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D7.1 Report on Future Evolution of the RI

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

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Executive summary

This report outlines the strategic directions and key technological advancements essential for the evolution of the SLICES Research Infrastructure (RI) to address emerging challenges and opportunities in computing and communication research. It also exposes the methodology and principles for the continuous deployment of the SLICES-RI. The main areas in which the report focuses are the pathways towards 6G, the cloud-edge components, integrated sensing and communication (ISAC), security, sustainability, experiment reproducibility, Artificial Intelligence and Machine Learning, MetaData and Data Management, Internet of Things and Quantum Computing. In each of the areas, an analysis on the needs and requirements from the community are provided, along with the potential impact that they will have on enhancing the SLICES-RI. This report highlights the strategic vision and necessary advancements for the future evolution of the SLICES Research Infrastructure. By focusing on these key areas, SLICES aims to continue to support a wide range of research activities that address both current and future technological challenges.

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1. Introduction

SLICES RI is meant to support the research in digital infrastructures, which associates a large set of communities including but not limited to Internet, Telecommunications, Cloud, Edge, HPC, IoT, Wireless, Security, Energy efficiency… Digital Infrastructures provide the foundation for the digital transformation of our societies. They evolve rapidly at the crossroad of several scientific domains and technologies. The mission and vision of SLICES is therefore to provide a test platform to these communities to support their research through an experiment-driven approach.

The broad set of scientific questions to be addressed raises an important challenge regarding the capacity to build such a scientific instrument as well as the methodology to deploy it. This is also challenged by the fact that we want to investigate concepts that have not been designed yet (e.g., 6G).

In addition, experimentally-driven research is not well recognized in digital sciences and in particular in digital infrastructure research. It is mostly used in order to support the evaluation process but in a way that is limited. Most experiments are not reproducible, neither on their original test platforms nor as a benchmark. We expect that SLICES will have an impact on the research community by supporting a robust methodology, empowering researchers and engineers.

This clearly differs from the value of experimentally-driven research in other science domains. This is for example illustrated by the Nobel prizes in Physics 2022 and 2023 that were delivered to the recognition of “Groundbreaking experiments using entangled quantum states, where two particles behave like a single unit even when they are separated” (2022) and “experimental methods that generate attosecond pulses of light for the study of electron dynamics in matter”. It highlights the concept of “Thought Experiments”, namely a kind of experiment that Schrödinger considered impossible to realize, that Einstein and Bohr discussed when preparing their Photon box.

This principle of “Thought experiment” is the foundation that provides the guidelines for SLICES to design and build our facility as we will discuss in the sequel.

A second key aspect is related to the data management. At a time where research is driven by data, it is of utmost importance to support the full research lifecycle, fair data management and reproducibility. This part is addressed in SLICES by advancing our Data Management Infrastructure (DMI) as well as EOSC interoperability and the pos framework for reproducibility.

The methodology to identify the scientific questions on various research domains within our radar is presented in Section 2.

A challenge that is faced by SLICES is its broad set of technologies and components to support an even broader set of research questions. Therefore, we are convinced that the way to manage this complexity is to develop an “intent-based” infrastructure, which solution is based on the concept of a BluePrint (BP). The BluePrint defines a common terminology that will unite the community, clearly state the environment and provide deployment solutions. It is perceived as a baseline system that can be built to validate requirements, reviewed and refined.

The scientific questions are formulated by the relevant scientific communities. They are strategic as they will define the target reference platform that can be considered as a benchmark for the respective research community.

We started by the Post5G BluePrint because the research community was solid and mature enough to develop this exercise.

The main scientific questions are related to (non-exhaustive):

- ***Type 1*** – Vertical service integration and testing
- ***Type 2*** – Software-Defined Networking (e.g., xApp)
- ***Type 3*** – Radio/Network dev software (e.g., new MAC)
- ***Type 4*** – Novel hardware (e.g., RIS, THz, crypto functions)
- ***Type 5*** – Digital twin (GPU RT 3D radio emulator)

The SLICES Post5G BluePrint has been designed in order to be able to support the above type of questions. It was first specified in June 2022, deployed in December 2023 and a second version has been released in March 2024. It will provide the core for the pre-operation service that SLICES will offer to its experimenters in fall 2024. This Post5G BP is aimed at being diversified and extended as requested by the research community whose main research challenges are described in Section 3.

