proximity Services (ProSe), first mechanisms for Device-to-Device communications between UEs have been standardized by 3GPP at early as in its 12th release for LTE. It was, however, strongly restricted to Public Safety (PS), and a lack of clear market strategy made that 3GPP Prose Rel.12 never appear on any LTE device. With the growing interest for the automotive market, 3GPP updated its LTE D2D specification and extended it for specific V2X functions in its 14th release for LTE. The clear market impact for V2X communications drew a lot of attention to this 3GPP LTE rel.14 V2X specification, which eclipsed the ProSe specification, and is generally considered to be one intendent proximity service falling within ProSe (a bit as Wi-Fi OCB enables V2V communications totally outside of the framework of a WiFi service). Various cellular stakeholders developed prototypes and products for the automotive market, but due to various lobbying, performance limitations and standardization restrictions, 3GPP LTE rel.14 V2X devices are not widely available in the market.

Several reasons might explain the delayed deployment of LTE-based V2X technologies, but the most likely one is the largely improved features and performance of the 5G NR-based V2X specification in 3GPP 16th for 5G. Indeed, 3GPP NR V2X Rel.16 provides several improved mechanisms over the LTE specification, such as groupcast, a new feedback channel, increased numerology enabling sub millisecond V2X communications or larger functionalities for radio resource allocations. Accordingly, it is likely that the automotive industry is currently waiting for the first NR V2X prototypes for a larger-scale market deployment.

In parallel, the D2D specification also evolved in the 17th 3GPP NR release for 5G to benefit from the improved flexibility of the NR technology, but the community often confuses both D2D and V2X specifications. In the following sections, we will describe first the 5G ProSe, then 5G V2X as a sub-group of ProSe, although 5G V2X appeared earlier than 5G ProSe in the 3GPP releases.

4.1 Proximity Services for 5G Systems

The 3GPP Proximity Service architecture for 5G network (5GS) is described in 3GPP TS 23.304. It is a rel.17 version, which indicates that it is a later specification than the NR V2X specification (rel.16) or even the 5G NR specification (rel.15). This should not be confused with the 3GPP TS 23.303 Rel. 16, which is an LTE specification and enhances the LTE ProSe architecture. TS 23.304 adapts the ProSe architecture and service definition from TS 23.303 Rel. 16 to a 5G system. The descriptions of proximity services for 5G systems in TS 23.304 are still not frozen, which means they are still being developed.

4.1.1 PROXIMITY SERVICE ARCHITECTURE FOR 5G SYSTEMS

The 5GS enablers for ProSe include the following functions:

- **5G ProSe Direct Discovery -** ProSe-enabled UE are able to discover services offered by neighbouring ProSe-enabled UEs.
- **5G ProSe Direct Communication -** ProSe-enabled UEs are able to directly communicate to each other's without requiring or going through a 5G gNB.
- **5G ProSe UE-to-Network Relay –** A ProSe-enabled UE may act as a relay to extend the reach of gNBs. This mode is not described in this document.

Figure 44 depicts the ProSe architecture for the non-roaming case, along with the specific entities and reference points.

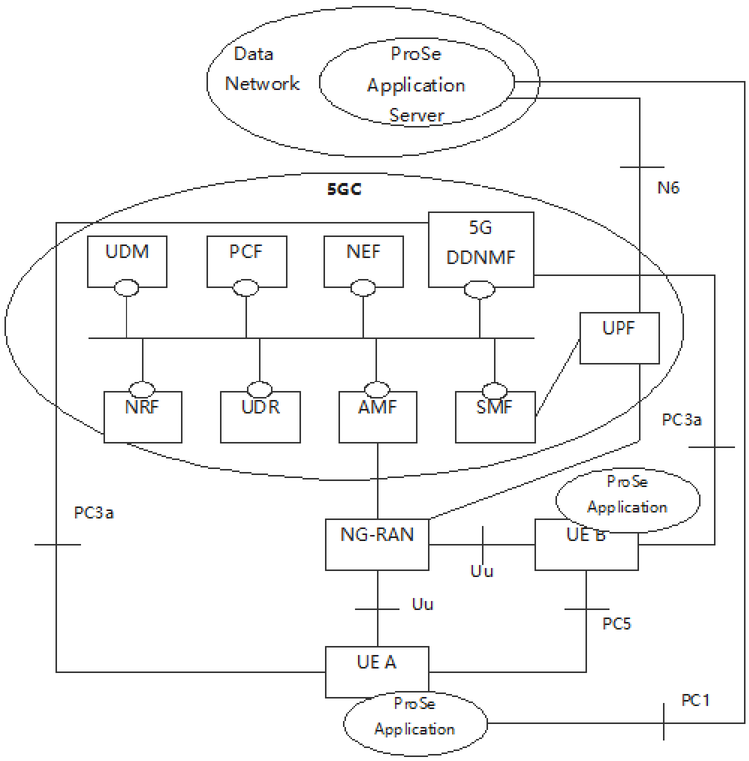


Figure 44 5GS architecture for 5G ProSe

ProSe defines three new main entities:

- **ProSe Application –** a Proximity application running on a UE.
- **ProSe Application Server –** Server authorizing one or more UEs to use a particular Prose Application.
- **Direct Discovery NMF -** connects to the NR RAN (PDCP, RRC and MAC) on the UE-side and to the 5GC functions on the infrastructure side to trigger the required service discovery, authorization and link configuration procedures. This entity replaces the *ProSe Function* from the LTE specification.

ProSe operates on three main reference points in rel.17:

- **PC1 –** It connects a ProSe application running on a UE with the ProSe Application server running in a distant data network or an Edge/MEC server. It is used to define application-level signalling requirements. This reference point is not specified in rel.17.
- **PC3a -** The reference point between the UE and the 5G DDNMF (Direct Discovery Network Management Function). PC3a relies on 5GC (5G Core) user plane for transport (i.e., an "over IP" reference point). It is used to authorise 5G ProSe Direct Discovery request, and perform allocation of ProSe Application Codes / ProSe Restricted Codes corresponding to ProSe Application Identities used for 5G ProSe Direct Discovery.
  - **note:** the 'a' is provided to differentiate with the PC3 reference point connecting to the LTE-based ProSe function.
- **PC5 –** The reference point between ProSe-enabled UEs used for control and user plane for 5G ProSe Direct Discovery, ProSe Direct Communication and ProSe UE-to-Network Relay. It is also often confused with the term 'sidelink', which instead refers to 'communications' not a reference point.

4.1.2 5G PROSE DIRECT DISCOVERY

ProSe Direct Discovery is carried out on the PC5-D (PC5 Discovery) reference point. As depicted on Figure 45, a specific ProSe Discovery Protocol is defined to discover or offer ProSe Services.

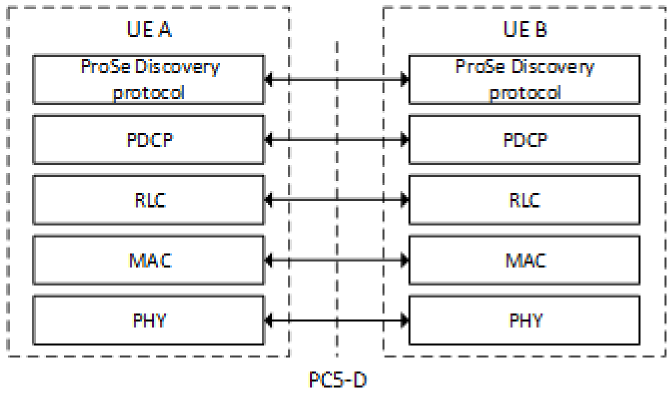


Figure 45 ProSe PC5-D (Discovery) Interface

ProSe defines two times of Discovery modes:

- **Model A** – A service producer, called 'announcer' sends an Announcement message, while any service consumer will be monitoring for any service announcement. If a match is found, a transaction may begin.
- **Model B –** Two types of actors, 'Service Discoverer' and 'Service Discoveree' are defined. Then two types of messages are defined: *service solicitation* and *service response* to match a discoverer and a discoveree.

Figure 46 depicts a ProSe Model A direct discovery procedure.

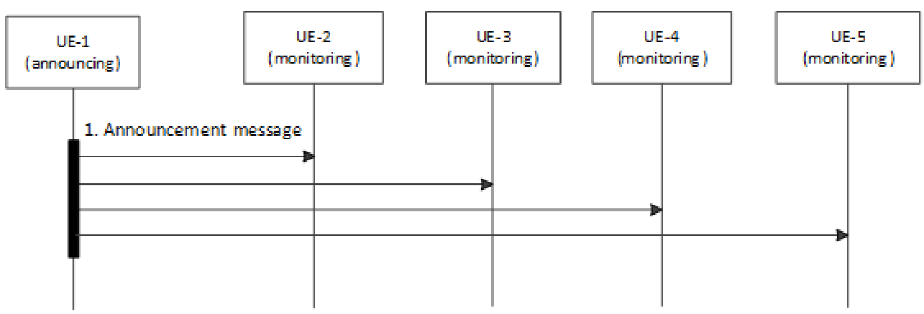


Figure 46 5G ProSe Model A Discovery

4.1.3 5G PROSE DIRECT COMMUNICATION

5G ProSe Direct Communication over PC5 reference point is supported when the UE is "served by NR or E-UTRA" or when the UE is "not served by NR or E-UTRA". A UE is authorized to perform 5G ProSe Direct Communication when it has valid authorization. 5G ProSe Direct Communication supports both the cases of public safety and commercial service. 5G ProSe Direct Communication over NR based PC5 reference point supports broadcast, groupcast and unicast modes.

