slices SC

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D2.1 Requirements analysis for exposing the RI

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Scientific
Large-scale
Infrastructure
for Computing
Communication
Experimental
Studies
Starting
Communities

www.slices-sc.eu

Executive summary

This deliverable aims to present the research community demands on Digital Infrastructures, what is existing in terms of research infrastructures, inherited by previous research projects, as well as the interfaces and the intercommunications between the current infrastructures, in order to organize how all the different experimental components in SLICES-SC are exposed for users.

Having in mind the ongoing digital transformation of the human societies, it is more than certain that the Digital Infrastructures will pave the way for significant improvements on the industrial, economic and political dimensions. In order to create fully exploitable infrastructures, the research community needs to address significant challenges regarding their efficiency, trust, availability, reliability, range, end-to-end latency, security and privacy. A requirement analysis has been completed through a survey, which is presented analytically to this deliverable. The results of this survey indicate to us which are the main research directions that should be assisted by SLICES.

Moreover, SLICES ambitions to exploit all existing assets at the European level of research infrastructures. SLICES-SC will rely on the current resources to enhance their utilization and incorporate them in order to create a European-wide test-platform with advanced compute, storage and network components, which are interconnected by dedicated high-speed links. This deliverable presents analytically the current infrastructure resources and the services that are offered nowadays by the European research community, as well as the current tools and APIs that exist across the different testbeds that comprise SLICES-SC. Our goal is SLICES to be the main experimental collaborative instrument for researchers at the European level, exploring and pushing further the envelope of the future Internet.

Table of content

Acronyms

API	Application Programming Interface
ASIC	Application Specific Integrated Circuit
CI/CD	Continuous Integration/Continuous Development
CN	Core Network
CNF	Containerized Network Function
CP	Control Plane
CU	Central Unit
CUPS	Control/User Plane Separation
DU	Distributed Unit
eNB	evolved NodeB
EPC	Evolved Packet Core
FPGA	Field Programmable Gate Array
FRCP	Federated Resource Control Protocol
FTTH	Fiber to the Home
gNB	gigabit NodeB
GPP	General Purpose Processor
GPU	Graphics Processing Unit
HPC	High Performance Computing
IaaS	Infrastructure as a Service
ICT	Information and Comunication Technology
IoT	Internet of Things
KPI	Key Performance Indicator
LTE	Long Term Evolution
MANO	Management and Orchestration
MEC	Multi-Access Edge Computing
ML	Machine Learning
NEF	Network Exposure Function
NFV	Network Functions Virtualization
NFVI	NFV Infrastructure
NIC	Network Interface Card
NRF	Network Repository Function
NSI	Network Service instance
NSSF	Network Slicing Selection Function
ODL	OpenDayLight (SDN controller)
ONAP	Open Networking Automation Platform
ONF	Open Networking Foundation
O-RAN	Open-RAN
OSM	Open Source MANO
PCF	Policy Control Function
RAN	Radio Access Network
RIC	RAN Intelligent Controller
RU	Radio Unit
SBA	Service Based Architecture
SDN	Software Defined Networking
SDR	Software Defined Radio
SD-RAN	Software Defined RAN
SFA	Slice Federation Architecture
SMF	Session Management Function
UAV	Unmanned Aerial Vehicle
UDM	Unified Data Management
UP	User Plane
UPF	User Plane Function
V2X	Vehicle to Everything
VNF	Virtual Network Function

1. Introduction

Digital Infrastructures and the Internet technologies lie at the heart of the digital transformation of our society. The recent global crisis caused by the COVID-19 pandemic pinpoints the important role of Digital Infrastructures, and outlines how they should be reinforced for the coming years. SLICES aspires to design, deploy and operate a heterogeneous highly distributed infrastructure that will drive experimentally-driven research over real, scalable Digital Infrastructures. Nevertheless, as the research in the sector covers simultaneously different fields, the principles need to be identified and prioritized, based on the requirements that have been given by the respective community.

This document provides the requirement analysis of SLICES. It presents whatever is identified as demand of the research community and concludes to a set of research fields, which will be assisted by SLICES. Towards collecting the real demands of the research community working for 6G, we conducted a survey in the relevant ICT communities for assessing their needs, and now, we report in this deliverable the detailed results of this survey. The responses of the research communities to this survey allowed SLICES to determine the demands for the future testbed infrastructures. The SLICES infrastructure will be focused on the most interesting of the aforementioned topics, and the use cases that are mostly related to these topics will be identified and supported. The new research infrastructure will prioritize topics such as Cybersecurity, telecommunications and network technologies, privacy and data protection, but will also take care of other topics, such as Artificial Intelligence, e-Health, mobility and connected vehicles, clean and sustainable energy. These outcomes will be reviewed and continuously monitored during the journey of the project.

The capabilities of the current infrastructures are analyzed considering all possible alternatives and converging to the most optimal exploitation of them. There is a rich variety of European research infrastructures which are partially satisfying most of the current research requirements, however, they need to be redesigned and reorganized in a centralized manner in order to unleash their hidden potential and deal also with the future research necessities. In this report, SLICES analyses the current status of the European infrastructures and designs the new SLICES infrastructure, based on the enriched experience gained by all relative European research initiatives run until now.

The document is organized as follows. Section 2 provides a brief overview of the demand analysis for the SLICES research infrastructure. Section 3 presents the current status of the existing European infrastructures, outlining their capabilities. Section 4 presents the requirements for computing and connectivity towards experimenting with key technologies for 6G, transport network and cloud computing. Section 5 briefly presents the interfaces used by the existing infrastructures, as well as their interconnections. Finally, in section 6 we conclude the document and present future directions in deploying and operating the SLICES research infrastructure.

2. Demand Analysis

The networking technologies (including wireless, IoT, Cloud/Edge, as well as AI/ML and HPC) have been significantly emerged nowadays. Regarding the mobile broadband communications, cellphone users are already experiencing the initial 5G deployments in several countries, while simultaneously to the 5G development activities, there are also enriched research initiatives prospering the 5G evolution towards 6G. The 6G research is conducted by many projects, organizations, academia and standardization forums, based on their experience regarding the 5G limitations. Testbeds are very critical for enriching the 5G related experience of all these stakeholders, enabling the enhanced and accurate evaluation of realistic scenarios of usage of mobile communication services. The design and deployment of such testbeds for enabling the research on 5G and beyond is significantly complex and time-consuming, since it requires a lot of human effort from multiple engineers and experts on wireless, IoT, cloud, SDN, AI/ML and HPC. One of the project contributions that is reported to this deliverable is the collection of the market and research community demands for these testbed infrastructures.

During the long evolution of mobile communication systems from 1G to 5G, the industry has succeeded significant advances in supporting outstanding applications that will be further improved, if and only if they are evaluated on real deployments with use of testbeds. These applications include high-definition media streaming, low-latency V2X communication, reliable-critical emergency networks, power-efficient IoT communications and unmanned aerial vehicles. There is still a significant amount of research, which is necessary to unleash the full potential of all these applications. The commercial rollout of 5G is underway, but the outcomes of the research on these testbeds will constitute the fertile ground for the 6G foundation, which will most probably be commercialized by 2030.

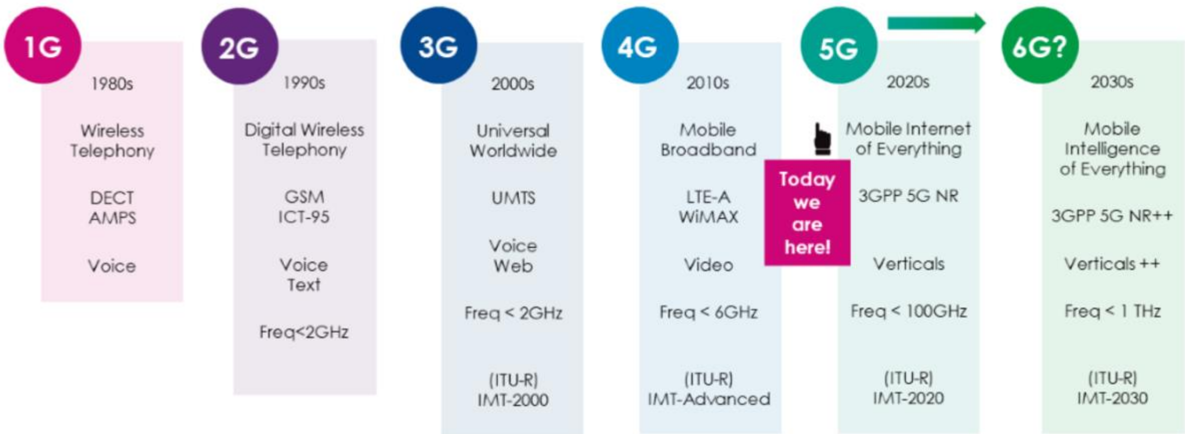


Figure 1: 5G and beyond KPIs

6G is expected to significantly extend the mobile communication capabilities, comparing to 5G, enabling a vast variety of advanced verticals and use cases that are not yet realized. The current and upcoming technological developments and advancements will be able to support new use cases requiring wireless communication. For example, the wireless connectivity for Oceans, Space, Air-to-ground (including aerial vehicles), High-speed trains (supporting more than 500 kms/h) and satellite networks are paving the way for 6G. Moreover, the exploitation of the Terahertz frequencies will be a significant boost towards 6G. The maturation of all these technologies requires their comprehensive evaluation on testbeds, in order to check if the 6G KPIs are satisfied, which will be 10 to 20-fold stricter than the 5G ones, as it is depicted in Figure 1. Below, the SLICES research for collecting the real demands of the research community working for 6G is presented.

1.1. Methodology

In the context of the SLICES-DS project, a complete analysis of the demand from the scientific communities was undertaken and reported in the SLICES-DS deliverable D1.2 "Requirements and needs of scientific communities from ICT-based Research Infrastructures"[1]. This deliverable has collected through a survey created by SLICES the needs, the requirements and the expectations coming from the potential SLICES users from the research community. The analysis done in the previous deliverable was global and so, covered all the aspects of the future research infrastructure, including the technical and operational requirements from the scientific community. As background information, the survey was conducted during December 2020 and January 2021 with 226 participating people; 67 of them answered all the questions of the survey.

As one of the main objectives of the SLICES-SC project is to develop different types of access to the SLICES research infrastructure, this section is presenting the demand analysis with the viewpoint of SLICES-SC. It concretely means that the results of the user survey were reexamined with a strong focus on the needs and requirements from the research community on the aspects concerning the access to the research infrastructure and how to expose the services to the users.

1.2. Demand Analysis from the Survey

The first question which is of interest for the SLICES-SC project is the expected capabilities or functionalities currently missing in terms of ICT research infrastructure. Among the numerous answers received for this open question, several of them highlight the needs and the expectations from the research community in terms of access and services. Some features should be implemented by the SLICES research infrastructure and exposed to the potential users.

The first of them is the openness. Indeed, the research infrastructure should be open for the research community as a basic requirement. The potential users expect that the provided research infrastructure will be very similar to real testbed deployments; it probably means to have also similar accesses and services related to existing testbeds from the industry in general. One of the most expected features is the possibility that the experimenters can manage the network of the research infrastructure in function of the needs of their experiments. Furthermore, a catalogue of real data sets should be provided by the research infrastructure as a service. Other expected service is the traffic generators and simulators which can be used in the experiments.

Some other functionalities were suggested by the potential SLICES users. For instance, the energy monitoring should be available in the research infrastructure to assess the energy consumption. The research infrastructure should be of course energy efficient. As suggested by several potential users, the access to the SLICES research infrastructure should also encompass the access to computers, robots, UAVs, connected vehicles, SDN/NFV, HPC resources, IoT and different kinds of networks such as low power wireless, aerial, space and maritime networks. The research infrastructure should also list the different testbeds included and their related Terms and Conditions (T&C).

In a general manner, the research infrastructure should permit the replication of experiments, a good capacity of data storage and streaming functionality. Other tools should be available in the research infrastructure like big data analytics tools, collaborative tools, third party tools integrable in the research infrastructure. Non-European services should be also avoided in regards of the data protection, transparency and cybersecurity.

The potential users would like to have qualified technicians, tutorials and courses to help them to properly use the services and the experiments provided by the research infrastructure. Finally, the research infrastructure should provide tools to evaluate the experiments under the point of view of the users. For instance, this kind of tools should answer to the questions such as the cost reduction or the comfort or the user experience brought by the new solutions tested in the experiments. It will allow to validate these solutions based on non-technical criteria.

Some requirements were evaluated in the survey by the research community to determine their importance with the point of view of the future users. These requirements are namely the scalability of the research infrastructure, the user-friendliness of the user interface, the data analytics tools and functions, the diversity of the communication protocols supported, the security and confidentiality of the experiment and finally, the remote access.

75.38% of the responders determine that the scalability of the research infrastructure is important. Concerning the user-friendliness, 73.85% of the responders think it is an important requirement. The data analytics tools and functions are important for 78.46% of the responders. The diversity of communication protocols is evaluated by 70.77% of the responders as important. 61.54% of the potential users estimate that the security and the confidentiality in the research infrastructure are an important requirement. Finally, the remote access is considered by 87.69% of the future users as important. The following table contains the requirements classified by their importance:

Table 1 - Importance of the requirements

Requirements	Important [%]
Remote access	87.69
Data analytics tools and functions	78.46
Scalability	75.38
User-friendliness	73.85
Diversity of communication protocols	70.77
Security and confidentiality	61.54

So, the remote access is the most important requirement for the potential users of the envisioned SLICES research infrastructure. This requirement is currently studied with high care by the project and the other requirements are also taken into account in the different Work Packages.

3. Current Node Status

3.1. SU Node

Name of the current infrastructure: **SILECS-FIT / OneLab**

Location:

- Distributed infrastructure:
- FIT current sites: Network Operation Center (NOC) (Paris); FIT IoT-Lab (Grenoble, Paris, Rocquencourt, Lille, Strasbourg); FIT Wireless (Paris, Sophia-Antipolis, Lyon, Evry); FIT Cloud (Paris, Evry).
- Future planned structure:
  - Further collaboration with Grid'5000's sites through the SILECS merger, located in Lille, Nancy, Grenoble, Lyon, Sophia-Antipolis, Rennes, Nantes, Luxembourg, Toulouse.
    - 1 central hub (Paris), 2 intermediary sites.
    - NOC (Network Operation Center, Paris).

  Other: edge datacenter, coverage of the cities of Strasbourg and Lille in LORA, Sigfox network (Lyon), 3G, 4G, 5G radio front-end and WIFI, NB-IOT and BBU extensions (Sophia and Lyon).
- Head quarter (FIT): Sorbonne Université – 4 Place Jussieu, 75005 Paris, France.

Web site: https://fit-equipex.fr/
https://onelab.eu/
https://www.silecs.net/

Annual operating costs: 3.6 million € (including amortization of investment costs).

