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HORIZON 2020
H2020 - INFRADEV-2019-3

D2.1 Initial description of the SLICES architecture

Acronym	SLICES-DS
Project Title	Scientific Large-scale Infrastructure for Computing/Communication Experimental Studies – Design Study
Grand Agreement	951850
Project Duration	24 Months (01/09/2020 – 31/08/2022)
Due Date	31 August 2021 (M12)
Submission Date	24 September 2021 (M13)
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Reviewers	All partners

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951850. The information, documentation and figures available in this deliverable, is written by the SLICES-DS project consortium and does not necessarily reflect the views of the European Commission. The European Commission is not responsible for any use that may be made of the information contained herein.

Scientific
Large-scale
Infrastructure
for Computing
Communication
Experimental
Studies
Design
Study

Executive Summary

This deliverable aims to organise the discussions regarding the reference architecture of SLICES-RI. In this document, different scenarios are analysed and presented as a baseline for the future discussions regarding the SLICES-RI's reference architecture. Other scenarios, in addition to the above-mentioned ones, might be considered by the partners in the future.

At a time calling for the digital transformation of our societies, by all means, Digital Infrastructures (DI) as the future Internet, play a strategic role with a tremendous impact on the industrial, economic and political dimensions. Mastering Digital Infrastructures is of utmost importance for Europe as none of the advanced services envisaged is otherwise feasible or will rely on third parties' solutions. In order to research and master Digital infrastructures, the research community needs to address significant challenges regarding their efficiency, trust, availability, reliability, range, end-to-end latency, security and privacy. SLICES ambitions to provide a European-wide test-platform, providing advanced compute, storage and network components, interconnected by dedicated high-speed links. This will be the main experimental collaborative instrument for researchers at the European level, to explore and push further, the envelope of the future Internet. SLICES is our answer to this need. It is ambitious, practical but overall timely and necessary.

This document contains the initial design for the end-to-end test platforms that comprise SLICES. The design has been based on the feedback that the consortium has received from the relevant ICT communities, collected through multiple methods as detailed in SLICES DS D1.2 – "Requirements and needs of scientific communities from ICT-based Research Infrastructures". The feedback from the community has been in line with the recent trends and practices for resource management, disaggregation, virtualization and programmability of services. These constitute the foundational principles for operating the distributed SLICES infrastructure. The document details such approaches, and analyses the current state of the art in terms of open-source platforms that will be used, and current approaches for similar testing infrastructure worldwide. SLICES will advance current state of the art and state of practice, and offer a versatile facility that almost any ICT related experiment will be made feasible.

Towards promoting user-friendliness and ease of use for the facility, single sign-on processes will be adopted for the SLICES ecosystem. The process will be based on existing know-how that the SLICES members have from provisioning smaller scale RIs prior to SLICES. Regarding the resource management, SLICES will adopt and extend existing methodologies for 5G resource management, including APIs for advanced network and hardware programmability (e.g., P4, Open-RAN), integrated in a single end-to-end framework. The framework will make extended use of resource virtualization where applicable, and unify the different heterogeneous domains (isolated testbed islands) into a single SLICES facility. The data produced within the facility will be appropriately annotated and published, towards promoting research reproducibility and repeatability. These functionalities and related motivation are covered in detail in the document, concluding in the initial centralized SLICES management architecture.

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Acronyms

3GPP	Third Generation Partnership Project
5GC	5G Core Network
5GPPP	5G Public Private Partnership
AI	Artificial Intelligence
AMF	Access and Mobility Function
AP	Access Point
API	Application Programming Interface
AUSF	Authentication Server Function
CAPEX	Capital Expenditure
CN	Core Network
CNF	Containerized Network Function
CORD	Central Office Re-architected as a Datacenter
COTS	Commercial off-the-Shelf
CP	Control Plane
CPRI	Common Public Radio Interface
CU	Central Unit
CUPS	Control and User Plane Separation
DI	Digital Infrastucture
DMP	Data Management Plan
DS	Design Study
DU	Distributed Unit
EIRA	European Interoperability Reference Architecture
EOSC	European Open Science Cloud
EPC	Evolved Packet Core
FAIR	Findable Accessible Interoperable Re-usable
gNB	Gigabit NodeB
HPC	High Performance Computing
ICT	Information and Communication Technology
IoT	Internet of Things
KPI	Key Performance Indicators
LAN	Locan Area Network
MANO	Management and Orchestration
MEAO	MEC Application Orchestrator
MEC	Multi-access Edge Computing
ML	Machine Learning
NEF	Network Exposure Function
NFV	Network Functions Virtualization
NFVI	NFV Infrastructure
NFVO	NFV Orchestrator
NGI	Next Generation Internet
NIC	Network Interface Card
NMS	Network Management System
NOS	Network Operating System
NR	New Radio (5G RAN)
NRF	Network Repository Function
NRM	Network Resource Manager
NS	Network Service
NSaaS	Network Slice as a Service
NSD	Network Service Descriptor
NSO	Network Service Orchestrator
NSSF	Network Slicing Selection Function
OAI	OpenAirInterface
ONAP	Open Networking Automation Platform
ONF	Open Networking Foundation
ONOS	Open Networking Operating System
OPEX	Operational Expenditure
O-RAN	Open RAN
OS	Operating System
OSM	Open-Source MANO
PCF	Policy Control Function
PDCP	Packet Data Convergence Protocol
PNF	Physical Network Function
RAN	Radio Access Network
RI	Research Infrastructure
RIC	Radio Intelligent Controller
RLC	Radio Link Control
RO	Resource Orchestrator
RRC	Radio Resource Control
RU	Radio Unit

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 identified by the respective community.

This document explores the design space of SLICES. This work will evolve during the course of the design phase in order to properly identify the demand of the research community, consider alternatives and converge towards a reference architecture. There is an important trend that the network will evolve towards a programmable platform and there exists already important community initiatives engaged in providing open-source solutions for some of the major components. It is of utmost importance for SLICES to understand how we can benefit from these important efforts, as well as what should we develop ourselves to match our case. This will also help us to onboard more real life and industrial scenari.

This deliverable reports on the advances in order to prepare the implementation of the test platform. It is based on the scientific excellence of our community and presents the overall articulation of the required technologies and services and the foreseen components including the reference architecture backbone that will rule them all. The identified technologies are evolving around the latest trends in research in Digital infrastructures, as well as the services that can be offered over the top. The starting point of SLICES has been identified as a mixture of the most mature research infrastructures in Digital Infrastructures covering different types of resources; from advanced highly programmable radios spanning the entire wireless spectrum with mature off-the-shelf radios or experimental prototypes, to configurable wired/optical transnational links able to transport data with speeds of multiple Gbps, and a wide range of IoT devices backed by special purpose processors and vast computing resources. Given the geographical span of the resources, multiple topologies (e.g., edge vs core cloud computing, star/mesh topologies) can be realized. SLICES will delve into the decoupling of the experimentation process and the hardware infrastructure with the wide application of resource virtualization. Moreover, and towards ensuring the smooth operation of the infrastructure, tools for facilitating access will be developed and deployed. Open-source software shall be employed, based on the paradigms of existing testbed access schemes, including user authentication and authorization. This software will be appropriately tailored with new modules for managing the new equipment deployed through SLICES. In terms of integration of the various components, the software tools shall encompass single-sign in procedures, with access certificates issued by a single SLICES authority. The resource discovery, reservation, and allocation shall comply with the access policies for SLICES and be interchanged with the respective facility authorities through a standardized process. Dedicated services taking advantage of virtualized resources, even at the radio level, shall be employed. The services shall be devoted to either the experiment orchestration for the efficient deployment of experiments, in an entirely remote manner, or for supporting the experimentation process through advanced monitoring solutions and facilitating the collection and distribution of data regarding the experiment results, methodology, etc. The infrastructures participating in SLICES will harmonize their interfaces with a standardized approach, so as to advocate the integration of new sites in SLICES. The framework shall span a wide variety of resources (compute, storage, networking and IoT) through a common interface. Finally, the SLICES infrastructure will adopt a secure-by-design architecture for resilience against cyber-attacks. The experimentation infrastructure will be supported by cloud and edge compute and storage resources, allowing the support of several thousands of users concurrently.

The experimentation services that shall be provided by SLICES feature easy experiment setup and execution, as well as user access to experiment data (results/configuration). The experimentation services of SLICES shall be provided under two different modes: 1) transnational access, with either physical access to the infrastructure components or remote access (transnational virtual access) through advanced tools that allow fine grained control over the experiment properties, and 2) virtual access to the data produced over SLICES. These data regard either experiment output or older experiments/protocols that can be used to either bootstrap a new experiment or directly compare experimental results with past measurements. The data produced over the infrastructure will be annotated based on the respective EOSC guidelines and published through SLICES according to the respective Data Management Plan (DMP)[1].

The document is organized as follows. Section 2 provides a brief overview of the SLICES vision and key contributions in the research infrastructures landscape. Section 3 presents the cornerstone of the envisioned contributions, being the evaluation of the actual user demand. Section 4 presents the foundational principles on which the SLICES architecture shall build upon. Section 5 briefly presents the current state of the art in platforms and experimentation testbeds worldwide, and the current choices that have been made in terms of managing and providing access to their infrastructure. Section 6 presents the envisioned end-to-end SLICES hardware and software architecture, building upon and extending beyond state of the art. Finally, in section 7 we conclude the document and present future directions in deploying and operating the SLICES research infrastructure.

2. SLICES at a Glance

Digital Infrastructures as the future Internet, constitutes the cornerstone of the digital transformation of our society. As such, innovation in this domain represents an industrial need, a sovereignty concern and a security requirement. Without Digital Infrastructure, none of the advanced services envisaged for our society is feasible. They are both highly sophisticated and diverse physical systems but at the same time, they form even more complex, evolving and massive virtual systems. Their design, deployment and operation are critical. In order to research and master Digital Infrastructures, the research community needs to address significant challenges regarding their efficiency, trust, availability, reliability, range, end-to-end latency, security and privacy. Although some important work has been done on these topics, the stringent need for a scientific instrument, a test platform to support the research in this domain is an urgent concern.

SLICES-RI (Research Infrastructure) ambitions to **provide a European-wide test-platform**, providing advanced compute, storage and network components, interconnected by dedicated high-speed links. This will be the main experimental collaborative instrument for researchers at the European level, to explore and push further, the envelope of the future Internet. A strong, although fragmented expertise, exists in Europe and could be leveraged to build it. SLICES-RI is our answer to this need. The main objective of the SLICES Design Study (SLICES-DS) is to adequately design SLICES-RI in order to strengthen research excellence and innovation capacity of European researchers and scientists in the design and operation of Digital Infrastructures. SLICES-DS builds upon the experience of the existing core group of partners, to **prepare in detail the conceptual and technical design of the new leading-edge SLICES-RI for the next phases of the RI's lifecycle.**

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[1] SLICES Deliverable D4.1- Data Management Plan, March 2021.

Regarding the objectives, all SLICES-DS objectives have been defined in relation to the list of Minimal Key Requirements of the ESFRI 2021 Roadmap for the Preparatory phase[2], in order to be reached at the end of the Design Study. SLICES-DS consortium has identified 5 main objectives to be reached during the 24-month duration of the project, keeping in mind the overall SLICES-RI initiative:

1. To adequately design SLICES-RI in order to strengthen research excellence and innovation capacity of European researchers and scientists in Digital Infrastructures;
2. To accomplish preparatory work and planning of the new Research Infrastructure;
3. To define governance and management of the new Research Infrastructure;
4. To define models for the financing of the new Research Infrastructure;
5. To define stakeholder and engagement strategy on community-based research.

SLICES-DS consortium gathers partners from **nine countries** (France, Greece, Poland, Switzerland, Spain, the Netherlands, Cyprus, Italy, Belgium) with a special focus in networking and wireless research; Future Internet; Internet of Things and Internet of Services; mobile communications, security of telecommunications and applications; Network protocols and architectures, NFV, cloud/edge/fog computing, artificial intelligence; deployment of 5G testbeds for experimentation; Data Management, Data Analytics.

However, SLICES-DS is one activity among several efforts to develop SLICES and therefore serve our community. As a consequence, it is important to note that the entire SLICES community is involved in the discussion regarding the reference architecture as for all other tasks.

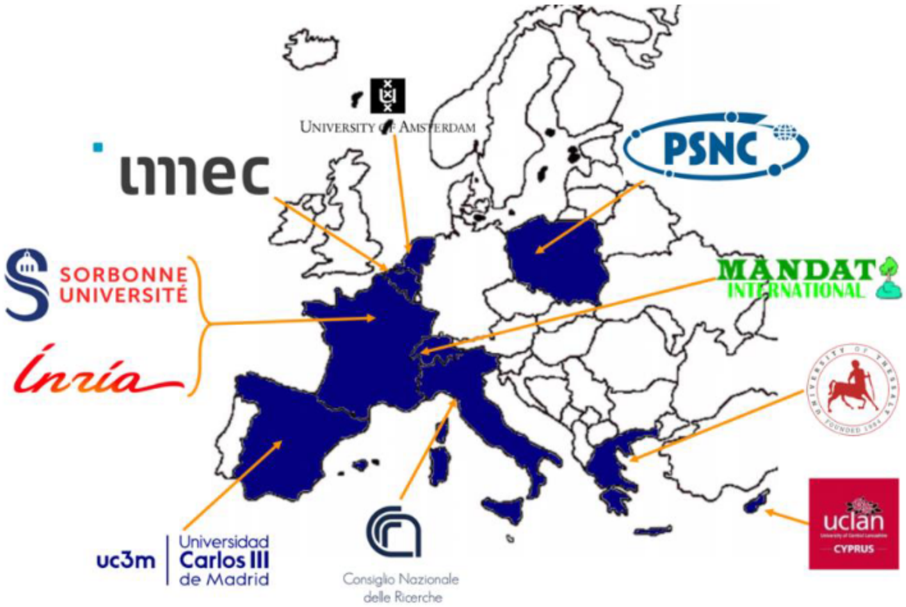

Figure 1: Overview of SLICES-DS partnership and deployments in Europe

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[2] ESFRI Strategy Report on Research Infrastructures, "Roadmap 2021 – Public Guide", 2019, [Online] https://www.esfri.eu/sites/default/files/ESFRI_Roadmap2021_Public_Guide_Public.pdf, [Last accessed 20 September 2021].

3. Evaluation of the Demand

In the last couple of years, there has been enormous growth in the technology domain including wireless, IoT, Cloud/Edge, AI/ML, HPC etc. For example, in the field of wireless technology, end users are witnessing initial 5G deployments in several countries along with research and development activities happening on several key aspects of 5G technology. In parallel, research on 6G has been initiated by many projects, organizations, academia, and standardization forums, which is inspired by the limitations of 5G technology. In this research path, state-of-the-art testbeds are essential to provide advanced evaluations of the scenarios with accurate results. Designing and constructing testbeds for 5G and beyond now requires joint expertise on many engineering aspects such as wireless, cloud, SDN, IoT, AI, hardware, and software which is complex and time-consuming. This delivery aims to discuss several design aspects and components of testbed infrastructure that will be useful for the research community.

Over the course of the long history of mobile communication systems from the first generation to 5G, the industry has achieved enormous advances in data communication. 5G will support many new applications, like high-definition media streaming, low-latency V2X communication, reliable-critical emergency networks, power-efficient IoT communications, and unmanned aerial vehicles. However, there is still a significant amount of research necessary to let all these applications become reality. As the commercial rollout of 5G is underway, wireless communications researchers are already investigating the technology and ideas that will serve as the foundation of 6G, which may be commercialized by 2030.