ProSe Direct Communication (through a ProseApp) support IPv4, IPv6, Ethernet and Unstructured as depicted on Figure 47, which relates the user plane of the PC5 end point:

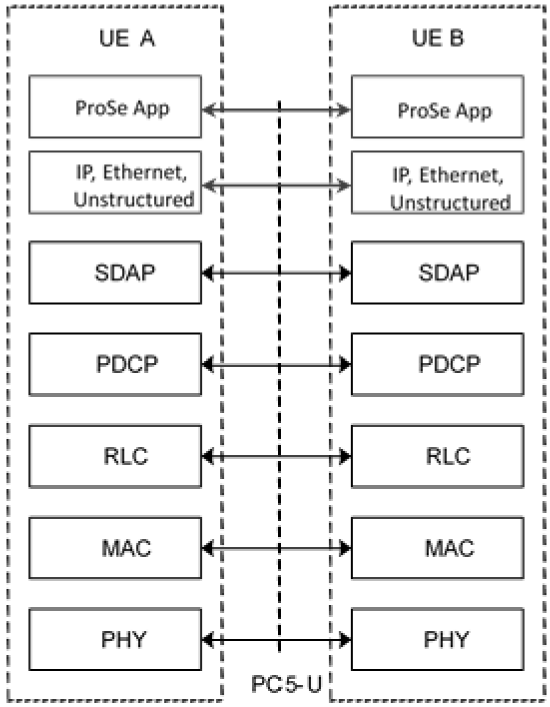


Figure 47 5G ProSe PC5-U Protocol Stack

ProSe also describes the QoS (Quality of Service) metrics called Packet Quality Indicator (PQI) extending the ProSe Per Packet Priority (PPPP) of the LTE and NR V2X specification. A PQI includes IP and non-IP packet filtering according to but not limited to packet source/destination address, UE ID, ProSe Application ID or channel load.

Table 2 5G ProSe PQI Table

PQI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
24	GBR (NOTE 1)	1	150 ms	10^{-2}	N/A	2000 ms	Mission Critical user plane Push To Talk voice (e.g. MCPTT)
25		2	200 ms	10^{-2}	N/A	2000 ms	Non-Mission-Critical user plane Push To Talk voice
26		2	200 ms	10^{-3}	N/A	2000 ms	Mission Critical Video user plane
60	Non-GBR	1	120 ms	10^{-6}	N/A	N/A	Mission Critical delay sensitive signalling (e.g. MC-PTT signalling)
61		6	400 ms	10^{-6}	N/A	N/A	Mission Critical Data (e.g. example services are the same as 5QI 6/8/9 as specified in TS 23.501 [4])

92	Delay Critical GBR (NOTE 1)	5	5ms	10^{-4}	20000 bytes	2000 ms	Interactive service - consume VR content with high compression rate via tethered VR headset (See TS 22.261 [6])
93		6	10ms	10^{-4}	20000 bytes	2000 ms	interactive service - consume VR content with low compression rate via tethered VR headset; Gaming or Interactive Data Exchanging (See TS 22.261 [6])
NOTE 1:GBR and Delay Critical GBR PQIs can only be used for unicast PC5 communications.							

4.2 Vehicle-to-Everything (V2X) Communications for 5G Systems

As mentioned in the previous section, although the 5G NR V2X may be considered as a special case of the more general 5G NR ProSe services, the NR V2X architecture has been defined before ProSe already in the 3GPP rel.16 specification. It makes the only ProSe service currently defined for 5G NR at the time of writing. Accordingly, IntellIoT will use the 5G NR V2X specification as a realization of D2D communication

In a nutshell, 5G NR V2X operates similarly to 5G NR ProSe, but considering only a single service (V2X) and a basic group management (all vehicles belonging to the same group). Accordingly, 5G NR V2X does not have a Service Discovery mode.

4.2.1 V2X SERVICE ARCHITECTURE FOR 5G SYSTEMS

Figure 48 depicts the 5G NR architecture for V2X applications for non-roaming case. As it can be observed, it is similar to the ProSe architecture, with the main differences being the following entities:

5G NR V2X defines three new main entities:

- **V2X Application –** Replaces the ProSe Applications, with the same functions.
- **V2X Application Server –** Replaces the ProSe Application Server, with the same functions.

Direct Discovery NMF is not present as discovery services are not supported for V2X in rel.16. However, V2X service authorization, capacity provisioning and QoS handling is provided by the 5G core entity AMF over two reference points N1 and N2.

5G NR VX operates on three main reference points in rel.16:

- **V5 reference point** – replaces the PC5 with V2X adapted terminology between V2X applications
- **V1 reference point** – replaces the PC1 reference point with V2X adapted terminology between a V2X application and the V2X application server.
- **PC5 –** same reference point as for ProSe.
- **N1** – reference point conveying V2X service policies and authorization between a UE and a 5G core
- **N2** – reference point conveying V2X service policies and authorization between a gNB and a 5G core.

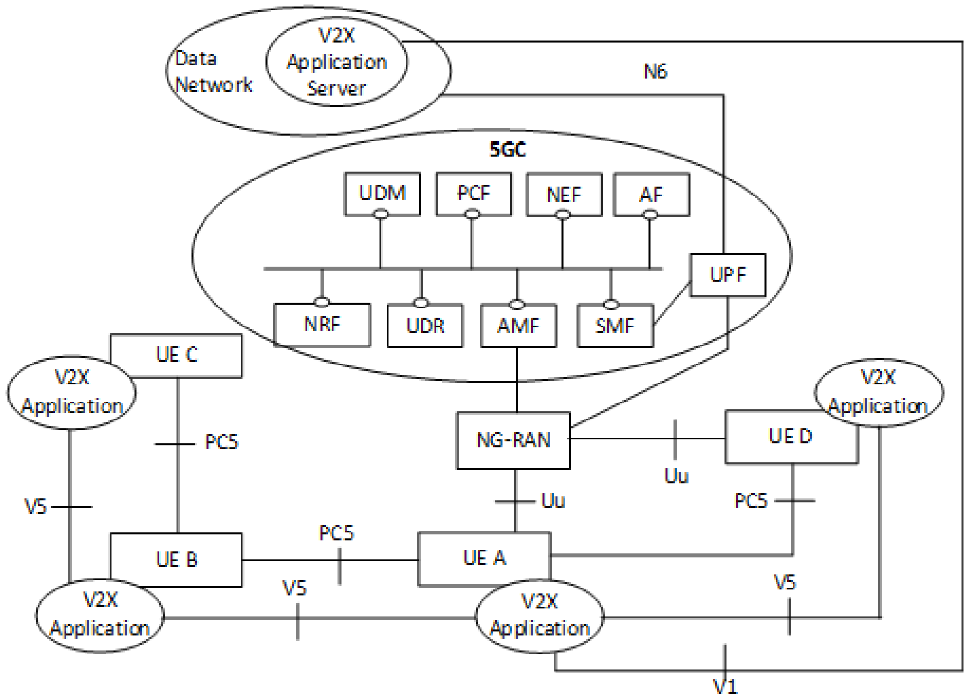


Figure 48 5G V2X Architecture

4.2.2 V2X COMMUNICATIONS FOR 5G SYSTEMS

5G NR V2X may be seen as an extension of the LTE V2X architecture for 5G NR. It, however, has key major service enhancements compared to LTE V2X. The first one is the V2X Unicast support, which was no supported for LTE V2X.

4.2.2.1 V2X BROADCAST COMMUNICATION

This corresponds to a similar service as for LTE V2X and enables one vehicle to communication to all vehicles within 5G NR V2X range.

4.2.2.2 V2X GROUPCAST COMMUNICATION

This is a new service not available in LTE V2X, which enables one vehicle to communication to a selected group of vehicles. 5G NR V2X groupcast is used to build clusters of vehicles belonging to different groups.

4.2.2.3 V2X UNICAST COMMUNICATION

Although unicast communication is available for 5G NR as well as LTE ProSe, it was not supported for LTE V2X. Figure 49 illustrates examples of PC5-U unicast links. As it may be seen, in addition to supporting unicast links, 5G NR V2X also provides multiple QoS flows, opening the door for prioritizing between V2X communication flows. It also enables various V2X services within a V2X application to operate separately. As for LTE V2X, NR V2X supports IP and non-IP unicast links, however, only IPv6 is supported as IP protocol in rel.16 specification. V2X services managements are handled between V2X applications and with V2X application servers over V5, resp. V1 reference points and not on PC5 (as PC5-D is not defined in 5G NR V2X).