FIT is a French Equipex since 2011, which became a French National Research Infrastructure in 2015, and merged with Grid'5000 in 2018 to become the French National Research Infrastructure SILECS (SILECS Infrastructure for Large-scale Experimental Computer Science). SILECS is the French part of the SLICES-RI which is being formed since 2017 and will be submitted to the ESFRI Roadmap 2021.

FIT is also part of the OneLab federation of testbeds since 2014, which allows connection and experimentation with other testbeds and technologies in Europe and beyond (e.g. with your OneLab account credentials you can now access all CloudLab sites infrastructure including sites in the US).

The evolution towards an ever more digital world requires tools for testing and experimenting in support of the design and validation of new technologies. These tools can be built around core technologies such as cloud and infrastructure networks but also around the "vertical" domains such as health, transport, and energy, which require data capture technologies to feed their knowledge chains.

This is why SILECS-FIT provides a wide choice of technologies (Internet of Things, Wireless and Cloud) and also a single interface through which to access the system and a large number of configuration and monitoring tools. SILECS-FIT aims to:

- Enable experimentation across a broad range of subject, greatly reduce the cost and time required to design, establish and monitor an experiment, and through testing, the robustness of the solutions is increased.
- Provide a large-scale experimentation environment through the federation of testbeds that are competitive at the worldwide level, allowing to incubate advanced experiments and to stimulate a large base of users coming from the research world as well as industry.
- Offer large-scale state-of-the-art wireless, sensing and mobility infrastructures for any builder of tomorrow's systems and services, who wish to try out, test and validate his/her solution before implementing it in real-life.
- Propose platforms located across France: in Paris, Lille, Strasbourg, Lyon, Grenoble and Sophia Antipolis. They offer easy access, a library of tools and online support for wireless and wireless sensor networks including robots. The users can even plug their own devices in FIT's testbeds and run their tests there as well.

Depending on the users' needs and level of support, the users can either manage their set up and configurations autonomously or get support from SILECS-FIT's experts on anything ranging from the brainstorming of your testing needs all the way to the benchmarked test results and conformance guarantees.

SILECS-FIT infrastructure is structured in three pillars:

- FIT Wireless: Highly flexible experimentation on a wide array of wireless networking issues.
  - Locations: R2 Lab (Inria-Sophia-Antipolis), In Lab (SU-Paris), NC Lab (IMT-Evry), Cortex Lab (Inria-Grenoble).
- FIT IoT-Lab: A large-scale infrastructure for testing the Future Internet of Things.
  - Locations: Inria Grenoble, Inria Lille, ICube Strasbourg, Inria Saclay, Inria Rennes and Institut Mines-Télécom Paris.
- FIT Cloud: Related to Cloud design, development of OpenStack components and cloud services (FIT CloudLab). It provides also a Cloud infrastructure (FIT OpenStack), in which compute and storage resources are made available to the users.
  - Locations: FIT OpenStack (Sorbonne Université), FIT OpenStack NC Lab and FIT CloudLab.

In this context, FIT and another French infrastructure merged to create large-scale infrastructure: SILECS.

SILECS deploys and operates a large-scale infrastructure allowing controlled access to advanced technologies. It responds to the need to support basic research in these areas where access to such instruments is essential. In addition, it creates synergies between university, industrial and commercial players in order to accelerate access to the market for basic ICT technologies, but also in the vertical sectors (application sectors). SILECS is built on existing infrastructures (FIT and Grid'5000) which already offer a service used by hundreds of institutions which have carried out thousands of experiments, mainly in the university environment (in France and abroad) but also in industry.

To summarize, at SILECS scale, the expected infrastructure's goals are:

- Have a wide variety of advanced IT resources of various sizes and in sufficient quantity (objects connected to clusters of "datacenters" with various processors and accelerators) connected by a dedicated network (provided by Renater) for testing, qualification and analysis of hypotheses of models and algorithms and solutions;
- Mobilize and federate the communities of researchers and industrialists working on these subjects from IT architects to transverse (vertical) fields of application;
- Provide test, collection, measurement, benchmark, reproducibility, "data repository" tools and support an open data approach for these communities;
- Combine the effort of the National Research Strategy with European and International space;
- Establish an international positioning. Our strength lies in the diversity of resources that we can mobilize and associate and in the international recognition of the positioning of its scientific community. We cannot have the size of the systems mobilized by Google or Amazon but we can associate various resources in the same experiment while preserving more controllability and reproducibility of the experiments.

Main and secondary scientific fields to be covered by the whole SILECS infrastructure:

- SHS, SSTE, ENE, B&S, SMI, PNHE, AA, STNM, IST
- Main area: IST
- Secondary domains: STNM
- Others: HS, SSTE, ENE, B&S, SMI, PNHE, AA

The SILECS infrastructure provides the following services:

1. On the one hand, it provides a service platform for testing and testing protocols and applications for the Internet (FIT infrastructure). It is organized on the basis of a federation of autonomous platforms, of various technologies, making it possible to stimulate a large base of academic and industrial users. SILECS also provides an environment and tools for accessing this platform, as well as measurement means for collecting data from experiences. It is thus an accelerator for the design of advanced technologies for the Internet of the Future. Open and free, the infrastructure provides the users with an access (regardless of geographic location) via the web interface or via ssh access, for example, in the case of FIT IoT LAB.
2. On the other hand, and thanks to the further integration with Grid'5000, SILECS can be seen as a Hardware-as-a-Service platform, highly reconfigurable and controllable: researchers can experiment with a fully customized software stack thanks to bare-metal deployment features, and can isolate their experiment at the networking layer. It also provides advanced monitoring and measurement features for traces collection of networking and power consumption, providing a deep understanding of experiments. It has been designed to support Open Science and reproducible research, with full traceability of infrastructure and software changes on the testbed. It is a large-scale and versatile testbed for experiment-driven research in all areas of computer science, with a focus on parallel and distributed computing including Cloud, HPC and Big Data.

SILECS has a significant community of 1500+ users supported by a solid technical team. SILECS targets 2,000 users out of an academic and industrial population of more than 10,000 people. We can expect around 20% of users from the industrial world, or around 400 users at European level, including SMEs, very small businesses, and large groups.

SILECS, through FIT and Grid'5000, has been used since the opening of the platform by different types of actors: public actors, industrialists, SMEs, local ecosystems, French research projects and European projects. Partnerships are most often made in the context of research projects. The main target community is French academics but there are also possibilities for academics outside French and private companies.

3.2. UTH Node

Name of the current infrastructure: **NITOS**

Location: Volos, Greece

Web site: *http://nitlab.inf.uth.gr/NITlab/index.php/nitos.html*

Annual operating costs: >350k€

UTH provides in its premises an integrated infrastructure, named the NITOS Facility, which is a union of heterogeneous testbeds focusing on experimentation-based research in the area of wired and wireless networks. NITOS is remotely accessible and open to the research community 24/7 through the NITOS portal, allowing users from around the globe to take advantage of highly programmable equipment. The testbed is based on open-source software that allows the design and implementation of new algorithms, enabling new functionalities on the existing hardware. Parallel experimentation (slicing) of different users is enabled, through the utilization of the NITOS scheduler software. NITOS has an established user base of over 4000 users in the past years, with over 20 researchers using the infrastructure in a daily basis. It is federated with several infrastructures all over the world (Europe, Brazil, South Korea) in the context of various projects, like OpenLab, FLEX, Fed4FIRE, SmartFIRE, MONROE, 5GinFIRE, 5G-XHAUL, 5G-PICTURE, 5G-VICTORI while it is also part of the OneLab federation.

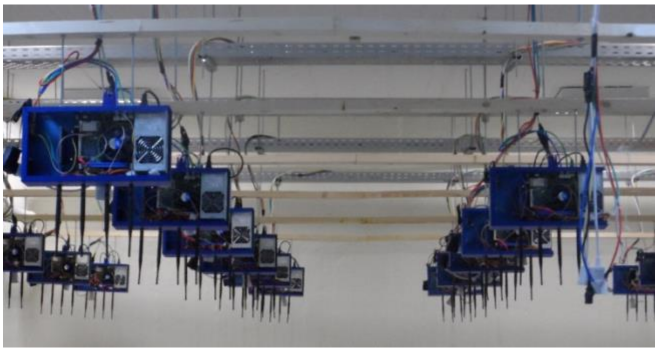


Figure 2: NITOS indoor testbed

Figure 3: NITOS outdoor testbed

Figure 4: NITOS LTE deployment

Services currently offered by the infrastructure:

- A **wireless experimentation testbed**, which consists of 100 powerful nodes (some of them mobile) in indoor and outdoor deployments that feature multiple wireless interfaces and allow for experimentation with heterogeneous (Wi-Fi, WiMAX, LTE, Bluetooth) wireless technologies.
- A **wireless sensor network**, consisting of a controllable testbed deployed in an indoor environment, a city-scale sensor network in Volos city and a city-scale mobile sensing infrastructure that relies on bicycles of volunteer users. Most of the sensor platforms are custom-made, developed by UTH, and some others commercial, all supporting open-source and easy to use firmware and exploit several wireless technologies for communication (ZigBee, Wi-Fi, BLE, LoRa and 6LoWPAN).
- A **Software Defined Radio** (SDR) testbed that consists of Universal Software Radio Peripheral (USRP) devices attached to the NITOS wireless nodes. USRPs allow the researcher to program a number of physical layer features (e.g. modulation), thereby enabling dedicated PHY layer or cross-layer research.
- A **mmWave** testbed, consisting of six different nodes supporting multi-Gbps over the air speeds, and beam-steering with 15 degrees step.
- A drone base testbed, consisting of five high-performing drones that are able to carry NITOS nodes and setup wireless mesh setups with different technologies (WiFi, mmWave).
- A **Software Defined Networking** (SDN) testbed that consists of multiple OpenFlow technology enabled switches, connected to the NITOS nodes, thus enabling experimentation with switching and routing networking protocols. Experimentation using the OpenFlow technology can be combined with the wireless networking one, hence enabling the construction of more heterogeneous experimental scenarios.
- A **Cloud infrastructure**, which consists of 7 HP blade servers and 2 rack-mounted ones providing 272 CPU cores, 800 GB of Ram and 22TB of storage capacity, in total. The network connectivity is

established via the usage of an HP 5400 series modular OpenFlow switch, which provides 10Gb Ethernet connectivity amongst the cluster's modules and 1Gb amongst the cluster and GEANT.

3.3. EURECOM Node

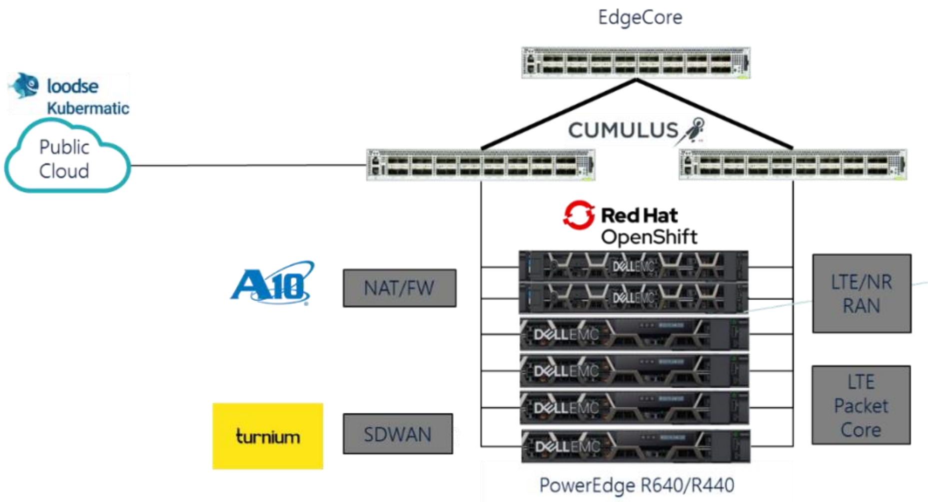
Name of the current infrastructure: **Open5GLab**

Location: Sophia Antipolis

Web site: http://open5glab.eurecom.fr/

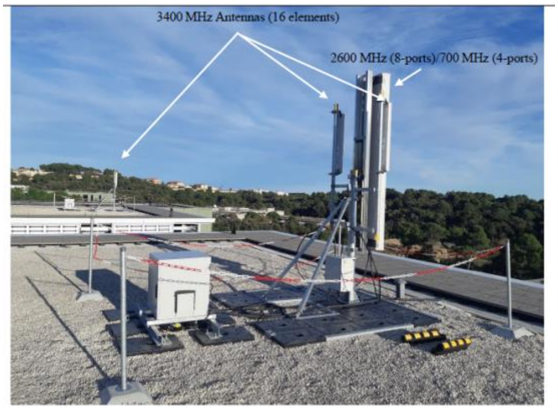
Annual operating costs: 80 k€

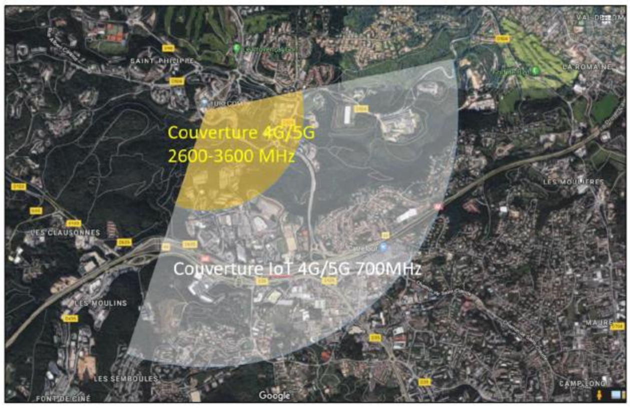
Open5GLab at EURECOM is one of 3 experimental 5G sites in France in the context of the 5G-EVE ICT-17 project. Construction began in July 2018 and 5G experimentation is now available. The site is interconnected with similar sites in Europe in the 5G-EVE network. It is also one of the test sites for the OPNFV VCO 3.0 (Virtual Central Office) project and as such is interconnected with sites in North Carolina, USA and Montreal, Canada.



Open5gLab provides experimental 5G services including so-called Enhanced Mobile Broadband (eMBB) and massive machine-type communications and is based on fully open-source tools and open-architecture design. It is the main experimental playground for OpenAirInterface (OAI) and Mosaic-5g (M5G) software packages. The site's cluster computing resource makes use of RedHat's OpenShift 4.2 Kubernetes container platform and benefits from technical support from RedHat. The cluster is used for radio-access, core network and mobile-edge functions. Some bare-metal nodes with in-lab 5G-capable radio devices can be used by experimenters and developers and are interconnected with the Kubernetes cluster. External access for onboarding software, collecting measurement data and developing basic software for the site is available for partners using secure-shell access. Interfaces for an external orchestrator (e.g. ONAP) is currently being integrated in the Open5GLab. The nodes of the site are also used by OpenAirInterface Jenkins-based continuous integration / continuous delivery (CI/CD) framework.