Like all previous generations, 6G is expected to expand beyond the capabilities of 5G. 5G will support a vast variety of verticals and use cases but still, some use cases are not yet realized, and more advanced verticals and use cases are emerging in the context of 6G. There are many technological developments and advancements happening that will introduce many new and exceptional use cases for wireless communication to support them. Use cases such as wireless connectivity for Oceans, Space, Air-to-ground (including aerial vehicles), High-speed trains (supporting more than 500 kms/h) and satellite networks are setting the stage for 6G. Terahertz frequency will be an initial focus area for 6G spectrum research. Target service KPIs for 6G are expected to have almost 10 to 20-fold times stricter than 5G, below figure presents a comparison of basic KPIs between 5G and beyond wireless generations.

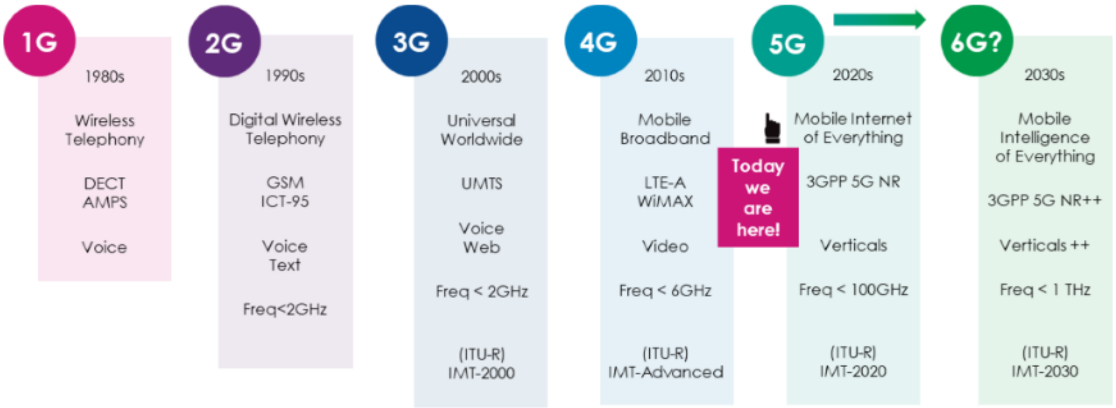

Figure 2: 5G and beyond KPIs

Towards evaluating the real demand coming from users, SLICES consortium conducted a survey in the relevant ICT communities for assessing the actual need from relevant researchers. The detailed results have been reported in SLICES Deliverable D1.2- Requirements and needs of scientific communities from ICT-based Research Infrastructures[3]. The consultation of the research community through the user survey allowed the consortium to determine the real demand for an ICT research infrastructure. The audience reached by the user survey was relatively broad as more than 200 people have answered the survey. 95% of responders are European, the continent which is the target of the new SLICES research infrastructure. 70% of the responders are coming from the academic world and 25% from the industry or SMEs. So, the panel for the user survey was representative of the current situation in Europe in terms of RI.

Some of the key topics and challenges that were identified by the survey show that the SLICES infrastructure should be able to handle at the same time the distribution of computing (cloud, fog, edge) and the processes running on top of computing, which should be optimized thanks to Artificial Intelligence (AI) and Machine Learning (ML). AI and ML will also play an important role to manage the underlying layers, in particular, to improve the performance and the energy efficiency of the wireless and network technologies (SDN/NFV) in the context of 5G networks and beyond. The research infrastructure should use the latest communication technologies such as beyond 5G and 6G, in a real environment including components deployed at the cloud, at the fog, and at the edge. More realism in the RI is also required by the researchers to ensure experiments closer to the industry; this means that the scalability should be improved compared to the current testbeds. The open-access and the configuration of the research infrastructure are very important for the research community. Finally, the close involvement of the industry and the RI openness can be applied with the utilization of open-source solutions already used by the industry, like ONAP (Open Network Automation Platform) and OAI (Open Air Interface) in the context of 5G and beyond.

For understanding the demand, the two methods for conducting the requirements analysis were a user survey, and a two-day SLICES workshop, open to the community. The produced results seem very interesting for extracting the requirements analysis for the infrastructure. In detail, the consultation of the research community through the user survey allowed the consortium to determine the real demand for an ICT research infrastructure. Based on the results, the future ICT research infrastructure should be able to handle at the same time the distribution of computing (cloud, fog, edge). The security, privacy and scalability are very important features to be implemented by the research infrastructure with the possibility to assess them directly in the RI. Another important challenge to be addressed by the future RI is the possibility given to the researchers to configure for themselves the network used in the different kinds of experiments. The federation of RIs is also a goal for the research community as new use cases could be created in a federation.

The European research community has also evaluated the importance of several requirements to be implemented in the SLICES research infrastructure. The remote access, the data analytics tools and the scalability are the most important requirements, followed by the user-friendliness, the diversity of communication protocols and finally, the security and the confidentiality. All these requirements will be taken into account during the elaboration of the SLICES research infrastructure, notably during the design of the architecture.

The research community has given its opinion about the importance of the research areas to be undertaken in the research infrastructure. The proposed architecture is mainly focusing on the advanced wireless research and not on AI/ML. This is normal due to the technological aspects brought by the low networking layers. However, research on AI/ML topics will be supported as applications

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[3] SLICES Deliverable D1.2 – Requirements and needs of scientific communities from ICT-based Research Infrastructures, September 2021.

running on the infrastructure. They are followed by data analytics and Internet of Things, representing the second order of priority. Cellular networks, future network architecture and cloud computing follow data analytics and IoT. Finally, the green and energy efficient ICT and blockchain are the lowest priority topics with a score under 50%. Responding to the usefulness and need of the RI from the research community, the results permit identifying use cases for core network and verticals in function of the usefulness estimated by the researchers. So, the cybersecurity, telecommunications and network technologies, the privacy and the data protection are the topics most useful for the responders in the frame of a dedicated research infrastructure. The new research infrastructure should prioritize these topics and then, take care of the following ones, namely Artificial Intelligence, e-Health, the mobility and the connected vehicles, the clean and sustainable energy. At the end, the responders estimate that the need of RI for domains like smart manufacturing and supply chains, smart farming, nanotechnology and electronic components is relatively less evident at this stage. These current outcomes will be reviewed and continuously monitored during the journey of the project.

The results obtained from the SLICES workshop denote that the participants share the same view on the requirements and need for SLICES-RI as the survey user community. The workshop results highlight the need for repeatability and reproducibility of results across different testbeds, so as to better validate the research contributions. Results shall be made publicly available as data, provided ideally as an Experimental Data as a Service, so as the research community can be highly involved with further extending them and creating further innovations. Finally, the target use-cases and business models applicable to an RI of such a scale as SLICES shall be driven by the expertise provided from industrial users. Therefore, the RI shall be harmonized with existing industry standards and approaches for reaching experimental results, minimizing the gap in the approaches in the general research community and the industrial users.

4. Foundation Principles

The foundation principles will shape and derive the ability to build a distributed RI, where we have to properly articulate the distributed nodes into a centrally controlled and managed infrastructure. We will have to associate various “national” deployments into a single pan-European facility accessible through a single-entry point (e.g., a portal service) with state-of-the-art design tools, taking into consideration best practices and methodologies based on current state of the art and state of practice. This prior work defined the minimum set of functionalities that a test platform has to include in order to be integrated into a global facility, i. e., a common resource description framework, a trusted architecture and a standardized control plane and API. The main finding shows that there exists a broad community of researchers focusing on a wide range of topics from very specific research (wireless protocols) to more global architectural concepts (inter-cloud and Edge, for instance) to disruptive Internet paradigms. The examples of key technologies include (but are not limited to) evolution of 5G towards 6G in the telecommunication sector, evolution of public/private cloud technologies, Internet of Things, Fog/Edge computing, human-centric networking.

The facility should be able to serve this diversity of needs, with the right level of abstraction, providing the ability to access different APIs remotely, fully program the resources and control the entire life-cycle of the experiment. The intended infrastructure shall incorporate recent technologies for deployment automation and continuous improvement, powered by the composable (micro) services platforms, chained to a full industrial-grade experimental environment. The community is asking to constantly keep the facility at the state of the art whilst decreasing the entry cost for an experimenter. Likewise, reproducibility and repeatability of results, decoupled from the platform where they were obtained, is a must and is severely lacking at present. Therefore, SLICES aspires to fill this gap by designing a novel set of services for experimenters that will address repeatability and reproducibility for cutting-edge future Internet research.

From the survey outcome, below capabilities or functionalities are currently missing in terms of ICT research infrastructure:

- 5G and 6G experiments;
- Support for 5G and beyond 5G: It should be possible to create experiments linked to 5G in the research infrastructures;
- Large-scale operational testbed: It should be very similar to real deployments in the industry;
- RI network management: The experimenters should be able to manage the network used for their experiments;
- Openness: using open interfaces between various building blocks of the RI;
- Support for AI and ML: More experiments associated with AI and ML should be realised in research infrastructures;
- Support for cloud, fog and edge computing;
- RI federation: Mainly to ensure the scalability required for some tests;
- Real data: The research infrastructure should provide a catalogue of real data sets to be used in the experiments;
- Traffic generators and simulators: Several responders point out the lack of traffic generators and simulators in the current research infrastructures.

The SLICES design will overcome the challenges of current ICT research infrastructures and will include the above capabilities and functionalities. So, the ideal research infrastructure is dedicated to experiment all the interactions between the cloud, the fog and the edge in a real environment, using the latest communication technologies (e.g., 5G and beyond). The research infrastructure should be sufficiently large and similar to real industrial deployments to conduct very realistic tests. The experimenters should be able to manage the network provided by the research infrastructure and the access to the research infrastructure should be completely open. The RI permits also to use AI and ML for all kinds of experiments, in particular for the interactions with the cloud, the fog, the edge and the network. New tools should be incorporated in the new RI like traffic/usage generators and real data sets. These tools should at the end help the development of AI and ML in experiments. And the scalability should be improved compared to the current testbeds.

The foundation principles of SLICES will provide better exchanges between the industry and the academic world through a permanent dialogue and a market-based access.

The architecture of SLICES has to be designed considering the experimental environment as a fully controllable, programmable and virtualized digital global infrastructure test platform. This architecture will provide high quality experimental services using emerging technologies around the area of digital sciences. The **primary technologies and approaches** to address the requirements for SLICES test-bed can be classified as follows in the next subsections.

4.1. Software Defined Network and Network Function Virtualization

Following the major evolutions of telecommunications networks with the adoption of the internet technology and the emergence of cellular networks, we are now facing a paradigm shift in the way the design and operate digital infrastructures. Indeed, recent advances in networking such as Software Defined Networking (SDN) and Network Function Virtualization (NFV) are changing the way network operators deploy and manage Internet services. SDN and NFV, together or separately, bring to network operators' new opportunities for reducing costs, enhancing network flexibility and scalability, and reducing the time-to-market of new applications and services. They are considered by the 3GPP 5G standardization process as fundamental pillars to support the heterogeneous key performance indicators (KPIs) of the new use cases in a cost-efficient way. On the one hand, SDN introduces a logically centralized controller with a global view of the network state. On the other hand, NFV allows to fully decouple network functions from proprietary appliances and to run them as software applications on general–purpose machines.

SDN is a technology that separates routing control traffic from data traffic, and that allows a centralized software (rather than individually configured parts of specialized hardware) to dynamically control the network. In the 5G ecosystem, the SDN architecture includes 3 different layers:

- A WAN Resource Manager (i.e., SDN application) that represents the functional element that triggers SDN control plane operations. It translates the abstracted view at orchestrator level into a network domain-specific view;
- Two kinds of SDN controllers, one used to configure the core network domain and the other one dedicated to the configuration of the RAN domain;
- A data-plane composed of Core NFV Infrastructure (NFVI), backhaul network, Edge NFVI, fronthaul network, WLAN Access Points and LTE small cells. Those network elements are considered as part of the infrastructure layer;

NFV transforms the way network operators and providers design, manage and deploy their network infrastructure by exploiting virtualization technologies. It enhances the delivery of network services to end users while reducing CAPEX and OPEX. Traditionally, network functions, such as middleboxes have been deployed on vendor-specific hardware and software, implying a heavy cost, important production delays and refraining innovations to deploy new network services. The NFV paradigm advocates the use of standard commercial off-the-shelf (COTS) hardware located in the network and enables deploying new network services rapidly, on an on-demand basis, which provides benefits for both end users and network providers. It is a scalable approach as it gives the operators the ability to scale their network architecture across multiple servers to adapt quickly to the changing needs of their customers. Furthermore, NFV enables configuring hybrid scenarios where functions running on virtualized resources can coexist with those running on physical resources.

4.2. Network Slicing

Another disruptive concept that could help in realizing the 5G vision is network slicing, which allows a single 5G physical network to be segmented into multiple isolated logical networks of varying sizes and structures dedicated to different types of services. It is a multi-tenant virtualization technique in which the various network functionalities are extracted from the hardware and/or software components and then offered in the form of slices to the different users of the infrastructure (tenants). Basically, each slice includes a number of physical resources that are isolated from other slices and provides specific functionalities including RAN and core network. Network slicing aims to offer operators the possibility of creating, in real-time and on-demand, various levels of services for different enterprise verticals, enabling them to customize their operations. In particular, it allows service differentiation with different security requirements and amount of resources. Network slicing requires a continuous reconciliation of customer-centric service level agreements (SLAs) with infrastructure-level network performance capabilities. However, one of the main issues to solve is how to meet the requirements of different verticals over 5G networks.

4.3. Network disaggregation

Legacy aggregated networking devices have been developed and commercialized by vendors for decades. The term aggregation refers here to the vertical integration of software and specialized hardware components, bundled into a proprietary networking device. Network device disaggregation is the ability to source switching hardware and network operating systems separately. The term white box switches refer to switches built on commodity hardware that run different possible Network Operating Systems (NOS). This approach is putting pressure on the legacy aggregated networking vendors, but requires talented developers to build and grow the solution. This concept has been extended to the radio access network: RAN disaggregation was specified by 3GPP and detailed by the Open Networking Foundation (ONF) as an important step allowing for dynamic creation and lifecycle management of use-case optimized network slices. The idea here is to split the RAN protocol stack so that the individual components can be developed independently by different vendors. This horizontal disaggregation also enables distributed deployment of RAN functions in the network.

4.4. Distributed Platform

All the aforementioned techniques SDN/NFV, network slicing and disaggregation can be combined in a distributed platform to test advanced networking scenarios in realistic large-scale environments. This could be done by leveraging virtualized computing and networking resources in a flexible way to provide support for solutions based on the use-case, geography and experimenter choice. In such a distributed platform, the functions of the RAN nodes (the base stations) may be deployed as a "Central Unit", centralizing the packet processing functions and executed as Virtual Network Functions (VNFs) on commodity hardware in edge cloud locations, one or more "distributed units" performing the baseband processing functions as VNFs on commodity hardware with possible hardware acceleration and several "radio units" running the radio functions with specialized hardware on antenna sites. In a more general setting, different functions can be deployed on different sites in the network in order to realize the required flexibility and assess performance of the different split options.

4.5. Control and User-plane Separation

Another vertical disaggregation consists in the separation of Control and User Planes (CUPS). In fact, with the densification of the next generation radio access networks, and the availability of different spectrum bands, it is more and more difficult to optimally allocate radio resources, perform handovers, manage interfaces, and balance load between cells. It is therefore necessary to adopt centralized control of the access network in order to increase system performance. This approach can be realized by decoupling the intelligence from the underlying hardware in all parts of the network.

4.6. Configuration and Orchestration of Experiments

An experiment is composed of a list of steps that include a specific set of tuning parameters for the system components, the configuration parameters for background traffic components, and the deployment and execution of the components to the testbed nodes and network elements.