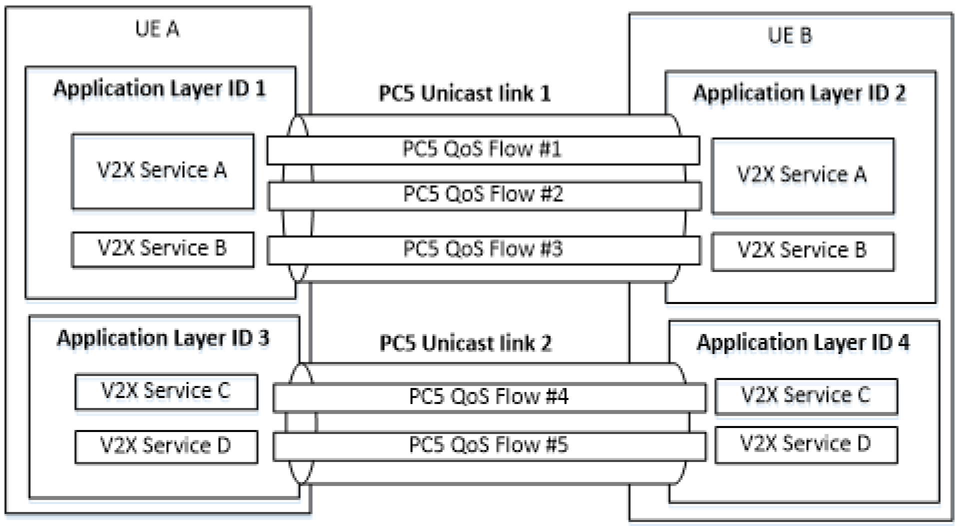


Figure 49 5G V2X QoS-driven Unicast Links

4.2.2.4 5G NR V2X QOS HANDLING

Another difference in 5G NR V2X is the QoS handling. LTE V2X handles QoS through ProSe Per Packet Priority (PPPP) or Prose Per Packet Reliability (PPPR). In 5G NR V2X, a similar QoS architecture as communication over 5G infrastructure is used. It is based on a 5QI (5G quality indicator) metric. A PC5 5QI, called PQI for 5G NR V2X, includes a *Flow Bit Rate* parameter supporting only a Guaranteed Flow Bit Rate (QFBR) and Maximum Flow Bit Rate (MFBR), a PC5 per *Link Aggregated Bit Rate* parameter (aggregating bits from various flows on a same V2X link), and finally *Range* parameter, which provides the minimum distance over which the PQI must be fulfilled. 5G QoS in addition depends on 6 additional metrics: a V2X resource type, a V2X Priority Level, a V2X Packet Delay Budget, a V2X Packet Error Rate, a finally a Maximum Data Burst Volume. Table 3 illustrates the characteristics of various PQI and the mapped V2X services.

Table 3 5G V2X PQI table

PQI Value	Resource Type	Default Priority Level	Packet Delay Budget	Packet Error Rate	Default Maximum Data Burst Volume	Default Averaging Window	Example Services
21	GBR	3	20 ms	10^{-4}	N/A	2000 ms	Platooning between UEs – Higher degree of automation; Platooning between UE and RSU – Higher degree of automation
22	(NOTE 1)	4	50 ms	10^{-2}	N/A	2000 ms	Sensor sharing – higher degree of automation
23		3	100 ms	10^{-4}	N/A	2000 ms	Information sharing for automated driving – between UEs or UE and RSU - higher degree of automation

55	Non-GBR	3	10 ms	10^{-4}	N/A	N/A	Cooperative lane change – higher degree of automation
56		6	20 ms	10^{-1}	N/A	N/A	Platooning informative exchange – low degree of automation; Platooning – information sharing with RSU
57		5	25 ms	10^{-1}	N/A	N/A	Cooperative lane change – lower degree of automation
58		4	100 ms	10^{-2}	N/A	N/A	Sensor information sharing – lower degree of automation
59		6	500 ms	10^{-1}	N/A	N/A	Platooning – reporting to an RSU
90	Delay Critical GBR	3	10 ms	10^{-4}	2000 bytes	2000 ms	Cooperative collision avoidance; Sensor sharing – Higher degree of automation; Video sharing – higher degree of automation
91	(NOTE 1)	2	3 ms	10^{-5}	2000 bytes	2000 ms	Emergency trajectory alignment; Sensor sharing – Higher degree of automation
NOTE 1:GBR and Delay Critical GBR PQIs can only be used for unicast PC5 communications.							

4.2.2.5 5G V2X COMMUNICATION PROCEDURES

Figure 50 depicts the V2X communication procedures for Groupcast communication. As it is shown, group management is handled by the V2X application layer and not a discovery layer as for ProSe. The Application layer will provide the list of L2 ID and target QoS metrics of vehicles participating to the groupcast communication.

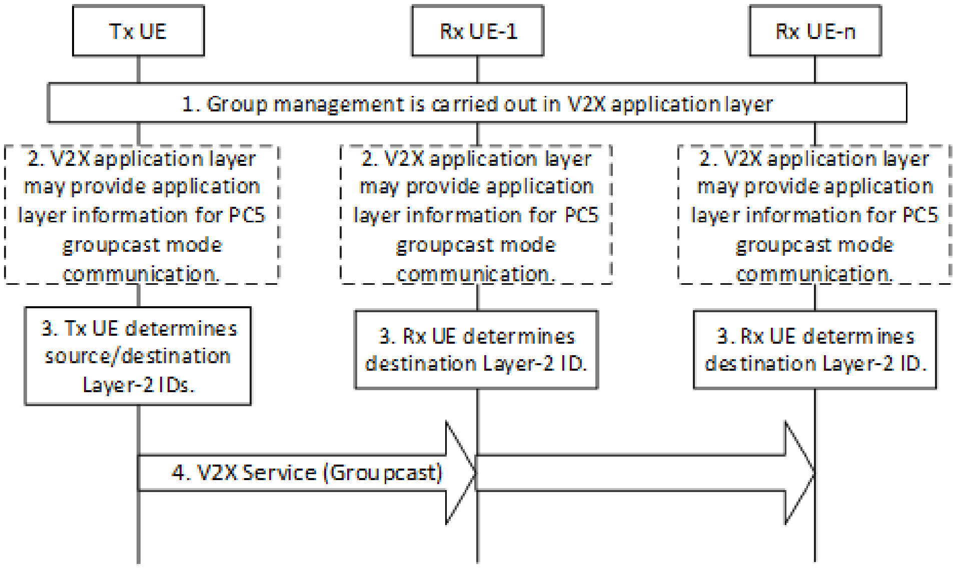


Figure 50 5G V2X Groupcast Communication Procedure

5G V2X unicast communication procedures have in addition a security establishment between two vehicles, which is handled over the PC5-S interface, in a similar way as for LTE V2X.

4.3 5G ProSe D2D Spectrum

As for LTE, 5G NR ProSe does not have an explicit frequency spectrum, although it is anticipated that any PS ProSe would be operated on PS spectra, and any other ProSe communications be operated on commercial spectra. A significant standardization activity within 3GPP is to extend the support of 5G NR SL & ProSe for Unlicensed band.

5G NR V2X on the other hand, has explicit spectrum bands reserved for V2X services, both in FR1 and FR2. It corresponds to the ITS spectra (5.9GHz for FR1 and 64GHz for FR2). Following the EU technology neutral access to the ITS bands, NR V2X must coexist with LTE V2X and ITS-G5 devices.

4.4 5G D2D Radio Resource Management

This section provides an overview of the 5G NR V2X radio resource management according to target bit rates, delay and scheduling.

4.4.1 BIT RATE

The target bit rate for NR V2X is not fully clear at the time of writing, notably due to the lack of advanced prototypes. However, NR V2X is a 5G technology, and as such, it should reach the 5G target bit rate:

- **Middle Band (sub 6Ghz)**: < 2-3 Gbps
- **Higher Band (>20Ghz)**: < 20Gbps

4.4.2 DELAY CONSIDERATION

LTE V2X has two major weaknesses in terms of delay. First, the LTE V2X LBT (Listen-Before-Talk) SBS (Semi-Persistent-Scheduling) requires to select resources over a 20ms time windows, and assuming a 100ms resource statistic history. At the time of writing, a LBT SBS approach remains the main candidate for the NR V2X mode 2(a) (default ad-hoc mode) scheduler. However, new NR V2X scheduling capabilities (see Figure 7) are expected to improve its access delay and reliability.

Second, an LTE V2X slot is 1 ms, which means that regardless of the message size, it will occupy 1ms time. Considering that most of the V2X messages are approximatively 500 ms and a limited number of messages allowed in frequency (usually 2), E2E delay can grow beyond what is required for time sensitive communications. NR V2X introduces the concept of mini-slot, which jointly with a more flexible frequency usage (15kHz, 30kHz, 60kHz) provides sub-ms subframe time.