Open5GLab's radio infrastructure includes indoor and high-power outdoor radio-units operating in several 4G and 5G bands in the immediate vicinity of the test site, specifically Band 28 (700 MHz), Band n38 (2.6 GHz TDD), Band n78 (3.5 GHz TDD), Band n258 (25 GHz TDD). The outdoor units are interconnected with the switching fabric using 300m fiber (10/25 Gbit/s). The units are a combination of in-house designs and commercial remote radio-units.





Open5GLab provides remotely-controllable 4G and 5G user-equipment, including both off-the-shelf smartphones and cellular IoT modules. This allows experimenters to control and extract measurements from the user-equipment in a running experiment. With the help of regional partners, Open5GLab provides embedded vehicular user-equipment nodes. Two drones are also equipped with 4G and soon 5G user-equipment and OAI-based 4G radios for mobile base station experiments. With the help of EURECOM, software can be on-boarded into the user-equipment devices.

The Open5GLab site provides the means to on-board new network functions to a running 5G infrastructure and test them in both a controlled laboratory setting and in a deployed live network. Experimenters can either make use of existing network functions and basic applications or choose to on-board their own software to test with Open5GLabs infrastructure. This allows scientists to focus on their function of interest and its interconnection with a full network and collect measurements of the new design. In addition, if the network function enhances either the OAI or M5G implementation, it will automatically be reusable by a global network of researchers using OAI/M5G since it will be redistributable with OAI/M5G.

OAI and M5G software packages are used extensively around the globe. The Open5GLab site allows this community to have access to the laboratory used by the main developers of OAI and M5G. It is thus a crucial infrastructure for testing OAI and M5G in both laboratory and outdoor deployments. Since the site is used in OAI's CI/CD framework the entire OAI/M5G communities will be using the site automatically when committing code. The site is already used by the Linux Networking Foundation VCO project and benefits from software resources from this community. The greater research community can thus benefit from.

3.4. PSNC Node

Name of the current infrastructure: **PIONIER-LAB**

Location: Ul. Jana Pawła II 10, Poznan, Poland

Web sites: http://pionier-lab.pcss.pl

https://www.fed4fire.eu/testbeds/pl-lab/

http://pl-lab.pl

Annual operating costs: Estimated at 250k€

In SLICES PSNC will provide access to nine laboratories (eight implemented in PIONIER-LAB, one implemented in PL-LAB2020); all laboratories are located in Poznan, Poland.

PIONIER-LAB - National Platform for Integration of Research Infrastructures with Innovation Ecosystems is located on the Polish Roadmap for Research Infrastructures. The project builds eight unique research laboratories based on the national fiber optic network PIONIER. The goal of the Project is to make the platform available to entrepreneurs and other entities interested in conducting scientific research and development works based on the new, nationwide research infrastructure.

PL-LAB2020 is a research network infrastructure. PSNC provides access to heterogeneous resources located in Poznan, including SDN, ICN, IoT and Wireless laboratories. PSNC also operates the central services supporting PL-LAB2020 infrastructure management, monitoring and user access. All resources of PL- LAB2020 are located in 6 research centers forming a single distributed research and experimentation environment. When requested by a user, resources from other locations can be also made available for experiments.

The research infrastructure within PIONIER-LAB is under construction and will be available to end users in 2023. The laboratory from PL-LAB2020 is already offered to scientists under the umbrella of the Fed4FIRE+ project.

The list of laboratories offered in SLICES includes:

- Laboratory 1 - Laboratory of innovative network technologies,
- Laboratory 2 - Distributed Time and Frequency Laboratory,
- Laboratory 3 - Smart Campus as a Smart City laboratory,
- Laboratory 4 - Regional "Living" Innovation Laboratories inspired by ICT,
- Laboratory 5 - Cloud Services Laboratory,
- Laboratory 6 - Multi-Scale Simulation Laboratory,
- Laboratory 7 - Laboratory and e-training services,
- Laboratory 8 - Pre-incubation laboratory,
- Laboratory 9 - SDN, ICN, IoT and Wireless laboratory.

A short summary of each laboratory is provided below.

Laboratory 1 - Laboratory of innovative network technologies

The laboratory will be equipped with advanced network devices, including transmission systems, backbone and access switches, measuring instruments, and management software.

This equipment will be connected with the PIONIER fiber optic infrastructure and will constitute a connected network ecosystem. The laboratory will be able to test and verify new network protocols, software for control and management of network devices and network applications. The laboratory will also be used to verify solutions for cooperation with individual network elements (such as long-distance optical transmission systems, packet transmission systems or passive infrastructure monitoring elements) or service applications (e.g. distributed services provided by cloud systems).

Laboratory 2 - Distributed Time and Frequency Laboratory

The main aim of the construction of the Time and Frequency Distributed Laboratory is: i) to provide access to ultra-precise time and frequency signals to all PIONIER-LAB users regardless of their geographical location; ii) to build a time and frequency transmission network that will enable the development of a number of modern services. The Laboratory will be equipped with atomic clocks for generating standard time and frequency, satellite transmission systems for synchronization of individual clocks placed in different MAN, as well as a set of auxiliary devices for transmission, switching and supervision, and measurement of time and frequency signals. Atomic clocks of the highest possible accuracy - active hydrogen masers will be located in 3 locations (Poznań, Warsaw, Gdańsk), and in 8 locations (Koszalin, Olsztyn, Bydgoszcz, Białystok, Łódź, Puławy, Kielce and Rzeszów) there will be atomic clocks - passive hydrogen masers or caesium clocks. The whole distributed laboratory will provide users with access to time and frequency patterns.

Laboratory 3 - Smart Campus as a Smart City laboratory

The Laboratory is designed as an interactive research platform installed in the Student Campus, allowing the testing of functions in the real world, and then it is possible to disseminate the results of the tested functionalities (implementing them for universal use, within the Smart City). The purpose of building the laboratory is, among others: i) to enable research on the development of innovative campus services based on the latest Internet of Things (IoT) technologies; ii) to develop an ecosystem enabling R&D work in the field of Internet of Things and Smart City infrastructure in various areas of human activity (e.g. work, study, information acquisition, mobility); iii) to develop a controlled environment enabling the development of network applications and services using Internet of Things infrastructure in the context of Smart City.

Laboratory 4 - Regional "Living" Innovation Laboratories inspired by ICT

The living laboratory is creating the conditions for future research and development using advanced technologies for data capturing (through sensors and wired/wireless networks) and information processing. Equipment installed in the laboratory will be available to end users to carry out experiments in different fields of disciplines, including (but not limited to): multimedia, e-health, social networking, security and gaming.

Laboratory 5 - Cloud Services Laboratory

The Laboratory will constitute a platform for conducting research on the construction and management of a reliable, scalable and economically efficient cloud infrastructure and providing cloud services on its basis, including IaaS (Infrastructure as a Service) and PaaS (Platform as a Service) mechanisms.

Laboratory 6 - Multi-Scale Simulation Laboratory

The laboratory will be used to perform large-scale and multi-scale simulations of research problems with different time and space scales. Simulations will be possible thanks to the use of High Power Computers (HPC) and data transmission within the PIONIER fiber optic network. The functionality of the laboratory will also be made available in a cloud model.

Laboratory 7 - Laboratory and e-training services

The laboratory will enable research on increasing the effectiveness of the educational process (acquiring knowledge) based on e-training. In their case, due to the lack of teacher-pupil interaction of the nature of the traditional learning model, it is necessary to select appropriate training instruments so that the content is assimilated in an optimal way. The laboratory will enable testing solutions in order to improve the quality of education based on educational Internet services, thus addressing the problem of "mismatch" as is still the case with e-training.

Laboratory 8 - Pre-incubation laboratory

The construction of the laboratory will enable the study of new trends and models of cooperation between science and business, with particular emphasis on the impact of the availability of advanced ICT infrastructure and related R&D services on the innovativeness of companies and regions.

Laboratory 9 - SDN, ICN, IoT and Wireless laboratory

The hardware available in SDN laboratory is categorized and listed in the following table.

Servers	HP ProLiant DL360
Programmable switching devices	Platforms with programmable network processor NP-3 EZappliance (EZchip) Servers with NetFPGA cards (Virtex2/Virtex5)
Measurement devices	Hardware-based traffic generators and measurement devices (Spirent)
Routers	Juniper MX80/240 (with routers virtualization features on-board)
Application specific devices	WiFi access points 4K/3D streaming sources and 2 4K/3D projectors

The variety of deployed hardware creates opportunities to perform experiments on subjects like Content Aware Networks, IPv6 practical deployment, 4K 3D video streaming, or introducing Parallel Internets concept based on infrastructure virtualization. The combination of network, applications, protocols and unique hardware gives high potential for solving Future Internet problems and allows validation of solutions and architectures which are expected to fulfill current and arising demands for connectivity services at the global level.
Currently, only SDN laboratory offers research services to Polish and European scientist. The laboratory is available through i) PL-LAB Portal, targeting mainly Polish researchers, SMEs and entrepreneurs and ii) Fed4FIRE project, targeting European researchers, regardless of their location. SDN laboratory is used by Polish universities to support scientists with their day-to-day duties, including scientific work and educational aspects. Some examples of the use of SDN Laboratory by SMEs:

- Distributed Deep Learning Platform: https://www.fed4fire.eu/demo-stories/oc1/ddlp/
- Transmission optimization and performance evaluation of a real-time ultrahigh definition medical collaboration platform: https://www.fed4fire.eu/demo-stories/oc1/ubimed4k/

PIONIER-LAB research infrastructure will be gradually offered to the scientific community, starting from early 2022, with operational services ready in 2023.

3.5. OULU Node

Name of the current infrastructure: **5GTN**

Location: Oulu, Finland

Web site address: *https://5gtn.fi/*

Annual operating costs: >250k€

The 5G Test Network (5GTN) is a national Finnish joint effort of University of Oulu, Technical Research Center of Finland (VTT) and 15 different industry partners. It is a complete 5G test system and worlds first open 5G test network. 5GTN targets to serve multiple application developers by providing extensive test facility services in a carrier-grade state-of-the-art network and it has radio coverage in several locations in Finland: Oulu, Tampere, Ii, Sodankylä and Ylivieska. In northern Finland 5GTN includes the University of Oulu campus, VTT and the technology village area together with several distant locations around Oulu, like, Oulu University Hospital Test Lab and Nokia factory in Rusko area in the City of Oulu. Additionally, outside of the Oulu Region, there is remote Ylivieska test network with approximately 15 base stations, Ii Micropolis and Sodankylä airport, where 5GTN is used for testing vehicles in winter conditions and in general, for future self-driving technology development. The 5GTN Oulu are coverage map can be seen in Figure 5 below.

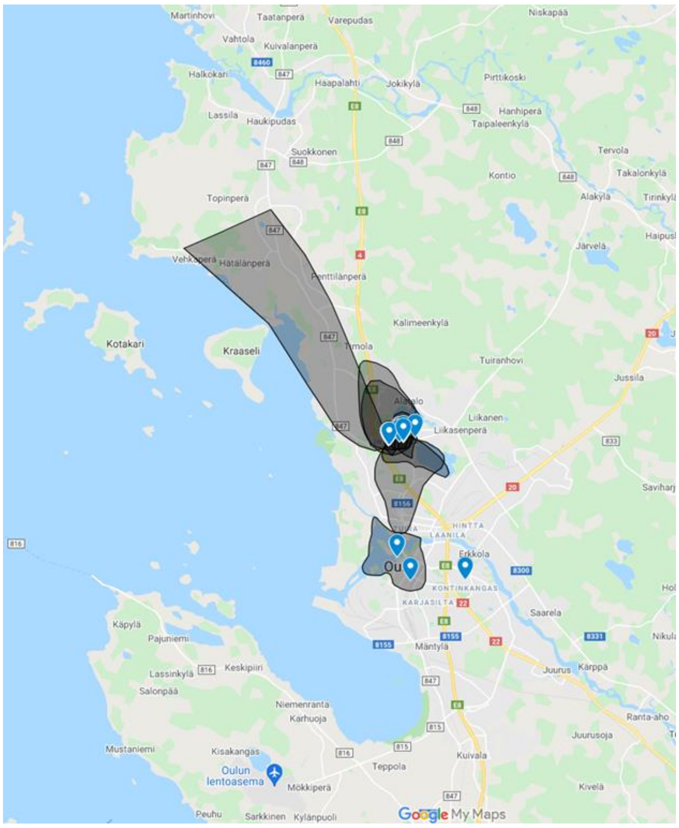


Figure 5: 5GTN coverage map

5GTN is currently part of the 6G Flagship that is part of the Finnish Flagship Programme funded by the Academy of Finland. The Programme supports high-quality research and increases the societal impact emerging from the research. The Flagships are clusters that combine close cooperation with business and society, adaptability and a strong commitment from host organisations. More info about 6G Flagship can be found from https://www.oulu.fi/6gflagship/. The Flagship will promote the birth of start-ups via heavy investments in easy-to-use-tools and active promotion of the 5G Test Network (5GTN) within existing “start-up factories”.

<u>Architecture of the current infrastructure</u>

5GTN is a real micro-operator with its own SIM-cards. It uses mainly non-standalone (NSA) architecture with both 4G and 5G coverage and its core network is implemented in a cloud environment. Currently also standalone (SA) 5G core and radios have been introduced, tested, and taken into use in the 5GTN. On top of 4G and 5G radio coverage 5GTN has also Lora, WiFi, cellular IoT (LTE-M, NB-IoT) and Bluetooth coverage. The network architecture is defined in Figure 6 below.