Orchestration of experiments is thus the process of running the sequence of steps that define the experiment. It is a complex task due to the concurrent, heterogeneous, asynchronous, and prototype-based systems that must be integrated into realistic scenarios to conduct trustable evaluations. For instance, within the NFV context, orchestrating wireless experiments requires deciding among several possible VNF compositions which are the most suitable for each scenario. It is a key process for the right operation of NFV-based environments, since it has a direct impact on the network performance. Furthermore, its complexity is increased in a multi-domain environment because it must be instrumented to collect, analyse and share measurements from multiple locations.

4.7. Data-Storage Design

Data storage is an important feature to support in order to understand how the execution evolves during the experiments that generate detailed log traces with multiple levels of detail. Depending on the type of experiments, logs can be huge and saved locally on the testbed nodes as well as managed by a log collector and for instance saved in a MongoDB database in different locations, e.g., at the network edge infrastructure or in the public cloud.

The aforementioned approaches can be considered as necessary features that the SLICES infrastructure will support in order to fulfil the requirements of a reference architecture. The resulting architecture should allow for innovative solutions for network control to be deployed and tested in a heterogeneous vendor environment. The centralized control approach also allows the design and test of innovative solutions for radio resources management. The distributed platform brings the possibility to integrate performance-based decisions with use-case, geography and experimenter constraints.

5. State of the art for similar ICT platforms

Today's advanced testbed infrastructure is composed of several interconnected networking components and supporting technologies, such as current and next generation core-networks, radio-access-networks, edge-networks and infrastructure, end-devices, incorporating software-defined-networking, network-slicing, management and orchestration, and artificial intelligence frameworks. It is important to note that Open-source platforms will play an important role in this path to develop and utilize testbeds by the research community and will be a critical source to lead research activities for 6G and beyond platforms. SLICES should play a significant role in that domain, being at the front, providing the means to support the design, nicely complementing other approaches.

The requirement analysis from the obtained data from the ICT communities[4] indicated that the research infrastructure should use the latest communication technologies such as 5G and beyond, in a real environment including components deployed at the cloud, the fog and the edge. More realism in the RI is also required by the researchers to ensure experiments closer to the industry; this means that the scalability should be improved compared to the current testbeds. The open access and the configuration of the research infrastructure are very important for the research community. New tools should be incorporated in the new RI like traffic/usage generators and real data sets. These tools should at the end help the development of AI and ML in experiments.

The use cases that emerged from the user demand analysis cover a wide range of applications, but can be separated in two categories: core networking and verticals. The core network encompasses the

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[4] SLICES Deliverable D1.2 – Requirements and needs of scientific communities from ICT-based Research Infrastructures, September 2021.

communications technologies and how the interactions between the components interconnected through these technologies can be realized in an efficient way. Use cases associated with verticals (connected vehicles, smart grid, etc.) should be also supported by the research infrastructure and the underlying network configuration. It means that the new SLICES RI should be able to handle at the same time the generic technologies and their applications in the different ICT domains, taking into account the specific requirements and needs of each use case. The most relevant use cases can be combined. For example, AI and ML are applied in the context of IoT and 5G to optimize the collection and the analysis of data. The network layer can also be better managed using AI and ML in the SDN/NFV deployments. Some other proposed use cases are horizontal and concern energy efficiency, the scalability, the cybersecurity, and the privacy. An indicative list of the main use-cases that need to be supported by the SLICES RI are provided below:

- Optimization done by AI and ML: The dedicated experiments should demonstrate how the AI and ML can optimize the decision making;
- 5G and 6G experiments;
- IoT experiments;
- Cloud, fog, edge computing experiments;
- CO2 reduction, energy efficiency, smart grid;
- SDN/NFV experiments;
- C-V2X and autonomous cars;
- Augmented and Virtual Reality (AR/VR);
- Smart cities;
- Cybersecurity and privacy;
- Distributed infrastructure: How to handle a distributed infrastructure? Real experiments are to be set to have a clear vision for the future distributed infrastructure management;
- Large scale network testing and validation.

The objective of Section 5 is to provide a brief overview of the emerging technologies that could shape the design of future large-scale test platforms, and list some of the major open-source solutions that can be considered while designing SLICES architecture. The key enabling technologies which are most widely supported by various testbed organisations are wireless (5G & beyond, WiFi, LoRa), cloud/edge, IoT, SDN/NFV AI/ML, MANO etc.), wired, and Cloud based (e.g., HPC).

5.1. State of the art for Open-Source platforms for experimentation

In this section we provide an overview of 5G cellular network architectures, as well as their main components and building blocks. Such components are of major interest for a large part of experimenters, as they need to instantiate services on top, or introduce novel functionalities for the network. The components of a 5G network architecture are mentioned below.

5.1.1. 5G Core Network

The Core Network (CN) is the central element of a 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 a cloud-native and service-based-architecture

(SBA). 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.

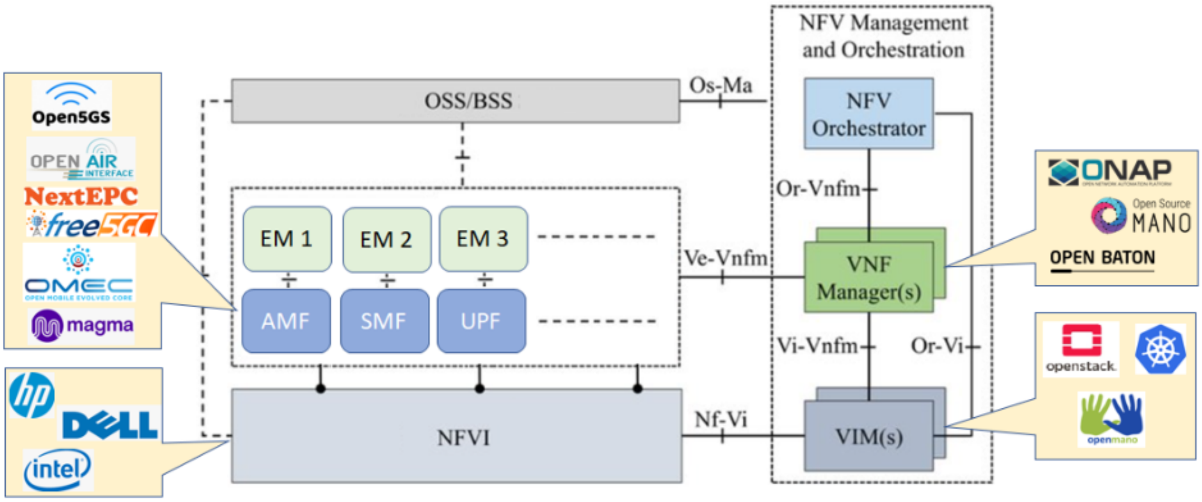

Figure 3: Cloud-native instantiation of the 5G Core Network

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 COTS hardware at the NFV Infrastructure (NFVI) layer. These hardware resources are managed by open-source Virtual Infrastructure Management (VIM) software such as Openstack[5], OpenVIM[6] or Kubernetes[7]. The following table summarizes the available open-source solutions.

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[5] O Sefraoui, M Aissaoui, M Eleuldj, "OpenStack: toward an open-source solution for cloud computing", International Journal of Computer Applications, 55(3), 38-42, 2012.

[6] T Sechkova, M Paolino, D Raho, "Virtualized Infrastructure Managers for Edge Computing: OpenVIM and OpenStack comparison", 2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB). IEEE, 2018. p. 1-6.

[7] D. Bernstein, "Containers and Cloud: From LXC to Docker to Kubernetes," in IEEE Cloud Computing, vol. 1, no. 3, pp. 81-84, Sept. 2014, doi: 10.1109/MCC.2014.51.

Table 1: Open-source 4G and 5G Core Networks

Name	Network domain	Description	References/links
Open5GS	CN	5G/LTE software	https://open5gs.org/
OpenAirInterace CN (OAI-CN)	CN	5G/LTE software	https://openairinterface.org/
NextEPC	CN	LTE EPC software	https://nextepc.org/
srsEPC	CN	LTE EPC software	https://github.com/srsran/srsRAN
Free5GC	CN	5G software	https://www.free5gc.org/
OMEC	CN	LTE EPC software	https://opennetworking.org/omec/
Magma	CN	LTE software	https://docs.magmacore.org/docs/basics/introduction.html

5.1.2. 5G and beyond RAN and Open-RAN platforms

5G RAN has evolved from 4G with significant improvements in capabilities and functionalities. With the usage of a wider range of carrier frequencies that includes part of millimeter Wave (mmWave) frequency spectrum, and flexible frame structure with variable number of symbols per subframe, 5G NR can utilize up to 400MHz of bandwidth per carrier. Several platforms exist that implement the 5G stack fully in software. By making use of Software Defined Radios (SDR), such platforms 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), and 2) the srsRAN platform. 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[8/9]) 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), 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. The NG-RAN Network Resource Manager (NRM) was designed to enable "separate" provisioning of CU, DU, CU-CP, CU-UP. Below Figure 4 (TS 28.541[10]) shows the "containment" relations between the managed objects in the gNB NRM. The gNB NRM is applicable to all deployment scenarios including monolithic gNB.

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[8] 3GPP TR 38.801 "Technical Specification Group Radio Access Network; Study on new radio access technology: Radio access architecture and interfaces".

[9] L. M. P. Larsen, A. Checko and H. L. Christiansen, "A Survey of the Functional Splits Proposed for 5G Mobile Crosshaul Networks," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 146-172, Firstquarter 2019, doi: 10.1109/COMST.2018.2868805.

[10] 3GPP TS 28.541 Management and orchestration; 5G Network Resource Model (NRM); Stage 2 and Stage 3, V15.1.0.

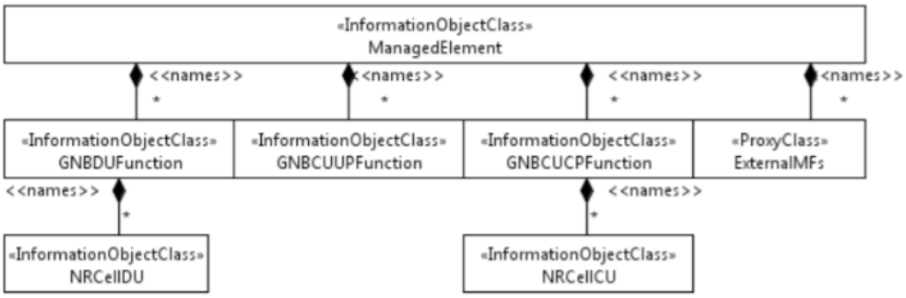

Figure 4: Network Resource Manager relationships in 5G-NR networks

Possible options for decomposition of the RAN environment are studied, resulting in the identification of eight options (3GPP Options 1-8)[11]/[12]. Building on top of the different disaggregation options, and especially delving into the CP/UP separation (CUPS), Open RAN (O-RAN) 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).

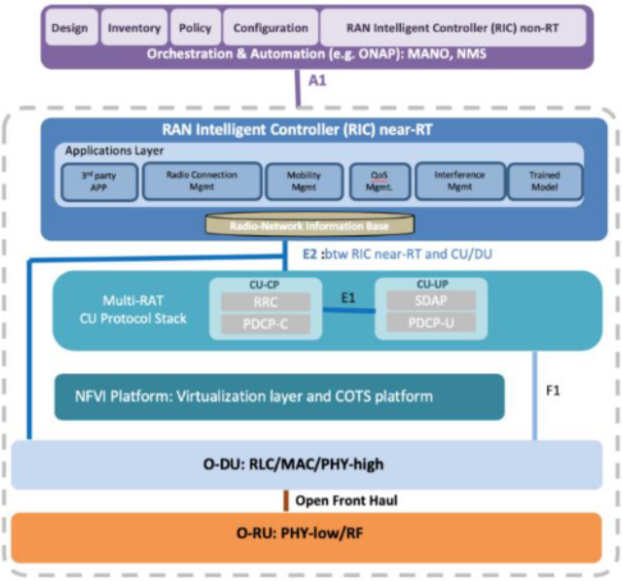

Figure 5: Open-RAN deployment and programmable interfaces

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[11] 3GPP TR 38.801 "Technical Specification Group Radio Access Network; Study on new radio access technology: Radio access architecture and interfaces".

[12] L. M. P. Larsen, A. Checko and H. L. Christiansen, "A Survey of the Functional Splits Proposed for 5G Mobile Crosshaul Networks," in IEEE Communications Surveys & Tutorials, vol. 21, no. 1, pp. 146-172, Firstquarter 2019, doi: 10.1109/COMST.2018.2868805.

It is reasonable to presume that the information model in O-RAN will be the extension of the 3GPP NRM presented at Figure 5, with additional Managed Element object classes for RIC and possibly with extension of the information models for CU, CU-CP and DU. 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 (also called as FlexRAN[13]), developed by Eurecom for OAI[14], allows the programmability of the OAI RAN in real-time, by exposing a REST interface. The interface can be used for retrieving statistics from the network as well, allowing for the advanced monitoring of the RAN in real-time. 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[15] platform 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) 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[16] 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, CORD and OMEC, for providing a fully-fledged solution for the deployment of the cellular network in an end-to-end manner.

Table 2 lists out different open-source frameworks and projects that can be utilized to implement RAN and MEC infrastructure.

Table 2: Open-source RAN implementations

Name	Network domain	Description	References/links
OAI	RAN	eNodeB, gNodeB and UE software	https://openairinterface.org/
srsLTE	RAN	eNodeB, gNodeB and UE software	https://github.com/srsran/srsRAN
SD-RAN	RAN and Edge	Framework for RAN components and RAN intelligence controller	https://opennetworking.org/sd-ran/
AETHER	RAN and Edge	5G/LTE, Edge-Cloud-as-a-Service (ECaaS)	https://opennetworking.org/aether/
FlexRIC	RAN	Real-time controller for software-defined RAN	https://mosaic5g.io/flexran/

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[13] OpenAirInterface FlexRIC, [Online] https://openairinterface.org/mosaic5g/, [Last accessed 20 September 2021]

[14] Navid Nikaein, Mahesh K. Marina, Saravana Manickam, Alex Dawson, Raymond Knopp, and Christian Bonnet. 2014. OpenAirInterface: A Flexible Platform for 5G Research. SIGCOMM Comput. Commun. Rev. 44, 5 (October 2014), 33–38. DOI: https://doi.org/10.1145/2677046.2677053, [Last accessed 20 September 2021].

[15] ONF SD-RAN, [Online] https://opennetworking.org/sd-ran/, [Last accessed 20 September 2021].

[16] ONF AETHER, [Online] https://opennetworking.org/aether/, [Last accessed 20 September 2021].

5.1.3. Softwarization and Software-defined Networking

SDN leverages 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. The main idea behind SDN is to separate the network's control and user planes which enables network control to become directly programmable which makes its ability to provide network virtualization, automation, and create new services on top of virtualized resources. In addition, 5G SDN network programmability will enable new business models and will drive revenue growth. The 5G SDN architecture will be dynamic, highly manageable, and cost-effective, making it perfect for the dynamic, high-bandwidth nature of 5G use cases. There are plethora of open source SDN solutions for mobile networks, these are Open Networking Operating System (ONOS), Central Office Rearchitectured as a Datacenter (CORD), O-RAN, Open Network Automation Platform (ONAP), AETHER and SD-RAN.