Along with a flexible control of resource blocks, **NR V2X aims at providing 1ms delay**. It should yet be noted that NR V2X, as LTE V2X needs to integrate wireless cooperative congestion control mechanisms, which are expected to negatively impact such delay.

4.4.3 5G NR V2X SCHEDULER

NR V2X has several improvements in terms of robustness and interference. The first one is the possibility to reserve retransmission opportunities to mitigate the impact of collisions as depicted on Figure 51. LTE V2X also support retransmissions (called semi-persistent scheduling) but it has been designed to reduce the scheduling delay overhead as well as to improve the receiver gain to increase communication range. LTE V2X could not optimize retransmission based on reception or non-reception of messages.

In order to fully take benefit of this retransmission option, NR V2X provides another innovation called NACK (i.e., Negative Acknowledgments), where messages scheduled but not received by V2X receivers would allow to notify the transmitter, thus enabling the retransmissions.

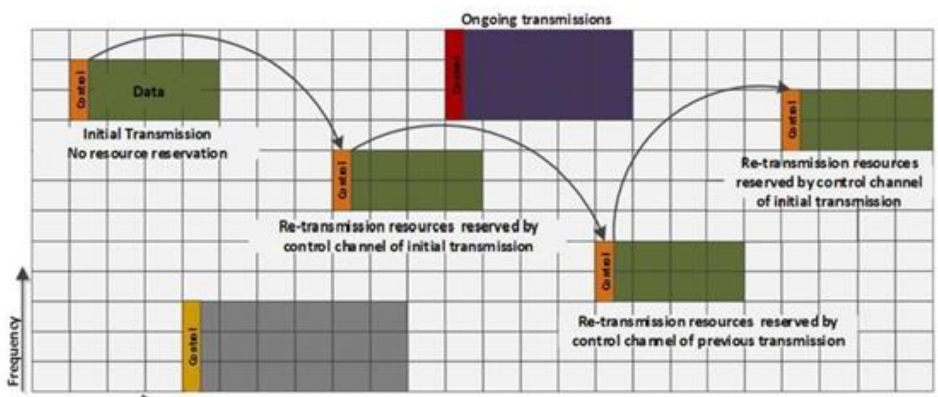


Figure 51 5G V2X Resource Scheduling for mode 2(a)

Finally, the third innovation of NR V2X is an increased flexibility in the scheduling support. The NR V2X ad-hoc mode, called mode 2, is decomposed in 4 sub-groups:

- **Mode 2(a) Autonomous resource selection –** same as LTE V2X mode 4
- **Mode 2(b) UE assists resource selection of other UEs –** a UE may indicate its preferred resources to other UEs
- **Mode 2(c) UE is configured with sidelink grants –** same as LTE V2X mode 4 SPS
- **Mode 2(d) UE schedules sidelink transmission of other UEs –** a cluster-head UE directs V2X communications, like LTE V2X mode 3, yet without eNB

4.4.4 PRACTICAL CONSIDERATION

NR V2X is an evolution of LTE V2X, correcting most of its weaknesses identified for future automated robotics and massive sensor communications. The 3GPP NR V2X Rel. 16 has been frozen in July 2020, with the first commercially available devices no earlier than 2025.

Moreover, if the 5G NR V2X describes 4 types of ad-hoc scheduler (mode 2), only mode 2(a) is specified in rel.16. Accordingly, 5G NR V2X has the same scheduler as LTE V2X.

4.5 5G D2D ProSe Services for IntellIoT use cases

5G D2D ProSe has only been studied from a theoretical aspect and evaluated via simulation based on KPIs related to UC1 and UC3. However, it has not been implemented for the two UCs. We describe below the prospective benefit of such implementation beyond IntellIoT.

4.5.1 UC1 – SMART FARMING

D2D communication could be envisioned in UC1 in two scenarios. First, a drone can connect to a tractor to provide extra sensory data or AI support. Accordingly, a D2D link will be established between the drone and the tractor. A second scenario envisions a D2D link between tractors in case they would be in range and could exchange sensing data or cooperate on AI.

4.5.2 UC3- SMART FACTORY

D2D communication could be envisioned in UC3 in two scenarios. First, robots and human interactions must be closely monitored and 5G NR ProSe can provide a robot virtual fencing service, notifying and stopping a robot when a human operator approaches within a given range. A second scenario enables robots to exchange information directly between each other either to synchronize movements or to share data or AI knowledge (cooperative training or knowledge services). It could finally also be envisioned to allow a robot operator to directly connect to the robot for remote operation, bypassing and offloading the 5G private backend.

4.6 5G NR V2X URLL Design & Performance Evaluation

Considering the lack of available NR V2X prototypes, 5G NR V2X has been investigated through simulations. The Network Simulator 3 (NS-3) has been selected as it has already a NR V2X architecture.

4.6.1 5G NR URLL PKI FOR V2X AND D2D

URLLC is defined in two aspects: reliability/delay requirements and specific traffic patterns. 3GPP rel.17[9] defines URLLC as providing a **10^{-5} reception reliability** with a **1 ms delay** for **32-byte packets**. 3GPP considers adapted requirements for **5G-NR V2X SL** as **10^{-5} reception reliability** with **3^{-10} ms delay** for **300-byte packets**.

3GPP does not provide details on how the delay should be distributed between 3-10 ms. A more suitable formulation requires defining the reliability level of the expected delay. For example, a 4 ms delay with reliability 10^{-5} (i.e. a prob. 10^{-5} for the delay to exceed 4 ms). Accordingly, in this work we define V2X URLLC in the following terms: reception reliability of 10^{-x} and a y ms delay with reliability of 10^{-z} . Evaluating 5G NR V2X capabilities to provide URLLC will require that we identify the x, y and z parameters.

We will focus less on a given delay value but rather on the reliability of that delay value. V2X traffic patterns for URLLC services are expected to be significantly different from regular (awareness) services, because they involve smaller data packets, a smaller transmit range and fewer users. Default 5G NR V2X SL parameters (numerology, sub-channels, MAC protocol, etc.) therefore need to be changed to adjust to such specific traffic patterns. V2X SL URLLC at 5.9GHz is challenging to meet. First, only 10 or 20 MHz of bandwidth is reserved for V2X communication, which might be insufficient if a higher numerology is involved. Second, the eV2X services cannot rely on the full availability of a 5GS

[9] ETSI, "5G;NR;Study on Scenarios and Requirements for Next Generation Access Technologies," 3GPP TR 38.913 version 17.0.0 Release 17, 2022-03.

infrastructure, and the default 5G-NR V2X SL mode 2 scheduler does not support time-deterministic channel access time

4.6.2 5G NR V2X SOFTWARE ARCHITECTURE ON NS3

Ns-3 is a widely adopted packet-level simulator to develop and evaluate the performance of network protocols and applications, due to the widely available libraries of network models and protocols (WIFI, BLE, LTE, 5G, V2X,..). Recently, a NR V2X architecture has been integrated. We describe here the software architecture of the NR V2X user and control planes. More details related to this NR V2X model may be found here[10].

The NR V2X architecture is built on top of the LTE architecture with NR and NR V2X specific extensions. For instance, NR V2X PHY and NR V2X MAC are extended to support NR Phy Slidelink channels as well as NR V2X MAC scheduler. NR functions above the NR PHY and MAC are also available as NR-specific APIs, although the models are still integrated into the LTE architecture. This current architecture allows to evaluate the performance of the NR V2X scheduler in challenging V2X environments and V2X traffic. However, the missing SDAP entity limits the current architecture to model real QoS management.

In our preliminary study, we are only interested in evaluating and comparing the performance of the NR V2X MAC at FR1 and FR2 with LTE V2X. The current architecture limitations are not impacting our study. However, extensions to the ns-3 model architecture to integrate SDAP will be performed in future research projects.

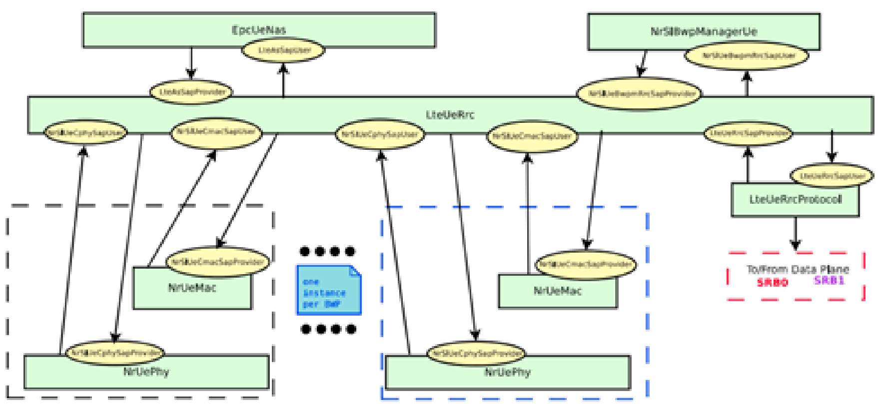


Figure 52 Ns3 NR V2X Control Plane architecture

[10] Z. Ali, S. Lagén, L. Giupponi and R. Rouil, "3GPP NR V2X Mode 2: Overview, Models and System-Level Evaluation," in IEEE Access, vol. 9, pp. 89554-89579, 2021, doi: 10.1109/ACCESS.2021.3090855.