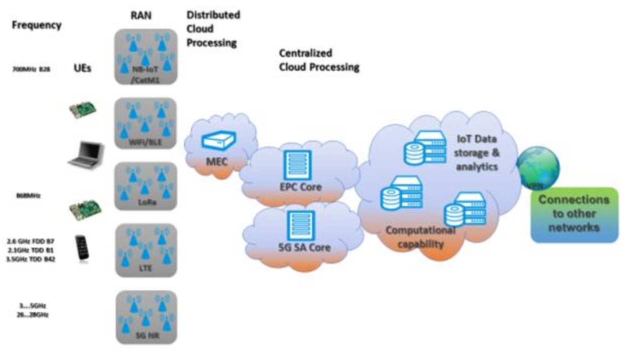


Figure 6: 5GTN architecture

Services currently offered by the infrastructure:

- **A Wireless 4G and 5G testbed:** 5GTN has both 4G and 5G wireless connectivity with its own SIM cards. 5G operates mainly in NSA mode but also SA can be offered as an alternative solution. 5G NSA is available through several Rel. 15 3.5 GHz outdoor macro Base Stations. NSA indoor coverage is enhanced by several 5G Base Stations also as a C-RAN deployment. 5G SA is supported through Open 5GS. The near future extensions include mmWave (24-25 GHz, 800 MHz bandwidth) base stations on sharing based frequency band and Rel. 16 URLLC base stations and devices.
- **A Wireless Sensor Network:** University of Oulu campus area and botanical garden are covered by over 400 wireless LoRaWAN and NB-IoT sensor platforms (total 2400 sensors). Current setup with map of installed sensors can be viewed at Smart Campus web pages https://smartcampus.oulu.fi/manage/map. Data collected by the sensor network is freely available as open data. Grafana can be used to view customized dashboards created from the data. REST API to access the network is offered.
- **Edge servers and Mobile Edge Computing (MEC):** 5GTN offers Edge servers as part of the platform offering. Customer applications can be installed to one or more of 5GTN Edge server virtual environment. Also, a MEC platform that enables low latency and brings the application services close to end user has been installed and is now being upgraded to newest version to enable state-of-the-art MEC functionality to 5GTN users.
- **5GTN External API:** An API has been defined so that 5GTN can be used from remote locations. API supports Network Slice Management and KPI Management Interfaces.
- **5G integrated devices:** The 5GTN team has integrated several small form factor devices to the 5GTN including cameras, lidars, hyperspectral cameras, AR/VR and medical devices.
- **Drones:** Several Drones at different sizes with small to large payloads and WiFi or 4G/5G connectivity are available.
- **Automobiles:** The university of Oulu has acquired two Toyota Rav 4 vehicles which have been instrumented with various sensing devices and also 4G/5G connectivity to the 5G test network to enable testing automotive use cases.
- **Excavator:** An excavator has been integrated with the 5GTN network to offer capabilities of testing remote controlled heavy machinery in professional use cases

- **3D imaging facility:** Cylindrical camera array of 144 separate cameras is used to make full body scan of a person or an object in a single "shot". Images are turned into a 3D model, with full color texture using photogrammetry software located at 5GTN Edge server. Process can be remotely controlled.
- **Test tools:** Automated test capabilities have been developed and can be offered to 5GTN users. Even remote test capability with remote pre-programmed drone flying capabilities is being developed and is currently under testing.

3.6. IMDEA Node

Name of the current infrastructure: **5TONIC**

Location: IMDEA Networks Institute, Avenida del Mar Mediterráneo 22 - 28918 Leganés (Madrid), Spain

Web site: https://www.5tonic.org/

Annual operating costs: >100k€

5TONIC - An Open Research and Innovation Laboratory Focusing in 5G Technologies provides an open innovation environment for research in 5G technologies, and their validation by equipment vendors, network service providers, and customers. The 5TONIC laboratory includes a solid baseline of facilities, infrastructure and equipment to support advanced experimentation in the 5G virtual network function and wireless systems areas. In this respect, the laboratory offers a datacenter with space for 24 racks, including two racks for communications among these racks and with other platforms. 5TONIC provides access to a common infrastructure with specific-purpose hardware, to assist in experiments, trials and demonstrations with particular 5G network technologies, as well as to commodity hardware, which allows a cost-effective approach to configure different network topologies of variable size and capacity.

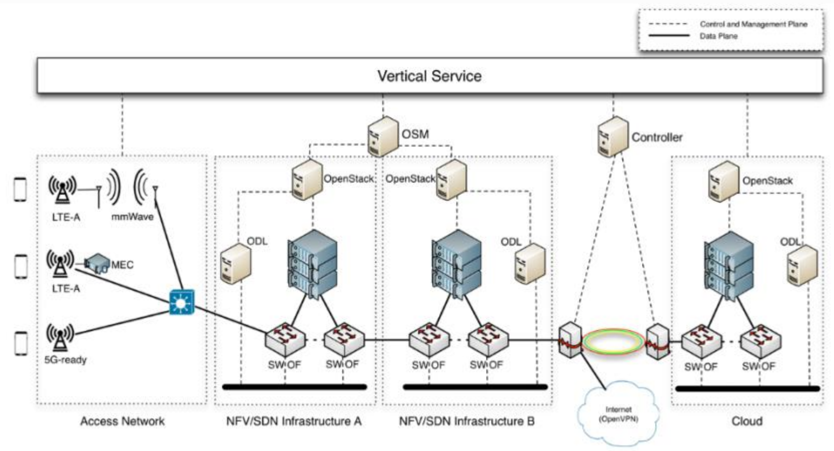
The 5TONIC lab is already being used to demonstrate a wide range of 5G use cases in direct collaboration with involved verticals: eHealth (collaborative emergency management). This case considers the monitoring of health parameters by means of smart t-shirts, and a coordinated; response of medical emergency teams with the help of registered volunteers. Industry 4.0 (edge-enabled robots). This case considers the application of control and/or coordination tasks for a set of cooperating robots, with these tasks running at nodes located at the network edge. Tourism (ER-enabled conventions). This case considers the usage of enhance reality environments to facilitate the experience of the attendees of conventions and conferences. Emergency recovery (micro-VNFs). This case considers the deployment of micro-VNFs on mobile platforms (drones) to provide a fast and flexible network edge to support access in case of emergencies, and probably other cases related with crowded events in remote locations.

With respect to the access network, the 5TONIC infrastructure includes equipment to support advanced experimentation with 5G-ready equipment, commercial LTE-A base stations implementing different functional splits and Software Defined Radio (SDR) systems. LTE-A equipment will allow the deployment of 3GPP rel. 15 extensions to test early 5G scenarios. The SDR equipment consists of a set of eNodeB with FPGA cards, to run high speed and computationally intensive physical layer operations in WiFi/LTE, radio frequency transceivers and a real-time controller, able to execute MAC and PHY control algorithms with micro-second resolution. Driven by the 5G vision, which considers to extend the use of the radio spectrum, the infrastructure also supports communications in the frequency band between 30Ghz and 300Ghz (mmWave), as well as low frequency communications. In particular, the testbed includes several scalable SDR platforms, along with a set of 60Ghz down/up-converters, supporting the generation and reception of arbitrary signals in the frequency bands under consideration. 5TONIC provides several end-user terminals to connect to all these access networks: smartphones, USB dongles and LTE-A routers.

The NFV/SDN infrastructure equipment includes high-power servers to test real deployments, supporting NUMA architecture, and 10Gbps Ethernet optical transceivers with SR-IOV capabilities. These servers are connected between them to deploy the data planes, by using a switching fabric with 10Gbps Ethernet optical ports. To complement this infrastructure, the laboratory provides an NFV/SDN infrastructure B including a set of mini-PC computers with DPDK capabilities, supporting the experimentation with Virtual Network Functions (VNFs) at smaller scale. Infrastructures A and B are interconnected using high-performance OpenFlow switches. Furthermore, the Management and Network Orchestration (MANO) part of the laboratory includes servers connected by 1Gbps Ethernet cards. The MANO stack is provided using OSM Release TWO for the service and network orchestration, OpenStack for the virtual infrastructure management (VIM), and OpenDayLight (ODL) for the SDN enabled part. The different elements of the testbed can be flexibly interconnected using a pool of low-power single board computers, with Ethernet and WiFi network cards, which can be configured to deploy diverse network functionalities, such as OpenFlow switches, wireless routers, WiFi access points, firewalls or load balancers. The cloud part of the laboratory is composed of medium-performance servers as compute/storage nodes as well as miniPCs to deploy OpenStack and ODL controllers. Servers are interconnected using OpenFlow switches, using a similar approach as in the SDN/NFV infrastructures. The goal of this system is to deploy servers and/or applications that can be used to perform E2E trials.

To interconnect SDN/NFV infrastructures with the cloud side, the 5TONIC laboratory includes a metro-core network, which is connected to the components described before by means of dedicated gateways. The metro-core network setup is composed of IP/MPLS and optical devices. The core control plane testbed is composed of GMPLS nodes with internally developed software. The experimental setup is built with a combination of real and emulated nodes. The latter nodes run on Ubuntu Linux servers. Each emulated node implements a GMPLS stack (including RSVP, OSPFv2 and PCEP) and a Flexible Node emulator.

Finally, the Vertical Service layer allows users of 5TONIC to prepare, deploy and analyze their trials. Remote users can connect to this service by using a dedicated OpenVPN.



5TONIC research infrastructure is involved in significant and relevant research projects that can help to create synergies within the objective of this proposal. Some examples are:

- 5GROWTH: 5Growth (5G-enabled Growth in Vertical Industries). The main objective of 5Growth is the technical and business validation of 5G technologies from the verticals' points of view, following a field-trial-based approach on vertical sites. 5TONIC, as one of the core sites of the project, is leveraging the existing and upcoming resources to give access to vertical experimenters to the last products and services of 5G networks. This will be boosted by the members of 5TONIC participating in the project: Ericsson, Telefonica, InterDigital and Universidad Carlos III de Madrid, and by collaborators like ASTI, Nokia and Innovalia.
- 5G-VINNI: 5G Verticals INNovation Infrastructure. It is a pan-European research and innovation project financed by the EU's Horizon2020 programme. 5G-VINNI facilitates uptake of 5G in Europe by providing an end-to-end facility that validates the performance of new 5G technologies, and explore solutions for vertical industries such as public safety, eHealth, shipping, transportation, media and entertainment and automotive. The project is scheduled to run for three years at sites in Norway, UK, Spain, Greece, Germany and Portugal, and has a budget of 20 million euros. 5TONIC is one of the four main sites in 5G-VINNI to create an end to end integration of experimental facilities. The other three sites are in Norway, UK and Greece. 5TONIC is currently integrating in the 5G-VINNI end to end facility and participate in the trials campaigns of use cases for vertical industries, in particular: public safety, eHealth, shipping, transportation, media and entertainment and automotive.
- 5G-EVE is creating an end to end facility that will provide the means for experimenting with: eMBB, mMTC, URLLC services; Access technologies, which will be heterogeneous including also 5G-NR technologies (therefore, going beyond the current and already included fixed/wireless means); Backhaul technologies; MEC capabilities; Core network and service technologies, including virtualization technologies, like the envisaged 5G VNF pool; Multi-x slicing and orchestration (cross domain and network segment/technology). As one of the core sites of the project, 5TONIC is leveraging our existing and upcoming resources to give access to experimenters to the last products and services of 5G networks. This will be boosted by the members of 5TONIC participating in the project: Ericsson, Telefonica, Universidad Carlos III de Madrid and IMDEA Networks, and by collaborators like ASTI and IFEMA (by means of SEGITTUR).

3.7. COSMOTE Node

Name of the current infrastructure: **LeonR&Do**

Location: Maroussi, Athens, Greece

Annual operating costs: >80k€

The **LeonR&Do testbed** (Figure 7) is composed of:

- A hybrid 5G/4G NSA testbed (with MEC/edge capabilities) (**Mobile Network testbed**)
- An OpenStack-based infrastructure (**ICT Cloud**)
- An e2e IoT platform/solution (**IoT testbed**)
- A FTTH platform (**FTTH Testbed**)

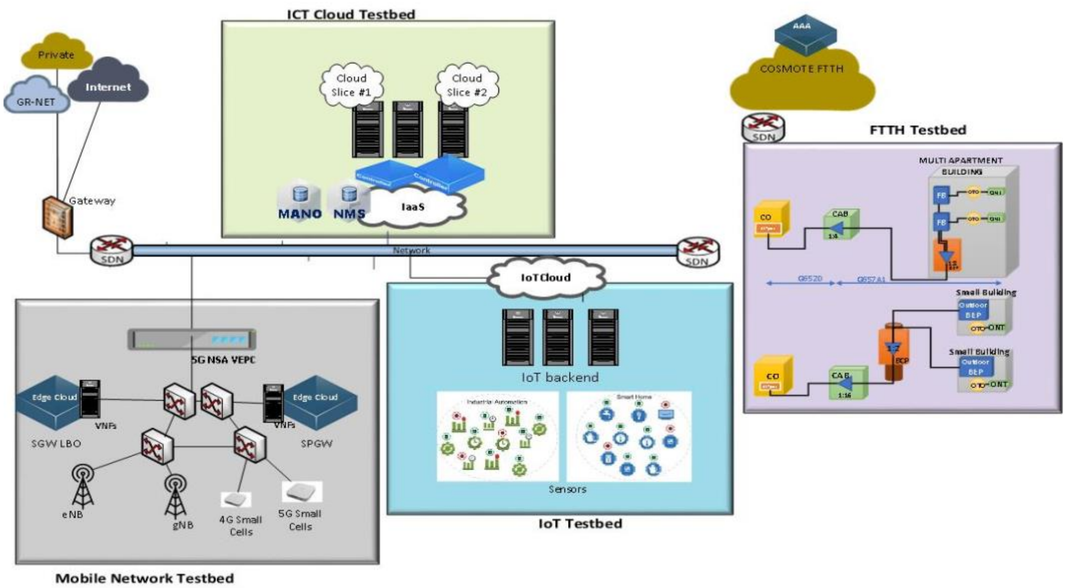


Figure 7: High-level architecture of COSMOTE Mobile Network/ Cloud/ IoT Testbed.

The **Mobile Network testbed** consists of a small-scale, end-to-end, mobile network and cloud components with a 10Gb/s broadband connection (over GRNET) towards the internet (Figure 8). It supports standardized 4G/5G EPC/IMS functions (such as, user/USIM/QoS profiles/APNs definition, network and service access control/network parameters' configuration) and allows remote access and interconnection with other/external network nodes/testbeds/etc. for further expansion of its capabilities/functionalities or other testing purposes. It is composed of:

- A lightweight 4G/5G EPC/IMS core network (running on 2 VMs on a Dell R630 server)
- MEC implementation: via SGW-LBO (Local BreakOut)
- Edge Clouds for deploying/hosting a number of edge services/applications;
- Two Nokia Airscale 4G/ 5G BTSs for providing 5G radio connectivity (supporting 4x4 MIMO @100MHz bandwidth)
- NOKIA 4G/WiFi Flexi-Zone Multiband Indoor Pico BTS, supporting standard network interfaces (such as S1 and X2), 5/10/15/20 MHz LTE carriers with 2x2 MIMO, along with Wi-Fi connectivity @2.4 and 5GHz delivering thus a HetNet solution while is being interconnected to the internet and other (national) research centers via a 10Gb/s broadband connection (over GRNET).