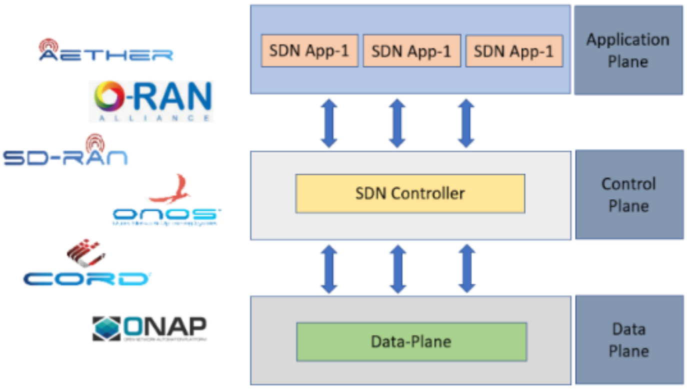

Figure 6: Key ONF SDN platforms

Management and Orchestration (MANO) frameworks build on top of the network programmability and extended softwarization for network functions, and are being used to meet the agile and flexible management solutions for virtual network services in the 5G and beyond era. There are popular open source NFV MANO projects namely OSM[17] and ONAP[18].

ETSI introduces the NFV MANO architecture[19], which comprises three main functional blocks, as further detailed below. MANO is an important component in managing the lifecycle of VNFs (including CFNs and PNFs) and hence managing overall infrastructure with agility and flexibility. The NFV MANO system entities, such as the Network Function Virtualization Orchestrator (NFVO), the Virtual Network Function Manager (VNFM) and the Virtual Infrastructure Manager (VIM), coordinate with each other over well-defined reference points to manage entities such as Network Functions Virtualization Infrastructure (NFVI), VNFs, CNFs, Physical Network Functions (PNFs) and Network Services (NSs). In the context of research testbeds, MANO framework provides efficiency by providing network functions to several experimenters (tenants/users) at the same time. Figure 7 illustrates these blocks with the reference points that connect them.

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[17] ETSI Open Source MANO (OSM), [Online] https://osm.etsi.org/, [Last accessed 20 September 2021].
[18] Open Network Automation Platform (ONAP), [Online] https://www.onap.org/, [Last accessed 20 September 2021].
[19] M. Ersue, "ETSI NFV management and orchestration-An overview". Presentation at the IETF, 88, 2013.

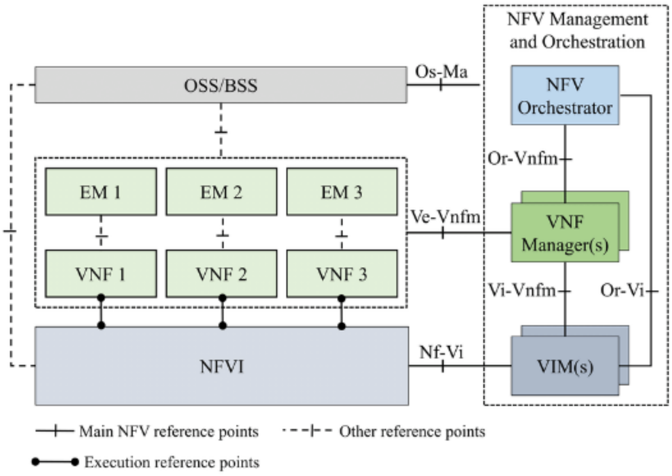

Figure 7: ETSI ENF-MANO architecture

The three main components of the NFV-MANO architecture are detailed below:

1. **Virtualized Infrastructure Manager (VIM)** performs controlling mechanisms for the NFV Infrastructure (NFVI) resources within an infrastructure provider. VIM is also responsible for receiving fault measurement and performance information of NFVI resources. Consequently, VIM can supervise NFVI resources allocation to the available VNFs;
2. **VNF Manager (VNFM)** conducts one or several VNFs and does the lifecycle management of VNFs. VNF lifecycle management involves establishing/configuring, preserving, and terminating VNFs;
3. **NFV Orchestrator (NFVO)** implements resource and service orchestration in the network. NFVO is split up into Resource Orchestrator (RO) and Network Service Orchestrator (NSO). First, the RO collects the current information regarding possible physical and virtual resources of NFVI through the VIM. Following this, the NSO applies a complete lifecycle management of multiple network services. In this way, the NFVO keeps updating the information about the available VNFs running on top of NFVI. As a result, the NFVO can initiate multiple network services. As part of the lifecycle management, the NFVO can also terminate a network service whenever no longer a service request is received for that specific service. In several solutions, NFVO and VNFM are integrated into the MANO section.

Different frameworks have been developed in accordance with the NFV-MANO architecture, mainly aiming at providing fully-fledged solutions for the virtualized services lifecycle management. Such frameworks include multi-tenancy aspects, providing isolated slices of the infrastructure to each tenant, initially aiming at the execution of different vertical services on top of shared 5G infrastructure. Such multi-tenancy aspects and isolation of traffic flows between each tenant of the infrastructure can be directly projected to the use of the same testbed infrastructure from multiple users concurrently, while providing guarantees for their performance. In the following table, we list the different open-source MANO frameworks that are currently widely utilized by the researchers as well as industry players like AT&T[20], Telefonica[21] and others. Table 3 below is presented to showcase the comparison between major open-source frameworks for VNF lifecycle management in terms of capabilities, multi-tenancy support, compliance or not with the NFV-MANO architecture, etc.

Table 3: MANO framework comparison

Management and Orchestration framework	Installation Ease	Resource Footprint	Multi VIM support	VNF, CNF & PNF Support	Multi-user Support (multi-tenancy)	Multi-site Support (multi-domain)	Network Slicing support	NFV-MANO compliance
OSM	✓	High	✓	✓	✓	✓	✓	✓
ONAP	×	High	✓	✓	✓	✓	✓	Partial
CORD	✓	Medium	×	✓	×	✓	✓	×
OpenBaton	✓	Medium	✓	✓	✓	×	✓	✓

5.1.4. Containerization

In the NFV world, containers are an emerging technology and the paradigm is standing between virtual machines and containers now. 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, 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. As shown in figure below, each VM includes a full copy of an operating system, the application, necessary binaries and libraries - taking up tens of GBs. VMs can be slow to boot, while Containers share the OS kernel with other containers, each running as isolated processes in user space. Containers take up less space than VMs (container images are typically tens of MBs in size), and thus handle more applications. Because they do not include the operating system, containers require fewer system resources and less overhead. They also tend to be faster to start/stop and they are ultra-portable across environments.

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[20] AT&T, “7 Principles of AT&T’s Network Transformation Disaggregation, Cloud, and Intelligent SDN”, Q2 2020, [Online] https://about.att.com/content/dam/snrdocs/7_Tenets_of_ATTs_Network_Transformation_White_Paper.pdf, [Last accessed 20 September 2021].

[21] Telefónica NFV reference lab releases OpenMANO NFV orchestration stack, [Online] https://www.telefonica.com/en/web/press-office/-/telefonica-nfv-reference-lab-releases-openmano-nfv-orchestration-stack, [Last accessed 20 September 2021].

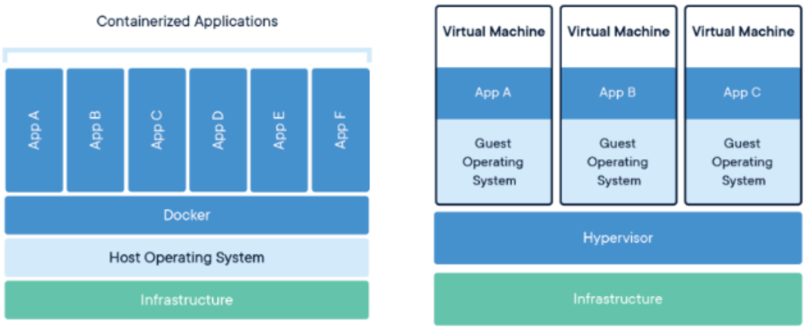

Figure 8: Container vs. Virtual Machines

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, that can deploy the services directly on bare-metal. Integration with the aforementioned NFVO tools like e.g., OSM is also possible. Open-source projects are moving towards cloud-native design, but until they become a reality, a mix of VM's and CNF's could be 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. Further, disaggregating RAN software and hardware in Cloud RAN has the potential of independent innovation on software and hardware. However, simply forklifting existing 5G RAN software to a COTS platform is not enough. To realize the value of Cloud RAN, one needs to embrace cloud native architecture. Cloud native architecture facilitates RAN functions to be realized as microservices in containers over bare metal servers, supported by technologies such as Kubernetes. Below table lists some of the widely used open-source container solutions.

Table 4: Container Orchestration solutions

Container Solution	Description	References/links
Kubernetes	Developed by Google, most widely used	https://kubernetes.io/
Docker	Software platform that allows you to build, test, and deploy applications quickly	https://www.docker.com/
Openshift	Container management tool created by RedHat	https://www.redhat.com/en/technologies/cloud-computing/openshift
Apache Mesos	Apache Mesos is an open-source cluster management system	http://mesos.apache.org/

There are some complexities about containers such as Security and achieving high performance in processing and networking. As containers share the same OS (within a compute node), it provides a less secure environment than Virtual machines (Openstack). High-Performance Networking Options are difficult to configure and operate in containers. There are some popular techniques which enhance the performance of applications running in virtual machines (Openstack) are either new features or are partially usable by containers. These techniques are CPU-pinning, NUMA-aware scheduling, HugePages, Topology Manager, CPU manager, and many other open-source solutions which are starting to emerge in the container world. However, many of these are still early in their maturity and are not entirely ready for large-scale production use. The authors in [22] highlight some issues and limitations in Kubernetes and proposes a couple of solutions to enhance performance by resource isolation.

5.2. State of the art on open testbeds

In this section, we provide a brief description of current testbeds that are available for experimentation with the aforementioned state of the art technologies.

5.2.1. 5G-EVE

The 5G EVE[23] concept is based on further developing and interconnecting existing European sites to form a unique 5G end-to-end (E2E) facility. The four interworking sites are located in France, Greece, Italy and Spain and provide both indoor and outdoor facilities. The four sites are interconnected to provide a seamless single platform experience for experimenters from vertical industries and the 5G EVE platform has enabled 12 vertical use cases, including the experimental validation of services and applications by verticals.

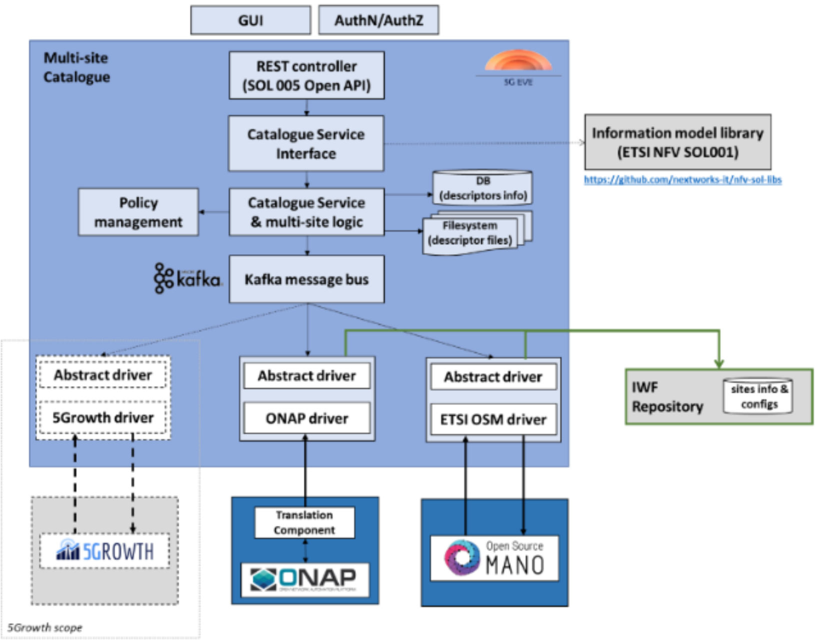

Figure 9: The 5G-EVE Reference Architecture

The 5G-EVE facility is allowing the deployment of 5G vertical services across multiple sites concurrently. Each site, has its own local orchestrator platform, which exposes standardized APIs to the central 5G-EVE entity. A multi-site catalogue service exists that glues the operations between a

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[22] B. Chun, J. Ha, S. Oh, H. Cho and M. Jeong, "Kubernetes Enhancement for 5G NFV Infrastructure," 2019 International Conference on Information and Communication Technology Convergence (ICTC), 2019, pp. 1327-1329, doi: 10.1109/ICTC46691.2019.8939817.

[23] 5G European Validation platform for Extensive trials (5G-EVE), [Online] https://www.5g-eve.eu/, [Last accessed 20 September 2021].

portal service and the underlying hardware architecture. These two features (multi-site catalogue, exposing standardized APIs) allow each new per-site NFVO driver instance automatically created when the Multi-site Catalogue application starts, to retrieve the proper information to access the given local site catalogue (e.g., in terms of credentials, tenants, URLs, endpoints) and automatically configure the NFVO driver itself. More information about the logical structure of the cross-facility experimentation stack is provided in [24].

5.2.2. 5G-VINNI

5G-VINNI's[25] main objective is to provide and enable the longer term evolution of an end-to-end (E2E) 5G facility demonstrating that the key 5G PPP network KPIs can be met, accessed and used by vertical industries to set up research trials, to further validate core 5G KPIs in the context of concurrent usages by multiple users, by serving end users with flexible and reliable services ranging from low bit rate high latency services to high bitrate low latency services and everything in between. 5G-VINNI adopts Network Slice as a Service (NSaaS) delivery model to offer customised service experience to verticals, basing its architecture on guidelines from telecom industry organisations and the normative specifications from standards bodies to ensure interoperability and reproducibility. For validating the NSaaS model, 5G-VINNI has assembled an end-to-end facility with the latest 5G technologies for radio access, backhaul, core networks, leveraging the most advanced virtualisation technologies and optimisation algorithms to test the model with demanding vertical sector driven applications and services. The 5G-VINNI facility site ecosystem is modular. This modularity guarantees the highest degrees of freedom of both 5G-VINNI facility site configurations and facility interworking. The conceptual E2E facility architecture is organised in three layers, as defined in the 5G PPP Architecture white paper, which are the Service layer, the Network layer and Resources & Functional layer.

Figure 10: 5G-VINNI multi-domain communication

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[24] 5G-EVE: 5G European Validation platform for Extensive trials D2.3 Final 5G -EVE end to end facility description, https://zenodo.org/record/4964933#.YT83350zYuU, [Last accessed 20 September 2021].

[25] 5G Verticals Innocation Infrastructure (5G-VINNI), [Online] https://www.5g-vinni.eu/, [Last accessed 20 September 2021].

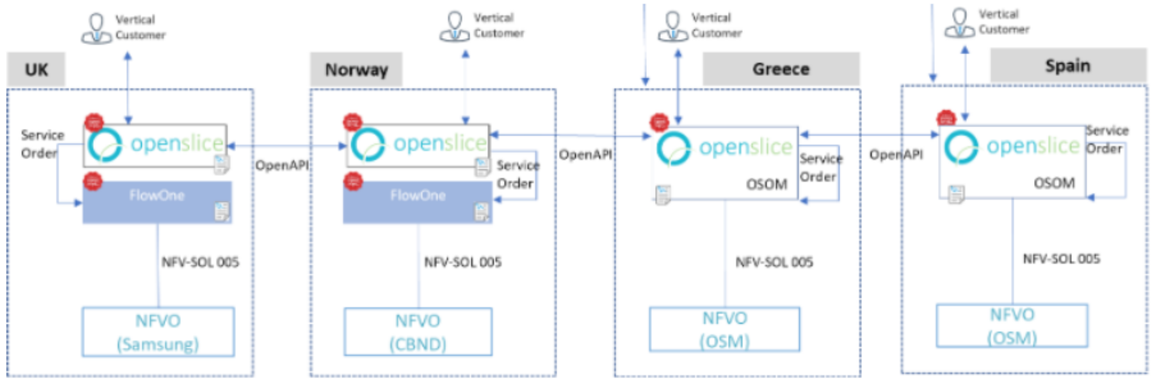

Figure 11: 5G-VINNI Reference Architecture

5G-VINNI assumes sites that are compatible with the NFV-MANO architecture. Towards enabling orchestration and deployment of services across different sites, 5G-VINNI have developed Openslice[26]; Openslice is a prototype open source, operations support system. It supports VNF/NSD onboarding to OpenSourceMANO (OSM) and NSD deployment management. It exposes a multi-site service catalogue, and can communicate with the SOL005[27] interface with the sites that are managed through it.