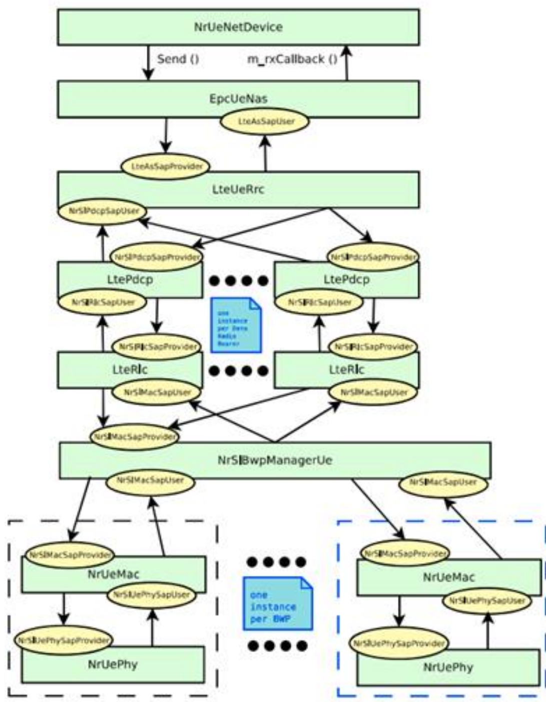


Figure 53 Ns-3 NR V2X User Plane architecture

4.6.3 NR V2X PERFORMANCE COMPARISON BETWEEN FR1 AND FR2

As for 5G NR, the V2X extension supports two frequency ranges FR1 and FR2, and similarly to NR, NR V2X FR2 is expected to be required to support the large amount of sensor or AI/ML data exchanged between vehicles and the infrastructure in the future. A first question could be to compare the performance of NR V2X in FR1 and FR2 considering capacity as the optimization point. The default parameters configured with ns3 are provided on Table 4

Table 4 Ns3 Simulation Parameters

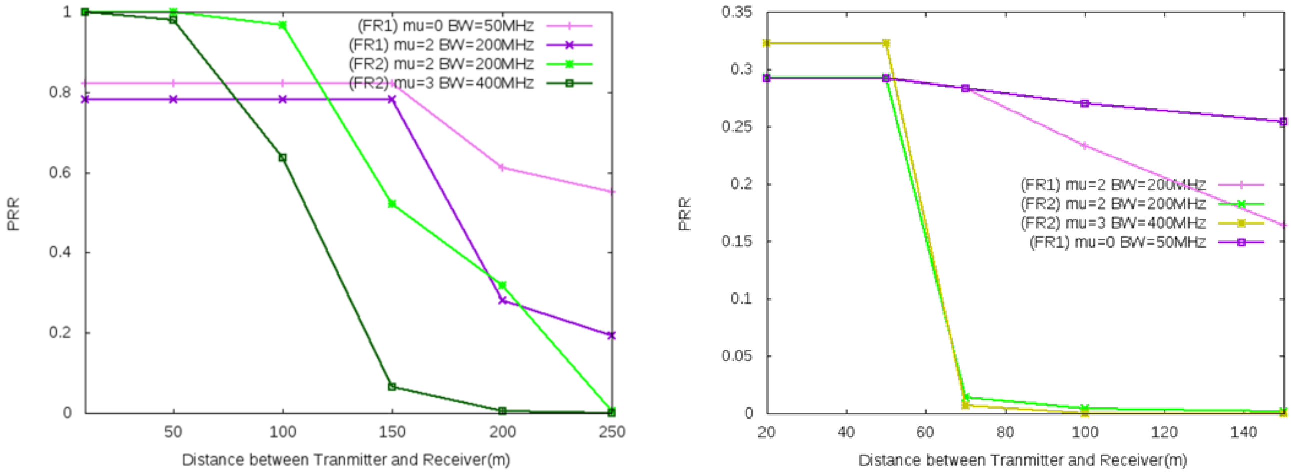
NR V2X Parameters		
Frequency Range	FR1	FR2
Random Seed	Seed:30, Run:200	Seed:30, Run:200
Performed Frequency	5.89GHz	26.89GHz
Topology	1TX 1RX	1TX 1RX
Bandwidth	50MHz	200MHz
SubChannel Size	10(smallest)	10(smallest)
MCS	0,14,28	0,14,28
Numerology	0	2
Available SL symbol per slot	8/14	8/14
Sensing Window	100	100

Selection Window	30	30
Reservation Period	20	10
No. Selected Slot per time	1	1
Re-transmission	Disabled	Disabled

Considering that NR V2X is planned to be used to exchange larger packet sizes at a higher Tx rate, we wanted to evaluate the impact of large packets (1500 bytes) as well as high Tx rate (1Mbps-> 100Mbps) on the performance of NR V2X both in FR1 and FR2. In our scenarios, except Figure 54, we only consider on Tx and on Rx and no interferences. Any packet loss may only come either from the impact of the wireless channel on the selected technology (FR1 or FR2) or from packet being dropped by the NR V2X stack due to the lack of radio resources.

Figure 54, depicts the Packet Reception Rate considering a 2Mbps Tx rate for regular CAM-type packets (200 bytes) both considering 1 Tx-Rx (i.e., no interference) or 10 Tx-Rx (including interferences). As it may by observed on Figure 54(a), the increased capacity available in FR2 enables a very reliable 5G V2X communication up to 100m radio range. Comparatively, FR1 never reaches a PRR higher than 80% due to packet being dropped by the lack of channel resources. We can also observe the impact of mmWAVE channels on NR V2X FR2, which PRR drops faster and as closer distance compared to FR1. We can, however, see that considering 1 Rx-Tx and no interference, FR2 has a significant benefit on the reliability of NR V2X communications. Considering now interferences created by 10 Tx-Rx, the performance of 5G V2X drops significantly and irrespectively to the FR, as the PRR never gets higher than 30% This is most likely due to the NR V2X mode 2(a) scheduler inheriting radio resource selection over a 20ms window and accordingly, dropping packets when resources are not available (and not specifically due to collisions as otherwise we would have observed less collisions in FR2). This limitation being at the NR V2X protocol stack, it impacts both FR1 and FR2. This 20ms (configurable) has been designed for LTE V2X in order to limit the mean delay to 10ms. However, NR V2X enhanced numerology could be improved to separate traffic requiring low delay and high capacity and dramatically increasing the resource selection at no impact on delay.

However, when the Tx-Rx distance increases, we can observe the impact of the mmWAVE channel on the PRR, as PRR drops quickly to 0 with distance. Although this performance depends on the beamforming strategy at FR2, it also shows the strong impact the wireless channel has on mmWAVE transmissions. NR V2X in FR1 keeps a higher PRR over distance.



(a) 1 Tx-Rx

(b) 10 Tx-Rx

Figure 54 Packet Reception Rate over distance for NR V2X in FR1 and FR2 in a saturation case (rate=2Mbps packet size: 200 bytes)

The second set of results shows the evolution of the PRR when the transmit rate increases up to 100Mbps. In this configuration, we also considered the largest V2X packet size of 1500 bytes in order to fully pressure the NR V2X scheduler. As it can be seen on Figure 55, the PRR remains 100% up to 3Mbps, which is an interesting observation of the impact of the packet size on the V2X scheduler. Indeed, in comparison with the previous figure (for 1Tx-Rx), considering a constant transmit rate, increasing the packet size de facto reduces the flow of packets at the scheduler, therefore, enabling it to operate better. As a consequence, we can observe that the current NR V2X specification, requires PDCP aggregated data over longer packet sizes when massive amount of data is exchanged. This, however, is opposite to the NR V2X specification, which forbids this functionality in order to gain in delay.

When the transmit rate further increases, we see that the higher bandwidth available for FR2 enables it to maintain a higher PRR until 10Mbps. After this limit, both FR1 and FR2 suffer from the scheduler saturation and have poor PRR. Nevertheless, we can also observe from this set of results that neither FR1 nor FR2 provides the required V2X capacity expected by NR.