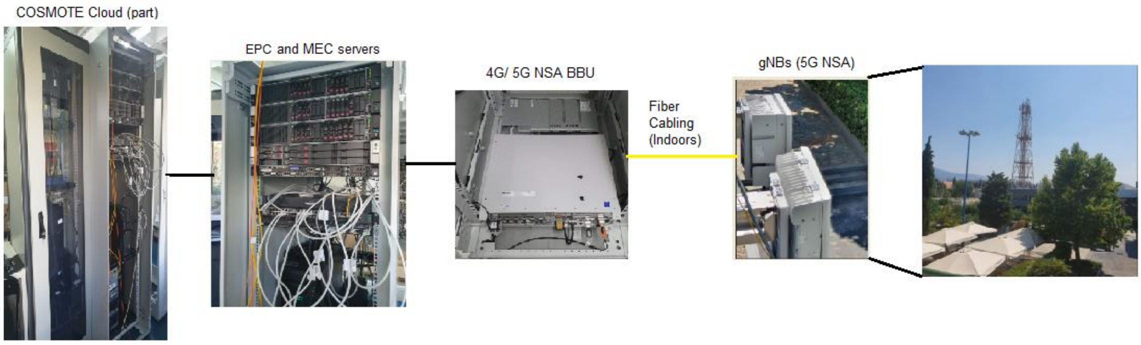


Figure 8: 5G NSA mobile network testbed deployment

The mobile network testbed will be upgraded to support SA 5G in 2022 using

- ATHONET 5G SA (Stand Alone) network, including:
  - Two UPFs to emulate edge and core 5G network Data planes
  - The following 3GPP Control Plane Network Functions: Access and Mobility Management Function (AMF), Session Management Function (SMF), Authentication Server Function (AUSF), User Data Management (UDM) Function

  Supporting 3GPP interfaces: N1, N2,N3,N4,N6

  to be hosted at COSMOTE Cloud facilities
- RAN:
  - Ericsson BBU 6630
  - Radio Unit 4480
  - IRU 8848 + Dot 4479 B78L

The ICT Cloud is an OpenStack cloud infrastructure available on Ubuntu Servers 16.04/18.04 LTS (Figure 9). A Red Hat OpenStack installation is planned for 2022. The testbed is being interconnected (mostly) via 10Gbps fiber/copper links. Compute and storage resources can be made available either directly or for hosting relevant services on a per project basis.

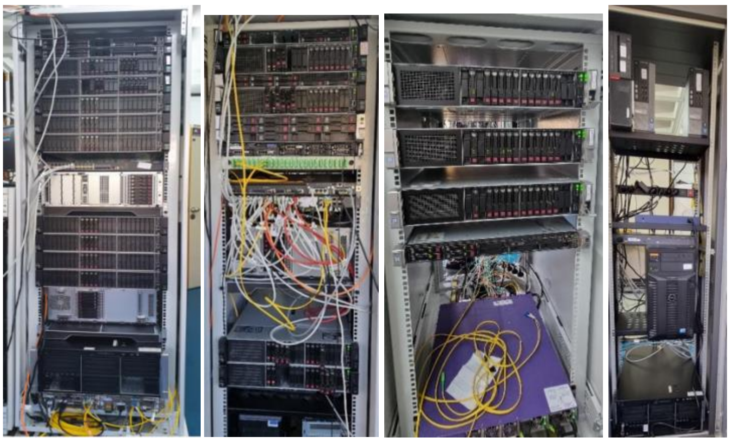


Figure 9: ICT Cloud HW

The **IoT testbed** is a flexible, scalable, vendor and technology agnostic, e2e solution developed exclusively by COSMOTE and is composed of (Figure 10):

- A wide range of custom and commercial end-devices/sensors such as, air-quality, temperature, humidity, pressure, activity, luminance, smoke/fire, activity as well as power/energy-related ones (relays, power meters, etc.)

- IoT hubs/gateways for facility automation and energy management/control (based on events/rules) supporting multiple HAN/BAN/LAN/WAN technologies/interfaces; over 150 technologies/protocols are currently supported incl. Ethernet, WiFi, z-wave, zigbee, BLE, LoRaWAN, 2G/3G/4G/4G+, NB-IoT.
- A (common) backend cloud infrastructure (Figure 11 Backend system overview) for storage, data processing, data visualization, and command exchange. It is based on open source software (TICK framework, homeassistant, pushover) and hardware (commercial and custom sensors, commercial HW for the gateways).

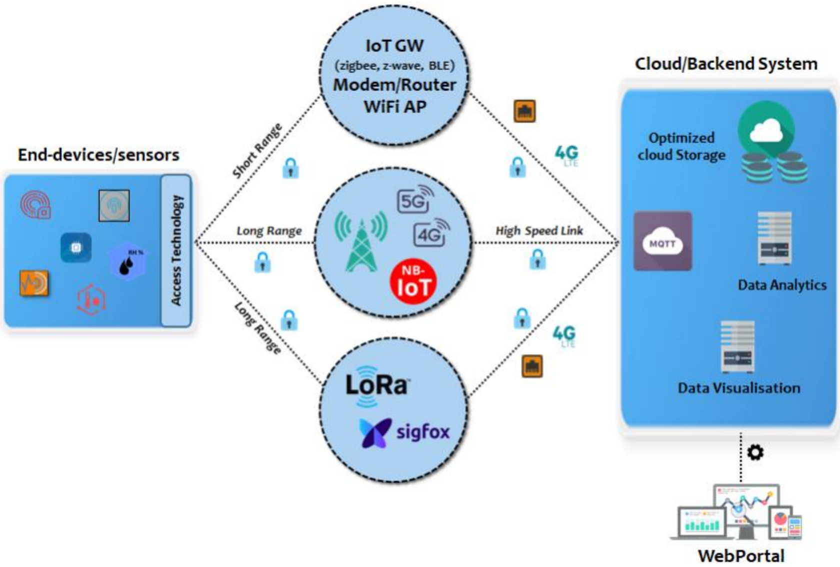


Figure 10: IoT-LeonR&Do testbed architectural layout

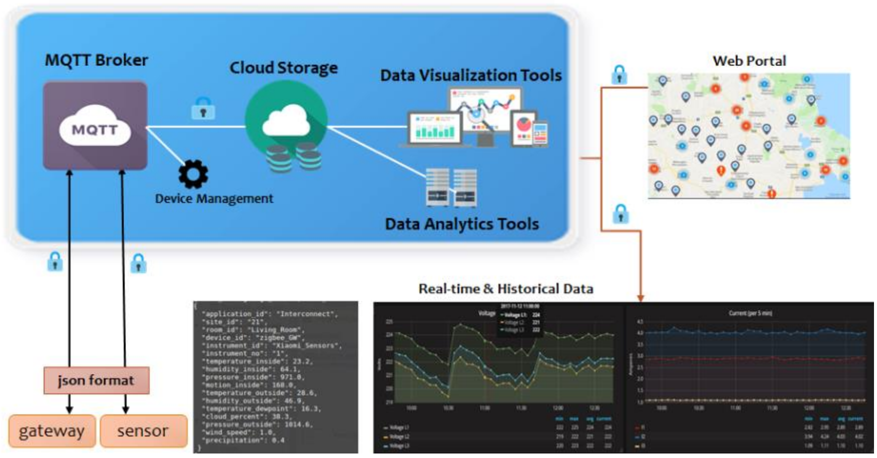


Figure 11: IoT-LeonR&Do testbed backend system overview

The **FTTH testbed** is a fully scalable to COSMOTE/enterprise scale FTTH network (Figure 12). It can be used as testbed for physical layer components and services implementations. It is fully configurable to support all network topologies (core, mesh, ring, access networks) and network services (access, metro, MPLS, Ethernet). Security applications can be tested using data encryption and physical layer (photon or transmission) cryptography components (QKD or other cryptography and security). In conjunction with the R&D datacenter and 5G network, it can combine multiple technologies through access networks.

Figure 12: FTTH testbed

The Mobile Network testbed is considered unique in the sense that it consists of small-scale, end-to-end, real network and cloud components. The testbed is being currently utilized in several European research projects where it has been interconnected for the purpose of testing innovative products and services in a wide range of technologies. It was part of the 2 (out of 4) pan-European experimental platforms that where developed in the context of the 5G-PPP ICT-17 projects (5GENESIS and 5G-MOBIX) where advanced, innovative use cases, demos and trials were conducted.

The ICT Cloud and IoT platform are being utilized in numerous EU-funded projects (e.g., 5GENESIS, 5G-DRONES, 5G-ESSENCE, MATILDA, CLOUDPERFECT, 5G-PHOS, 5G-VICTORI, 5G-PICTURE, INTERCONNECT, CYBERTRUST, RESISTO, LOCUS) for hosting the conduction of advanced, innovative use cases, demos and trials. In addition, the testbed is being utilized internally to the OTE Group for: (a) energy management, (b) automations, (c) environmental monitoring and physical security at telco sites (supporting object detection using AI/ML techniques and smart (object) tracking) and (d) for network performance monitoring applications.

The Mobile Network testbed constitutes a small-scale, real mobile network, allowing for the performance of standardized 4G/5G EPC/IMS functions such as, user/USIM/QoS profiles/APNs definition, network and service access control/network parameters' configuration. The testbed allows the users to deploy applications in a 5G environment and integrate and test new technologies and functions. Finally, the testbed allows for remote access and interconnection with other/external network nodes/testbeds/etc. for further expansion of its capabilities/functionalities for testing purposes. Indicative such capabilities include:

- Selective (local) traffic offloading (e.g. via MEC)
- Slicing (using standard 4G/5G NSA functionalities)
- Fully operational network with 50 SIMs

Regarding ICT Cloud, the current setup can be provided:

- For the time being the cloud infrastructure has been used for hosting:
  - >15 projects (5GENESIS, MATILDA, 5G-VICTORI, RESISTO, CYBERTRUST, YAKSA, INTERCONNECT, 5G-PHOS, 5G-COMPLETE, etc.) | separate cloud / project (if needed)
  - Other purposes (IaaS, General, NAS, Nextcloud, etc.)
  - Supports internal to the OTE Group projects: energy management, automations, physical security, voltage sensing, etc. at telco sites and for network performance monitoring applications.
- Core Network functions hosting:
  - vEPC (R15)

- MEC-LBO (under deployment)
- MEC Distributed S/PGW (to be installed)

The IoT testbed is currently utilized in the context of the EU Project INTERCONNECT for home automation, energy management and home comfort applications. The solution is currently "running" at twenty (20) friendly-user houses. Since it supports a wide variety of both custom and commercial sensors it could be utilized potentially for any IoT-related application. The testbed has been deployed utilizing open source software such as: (a) an mqtt broker for real-time info dispatching, (b) InfluxDB, a time-series database for fast access to measurements, (c) Grafana for measurements visualization, (d) telegraph for connectivity between the various subsystems, (e) Kapacitor for data analytics and (f) homeassistant as the user interface (actuate, monitor, set rules, etc.). It offers a single API to the backend infrastructure (i.e., from the sensor side independently of the technology/protocol utilized), it uses HTTP response codes, basic authentication, HTTP authentication, JWT Tokens, VPN security, etc. Finally, the responses (see queries to the InfluxDB) are returning in JSON format.

The IoT testbed is also used in the context of the EU project SAFE-CROSSING for wildlife monitoring, automated storage & processing of cameras' videos/snapshots via AI/Deep Learning, visualization and statistics extraction.

In addition, as mentioned above, both the ICT Cloud and the IoT platforms are being utilized internally to the OTE Group for energy management, automations and physical security at telco sites and for network performance monitoring applications.

Finally, the FTTH Testbed is used for multi-apartment building and small buildings simulations.

3.8. CNR Node

Name of the under-development infrastructure: **SLICES-ITA**

Location: Italy, distributed

Three main sites:

- CNR sites: Institute for Informatics and Telematics, Pisa, Italy
- CNIT sites: Smart and Secure Networks Lab (S2N), Genova and Wireless Communications Laboratory (WiLab), Bologna Area, Italy
- CINI sites: National Lab on Smart Cities & Communities (the lab includes several local nodes, such as the primarily involved ones at the University of Messina - Dept Engineering - and at the University of Bologna - Dept Computer Science and Engineering)

Annual operating costs: 350k€

The SLICES-ITA infrastructure node is a combination of heterogeneous testbeds independently operated by CNR, CNIT and CINI. In the following, we provide a brief description of these testbeds. It is important to point out that, while CNR, CNIT and CINI are all members of the SLICES initiatives, only CNR participates in the SLICES-SC project. Thus, transnational and virtual access activities will primarily be supported using CNR facilities.

3.8.1. CNR site

The CNR infrastructure is located in Pisa, and is provided by the Institute for Informatics and Telematics, specifically in the Ubiquitous Internet Lab (UI). The main focus of the current CNR infrastructure is to enable experiments for AI-based edge computing and networking solutions. It thus features several personal networking devices, IoT nodes, as well as a mini datacenter. Specifically, this computational node is a latest-generation cluster for HPC that includes: 3 bi-processor nodes (Intel Xeon Platinum) with 104 cores, 512GB RAM, and an NVIDIA Tesla T4 16GB GPU; 1 bi-processor node (Intel Xeon) with 40 cores, 128GB RAM, and an NVIDIA TITAN Xp GPU; 1 64-core quad-processor (AMD Opteron Processor 6282). This is used for conducting customized experiments of AI-based network services for edge/fog environments. In addition, the infrastructure comprises about 30 personal mobile devices including smartphones, tablets, wearables, to support dedicated experiments using fog computing equipment. The infrastructure also includes (15) IoT devices including sensors and gateway devices, supporting experiments on WSN for Industrial Internet applications.

3.8.2. CNIT sites

The CNIT infrastructure is composed of two National CNIT Laboratories, namely the Smart and Secure Networks Lab (S2N) located in Genoa and Savona and the Wireless Communications Laboratory (WiLab) located in Bologna, Cesena and Ferrara.

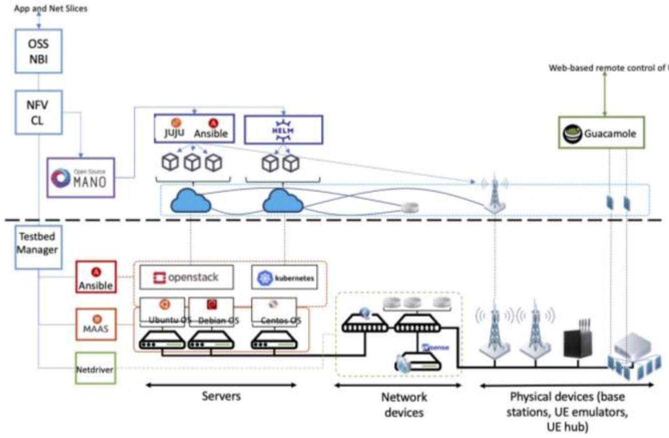
The S2N National Laboratory hosts an experimental infrastructure that provides

- complete support for the emulation of interconnections on both fixed and mobile high-speed networks, created on the basis of Software Defined Network (SDN) and Network Functions Virtualization (NFV) paradigms,
- an integrated and virtualized computing environment capable of hosting both general-purpose and security applications.