5.2.3. 5GENESIS

The main scope of the 5GENESIS[28] project is to allow researchers to run from remote experiments on the several testbeds that the project coordinates, thanks to the so called 5GENESIS Architecture. In order to do so, an experimenter can access a web interface called Portal, or use a non-graphical OPEN API. Figure 12 shows the three layers, each one composed of several components that constitute the 5GENESIS Architecture: the Coordination Layer, the Management and Orchestration Layer (MANO) and the different underlying Infrastructures.

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[26] Openslice, [Online] http://openslice.io/, https://github.com/openslice, [Last accessed 20 September 2021].

[27] ETSI GS NFV-SOL 005: "Network Functions Virtualisation (NFV) Release 2; Protocols and Data Models; RESTful protocols specification for the Os-Ma-nfvo Reference Point".

[28] 5th Generation End-to-end Network, Experimentation, System Integration and Showcasing (5GENESIS), [Online] https://5genesis.eu/, [Last accessed 20 September 2021].

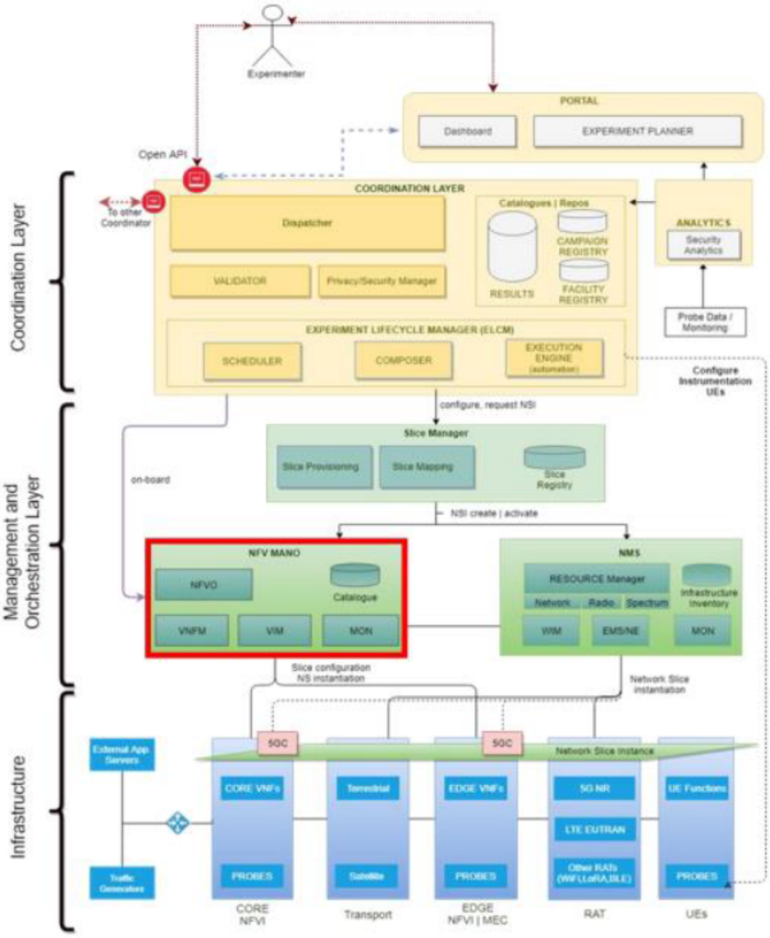

Figure 12: 5GENESIS Reference architecture

5GENESIS adopts the NFV MANO architecture. It allows flexible on-boarding, sitting between a Slice Manager and the physical infrastructure, solving the problems associated with the rapid span up of network components. In 5GENESIS, this module holds the VNF and NS catalogues, the NFVO, the VNFM and the VIM. Those components allow the management of the main datacentres and optionally, edge infrastructure. Besides a monitoring tool to gather information and statistics about the lifecycle of the network services. Some platforms include an edge infrastructure aside from the core NFVI, which according to ETSI GS MEC 003[29], can be managed by a centralised NFVO without the need of having a secondary edge orchestrator managing the edge infrastructure. The 5GENESIS Network Management System (NMS) is, on command by the Slice Manager, addressing the network configuration external to the services deployed by the NFVO. It is a common component to all the platforms but each one of them has different requirements and configurations. This is due to the fact that each platform implements completely different infrastructures.

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[29] Several authors, "Mobile-Edge Computing – Introductory Technical White Paper," Sept., 2014. [Online] https://portal.etsi.org/portals/0/tbpages/mec/docs/mobile-edge_computing_-_introductory_technical_white_paper_v1%2018-09-14.pdf, [Last accessed 20 September 2021].

5.2.4. Fed4FIRE/Fed4FIRE+

Fed4FIRE+[30] is a project under the European Union's Programme Horizon 2020, offering the largest federation worldwide of Next Generation Internet (NGI) testbeds, which provide open, accessible and reliable facilities supporting a wide variety of different research and innovation communities and initiatives in Europe, including the 5G-PPP projects and initiatives. Although the approach for federating the heterogeneous testbeds is looser than the previously mentioned efforts, similar experiment lifecycle management and workflow tools exist as critical components that enable the testbed federation.

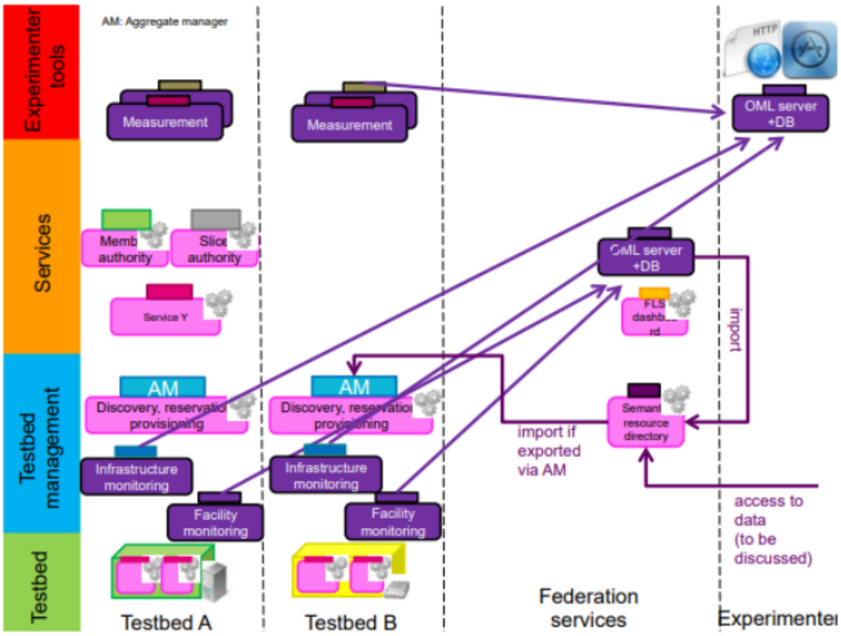

Figure 13: Fed4FIRE Reference architecture

Towards enabling the federation and ease of experimentation, Fed4FIRE has implemented over the past 10 years several tools that either manage user access, or enable testbed access to the infrastructure. Integral parts are the portal or other graphical interfaces (e.g., JFed[31]) that enable the access/experiment planning prior to starting the experiment. The experimenters can select the resources from testbeds within the federation, and plan the interconnection of their nodes based on their needs. This process is based on brokers that are running on each testbed, allowing the advertisement, leasing/releasing the resources of each testbed during an experiment round. For the communication of the different testbeds, the Slice Federation Architecture (SFA)[32] protocol is used. Through this process, the experimenters get full access to the deployed nodes, and can use several other tools provided by the federation for orchestrating their experiment.

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[30] Federation for FIRE+ (Fed4FIRE+), [Online] https://www.fed4fire.eu/, [Last accessed 20 September 2021].
[31] B. Vermeulen, W. Van de Meerssche, T. Walcarius, (2014, March). "jfed toolkit, fed4fire, federation". In GENI engineering conference (Vol. 19), 2014.
[32] Peterson, L. (2010). Slice-based federation architecture. http://groups.geni.net/geni/wiki/SliceFedArch, [Last accessed 20 September 2021].

5.2.5. NSF PAWR

The Platforms for Advanced Wireless Research Program (PAWR)[33] is enabling experimental exploration of new wireless devices, communication techniques, networks, systems, and services. Two are the current platforms offered in PAWR, the Powder-Renew and the COSMOS testbeds.

Powder-Renew

The POWDER-RENEW project[34] is a collaboration between the University of Utah, Rice University and Salt Lake City, with broad support from community, municipal and state leadership. The POWDER advanced wireless research platform will cover 2.3 square miles of the University of Utah campus, 1.2 square miles of downtown Salt Lake City, and a two-mile corridor in between, reaching a potential population of 40,000 people.

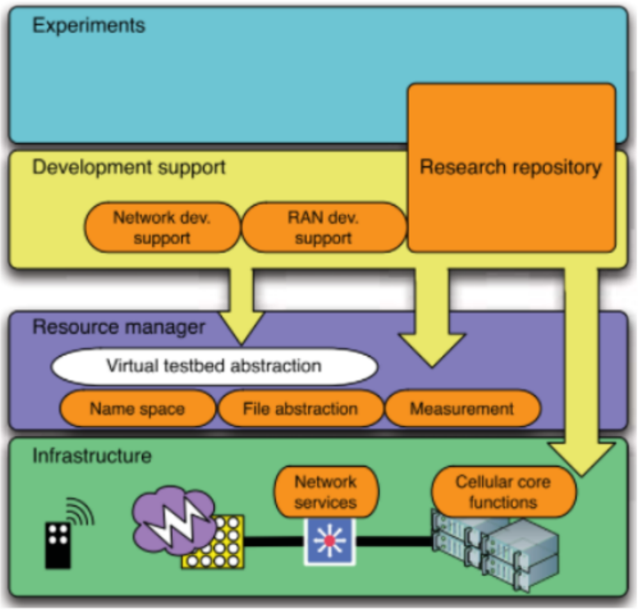

Figure 14: POWDER-RENEW Reference architecture

For managing experiments within POWDER-RENEW, the GENI (Global Environment for Network Innovations)[35] APIs are used. GENI provides a virtual laboratory for networking and distributed systems research and education. It is well suited for exploring networks at scale, thereby promoting innovations in network science, security, services and applications. GENI allows experimenters to:

- Obtain compute resources from locations around the United States;
- Connect compute resources using Layer 2 networks in topologies best suited to their experiments;
- Install custom software or even custom operating systems on these compute resources;
- Control how network switches in their experiment handle traffic flows;

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[33] Platforms for Advanced Wireless Research (PAWR), [Online] https://advancedwireless.org, [Last accessed 20 September 2021].
[34] POWDER-RENEW, [Online] https://powderwireless.net/, [Last accessed 20 September 2021].
[35] R. McGeer, et al. "The GENI book", Springer International Publishing, 2016.

- Run their own Layer 3 and above protocols by installing protocol software in their compute resources and by providing flow controllers for their switches.

GENI APIs are similar to the Fed4FIRE/Fed4FIRE+ APIs in Europe, as they implement the SFA protocol for discovering resources within the federation, and enabling access to experimental resources.

COSMOS

COSMOS[36] is partnering with New York City, Silicon Harlem, City College of New York, University of Arizona and IBM, to bring this advanced wireless testbed to life in New York City. The testbed will cover 1 square mile in a vibrant, densely-populated neighbourhood in West Harlem. The technical focus of the COSMOS platform is on ultra-high-bandwidth and low-latency wireless communications, with tightly coupled edge computing, a type of cloud computing enabling data processing at the edge of the network.

Researchers are able to run experiments remotely on the COSMOS testbed by logging into a web-based portal[37], which provides various facilities for experiment execution, measurements, and data collection. The portal is based on the GENI specifications, and thus is using the SFA protocol for advertising/leasing/releasing resources from the testbed.

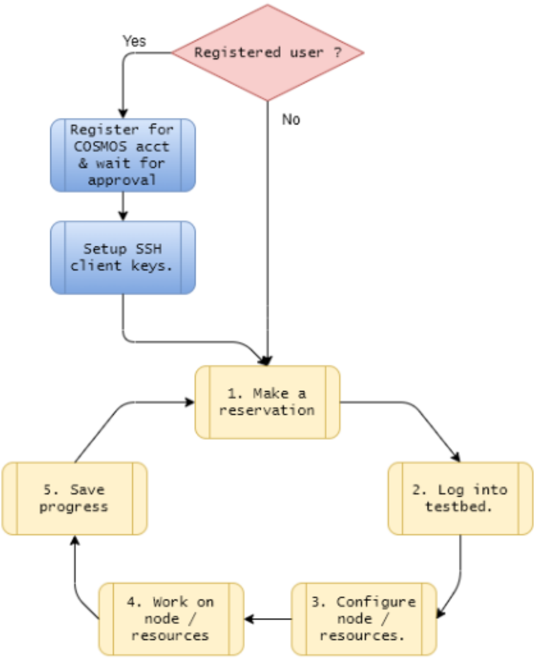

Figure 15: COSMOS testbed experimentation process

The COSMOS testbed is closely collaborating with the Orbit Wireless Lab (OWL)[38], located at Rutgers State University of New Jersey. The lab provides high-end hardware resources, including wireless

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[36] Cloud Enhanced Open Software Defined Mobile Wireless Testbed for City-Scale Deployment (COSMOS), [Online] https://www.cosmos-lab.org, [Last accessed 20 September 2021].

[37] COSMOS Portal for experiments, [Online] https://www.cosmos-lab.org/portal-2/, [Last accessed 20 September 2021].

[38] Open Wireless Lab (OWL), [Online] https://wiki.onap.org/display/DW/Open+Wireless+Lab?src=contextnavpagetreemode, [Last accessed 20 September 2021].

transport devices, distributed antenna systems, high-end switches, and several communication networks for Control, Data, Devices, Openstack, Kubernetes, ONAP. The testbed is providing access through GENI credentials to users, and allows them to deploy experiments using the ONAP platform. The testbed maintains strong relationships with different communities, like ONAP, O-RAN Alliance, IEEE, O-RAN-SC[39], ONF, and is used as the state-of-the-art platform for developing and experimenting with several emerging concepts.