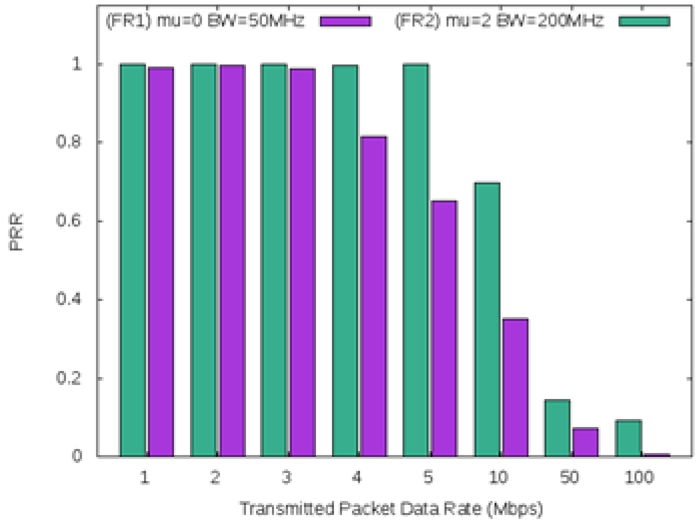


Figure 55 Packet Reception Rate as function of the Tx data rate for NR V2X in FR1 and FR2, considering max packet size (1500byte)

In the previous results, a default MCS 14 has been selected (as recommended for V2X). On Figure 56**Error! Reference source not found.**, we evaluate the impact of increasing the MCS for FR1 and FR2. This scenario is not fully representative of the true impact of MCS, as we do not consider interferences and we only consider broadcast/groupcast traffic. However, it already shows that when transmitting large amounts of data, FR2 may better support the MCS increase and provide a higher total capacity. A more complete study should be performed to evaluate the impact of interferences to select the most optimal MCS according to a particular context.

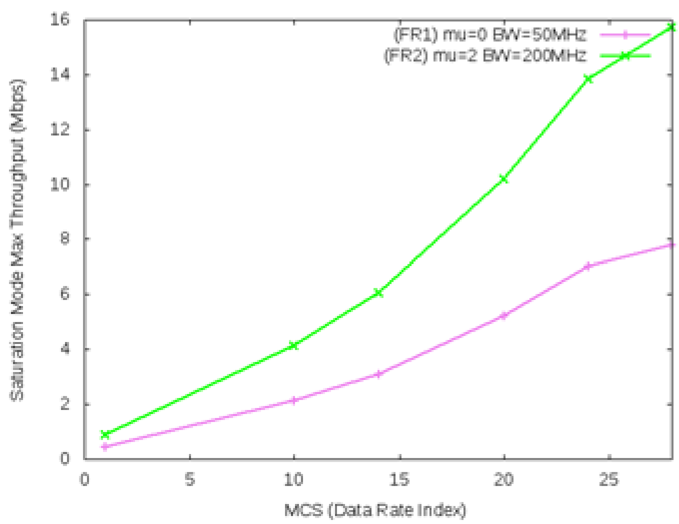


Figure 56 Maximum Saturation Capacity as function of the modulation rate (MCS) for NR V2X in FR1 and FR2

To conclude, this study aimed at testing NR V2X considering capacity as an optimization point. Accordingly, large packets or transmit capacity up to 50-100 Mbps have been tested for NR V2X. We could observe that NR V2X both considering FR1 and FR2 do not meet the optimal capacity targeted by the 3GPP NR V2X rel.16 standard, but improvement could be envisioned.

4.6.4 URLL FRAMEWORK FOR 5G NR V2X

In this section, we develop and evaluate the performance of a URLL framework for 5G NR V2X SL.

4.6.4.1 DESIGN

Meeting 5G-NR V2X SL URLLC requires the following 3-block framework: higher physical layer numerology, a deterministic scheduler and URLLC admission control.

Since a higher numerology can effectively reduce the duration of a mini-slot, which is compensated for by its expansion of the frequency domain, we therefore apply numerology-3, which enables a unit duration as small as 0.125 ms. Considering the limited V2X bandwidth in 5.9 GHz frequency, in order to meet the 300 bytes packet size specified for URLLC SL, and to avoid the half-duplexing problem, we consider a pure time-domain multiplexing. As depicted in the right-hand image on Figure 57 considering a 10 MHz assigned V2X bandwidth under numerology-3, all 6 available PRBs are uniformly assigned to one user.

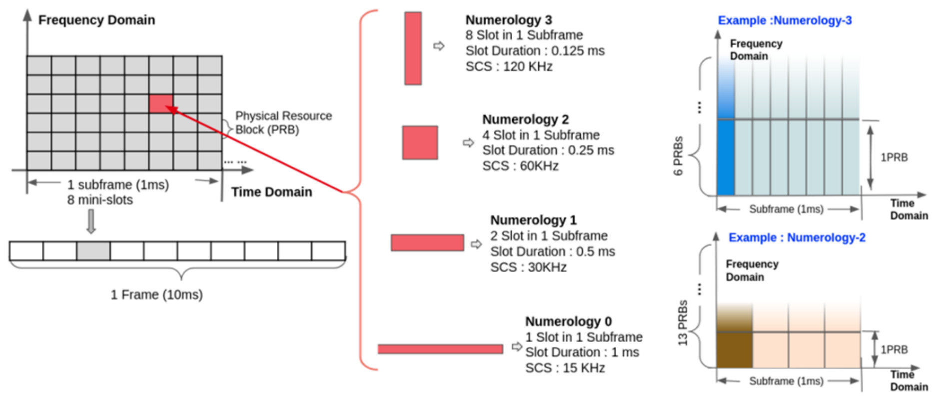


Figure 57 5G NR Numerology Schemes

According to 3GPP 5G NR SL scheduler options, mode 2(c) and 2(d) enable potential scheduling strategies suitable for URLLC services. Contrary to the collision-prone default listen-before talk (LBT) 5G NR SL scheduler, we propose an Optical Orthogonal Code (OOC)-based deterministic mode-2(c) scheduler supporting channel access delay bounds. OOC has been adapted to a variety of channel access technologies, in particular by Gallo et al.[11] for C-V2X. This technique improves delivery reliability by restraining the maximum cross-correlation between binary codewords among any pairs of codewords. The OOC-based deterministic scheduling procedure is listed below.

- A L-bit long OOC codewords transmission pattern is pre-configured while satisfying the cross-correlation constraint condition. Each bit is associated with one mini-slot (duration of 0.125 ms).
- VUEs can transmit a packet in a mini-slot when the corresponding OOC indicator is 1-bit; VUEs switch to receiving mode while the OOC indicator is 0-bit.

[11] L. Gallo and J. Harri, "Short paper: A LTE-direct Broadcast Mechanism for Periodic Vehicular Safety Communications," in 2013 IEEE Vehicular Networking Conference, 2013, pp. 166–169.

- The transmission status is illustrated in Figure 58, where red 1-bits refer to transmission collisions while green 1-bits indicate successful, collision-free receptions.
- The parameter **w** determines the re-transmission rate, which corresponds to the total number of 1-bits within one code-word.

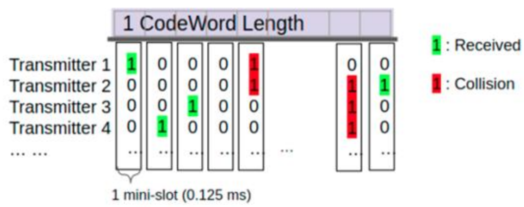


Figure 58 Illustration of an OCC codeword for 4 transmitters

URLLC services require restricting access to a limited number of users. To analyze such a limit, the maximum capacity for the accessible VUE needs to be evaluated. We formulate the admission control problem into an optimization equation maximizing SL access link connections. Constraints for the optimization problem relate to both reliability and latency URLLC service requirements. We focus on a reception reliability of 10^{-5} , and a 1ms with a reliability of 10^{-2}.

4.6.4.2 PERFORMANCE EVALUATION

The mechanisms previously described are evaluated by Matlab simulations according to parameter settings described in Table 5. All vehicles are allocated on a one-lane road scenario sending messages in broadcast to one reception vehicle. A configurable number of transmitters are randomly generated according to the target 1km-wide communication density. Analysis of the impact created by channel fading, phase shifting, and other physical layer criteria is left for future studies. Data traffic is generated at 10 Hz (100 ms) over the total simulation time to allow an ergodic analysis.

Three key performance indicators (KPI) are selected in this paper:

- Packet Reception Rate (PRR): This parameter is expressed in a Complementary Cumulative Distribution Function (CCDF) in relation to the number of transmitters.
- Delay: Delay is considered from two dimensions as depicted in Figure 59b: the absolute delay measures the time interval from the generated data packet; the relative delay only considers the exact airtime including channel access delay. Without re-transmission, this value is set to one mini-slot (0.125 ms), whereas with re-transmissions this value is calculated as the time between the first successful reception and the relative starting time.
- Number of controlled admissions: This indicates the maximum number of admitted V2V (SL) links when both the packet reception rate and the delay conditions are satisfied.