In particular, the platform consists of a physical networking infrastructure integrated with a powerful mini-datacenter (20 high-end servers providing more than 600 physical CPU cores, 1.7 TB of RAM and 100TB of high-speed SAS and SSD storage) capable of hosting network functions (VNFs and PNFs) and services of various kinds, including vertical applications also in MEC mode (Multi-access Edge Computing). More in detail, the access network is made up of 3 highly programmable devices capable of creating 5G and 4.5G multi-cell Base Stations. These devices operate by using Software Defined Radio (SDR) cards and relative signal couplers. The mobile part of the testbed is completed by mobile devices, which range from drones and smartphones and commercial tablets to LTE modems and sensors programmable with Narrow Band - IoT (NB-IoT) modems. The network facilities include SDN switches that offer a total of 918 ports with Ethernet connectivity from 1 to 46 Gigabits/s, for an overall switching capacity of more than 7 Terabits/s.

The entire testbed hardware platform is used, configured and managed in a completely automated way according to a "Metal-as-a-Service" (MaaS) approach *through a platform designed and built by S2N staff.* In particular, the MaaS approach allows automatically installing and configuring the computational and network resources present on the platform, instantiating the operating system on servers on request, and reconfiguring the network part in a completely isolated way to every single project hosted in the testbed in unattended fashion. Complex software (such as the OpenStack suite for the creation of Virtual Infrastructure Managers – VIMs), orchestrators for applications (such as Kubernetes), or NFV orchestrators for 5G services (such as Open-Source MANO (OSM)), are also managed as-a-Service throughout tools like Canonical Juju or Red Hat Ansible.

The infrastructure is also able to monitor and control energy consumption of some devices and SW instances, for sustainability evaluations and optimizations.



(a) Hardware **(b) Architectural layout**

Figure 13: CNIT-S2N testbed

The Wireless Communications Laboratory (WiLab) makes available the following testbed facilities.

- Configurable end-to-end LoRaWAN network, with 25 programmable sensor devices and multiple LoRaWAN gateways connected to two Network Servers: one is developed by the headquarters and is fully configurable, the other is owned by A2ASmartCity with unlimited availability of use.
- Configurable end-to-end NB-IOT network, made available by TIM, with programmable sensor devices. The station is fully configurable in the radio interface parameters; TIM also provides a tool that allows the acquisition of all network KPIs.
- Semi-anechoic chamber for e.m. compatibility certified according to standards EN 50147-2 / ANSI C63.4 (NSA calculation), EN 50140, EN 61000-4-3 (uniformity of field) and others for EMC measurements at 3 m up to 18 GHz for emission and radiated immunity tests.
- End-to-end ultra-broadband localization network (UWB), a fully configurable indoor location network based on UWB technology. The network is available in both the decentralized and centralized versions and is suitable for the study and implementation of data fusion algorithms and context-based applications. This includes a drone arena equipped with Vicon infrared and ultra-wideband positioning system for the validation of location technologies and systems operating on drones (UAV).
- Lepida Regional network, the ICT network of the Public Administration including 100+ microwave links, 1000+ WiFi hot spots.
- A testbed for vehicle-to-vehicle (V2V) e vehicle-to infrastructure (V2I) with ITS-G5 technology. The testbed is composed of two road side units (RSU) and two on-board units (OBU) of different vendors for interoperability test and communication tests. Specific applications have been also implemented to test in a controlled environment, following a hardware in the loop (HIL) approach, the development of applications for vehicular environments based on ITS-G5.
- An Open-RAN platform *will be available in the current year*, which will provide an environment to configure and customize RAN functionalities, thus allowing researchers to test novel strategies (algorithms, AI-based techniques, decision policies…) to meet the service requirements (latency, throughput, reliability, ...) envisioned in challenging scenarios.

3.8.3. *CINI sites*

The CINI infrastructure is distributed among the several local sites constituting the Lab. In the following we provide a summary of what is located mainly in Messina (Mobile and Distributed Systems Lab) and in Bologna (Mobile Middleware Research Group), with other CINI units in the country that will be involved, by need, in the following steps of the project.

The Mobile and Distributed Systems Lab has deployed in the cities of Turin, Padua, Lecce, Syracuse, and Messina experimental testbeds that are built using the Stack4Things (S4T) framework, which is an OpenStack-based open-source framework that is designed to deal with Cloud and IoT integration. S4T is now a branch of OpenStack and is being used not only for research purposes but also for industrial use cases. These testbeds are currently used to offer several smart cities services, such as environmental monitoring, people counting, fleet management and more. The Mobile and Distributed Systems Lab plans to federate these S4T instances and to include them in the wider SLICES framework to provide useful environments for smart cities experiments. Dedicated open Hardware was also developed, named as the Arancino architecture, which integrates in one single device controller and processor and simplifies the data collection process (with edge computing) and the actuation processes. Several communication protocols can be used such as Bluetooth, WIFI, Lora, Sigfox, 4/5G. The infrastructure includes a range of IoT devices (Arduinos, single-board computers and industrial sensors/actuators-hosting custom boards designed and produced by the academic spin-off company smartme.IO, etc.), 3D printers, smartphones, wearables, and gateway devices, supporting experiments on fog computing for Industrial Internet applications. A local cluster is also available that is a latest-generation cluster that includes: 1 Admin Node + 3 Control Nodes + 8 Compute & Storage Nodes, with multiple GbE connectivity options, for a total of compute & storage of 80 cores @ 2 GHz, 452 GB RAM, 30 TB mass storage.

Mobile Middleware Research Group has deployed a testbed in Bologna to enable experimentation and quantitative performance evaluation in fog/edge/cloud computing for large-scale deployment environments, with stringent constraints on reliability and latency. Therefore, this testbed includes mobile IoT sensors and actuators, programmable AGVs, different types of wired/wireless connectivity technologies (also with Time Sensitive Networking solutions), a dedicated private 5G cell (provided by TIM), as well as a set of edge nodes (also compliant with Multi-access Edge Computing - MEC) integrated in the cloud continuum with a local datacenter (e.g., to support digital twins and AI-based networking). Specifically, the local datacenter is a latest-generation cluster that includes: 1 Admin Node + 3 Control Nodes + 3 Compute & Storage Nodes, Switch Mellanox (18 ports 10/25 Gb + 4 ports 40/100 Gb), for a total of compute & storage of 120 cores @ 2.1 GHz, 576 GB RAM, 23 TB RAW Fast Data HDs, and 144 TB RAW Slow Data HDs. This is used for runtime bottleneck identification and experimental evaluation of quality-constrained middleware functionality (e.g., proactive migration) for service continuity in large-scale smart city deployment environments and for latency-sensitive control of collaborative mobile actuators. In addition, the infrastructure includes about 50 mobile nodes including 2 industrial and programmable AGVs, IoT devices ("regular" sensors and industrial sensors/actuators from a small manufacturing line with 3D printers, CNC centers, etc.), smartphones, Raspberry PIs, wearables, and gateway devices, supporting experiments on network slicing, time sensitive networking, and edge computing for Industrial Internet applications.

3.9. iMEC Node

The node at iMEC exists out of 5 testbeds at two locations in Belgium (Gent and Antwerpen) (https://doc.ilabt.imec.be):

- Virtual wall (Gent): to perform wired networking, cloud, distributed software, service backends and scalability experiments. 550+ installed servers.
- w-iLab.t (Gent): pseudo shielded environment for wireless and IoT research with over 150 wireless nodes (fixed and mobile), including software defined radios
- Officelab (Gent): a real office environment for wireless and IoT research with over 110 embedded PCs spread over the building.
- GPULab (Gent and Antwerpen): testbed with 125+ GPUs with over 570.000+ cuda cores and 1.8TB+ GPU RAM for AI research and everything which needs GPUs
- CityLab (Antwerpen): testbed for wireless networking experimentation in the unlicensed spectrum in the city of Antwerp. 50 nodes are spread over an area of 1 square km.

The jFed tool (https://jfed.ilabt.imec.be/, see screenshot below, can also be used in a command line version) is used to access all testbeds. For GPULab also Jupyter notebooks are supported besides a command line version to launch jobs.

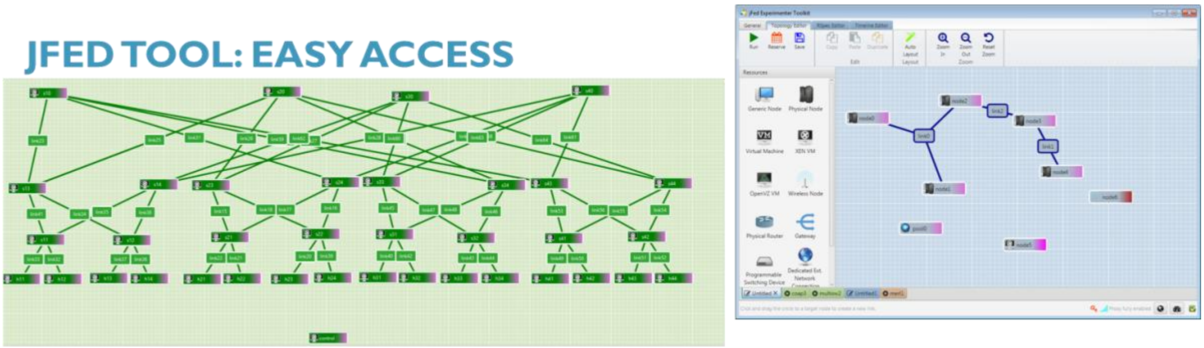


Figure 14: jFed

3.9.1. Virtual wall

The Virtual Wall testbed (https://doc.ilabt.imec.be/ilabt/virtualwall/index.html) consists out of 550+ servers in a datacenter (with varying CPU, RAM, storage and networking configurations) and can be remotely provisioned and used through the jFed tool. Below is shown part of the Virtual Wall. With the jFed tool you can define advanced network topologies and define all parameters for the bare metal or virtual machines you want to use in your experiment. After provisioning, you have full root access, so you can install and use all software you want for your experiment.

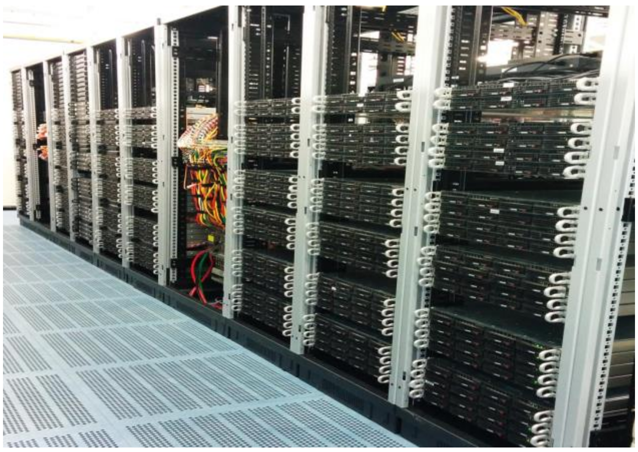


Figure 15: Virtual wall

3.9.2. w-iLab.t

The wireless lab w-iLab.t (https://doc.ilabt.imec.be/ilabt/wilab/index.html) has two locations: one pseudo-shielded industrial location as can be seen in the image below (which includes also mobile nodes), and one location in a datacenter with servers.

The wireless testbed can be used for wireless, IoT sensor, mobile, software defined radio experiments.

Figure 16: w-iLab.t

3.9.3. Officelab

As shown in the pictures below, the Officelab is based in a real office building with 110 embedded PCs with IoT sensors attached spread over 3 floors of the building. The nodes can be reserved with jFed and used for experiments on IoT, indoor localization (e.g. UWB), wireless.

Figure 17: Officelab

3.9.4. GPULab and JupyterHub

GPULab (https://doc.ilabt.imec.be/ilabt/gpulab/index.html) is a distributed system for running jobs in GPU-enabled Docker-containers. GPULab consists out of a set of heterogeneous clusters, each with their own characteristics (GPU model, CPU speed, memory, bus speed, …), allowing you to select the most appropriate hardware. Each job runs isolated within a Docker container with dedicated CPU's, GPU's and memory for maximum performance.

Our JupyterHub (https://doc.ilabt.imec.be/ilabt/jupyter/index.html) allows you to launch Jupyter notebooks on the imec iLab.t computing infrastructure with a simple mouseclick. It gives you access to an interactive environment where you can use Python, R, Julia, etc. for your research and data processing. We offer both plain and GPU-enabled environments.

GPULab contains over 570.000 cuda cores (spread over multiple types of GPUs such as 1080TI, 2080TI, 3090, V100, A100), 1.8TB GPU RAM and 2.2PFLOPG single precision and tensor performance.

3.9.5. CityLab

CityLab (https://doc.lab.cityofthings.eu/wiki/Main_Page) is a testbed for wireless networking experimentation in the unlicensed spectrum in the city of Antwerp. 50 nodes are spread over an area of 1 square km (see picture below).

The following technologies are deployed in the Citylab testbed:

- WiFi 802.11ac on 2.4 GHz and 5GHz
- WiFi 802.11n on 2.4 GHz and 5GHz
- Bluetooth 4.0
- IEEE 802.15.4 on 2.4 GHz and IEEE 802.15.4g on 868MHz
- DASH7 on 433MHz and 868MHz
- LoRaWAN on 868MHz (client only)

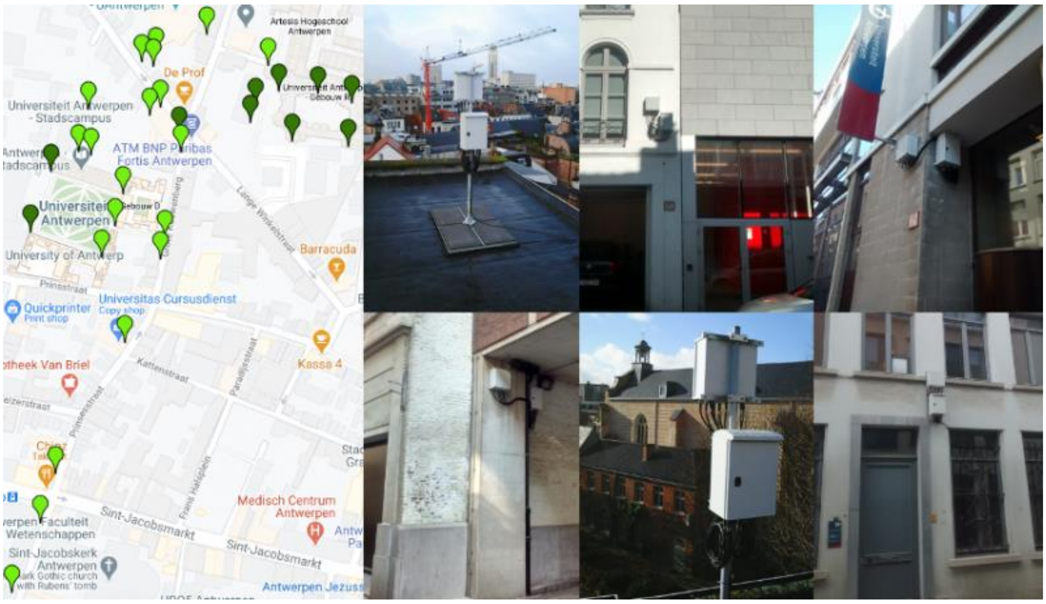


Figure 18: CityLab

1.1. SZTAKI Node

Name of the current infrastructure: **ELHK Cloud**

The primary goal of ELKH Cloud is to support the Hungarian scientific community by providing the essential e-infrastructure for their research. As opposed to the lengthy process of procuring and deploying the necessary IT tools, ELKH Cloud gives researchers the opportunity to quickly and easily create their desired research environment in as little as a few hours. In addition, the resulting e-infrastructure can be adjusted dynamically to the current needs of the ongoing project, and when the reserved resources are no longer needed, they become available for other researchers to use. This approach is more time and cost effective and all together results in a significantly more efficient e-infrastructure management for the scientific community and the entire ELKH network than what the traditional method of e-infrastructure procurement and operation offered.