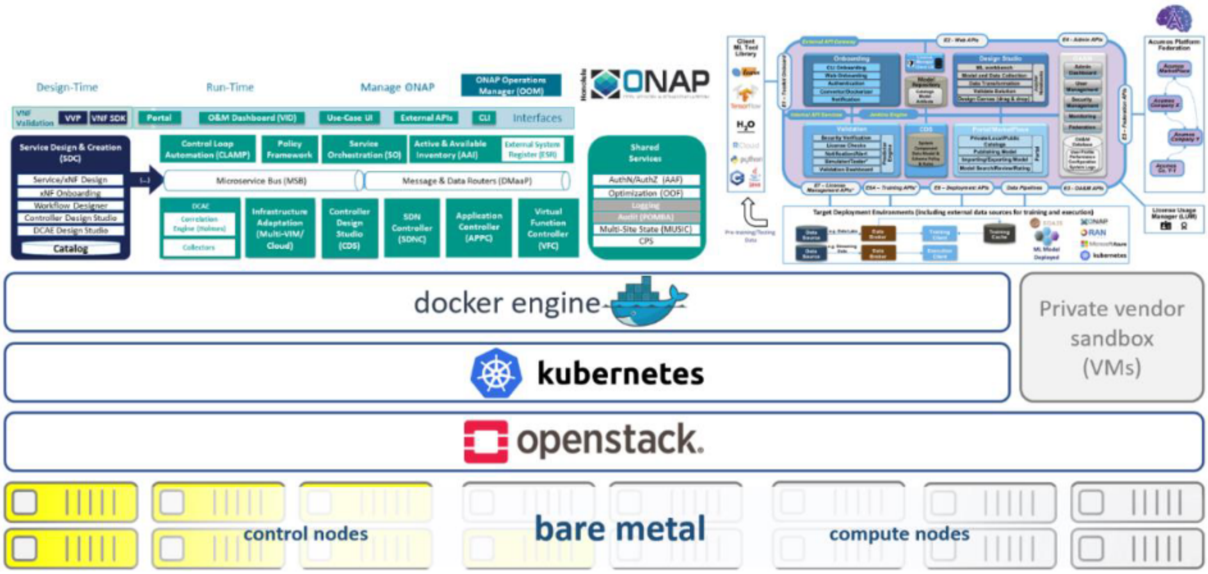

Figure 16: OWL (part of COSMOS) reference architecture

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[39] The O-RAN Software Community, [Online] https://docs.o-ran-sc.org/en/latest/, [Last accessed 20 September 2021].

6. Architecture Guidelines for SLICES

6.1. Hardware Architecture

The purpose of this section is to provide initial guidelines on the various hardware building blocks for different types SLICES facilities and can be categorized into four basic sub-systems:

- Inter-Facility Interconnections and Intra-Facility Switching Fabric;
- Real-time and Non-real-time Computing;
- Radio Infrastructure;
- End-user devices.

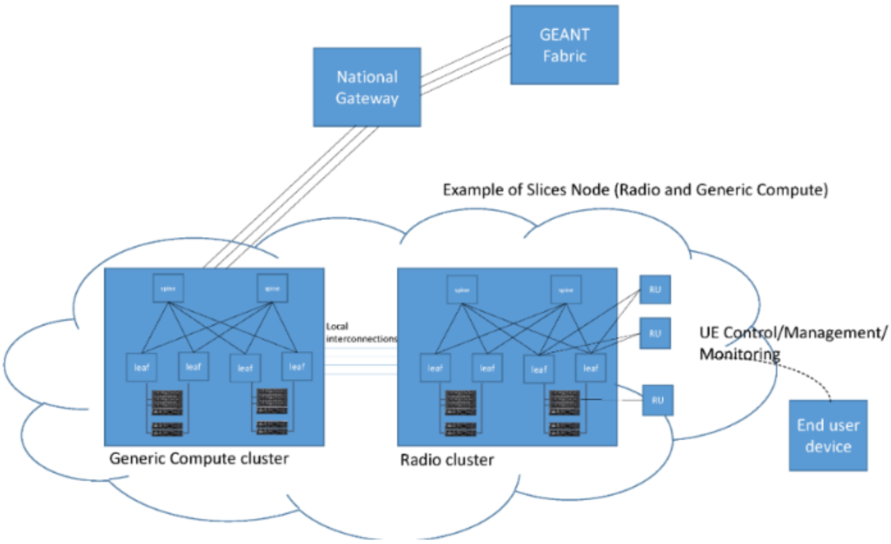

Figure 17: A high-level view of a SLICES node from an equipment standpoint

An example SLICES node is shown above. It comprises two interconnected clusters in the same geographic region, one of which is equipped with radio-units and the other is a more generic computing platform. The left cluster has a long-distance interconnection with the national gateway, which itself is interconnected with the GEANT fabric and the rest of the SLICES network. In the following subsections we provide some initial guidelines for the architecture of the various components.

As a general rule for hardware and network topologies, SLICES nodes should aim to mutualize as much as possible the types of computing and networking equipment in order to reuse deployment and configuration methods and to be able to share and establish common best practices. This will follow the spirit of similar large-scale platform projects such as Linux Networking Foundation OPNFV, Cloud-Native Computing Foundation and the Open Compute Foundation[40].

6.1.1. Interconnections and Switching Fabric

SLICES nodes will require varying degrees of networking capacity as a function of their role in the overall network which, in turn, will influence the dimensioning of the interconnections with the overall

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[40] Open Compute Project (OCP), [Online] https://www.opencompute.org/projects/networking, [Last accessed 20 September 2021].

SLICES infrastructure. The characteristics of the Interconnections (e.g., throughput, latency) of a site will clearly depend on the services provided by the site. For instance, sites offering 5G or later 6G radio-access network services, or even user-plane core network will typically require strong interconnections to GEANT via their national gateway, for instance 10-100 Gbit/s. Sites providing Data Processing services (e.g., IoT, data analytics, etc.) may have various requirements depending on the nature and location of the devices producing the data. Similarly local interconnections in some sites may require very high-throughput/low-latency optical links over short to medium distances (up to 10 km). An example would be the interconnection between INRIA and EURECOM in Sophia Antipolis which has been dimensioned for 400 Gbit/s over the 1.5 km distance between the two clusters. Such interconnections will allow for flexible use of computing resources between clusters of a particular site and even across sites within SLICES in some cases.

Within clusters, sites with high-capacity computing should aim to use state-of-the-art switching fabric, for instance leaf-spine switching topologies with link-aggregation (LACP) to provide resilience in the event of equipment malfunction. Good initial guidelines can be found in the documents of the networking group of the Open-Compute Project (OCP)[41] regarding switching fabric for high-capacity computing clusters. Generally-speaking, the switching fabric should make use of open tools for whitebox switches (e.g., HW support for OpenFlow API, CumulusOS[42]), potentially P4-based[43] or at the very least Linux-based OS for SDN support in the switching fabric. Some sites may allow for experimental deployment of software for a subset of the switching fabric to allow for low-level switching/routing experiments in the facility.

Certain sites aiming to experiment with accurate time synchronization protocols (e.g., IEEE1588v2[44]) for emerging time-sensitive networking applications should design switching fabric with appropriate protocols and network interface cards (NIC) to accommodate these less generic requirements. In addition, provisioning sources for synchronization (GPS, atomic clocks, etc.) should be considered.

6.1.2. Real-time and Non-Real-Time Computing

Computing platforms will generally be a combination of generic compute (i.e., Intel or ARM-based architecture) servers running some form of Linux combined with a virtualization/containerization layer. The virtualization/containerization is very likely a flavour of Kubernetes (k8s) at the onset of SLICES. Certain sites with real-time requirements (e.g., radio processing clusters or real-time edge computing) will have certain compute nodes operating with real-time operations. SLICES should aim to use Linux-based variants in these cases (i.e., real-time extensions to the Linux kernel). Some k8s variants like RedHat Openshift[45] provide support for real-time nodes. As a general rule, SLICES should aim to remain generic and use non-commercial versions of Linux and the virtualization or containerization layer, and ultimately maintain a few possibilities for the benefit of all SLICES sites. Some sites may have specific requirements to use commercial versions for parts of their clusters, in particular if real-time services are required or in order to support certain commercial software

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[41] Open Compute Project (OCP), [Online] https://www.opencompute.org/projects/networking, [Last accessed 20 September 2021].

[42] NVIDIA Cumulus Linux, an Open Network Operating System, [Online] https://www.nvidia.com/en-us/networking/ethernet-switching/cumulus-linux/, [Last accessed 20 September 2021].

[43] Pat Bosshart, Dan Daly, Glen Gibb, Martin Izzard, Nick McKeown, Jennifer Rexford, Cole Schlesinger, Dan Talayco, Amin Vahdat, George Varghese, and David Walker. 2014. P4: programming protocol-independent packet processors. SIGCOMM Comput. Commun. Rev. **44**, 3 (July 2014), 87–95. DOI: https://doi.org/10.1145/2656877.2656890, [Last accessed 20 September 2021].

[44] E. Shereen, F. Bitard, G. Dán, T. Sel and S. Fries, "Next Steps in Security for Time Synchronization: Experiences from implementing IEEE 1588 v2.1," 2019 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), 2019, pp. 1-6, doi: 10.1109/ISPCS.2019.8886641.

[45] RedHat Openshift, [Online] https://docs.openshift.com/, [Last accessed 20 September 2021].

packages. Some sites will complement generic compute with specific hardware acceleration services via FPGA or GPU-based extensions. Care should be taken that these hardware acceleration services integrate well with the Virtualization/Containerization framework used in SLICES.

6.1.3. Radio Infrastructure

We envisage three main types of radio infrastructure elements that can be added to a SLICES site. Firstly, a complete radio-access solution (e.g., eNB/gNB, WiFi AP, LoRa gateway, etc.) connected via Ethernet to the switching fabric of the site which does not use the computing facility to implement the radio-access protocols. Secondly, an Ethernet-based (or potentially CPRI-based[46]) radio unit that interfaces either with the switching fabric and can be accessed from multiple nodes in the cluster or in a point-to-point fashion with a particular computing node in the cluster comprising specific fronthaul NICs. These two cases are shown in Figure 17. Here the radio-units are used in conjunction with radio-access processing running on the cluster. Typically, these nodes implement an Ethernet-based fronthaul protocol such as UHD[47](for National Instruments USRP N or X series devices)[48], eCPRI/CPRI for devices from companies such as AW2S[49], O-RAN fronthaul for radio-units from various suppliers. In general, SLICES should aim to use open Ethernet-based fronthaul devices to allow for visibility and minimize proprietary radio control software. Finally, some sites may provide simpler USB-based radio devices connected directly to nodes in the cluster, although it is expected that this will occur less and less with time.

6.1.4. End User Terminals

The end user-terminals (UEs) will vary in type from smartphones, to laptops, embedded PCs with wireless access, or even fully experimental software-defined radio terminals. It is important to note that many of these will be equipped with a management, control and monitoring interface in order to remotely control the UE by software operating somewhere in the SLICES network (i.e., not necessarily in the node geographically closest to the UE itself). This interface can also be used to gather measurements from a remote UE. The actual technology used to interface with the UE will vary depending on the type of service provided by the site owner and could be wired (Ethernet) or wireless (WiFi or commercial cellular).

6.2. Software Architecture

As SLICES aspires to provide fully programmable remotely accessible infrastructure to the Digital Infrastructure community, the respective frameworks shall be developed for ensuring seamless and easy access to the experimental resources. The different site facilities will form an integrated single pan-European facility, adopting common tools for managing and orchestrating experiments over the infrastructure, as well as providing a single access and credentials to users. A first attempt to sketch our reference architecture, with respect to the tools used for its management, is described in Figure 18.

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[46] "Common Public Radio Interface (CPRI); Interface Specification", V6.0, August 2013

[47] USRP Hardware Driver (UHD), [Online] https://www.ettus.com/sdr-software/uhd-usrp-hardware-driver/,[Last accessed 20 September 2021].

[48] USRP Network Series (N-series), and X-series, https://www.ettus.com/products/, [Last accessed 20 September 2021].

[49] Aw2s – Advanced Wireless Solutions and Services, [Online] https://www.aw2s.com/ [Last accessed 20 September 2021].

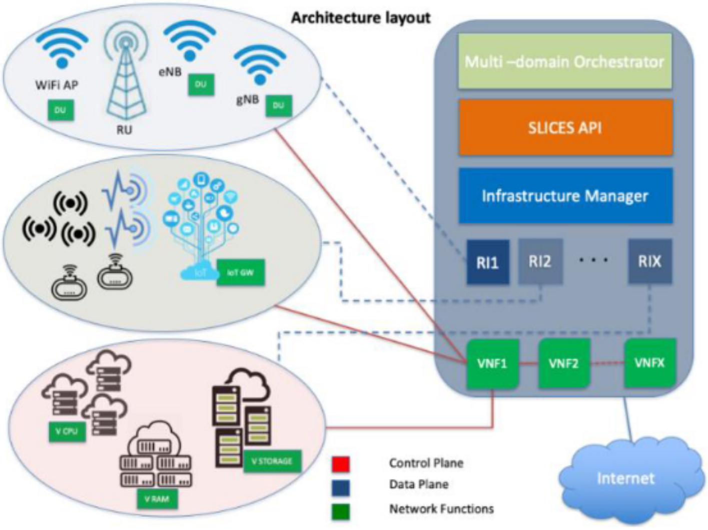

Figure 18: SLICES conceptual architecture

Towards achieving this integration, the sites will adopt network virtualization for their resources, compatible with the Management and Orchestration (MANO) architecture[50] for managing and deploying new services over the physical equipment. Each node will be considered as a single domain for experimentation, while the overall orchestration of experiments will be performed through a centralized infrastructure. Site and node selection frameworks will be developed in the context of SLICES, towards ensuring the optimal use of resources among the sites.

Moreover, and towards ensuring the smooth operation of the infrastructure, tools for facilitating access will be developed and deployed. Open-source software shall be employed, based on the paradigms of existing testbed access schemes, user authentication and authorization. This software will be appropriately tailored with new modules for managing the new equipment described in the previous section.

The table below provides a comparison between the existing tools for the experimentation plane of the experiments, and the progress beyond them.

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[50] Mijumbi, R., Serrat, J., Gorricho, J. L., Bouten, N., De Turck, F., & Boutaba, R. (2016). Network function virtualization: State-of-the-art and research challenges. IEEE Communications Surveys & Tutorials, 18(1), 236-262.

Table 5: Comparison of different proposed frameworks vs existing ones for the SLICES architecture

Existing Tools	Proposed Solution(s)	Benefits
cOntrol and Management Framework (OMF)	NFV-based orchestration solution	Current tools provide metal as a service access to the testbed resources, or in some cases virtualized access by interacting with the respective VIM interface of a testbed. On top, the experiments can be orchestrated by using a publish/subscribe scheme for the communication between a centralized controller and the actual resources. Adopting an NFV-based solution will allow the orchestration of experiments as Virtual Network Functions (virtualized access) or Physical Network Functions (Metal as a Service access), through the adoption of industry-grade tools. These shall allow higher utilization of the testbed resources, increasing the user capacity of each testbed, more secure end-to-end experiments, end-to-end network configuration and experiment reliability.
SDN programmability	SDN Assist	Current tools aim in providing a programmable interface for users that shall use their own controller for managing the flows in the network. In some cases, isolation of flows between different users on a switch is possible, through the adoption of tools like FlowVisor[51]. Moving to an NFV-based orchestration solution supporting features like SDN Assist[52] enables the programming of flows for an experiment during the instantiation time. Based on an end-to-end programmable SDN plane (based on Open-vSwitch or hardware OpenFlow/P4 switches) programmability extends to the entire datapath used for the experiments, isolating users and providing multi-tenancy over the infrastructure.
Wireless programmability	Open-RAN	Current tools for programming the wireless components rely on specific interfaces dedicated to specific equipment for the RAN. As such interfaces become standardized, through efforts like O-RAN alliance, adopting such APIs can increase the supported equipment, and open-up more programmability for the RAN. As such tools use standardized interfaces, they integrate with several NFV based orchestration solutions, allowing a truly end-to-end experiment configuration and instantiation.
Edge and Core Configuration	NFV-based orchestration solution	Current tools provide Virtualized access to the core and cloud network configuration, or in some cases metal-as-a-service access. Switching to the same NFV based orchestration solution as the rest of the nodes will enable the seamless network configuration, and move the edge/core cloud configuration to supporting a different number of settings (such as cloud-native 5G network configuration).