Table 5 5G NR V2X URLL scheduler parameter settings

Parameter	Value
Bandwidth	10 MHz
Applied Numerology	3
Hamming Weight w	1,2,3,4
Transmission Range	1000 m
Packet Rate	100 ms
Simulation time	30 s
Runs	300

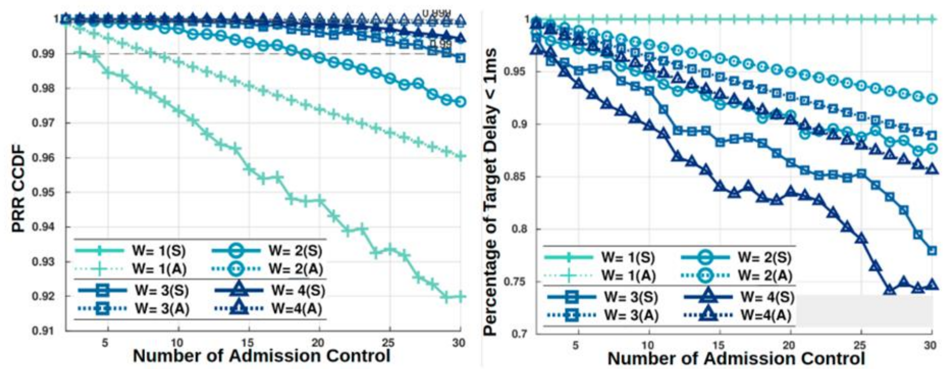


Figure 59 5G NR V2X mode 2.d scheduler performance

We investigate the performance regarding PRR and delay criteria under a fixed code-length of L = 90×8. Moreover, we focus on the strictest sub-ms (< 1ms) latency requirement depicted in Figure 59. Comparison between analytical (in dashed points) and simulation results (in bold lines) are indicated in both figures. Overall, the PRR and delay reliability both decrease as the number of admitted users increases. The analytical model over-estimates the optimal number of admitted users, as the simulation results are subject to near-far issues, where additional collisions occur from out-of-coverage users, reducing the number of admitted users. In a higher-density scenario, near-far characteristics result in a greater impact, consequently the difference between the analytical and simulation results widens. We therefore may consider the analytical model as an optimal benchmark.

We may also observe correlated relationships between the analytical model and simulations under different retransmission time w values: firstly a higher *w* can effectively improve the overall reliability suggested in Figure 59a, we can also verify that with lower w = 1, 2, it is extremely difficult to achieve the target reliability demand; secondly in terms of latency depicted in Figure 59b, as additional re-transmissions produce higher delays, the probability of fulfilling the sub-ms latency requirement is considerably reduced when more re-transmissions are generated. We can therefore identify that **w = 3** achieved the optimal number of users admitted (**6 connected UEs**) under the target URLLC requirement.

4.6.5 5G PROSE URLL SLICE SERVICE

Following the observation that 5G NR V2X URLL services requires a strong access control and a dedicated scheduler, one strategy to guarantee the 5G NR V2X URLL PKIs would require to design a specific slice dedicated to URLL 5G NR V2X communication.

4.6.5.1 DESIGN

We introduce a novel framework for integrated slice design tailored to platooning communication, as illustrated in Figure 60 on the right. Separate slices are allocated for both fundamental V2X communication and vehicular platooning to minimize interference and ensure independent operations. The slice for platooning is specifically aimed to support URLLC for critical intra-platoon messages. Additionally, ProSe is employed to announce platoon services and handle PMMs, notably the join and leave functions.

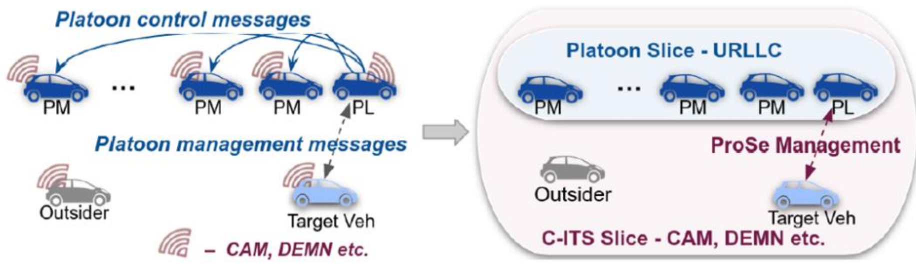


Figure 60 Platoon Management & Control with C-ITS messages

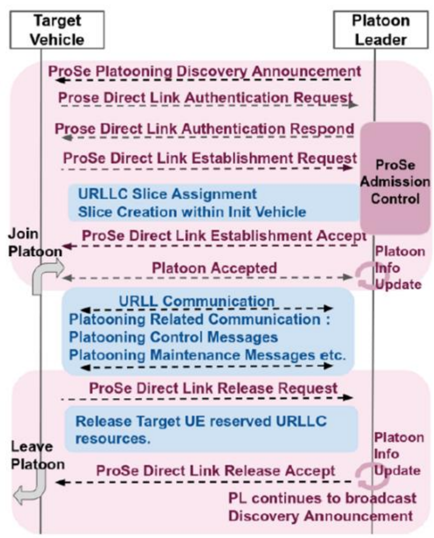


Figure 61 5G NR ProSe Platoon Service

This section presents the proposed ProSe-based platoon join&leave management and slice assignment procedures. Figure 61 details these in four main phases:

- Platoon Initial Announcement: Initially, the PL is authorised to act as the announcing UE, allowing it to transmit platoon service announcements to its neighbors via the ProSe PC5 Discovery Message. Nearby target vehicles who want to join platoon act as monitoring UEs, constantly listening to their neighbours' ProSe discovery messages from current adjacent platoons before they are accepted by any platoon.
- Joining Platoon: When a new vehicle wants to join a platoon, it will piggyback its joining request through a ProSe Direct-Link-Request message to the PL. The PL is obliged to compare the current platoon size with its local admission control capacity; this capacity is determined by its ability to provide high-quality URLLC

services to each PM. Only if there are still available spots can the current platoon accept this new arrival; otherwise, a rejection is issued.

- URLLC for Intra-platoon Communication: Upon acceptance, the new platoon member triggered by the ProSe establish messages, starts to allocate its local resources for URLLC slices according to the platoon slice design. Additionally, the PL assigns a slot to this new member based on a predetermined pattern from the deterministic Mode 2(c) scheduler scheme.

The platoon slice (depicted in light blue Figure 62) is designed for communication needs of high stringency with minimal resource demands. Consequently, the reservation period for the platoon slice is significantly shorter than that of the C-ITS slice. Additionally, adhering to the standard interpacket gap of 10 ms in V2X technologies, as recommended by 5GAA, only 1 ms is designated for the platoon slice within each 10 ms C-ITS slice.

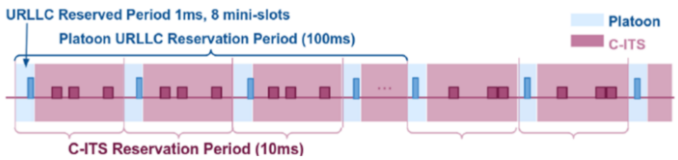


Figure 62 5A NR V2X URLL Slice

4.6.5.2 PERFORMANCE EVALUATION

The previously described framework has been evaluated via a joint simulation framework integrating SUMO and ns-3. The scenario depicted on Figure 63 is one formed platoon on a highway crosses external vehicle which increases the load on the wireless channel and reduce the performance of the NR-V2X scheduler. Consequently, platoon control messages (PCM) are delayed or lost, which in turn reduces the efficiency of the platoon control. A platoon is said to be "string-stable" if the acceleration values between various platoon members are stable and contained within a given bound. If the acceleration values between platoon members are drifting, the platoon is said to be string unstable.

Figure 64 depicts the acceleration difference between two vehicles (leader and one platoon member) . If acceleration values oscillate naturally (within a controlled bound), we can observe that round time step 7000 [s], it is no longer contained and drifts significantly. This corresponds to the passage of the external vehicles and their impact on the reception of PCM. We can see such an impact more clearly on Figure 65, where we depict the PCM reception delay. Without the NR V2X URLL slice management previously described, we see a sudden peak in PCM delay corresponding to the external vehicles crossing the platoon. Comparatively, when the PCM are sent in the protected URLL slice, PCM are not impacted by external vehicles, which in turn keeps the platoon string stable.

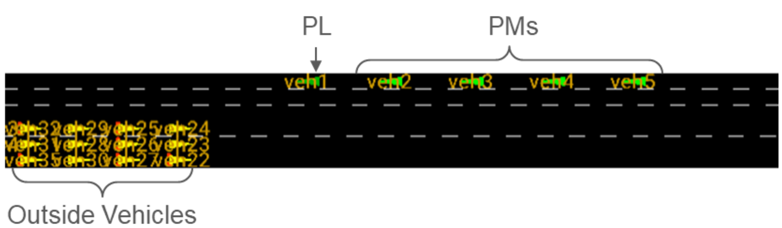


Figure 63 Platoon highway scenario with external vehicles crossing.