ELKH Cloud is an e-infrastructure framework that allows users to create an e-infrastructure tailored to their specific needs in a cloud environment. ELKH Cloud is based on a project-oriented approach meaning that users don't typically utilize the cloud as individual researchers but as members of a project. The launching of a project can be initiated by the project manager by filling out a request form describing the purpose, duration, and resource requirements of the project. If the project is accepted, it receives the required resource capacity in the form of a quota. Within this quota, the project is then free to create an e-infrastructure that is best suited to its objectives (e.g., Spark cluster, Kubernetes cluster, deep learning supporting environment, etc.). The project manager may allow individual researchers to join at any time. Project members share the e-infrastructure that was created within the project. The different projects are completely isolated from each other and cannot access each other's data.

Creating the desired e-infrastructure in a cloud environment is usually a complex task requiring expertise, so ELKH Cloud provides reference architectures for the most commonly used, typical e-infrastructures to help users build their desired infrastructures in minimal time. Reference architectures are premade, carefully tested, ready-to-deploy infrastructures that can be used to automatically deploy the desired infrastructure after some customization and adjustment of properties.

ELKH Cloud offers direct assistance to users wanting to build non-typical e-infrastructures and then aims to create reference architectures for all e-infrastructures created this way while also providing a repository for them for easy access and storage. This allows all ELKH Cloud users to utilize these unique reference architectures as well.

ELKH Cloud was built on the infrastructure of MTA Cloud created in 2016 and underwent significant development starting from the third quarter of 2020. The table below shows the updated resource capacity post-development.

Type of resource	ELKH Cloud capacity
number of vCPU	5.904
memory (RAM, TB)	28
HDD (TB)	1,248
SSD (TB)	338
internal bandwidth (Gbit/s)	100
number of GPU cards	68

GPU memory (RAM, GB)	2.400
GPU double (TFLOPS)	584
GPU single (TFLOPS)	1.174
GPU FP 16 tensor (TFLOPS)	13.736

The 3 main types of cloud computing service models are infrastructure-as-a-service (IaaS), platform-as-a-service (PaaS), and software-as-a-service (SaaS). ELKH Cloud currently offers the IaaS level with the possibility for the additional levels to be added in the future. Most of the available reference architectures already provide cloud services at the platform level.

As an IaaS Cloud ELKH Cloud allows researchers to create different types and sizes of e-infrastructures that are dynamically adjustable according to the current needs of their ongoing projects. With the help of the reference architectures, these infrastructures may range from a simple desktop computer (e.g., MS Windows, Linux) to high performance computing clusters (e.g., SLURM cluster).

ELKH Cloud also provides a large storage capacity for the temporary storage of scientific data while the applications running on the associated e-infrastructure are processing said data. The secure storage of data is ensured by OpenStack cloud middleware.

In accordance with its operational concept, the services that help the use of ELKH Cloud are provided in the form of reference architectures (see Figure 19). Projects can create their desired e-infrastructures after selecting the corresponding service below.

For the actual list of available reference architectures and their technical descriptions please visit URL: https://science-cloud.hu/en/reference-architectures

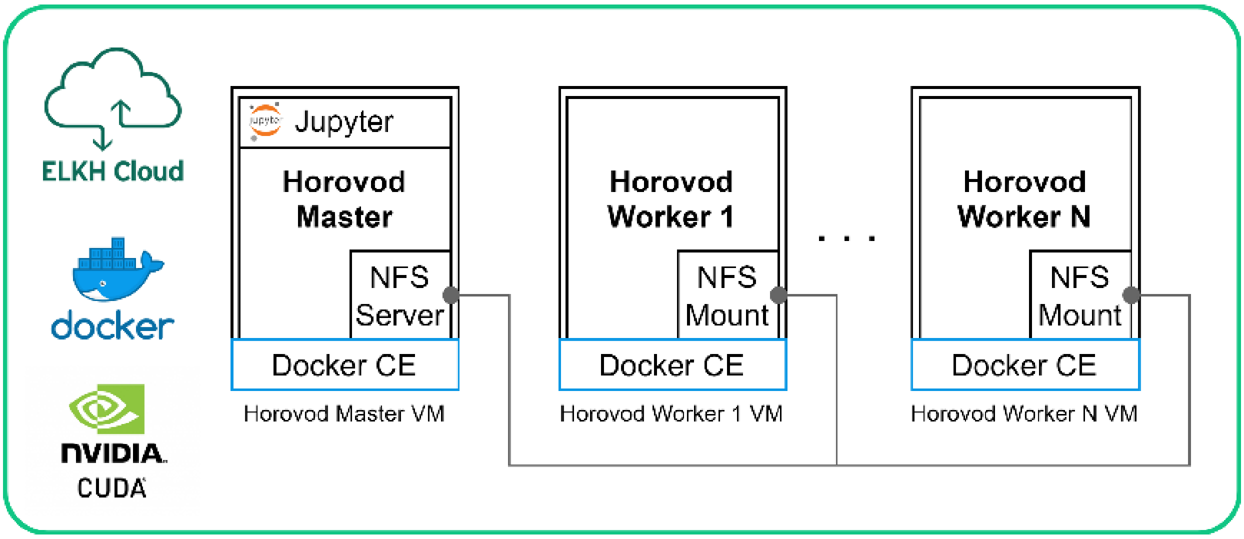


Figure 19: Reference Architecture for Horovod

Reference architectures are available in the following categories:

- General solutions for architectural, access control, orchestration, continuous integration and delivery.

- Clustering of various services based on industry standard solutions, such as Kubernetes, Docker-Swarm, CQueue as well as several tailor-made solutions like our own Occopus cloud orchestrator, gUSE grid user portal or Flowbster data workflow management.
- BigData oriented services, such as Jupiter, Apache Hadoop, Apache Spark, RStudio, DataAvenue.
- Applications for machine learning, like Tensorflow, Keras and Horovod.

4. Requirements for Connectivity and Computing

In this section we present the most recent trends on technology evolution and experimentation needs that the SLICES-SC architecture will evolve around. These are broken down to the following:

- Provisioning of beyond 5G Radio Access Networks;
- Providing access to 5G and beyond Core Networks;
- Provisioning large clusters of cloud computing resources;
- Network stitching among the different islands and experimental components.

4.1. Radio Access Network (RAN)

5G RAN [2] has evolved from the previous generations with significant improvements in capabilities, supported functionalities, and innovation potential. Access to higher carrier frequencies, including millimeter Wave (mmWave) frequency spectrum, and flexible frame structure with variable number of symbols per subframe, 5G NR can provide high bandwidth connections, allowing several innovative applications to be supported over the top. Wide softwarization that has been witnessed for different types of services in the recent years has expanded at the 5G RAN level, allowing several of the functions that have been running in monolithic hardware implementations of base stations to run as cloud-native functions. In terms of experimentation platforms, several tools exist that implement the 5G stack fully in software. Such platforms rely on Software Defined Radio (SDR) frontends, and can turn commodity equipment (e.g., with General Purpose Processors) to fully functional base stations. Two are the most prominent solutions in open source to implement such functionality as follows: 1) the OpenAirInterface5G platform (OAI) [3], and 2) the srsRAN platform [4]. Both platforms support the basic operations for the 5G-NR, though OAI has a wider user base and implements more features, such as disaggregated operation for the RAN, several different supported SDRs, etc. From an architecture perspective, 3GPP Release-15 has introduced CU/DU split (3GPP Option 2 split)[5] along with Virtualized RAN architecture. By splitting the higher layers of 3GPP software stack (SDAP, PDCP and RRC) and lower layers (RLC, MAC and PHY) into separate logical units, known as Centralized Unit (CU), Distributed Unit (DU) and Radio Unit (RU)[6], which can be deployed at separate locations. Further split of gNB-CU is induced by separation between the Control Plane (CP) and User Plane (UP) named as gNB-CU-CP and gNB-CU-UP.

Apart from the 3GPP Option 2 split, in total, eight options have been studied[6], decomposing the RAN at different levels (closer/higher from the radio part). Building on top of the different disaggregation options, and especially delving into the CP/UP separation (CUPS), Open RAN (O-RAN)[7][8] architecture defines open and standardized interfaces among the different elements of the disaggregated RAN. Through the use of such standardized interfaces, interoperability of functions between different vendors is enabled, while programmability of the RAN through dedicated interfaces is enabled. O-RAN Alliance is responsible for an additional split of the CU-CP into Radio Intelligence Controller (RIC) and remaining part of CU-CP. O-RAN defines the specifications for interface definitions between CU, DU, RU and RAN intelligent controller (RIC) that can be deployed at the edge of the network. Depending on the operation of the RIC and the programmable functions in the gNB, the RIC can operate in real-time mode (<1ms latency for programming the different functions, e.g., for Radio Resource Management) or near-real-time/non-real time mode (e.g., for the application and integration of Machine Learning models to the operation of the RAN)[9].

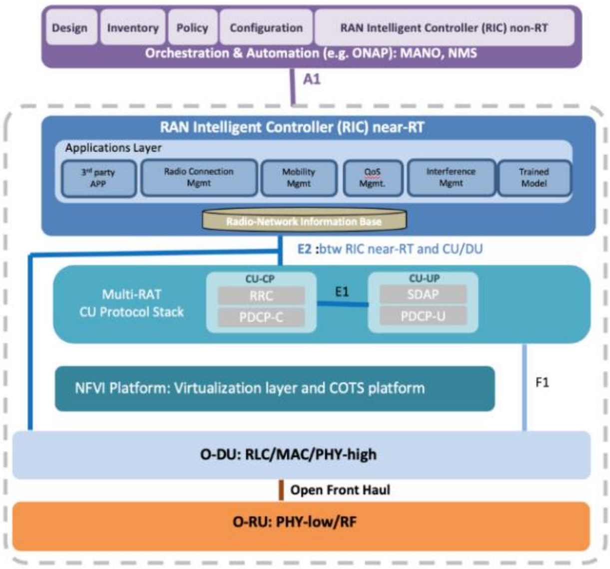


Figure 20: Open-RAN deployment and programmable interfaces

Similar to the O-RAN programmable interfaces, dedicated solutions for specific platforms exist, that open up the programmability of the RAN functions in practice. For example, the FlexRIC platform [10] (also called as FlexRAN), developed by Eurecom for OAI, allows the programmability of the OAI RAN in real-time, by exposing a REST interface. The FlexRAN controller is under further extension for becoming compatible with the O-RAN interfaces for programming the network. Similar to the FlexRAN platform, the SD-RAN platform [11] developed by the Open Networking Foundation (ONF) is complimenting O-RAN's focus on architecture and interfaces by building and trialing O-RAN compliant open source components. SD-RAN is developing a near-real-time RIC (nRT-RIC) and a set of exemplar applications that run on top (xApps) [12] for controlling the RAN.

Towards integrating all the above efforts for the end-to-end deployment of the cellular network with extended use of virtualized services, the AETHER framework [13] is currently under development by ONF. AETHER combines three main elements, namely, a control and orchestration interface to the RAN, an edge cloud platform (the AETHER edge), with support for cloud computing APIs, and a central cloud (the AETHER core), for orchestration and management. The AETHER project integrates several ONF efforts, including SD-RAN, ONOS [14], CORD and OMEC[15], for providing a fully-fledged solution for the deployment of the cellular network in an end-to-end manner.

4.2. Core Network

The Core Network (CN) is the central element of the telecommunications network that provides services to customers who are connected by the access network. The 5G core network is referred to as 5GC, it is an evolved version of EPC (LTE Evolved Packet Core network) as cloud-native, taking advantage of the service-based-architecture (SBA) [16]. The main components of the 5GC are the Access and Mobility Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Unified Data Management (UDM), Authentication Server Function (AUSF), Policy Control Function (PCF), Network Exposure Function (NEF), Network Repository Function (NRF) and Network Slicing Selection Function (NSSF). These 5G network functions are cloud-native by design, thanks to the Service Based Architecture (SBA) design of the 5GC. Therefore, their instantiation can take place as Virtual Network Functions (VNFs) or Container Network Functions (CNFs) in any of the available virtualization platforms.

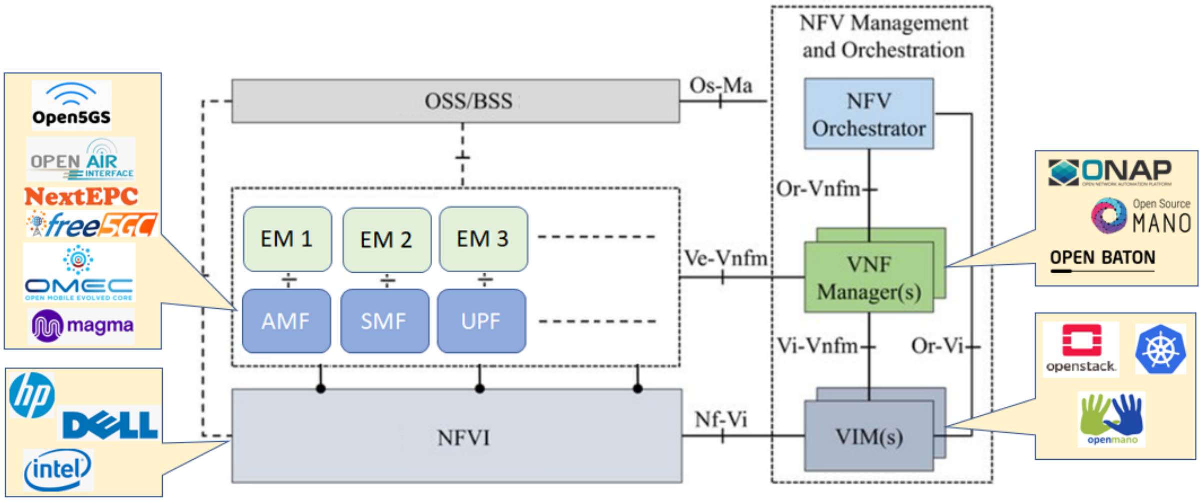


Figure 21: Cloud-native instantiation of the 5G Core Network

The main goal is to adapt them independently when the load increases for any specific service or set of services, which is a major advancement from previous mobile generations. To promote flexibility and reduce cost, it is possible to adopt generic hardware and use an NFV Infrastructure (NFVI) layer in order to host them.