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[51] R. Sherwood et al., "Flowvisor: A network virtualization layer", pp. 132, Dec. 2009, [online] Available: https://scis.uohyd.ac.in/~apcs/acn/flowvisor.pdf, [Last accessed 20 September 2021].

[52] SDN-Assist, [Online] https://osm.etsi.org/docs/user-guide/04-vim-setup.html#advanced-setups-for-high-i-o-performance-epa-and-sdn-assist, [Last accessed 20 September 2021].

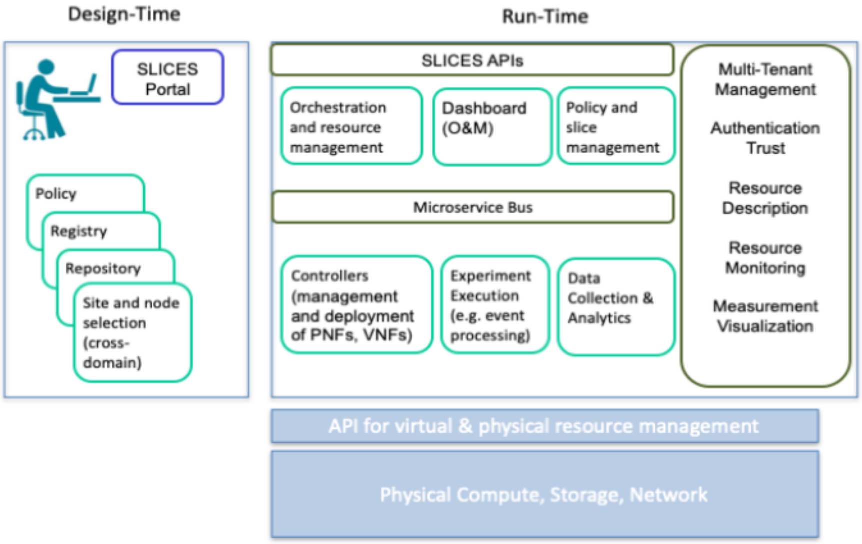

Figure 19: Software architecture and tools for experiment design and run-time

In terms of integration of the various components, the software tools shall encompass single-sign in procedures, with access certificates issued by a single authority. The resource discovery, reservation, and allocation shall comply with the access policies for SLICES (to be further specified during the project) and be interchanged with the respective facility authorities through a standardized process. For this purpose, the SFA[53] protocol has been extensively used in past and present solutions could inspire the candidate solutions together with new complementary or alternative solutions that will be considered as well.

Moreover, and towards realizing the full potential of the recent technology trends for network virtualization, SLICES will employ state-of-the-art resource management architectures, such as for example the Management and Orchestration (MANO) architecture for managing and deploying new services over the physical equipment. Through MANO, services and network elements are packed as Virtual Network Functions (VNFs) which can be instantiated over physical equipment; the same physical equipment can be used to execute different VNFs, whereas multiple VNFs can be instantiated over the same piece of hardware, thus allowing the equipment to be virtualized and shared among different operators (multi-tenancy). As the network infrastructure relies greatly on software, even for the RAN realization, the efficient and simple management and orchestration of these VNFs becomes of paramount importance. Specifically for the cellular RAN, emerging protocols and specifications like O-RAN and ONF SD-RAN will be adopted; such approaches will enable low level programmability of the cellular hardware, while creating the ground for further innovations beyond 5G and 6G networks.

Based on the automation tools complying with the MANO architecture (e.g., OpenSourceMANO[54], ONAP), we intend to equip new experimenters with a store in order to easily deploy services with a single click manner over the infrastructure. This can be achieved with these frameworks by using pre-compiled versions of services, and by supporting different methods for virtualization of resources (e.g., Virtual Machines, docker containers, Linux Containers). For example, public docker repositories provide different images that can be used to deploy commonly used services (e.g., databases, web

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[53] Peterson, L. (2010). Slice-based federation architecture. http://groups.geni.net/geni/wiki/SliceFedArch, [Last accessed 20 September 2021].

[54] Komarek, A., Pavlik, J., Mercl, L., & Sobeslav, V. (2017). VNF Orchestration and Modeling with ETSI MANO Compliant Frameworks. In Internet of Things, Smart Spaces, and Next Generation Networks and Systems (pp. 121-131). Springer, Cham.

services, applications and application servers) through a friendly interface. SLICES capabilities will also be used to support remote learning, enabling virtual labs based on advanced technologies that are barely available on site and therefore, will contribute to education and developing skills is very competitive. Moreover, the entire architecture will be augmented with the appropriate tools for experiment monitoring, experiment data and results visualization and cross-correlation analysis and inference with previous experiments executed over the infrastructure.

The low-level architecture for each site is shown in Figure 20. Each node will be connected over the GEANT network, and/or through the Internet. Computational infrastructure will be distributed, located at the central site of each node, supplemented with individual edge/core sites depending on the experimental equipment that they provide. Connections to the core datacenter for enabling acceleration of computational elements will be provided for all the nodes. Depending on the experiment type that is expected to be deployed, and the types of resources that will be used, the experiment will take advantage of either resource virtualization or metal-access to the resources. In the latter case, the appropriate APIs in the equipment will be developed in order to allow non-detrimental configuration that could stop the operation of the hardware (e.g., configuring an off-the-shelf AP to use more power than allowed in the area). In terms of wireless equipment, state-of-the-art equipment will be deployed, accompanied by the respective licenses for accessing spectrum in specific areas complying with local regulations.

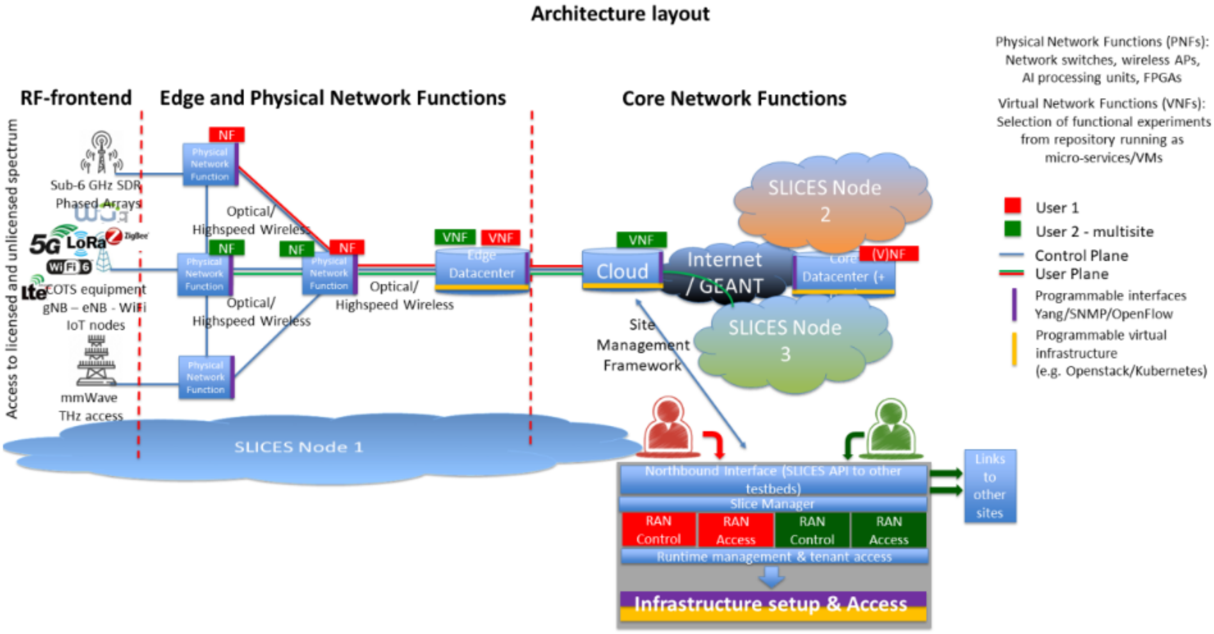

Figure 20: Low-level SLICES software architecture and tools

The overall architecture has been designed in order to allow experimentation with emerging and beyond-the-state-of-the-art algorithms, protocols and practices. SLICES will enable several scenarios that can currently be deployed only by large industrial players. For example, deploying a continent wide 5G-network can currently only be achieved by mobile network operators. From the beginning of the operation of SLICES-RI, such a scenario will be ready for deployment allowing several researchers to take advantage and evaluate new protocols over the infrastructure. The figure below illustrates such an experiment, that considers the deployment of the core network in central Europe, managing base stations in south Europe, and being able to migrate their functionality either to other datacentres or at the edge site.

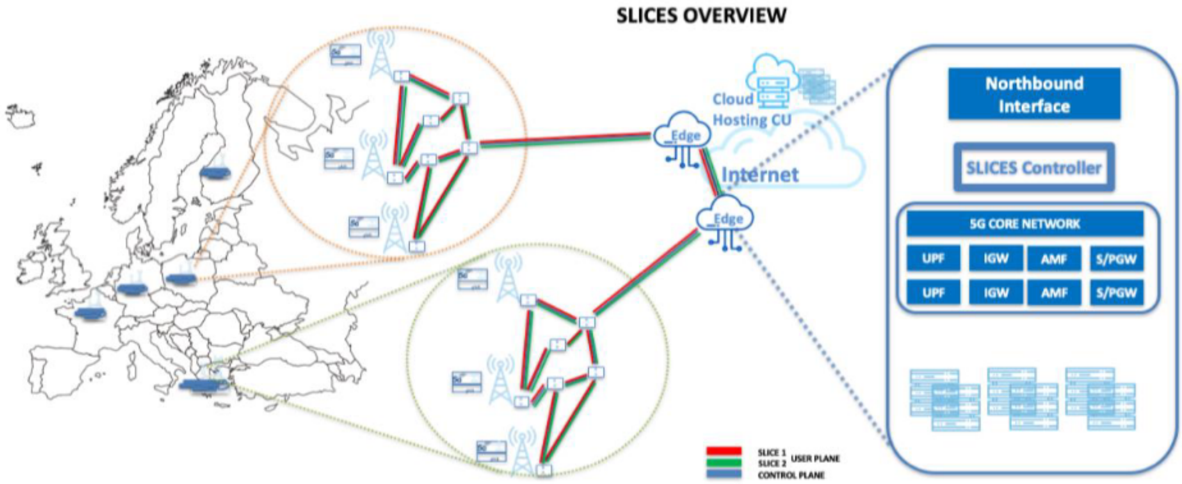

Figure 21: A SLICES use case that considers deployment of a 5G network spanning the entire continent

Depending on the type of the deployed experiment, images that take advantage of extended resource disaggregation will be used. For example, deploying a software base station will provide options for off-the-shelf deployment using different split levels (e.g., CP/UP splits, 3GPP Options 2/7.1/7.2 splits) depending on the availability of the respective platform, as well as Control/User Plane Separation (CUPS) capabilities for the 4G Core network and the Service Based (SBA) cloud-native 5G core network.

6.2.1. Enhancement of Existing Architectures

SLICES architecture can be designed considering the limitations and challenges of existing federation-based architectures such as SFA. For example, the SLICES architecture could be designed by advancing the Slice-based Federation Architecture (SFA) and further enhancements are required to overcome the limitations and complexities to integrate wireless, edge and other experimental resources. We can consider a layer-based architecture as shown below.

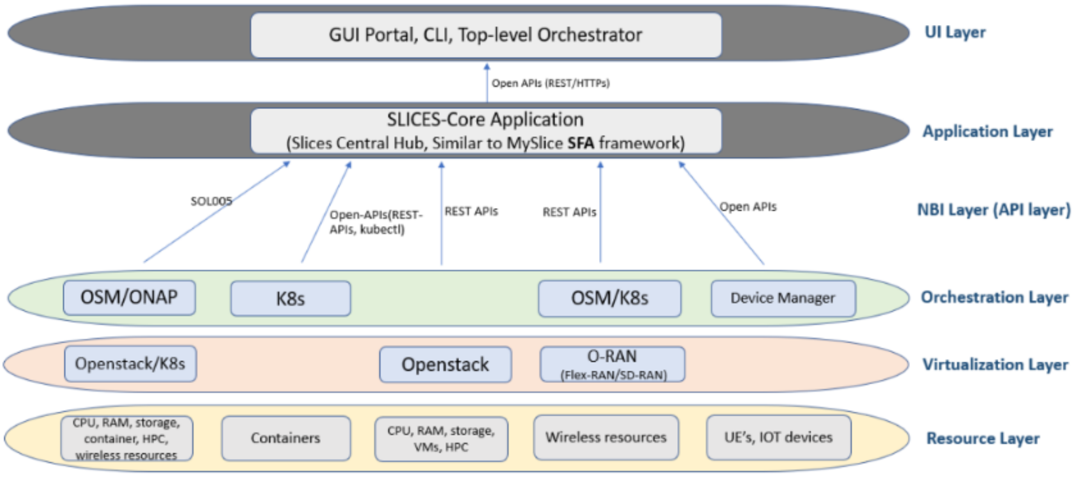

Figure 22: Layered architecture for SLICES

In this architecture, every component of SLICES testbed falls under a certain layer:

1. **Resource Layer**: It includes experimental resources such as CPU's, RAM, storage, containers, VM's, network, wireless, HPC and IoT devices;
2. **Virtualization Layer**: This layer includes cloud computing platforms (e.g., Openstack) that virtualize the underlying hardware resources and provide interfaces to the higher layers for programming/instantiating services over them. Examples of such programming interfaces are the ones defined by the O-RAN alliance (e.g., A1/E2 interfaces[55]), or the P4 programming abstractions for wired networks;
3. **Orchestration Layer**: It includes tools that orchestrate and instantiate services over the infrastructure equipment. Examples of such tools are OSM, ONAP and Kubernetes, mainly involved in NFV Management and Orchestration. It provides Network-Function-as-a-service and exposes northbound interfaces (NBI) APIs to be used by external entities;
4. **NBI Layer**: This Layer defines the Open APIs that can be used by the SLICES application framework. Examples of such interfaces are the SOL005, the SOL004 from the ETSI NFV-MANO architecture that can be found as the NBI interface of several MANO compliant tools, or even more generic ones, like TM-Forum[56] based APIs for service lifecycle control;
5. **Application Layer**: This Layer will host the SLICES-Core application, located at the SLICES central hub. It is responsible for managing all experimental resources that are exposed by lower layers, saved in the database and is further exposed to experimenters as a Service-Catalogue. It also exposes NBI API's that can be used by a 3rd party orchestrator. The architecture of SLICES-Core application will start from components similar to MySlice V2, and will be further enhanced at later stages;
6. **UI Layer**: This Layer defines the User Interface for the experimenters. It should abstract the experiments enough to make them more user friendly as possible.

6.2.2. Multi-domain orchestrator Architecture

The operation of the central-hub relies on the control of multiple-domains through the SLICES core application. Its operation resembles the functionality of a multi-domain orchestrator, that brings together different domains (in different locations, managed from different authorities) under the supervision of a single authority. The multi-domain orchestrator glues NFV, MEC and Cloud-Native orchestrators using API abstraction layers. Different groups of experimental resources on any of those testbeds might be virtualized and managed based on different technologies (e.g., VMs and containers). This in turn requires that multi-domain orchestrators use different orchestrators, managing different types of resources. For example, an NFVO and a MEC (Multi-access Edge computing Application Orchestrator-MEAO) are likely to be required in individual testbeds services, both managed concurrently through similar APIs from the same central entity.