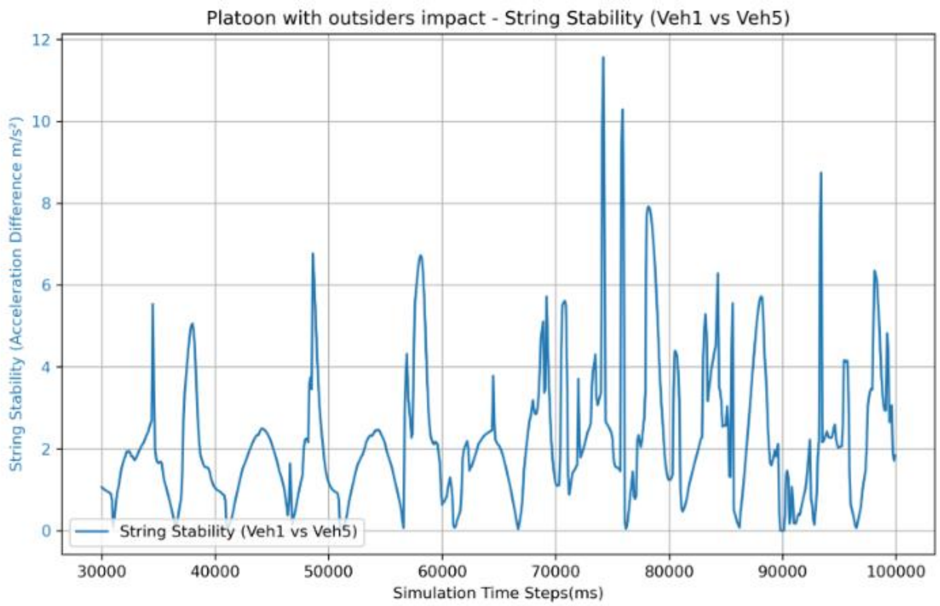


Figure 64 Platoon String Stability Evaluation

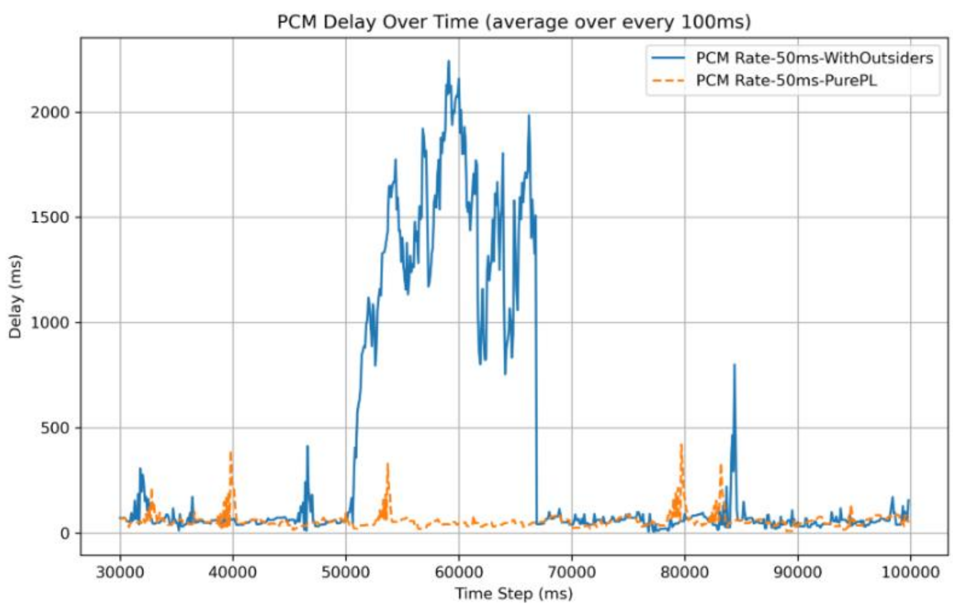


Figure 65 Platoon Control Messages Reception Delay

4.6.6 DISCUSSION

In this section, we have introduced an extension of 5G NR-V2X to support URLL communications. It takes the form of a dedicated URLL slice, with its own numerology, scheduler and admission control. URLL KPIs are be reached with a slice occupancy of up to 8 vehicles. Integrating the URLL slice with a platoon application, we also proposed a 5G NR ProSe platoon service providing URLL communication.

5 OPEN SOURCE ACCESS

OpenAirInterface is an Open Source and Open Access Software Defined Radio platform architecture, which has been developed under the OpenAirInterface Software Alliance (OSA) License 1.1. It is an industry friendly license baring similarities with Apache 2.0. Accordingly, all software architecture has been developed and is released a OpenSource. A full detail of the platform architecture is available on the official OpenAirInterface website: https://openairinterface.org/

The software code is available on three repositories according to 'Projects':

- 5G RAN: https://gitlab.eurecom.fr/oai/openairinterface5g/
- 5G Core Network: https://gitlab.eurecom.fr/oai/cn5g/oai-cn5g-amf/-/wikis/home
- OAI Operations and Maintenance (OAM) (ex. Mosaic5G):
  - FlexRIC: https://gitlab.eurecom.fr/mosaic5g/flexric
  - FlexCN: https://gitlab.eurecom.fr/mosaic5g/flexcn/
  - Multi-access Edge Computing platforms (MEP): https://gitlab.eurecom.fr/oai/orchestration/blueprints
  - Radio Network Information Service (RNIS): https://gitlab.eurecom.fr/oai/orchestration/oai-mec/oai-rnis

EURECOM hosts a the gitlab server in its premises, guaranteeing the code to be hosted within the UE.

Development performed on top of OpenAirInterface (e.g. the radio resource manager) are available on the Public IntellIoT Gitlab, available as function of the specific IntellIoT component:

- IntellIoT: https://gitlab.eurecom.fr/intelliot

6 CONCLUSION

This deliverable is the final output of Task 4.6 (“5G network functionalities”) and, as such, documented the design and development of the 5G components and their integration into the third pillar (“efficient, reliable and trustworthy computation & communication infrastructure”) of the IntellIoT proposed framework.

Considering the 5G components and their requirements described in deliverable D2.3 ("High level architecture"), this document introduces the components themselves. It first shed lights on the State-of-the-Art in the component specification in the respective standardization organizations, then depicted the software platforms in which these components are implemented, and finally described their specifications.

This document also provides an evaluation of the functionality of selected components (in particular 5G NR RAN SA and NSA) and simulation-based evaluation of the default components (NR V2X).

From the various components described in D2.3, the following components have been described in this document:

- 5G NR NSA & SA basic functionalities with a 5G dongle in FR1 & FR2.
- 5G FlexRIC components capable of controlling the radio resource allocation for the 5G RAN.
- 5G FlexCN component capable of handling MEC/Edge services and RAN monitoring.
- 5G NR V2X performance comparison between FR1 and FR2 and identification of potential extensions to support URLL communication on sidelink.

7 ACRONYMS

3GPP	Third Generation Partnership Project
5G	Fifth Generation
5GC	5G Core
5GS	5G System
5QI	5G New Radio Standardized Quality of Service Identifier
AF	Application Function
AMF	Access and Mobility Function
API	Application Programming Interface
AR	Augmented Reality
ARP	Allocation and Retention Priority
AS	Application Server
D2D	Device-to-Device
DDNMF	Device-to-Device Network Mobility Function
DL	Downlink
DN	Data Network
DNS	Domain Name Service
EAS	Edge Application Server
eNB	Evolved Node B
EPC	Evolved Packet Core
E-UTRA	Evolved Universal Terrestrial Radio Access
FR1	Frequency Range 1 (sub 6Ghz)
FR2	Frequency Range 2 (> 10Ghz)
IoT	Internet of Things
LBT	Listen Before Talk
LTE	Long Term Evolution
MAC	Medium Access Control
MEC	Multi-access Edge Computing / Mobile Edge Computing
NEF	Network Exposure Function
NF	Network Function
NG-RAN	Next Generation Radio Access Network

NR	New Radio
NRF	Network Repository Function
OAI	OpenAirInterface
PFI	PC5 QoS Flow ID
PQI	PC5 5QI
ProSe	Proximity Service
PS	Public Safety
QoS	Quality of Service
RAN	Radio Access Network
RIC	Radio Intelligent Control
RLC	Radio Link Control
RRC	Radio Resource Control
SCI	Sidelink Control Information
SDAP	Service Data Adaptation Protocol
SPS	Semi-Persistent Scheduling
TSN	Time Sensitive Network
UDM	Unified Data Management
UE	User Equipment
UL	Uplink
UPF	User Plane Function
URLL	Ultra-Reliable Low Latency Communications
UTRA	Universal Terrestrial Radio Access
VR	Virtual Reality
V2X	Vehicle to Everything

8 REFERENCE

3GPP TS 23.303 V16.0.0, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Proximity-based services (ProSe);Stage 2.

3GPP TS 23.304 V17.0.0, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Proximity based Services (ProSe) in the 5G System (5GS).

3GPP TS 23.287 V16.3.0, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Architecture enhancements for 5G System (5GS) to support Vehicle-to-Everything (V2X) services.

3GPP TS 23.501 V17.2.0, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; System architecture for the 5G System (5GS); Stage 2

3GPP TS 23.548 V17.0.0, 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; 5G System Enhancements for Edge Computing; Stage 2