4.3. Cloud Computing

Computing infrastructure is required across the different sites for either experimentation or management purposes. For the latter, resources are needed in order to support functions such as signal processing, controls and related computational, high performance and data intensive computations; In addition, such resources can provide the programmability framework for the experimenter, APIs, resource access, reservation and slicing, data storage, and the management part of the users, slices and experiments. Regarding the resources dedicated to experimentation, Clusters of compute infrastructure are needed for the cases where ample processing power is required. This is of high importance for several types of experiments, especially the ones involving Artificial Intelligence and Machine Learning, as the computational power needed for training is significantly high, and can be assisted by splitting the load across several interconnected clusters, or using special purpose hardware (e.g. FPGAs, GPUs) for higher computing power. As such, several state-of-the-art platforms exist for experimenting with cloud infrastructure, as detailed below.

OpenStack[17] is a free, open standard cloud computing platform. It is mostly deployed as infrastructure-as-a-service (IaaS) in both public and private clouds where virtual servers and other resources are made available to users. The software platform consists of interrelated components that control diverse, multi-vendor hardware pools of processing, storage, and networking resources throughout a datacenter. Users manage it either through a web-based dashboard, through command-line tools, or through RESTful web services. OpenStack has a modular architecture with various code names for its component. The most important with respect to the SLICES-SC architecture are the following:

- Nova (compute): Nova provides a way to provision compute instances as virtual machines, real hardware servers, and has limited support for system containers (e.g., through the Openstack ZUN[18]).
- Neutron (networking): Neutron provides “network connectivity as a service” between interface devices (e.g., vNICs) managed by other OpenStack services (e.g., Nova). OpenStack

Networking enables projects to create advanced virtual network topologies which may include services such as a firewall, and a virtual private network (VPN).
- Cinder (storage): Cinder is the OpenStack Block Storage service for providing volumes to Nova virtual machines, containers and more. Cinder volumes provide persistent storage to guest virtual machines - known as instances, that are managed by OpenStack Compute software.
- Keystone (identity): Keystone is an OpenStack service that provides API client authentication, service discovery, and distributed multi-tenant authorization.
- Glance (image repository): The Image service (glance) project provides a service where users can upload and discover data assets that are meant to be used with other services.
- Horizon (Dashboard): Horizon is the canonical implementation of OpenStack's Dashboard, which provides a web based user interface to OpenStack services.
- Heat (Orchestration): Heat is a service to orchestrate multiple composite cloud applications using templates, through both an OpenStack-native REST API.

Regarding the networking part of the cloud system, connections for cloud nodes within SLICES-SC are needed for the following:

- In the node itself: for building the clouds and for network experimentation
- connections between clouds are needed to experiment on distributed clouds in different locations or for interconnecting other infrastructure such as edge nodes or RANs

Such state-of-the-art platforms like OpenStack can be used for providing seamless interconnections between different islands, without the need of building testbed specific APIs for communicating with each island.

In the cloud-computing world, containers are an emerging technology and the paradigm is standing between virtual machines and containers now. Although much of the research in the domain has been conducted using Virtual Machines and underlying software like OpenStack, there seems to be a notable steer towards containerized services, which are more lightweight, can be easily instantiated over almost any hardware, and can be managed more efficiently. Containers show high utilization of computing resources and better performance than virtual machines. Multiple containers can be executed on the same host and share the same Operating System (OS) with other containers, each running isolated processes within its own secured space. Because containers share the base OS, the result is being able to run each container using significantly fewer resources than if each was a separate virtual machine (VM). Along with this trend, Network Functions Virtualization (NFV) industry has also been interested in Containerized Network Function (i.e., CNF) instead of conventional Virtualized Network Function (i.e., VNF) due to its scalability and efficiency for operation and management. For those benefits, various mobile operators are trying to replace conventional VM-based NFV platforms with container-based platforms. For low-latency use cases, 5G Core Network (CN) and RAN components are motivated to run as Containerized Network Functions (CNFs), instead of VMs in the case of Virtual Network Functions (VNFs), supported by tools like Kubernetes[19], that can deploy the services directly on bare-metal. Open-source projects are moving towards cloud-native design, but until they become a reality, a mix of VM's and CNF's has been adopted. Edge computing will have requirements for low-latency, cost-efficient infrastructure, secure with AI/ML capabilities. CNFs will be widely considered for the cases of Edge/Fog computing, due to the low complexity and fast instantiation of cloud-native services that can be achieved. Specific to ML tasks, several tools have emerged for managing the deployment of such workloads using containers. The most outstanding effort that is exemplifying this adoption is the Kubeflow framework [20], that can be used for splitting ML pipelines and workflows across several distributed nodes.

4.4. Node Interconnection

In order to support connectivity between currently isolated experimental islands, an efficient interconnection between them should exist, able to facilitate high-speed and reliable data transfer across the different sites. Network programmability for such connections is key in order to create custom experimentation environments, with specific SLAs, as mandated by each experiment configuration.

To this aim, Software Defined Networking (SDN) [21] shall be employed in order to provide fine grained control over the inter-networking aspects between testbed islands. SDN leverages network softwarization to decouple network control from the forwarding (or data) plane, thus separating routing and control procedures from specialized hardware based forwarding operations. SDN is designed to make networks more flexible, controllable and agile. There are plethora of open source SDN solutions/protocols for managing such networks, with the two most outstanding solutions being OpenFlow and the latest trend of P4 programming, allowing the control of high-speed (multi-Gbps) P4 switches. Details on the operation of each solution is provided below:

- OpenFlow: OpenFlow [22] is a communications protocol that gives access to the forwarding plane of a network switch or router over the network. It enables network controllers to determine the path of network packets across a network of switches. OpenFlow allows remote administration of a layer 3 switch's packet forwarding tables, by adding, modifying and removing packet matching rules and actions. This way, routing decisions can be made periodically or ad hoc by the controller and translated into rules and actions with a configurable lifespan, which are then deployed to a switch's flow table, leaving the actual forwarding of matched packets to the switch at wire speed for the duration of those rules. Packets which are unmatched by the switch can be forwarded to the controller. The controller can then decide to modify existing flow table rules on one or more switches or to deploy new rules, to prevent a structural flow of traffic between switch and controller. It could even decide to forward the traffic itself, provided that it has told the switch to forward entire packets instead of just their header.
- P4 [23] is a programming language for controlling packet forwarding planes in networking devices, such as routers and switches. In contrast to a general purpose language such as C or Python, P4 is a domain-specific language with a number of constructs optimized for network data forwarding. P4 programs are designed to be implementation-independent: they can be compiled against many different types of execution machines such as general-purpose CPUs, FPGAs, system(s)-on-chip, network processors, and ASICs. P4 is designed to be protocol-independent: the language has no native support for even common protocols such as IP, Ethernet, TCP, VxLAN, or MPLS. Instead, the P4 programmer describes the header formats and field names of the required protocols in the program, which are in turn interpreted and processed by the compiled program and target device. Such functionality allows truly any control over the network packets. Moreover, protocol independence and the abstract language model allow for reconfigurability–P4 targets should be able to change the way they process packets (perhaps multiple times) after they are deployed.

Several of the current nodes in SLICES-SC support the reconfiguration of the switching fabric within the node using either OpenFlow or P4 programming. Moreover, such support is provided over their interconnection with other sites, which takes place either over the GEANT network [24], using dedicated virtual circuits, or over the Internet. This process is to a high degree automated for the experimenter, that needs to conduct an experiment using multiple sites. For example, the Belgium node at IMEC uses VLANs over virtual circuits to interconnect to other nodes. When an experimenter wants to set up a connection, they can 'stitch' together nodes and VLANs at two locations to set up a layer 2 connection. Currently VLANs are available to University of Amsterdam, Grid5000, Fabric, UTH, Geant.

5. APIs specific to testbed operations

In this section we present some of the existing APIs for supporting the testbed operation and experimentation with the deployed resources. Such APIs are dedicated to resource control, slice reservation (booking of a part of the infrastructure for experimentation), and other testbed specific APIs.

5.1. API for Resource Control

The most widely used API for testbeds resource control, adopted by several testbeds around the Globe is the Federated Resource Control Protocol (FRCP) [25]. FRCP is a standardized resource control protocol that permits the control of resources provided by multiple federated facilities in a uniform way, even if they use different management software. It consists of a message being sent by a requester to a component (or resource). The component may accept the message and perform the requested associated actions. For the message exchange with the resources (physical or application resources), the necessary resource controller implementation, supporting the set of defined messages, should be running in the different resources of the facility.

The most significant features of FRCP are enlisted below:

- It is not required by the testbeds to use the same management software.
- The control of any type of resource is feasible.
- It defines a mechanism for signing each message to securely bind the message to a 'sender'. While it is outside the scope of the FRCP specification, the recommended 'best practice' for implementing this is the use of PKI public/private key encryption with X509 credentials.
- It keeps the centralized infrastructure as minimum as possible.
- It keeps each facility independent in a loose federation with the rest facilities.
- It is not a management software, but provides an interface to control resources.
- Its implementation is sufficiently modular.

Below, it is explained which is the FRCP message syntax. The content of a message is described in an XML format with the following convention.

```
<MSG_NAME xmlns="http://schema.mytestbed.net/omf/X.Y/protocol" msg_id= ID>
....
</MSG_NAME>
```

with:

- X.Y = the version of the protocol
- MSG_NAME = the name of message, either "create", "configure", "request", "inform", or "release"
- ID = a globally unique ID for this message

The element may then have child elements, which further describe various message properties specific to the message type. There are two different ways the value of a message property to be declared. The simple version provides the value as a text element with an optional 'type' attribute if the value is not of type 'xsd:string'.

```
<MSG_NAME ... >
<PROP_NAME type="TYPE">VALUE</PROP_NAME>
...
</MSG_NAME>
```

The more descriptive way employs a list of child elements to describe the property in more details. Basic elements are 'type' and 'value', but can also include 'unit', 'precision', or 'min-value', 'max-value' if the property is used a constraint in a 'request' message.

```
<MSG_NAME ... >
<PROP_NAME>
<type>TYPE</type>
<value>VALUE</value>
...
</PROP_NAME>
...
</MSG_NAME>
```

FRCP can be used to support control over the hardware provided from a testbed, by using the predefined message format for advertising/controlling the available resources.

5.2. API for Slice Reservation

The Slice-Based Federation Architecture (SFA) [25] provides a ‘thin waist’ for secure, distributed resource requests. This effort has been initiated by GENI in the US and Fed4FIRE in EU and fostered the emergence of an ecosystem of tools and services covering a wide range of applications not included in the SFA, such as enriched user interfaces, measurement and monitoring platforms, user registration and authentication services, and experimental management software.

A typical user willing to run an experiment across federated testing facilities is accommodated by the usage of SFA, releasing the user from switching between many heterogeneous and overlapping tools. With SFA assistance, he does not need to discover various tools, learn their processes and semantics, and often authenticate himself several times and manually make the bridge between them. As a response to this diversity and complexity, the notion of an experimenter’s portal is often advanced.

The SFA API is specifically intended for the retrieval of a description of the corresponding testbed. Each SFA API call returns a XML-RPC struct that describes which version of the API is used, the Resource Specification (RSpec) schemas supported, and the URLs where other versions of the API are running. This XML-RPC struct is also extended in some testbeds with information related to both the testbed and the tool directories. SFA is initially designed by GENI and later extended by Fed4FIRE.

5.3. GENI/Fed4FIRE APIs

The AM (Aggregate Manager) API (https://fed4fire-testbeds.ilabt.iminds.be/asciidoc/federation-am-api.html) is the default for testbeds (https://doc.fed4fire.eu/#testbed-owner-documentation) in GENI and Fed4FIRE (including the Belgium Slices node at IMEC). The SA (slice authority) and MA (member authority) (https://groups.geni.net/geni/wiki/CommonFederationAPIv2) are the default APIs for the authority. Resource Specifications (RSpecs) are the default to describe resources in GENI and Fed4FIRE as shown in the following link https://fed4fire-testbeds.ilabt.iminds.be/asciidoc/rspec.html.

5.4. Other APIs

Besides APIs that have been defined and adopted by several islands, some provide extended APIs for their dedicated equipment. For example, the 5GTN external APIs are exposed by the 5GTN facility adapter. It translates the generic requests coming from external controller or operator into facility specific requests so that the network performs the desired functions. Based on functionalities, the API interfaces have been divided into two groups:

1. Network Slice Management Interfaces
2. Key Performance Indicators (KPIs) Management Interfaces

The purpose of Network Slice Management Interfaces is to control the life cycle of a network slice in 5GTN. From creation to deletion each functionality is controlled by a respective interface. Currently 5GTN is supporting following interfaces:

- Network Slice Instance (NSI) Feasibility Check Interface: to verify the availability of resources to create a network slice instance.
- NSI Creation Interface: used to create a network slice instance in 5GTN.
- All NSIs View Interface: to retrieve the information of all the NSIs deployed in the 5GTN system.
- NSI View Interface: to get the information of one specific NSI.
- Delete NSI Interface: to delete an NSI and release the resources.

Once the NSI is created, real-time collection of performance data is needed to analyze the behavior of network slice to take appropriate actions. KPIs like throughput, delay, jitter, packet-loss etc. can be collected from two measurement points like source and the destination. Thus, for KPI monitoring 5GTN offers following interfaces:

- Create Measurement Job Interface: to start collecting the KPI data of one specific slice.
- Get Measurement Jobs Interface: to retrieve the information about all the KPI measurement jobs of all the slices.
- Get one Measurement Job Interface: to get the information of one specific measurement job.

Delete Measurement Job Interface: to delete a measurement job and stop collecting the KPIs from a specific slice.

6. Conclusion

The document emphasized the analysis of the current demands from relevant ICT stakeholders for the operation of the SLICES facility, and the foundational principles on which it will be grounded. These principles, alongside with the current trends in resource management (resource programmability, network virtualization, resource disaggregation) have resulted in the wide adoption of several frameworks, interfaces and resources for deploying experiments and applications over distributed infrastructures. The purpose of this document is to develop the discussion regarding the requirement analysis in order to provide a solid outcome about the solutions to be deployed in the long term during the construction and operation of the entire facility. It will be continuously refined. The service design and the architecture are based on the long experience of the participating members in managing test platforms infrastructures.

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