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[55] O-RAN Specifications for Intelligent Radio Access Networks, [Online] https://www.o-ran.org/specifications, [Last accessed 20 September 2021].

[56] T. Forum, "IG1167 Open Digital Architecture Functional Architecture, R19.0.1," TM Forum, 2019.

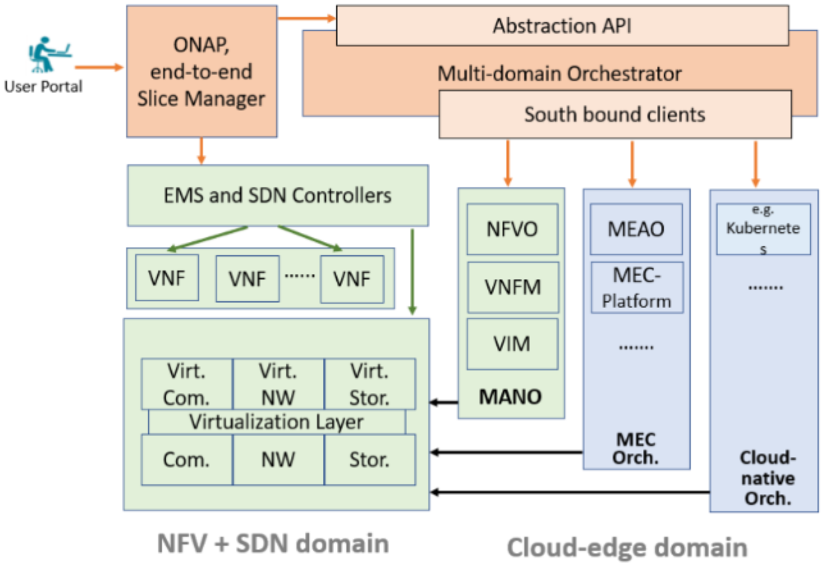

Figure 23: High level architecture of multi-domain orchestration solution

The central SLICES core application shall include an Abstraction API, used to trigger the required API invocation chains on different domain orchestrators when a high-level action is performed. A set of Southbound-clients is used in order to connect to NFV, MEC and Cloud-native local domain orchestrators.

6.2.3. API design for SLICES platform

For providing access to the experimental resources to each site, two different APIs shall be offered to the experimenters: 1) a first API shall be provisioned through the core SLICES application (multi-domain orchestrator) to deploy and provide access to the experiment, 2) a local API provided by the local orchestrator at each testbed. Even for the case of the local access, user authentication and authorization shall rely on the central SLICES entity and the protocols that it implements (e.g., SFA), and provide access to the resources under the SLICES authority.

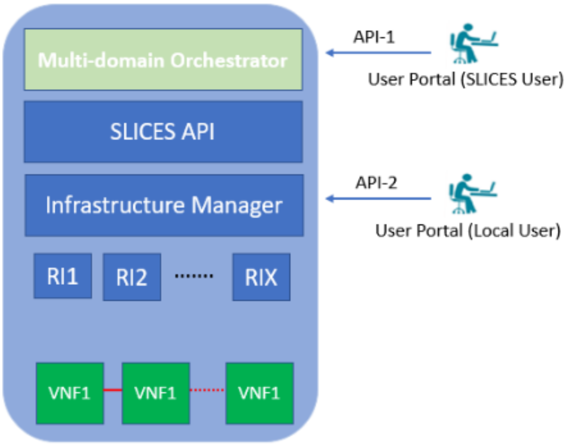

Figure 24: SLICES API design for experimenters

Regarding the actual level of detail provided from the first type of API, it shall feature different levels of complexity and control for each experiment. For the most experienced users, low level details will be available for the resources they request, allowing the fine tuning of complex experiments with a low-level access to the different hardware. Such features will allow the users to have full control over the experiment (e.g., setting the modulation of the transmitted wireless signal during the experiment), by exposing even virtualization level parameters (e.g., O-RAN interfaces for the cellular equipment) to the experimenter. Those APIs will be further used to develop higher-level tools to automate or simplify experiments for some specific communities. For the cases of inexperienced users, simplified versions of the same API will hide the low-level details of the experiment configuration. As SLICES covers a wide range of users, different levels of configuration might be needed depending on the experimenter type. For example, provisioning a simple wireless link can be sufficient for an application developer, while a new protocol designer will need a fully controlled environment with access to all the parameters affecting the experiment.

Both options will be made available through a portal web GUI and other graphical interfaces for ease of access. Such access will allow fast experiment bootstrapping for novice users, while on demand providing low-level control parameters for expert users. Providing access through such interfaces will enable the quick replication of the experiment across different sites and will foster the capabilities of the infrastructure on reproducing experimental results.

It is worth noticing that the different levels of access will also correspond to finer or coarser grain control over the deployment of experimental resources. More experienced users would be willing to control exactly which experimental resource to use from which facility at which site, while less-experienced users might not even know that their experiment is actually using heterogeneous resources composed out of different facilities spread across Europe. In the latter case, SLICES, through dedicated management components, will automatically assign resources to the users' experiments, in order to optimize the overall utilization of the RI's resources or simplify the work of the experimenter.

6.2.4. Energy Efficient Design targeting UNSDG

The roadmap for long-term evolution of SLICES will also target to reduce the environmental impact notably through energy efficiency, e-waste reduction and definition of requirements to host experiments in verticals with environmental (including climate-related) impact. It will contribute to the United Nations Sustainable Development Goals. To enable a sustainable progress for society, in line with the United Nations Sustainable Development Goals, it is crucial that SLICES addresses effectively pressing societal needs, while delivering new functionalities in its testbed infrastructure. To ensure that SLICES can be inclusive for all researchers across the Europe, it needs to be affordable and scalable, with a great coverage everywhere and highly energy efficient. SLICES research infrastructure will use technologies such as cloud, visualization, programmability, network slicing and AI/ML which will significantly reduce the energy footprint. Containerization is another technology that will greatly reduce the infrastructural resources and hence further reduce the carbon footprint. Furthermore, limited resources at the edge as well as the need for improved energy-efficiency, call for lightweight virtualization and more detailed orchestration methods.

SLICES RI needs to be designed even more as an energy optimized system including smart solutions (i.e., integrating AI to achieve optimizations), e.g., less energy demanding new radio technologies. KPIs can be defined on energy consumption per data bit as well as total consumption with be complementary. These KPIs will be necessary to measure the extent of emission reductions or resource consumption, along with the available Sustainable Development Goal target metrics.

6.2.5. Integration with EOSC infrastructure and services and international testbeds

Since SLICES aims to provide a pan-European experimental research platform by jointly utilizing the geographically dispersed computing, storage and networking RIs, it is highly important that the different RIs interacting in the experimental workflow are interoperable with each other. Similarly, existing research needs to be accessible and directly pluggable to SLICES services and sites. For example, considering a MEC use case, compute, storage and networking resources from different RIs would be used. In such a scenario, it is necessary that resource description, availability, execution and data exchanges are smooth. This can only be assured if a common interoperability framework is adopted across the SLICES ecosystem so that different subsystems have a common understanding of resources, data/metadata and are on the same page with respect to the licensing, copyright and privacy requirements. The SLICES infrastructure will be designed to ensure compatibility and integration with the EOSC and existing ESFRI infrastructures, and be ready to offer advanced ICT infrastructure services to other RIs and projects, with the special focus on the FAIR data management and exchange.

To achieve this, a dedicated interface SLICES-IF shall be developed. The interface will be built upon the foundations led by the European Interoperability Reference Architecture (EIRA), where interoperability is classified at four layers, namely: (i) technical, (ii) semantic, (iii) organizational; and (iv) legal. Although the target audience for EIRA (governance and administration) was very different from that compared to SLICES, core principles and objectives remain the same. Additionally, the different components (in particular technical and semantic) of SLICES-IF would be chosen in a such way that SLICES is fully interoperable with EOSC for uninterrupted data exchange pertaining to use of EOSC services and research data by SLICES as well as to enable the publications of SLICES infrastructure, services and data through EOSC portal. More details about the SLICES-IF interface to EOSC and external RIs is provided in SLICES-DS D4.2[57].

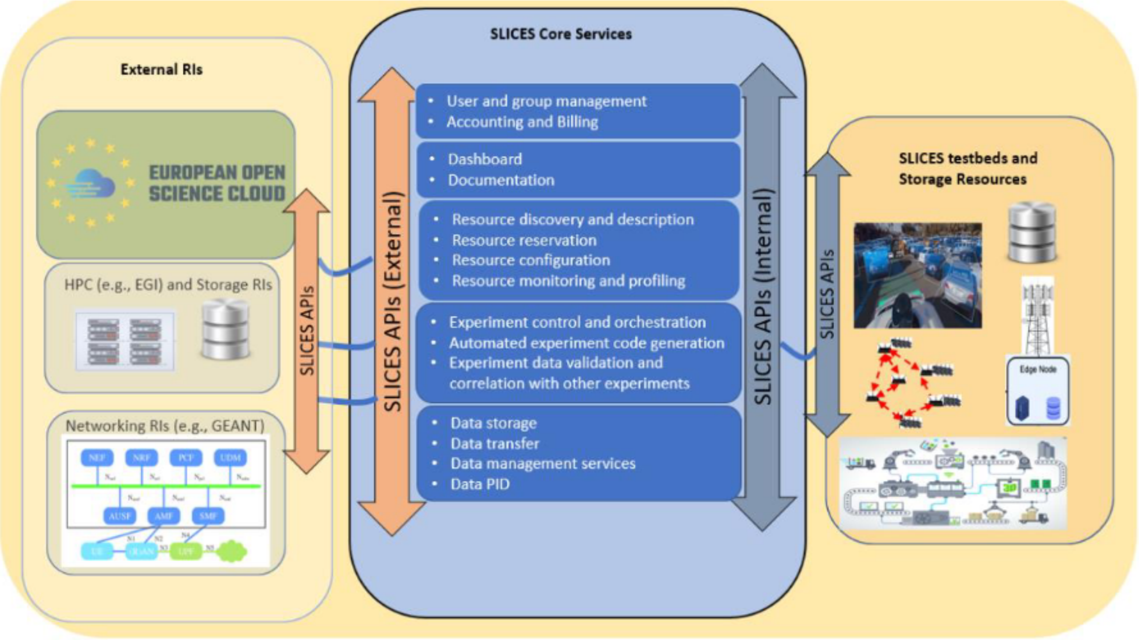

Figure 25: SLICES interface to EOSC

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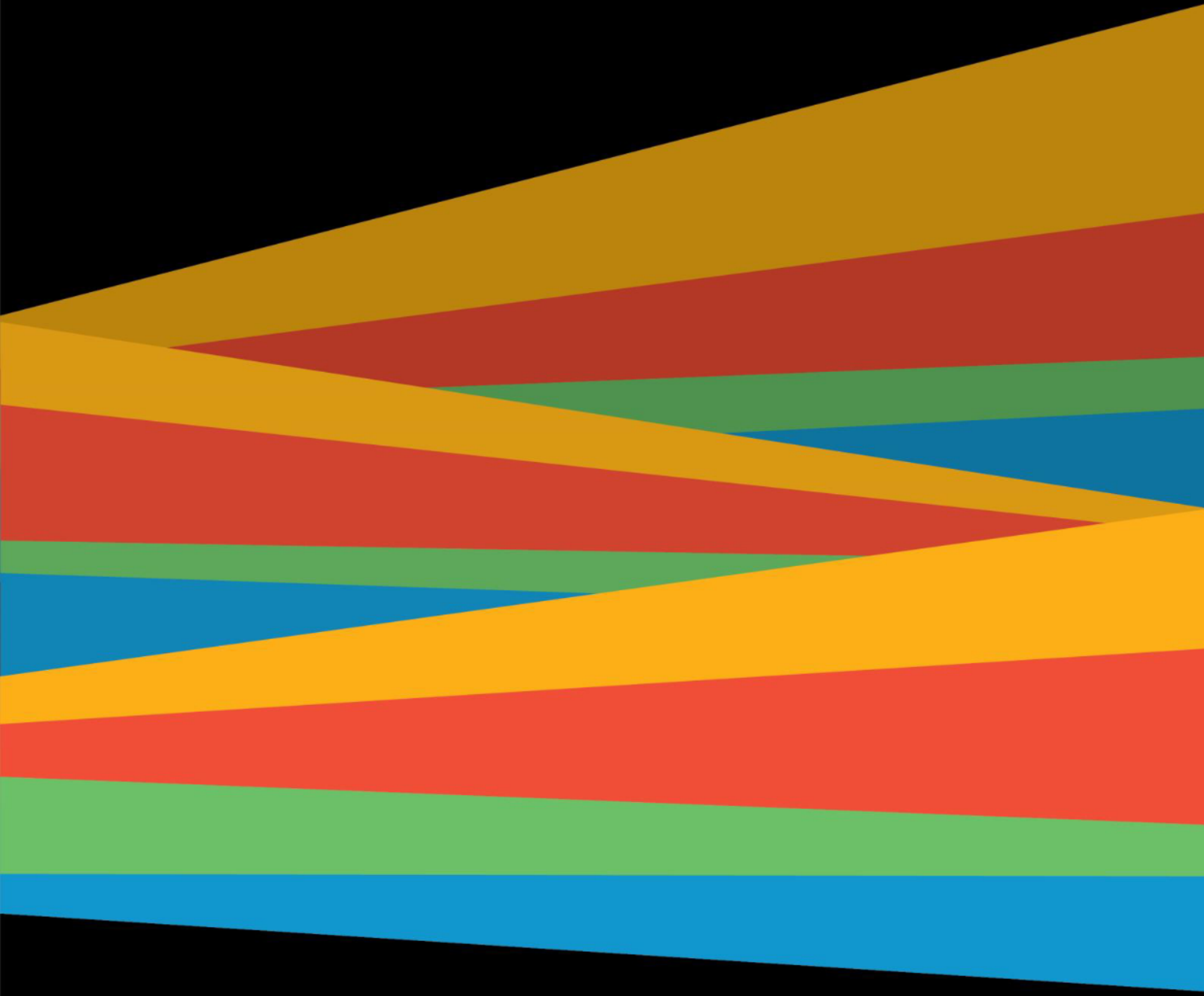
[57] SLICES Deliverable D4.2- SLICES Interoperability and integration with EOSC and other RIs, August, 2021.

7. Conclusion

The present document describes our continuous work aiming at designing the SLICES end-to-end reference architecture that will be adopted and evaluated for the SLICES-RI. This work will be pursued during the course of the Design Phase in order to consider several possible scenarios and articulations of the various components to accommodate the ambitious requirements and expectations of the scientific community. The document emphasized the analysis of the current demand 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 Management and Orchestration (MANO) frameworks for deploying experiments and applications over distributed infrastructure. This state of practice is briefly analyzed, by showcasing how current smaller scale ICT platforms orchestrate experiments (5G-EVE, 5G-VINNI, 5GENESIS, PAWR, Fed4FIRE). The document also discusses major open-source software that is used by the research community for wireless (and other technologies) experiments and should be supported in SLICES. The document further illustrates guidelines for creating the reference architecture of a large-scale testbed infrastructure, analyzing how the different domains for experimentation (different islands) can be combined through a multi-domain orchestrator. The design principles for the API design, modes of access, resource/experimental management services and integration and interoperability with EOSC infrastructure are also presented. The service design and the architecture are based on the long experience of the participating members in managing test platforms infrastructures.

The purpose of this document is to develop the discussion regarding a reference architecture 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 candidate frameworks that have been presented for managing and organizing experiments over SLICES will be further evaluated from the consortium members, towards assessing the extensions needed for integrating the different components of the RI under SLICES.



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