We have used the same methodology with the edge-cloud research community that is currently about to release its own BluePrint that will enable experiments in domains illustrated in Section 4. Last, we just started to mobilize the Intelligent Sensing and Communication (ISAC) community in order to produce its BP.

Obviously, many other domains are on the radar of SLICES. We need to engage with the relevant research community in order to invite them to realize a similar exercise. The main topics of interest are listed in Sections 6 to 12. These sections show the diversity of topics.

This deliverable describes the various research domains and questions that SLICES ambitions to address. The main challenges, needs, requirements and impact for SLICES-RI are presented and discussed. Experiments will be carried out under the umbrella of SLICES that will provide a unique portal with basic services such as authentication, experimenter management, resources management, accounting, storage service…

Most importantly is the role that SLICES aims to play as a repository for research data in our filed, calling for a Data Management Infrastructure (DMI) properly articulated with EOSC and the storage service. The experimental research data management infrastructure is decomposed into several components that capture the SLICES experimental data lifecycle model and dataflow (experiment/data lifecycle stages).

This together with the reproducibility objective are presented in Sections 8 and 10. They will be factorized for all BP that SLICES will support.

This process of identifying the research questions, engaging the research community and defining an appropriate BluePrint is a continuous and living process that will extend and be refined continuously. This is also a benefit for adopting a continuous deployment and integration approach that is facilitated by modern computer science and technology.

2. Methodology

The prioritization of research topics is an exercise SLICES-RI partners carry on continuously, starting from the beginning of the SLICES initiative in 2017. Overall, it is based on an established methodology, which is depicted in Figure 1. The application of this methodology led to a process that already identified and refined the research topics several times, as discussed in the rest of the document.

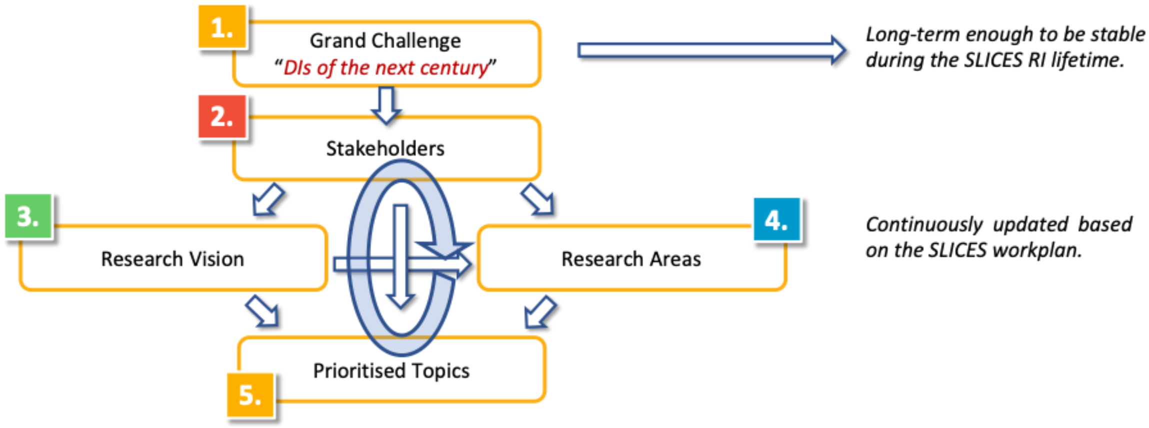

Figure 1. SLICES methodology for the prioritization of research topics

Following the results of the SLICES-DS project and in particular outcomes described in *Deliverable D1.4 Roadmap for long-term evolution of the Research Infrastructure*[1], in this project, we have identified key topics, which, according to feedback received from research communities, are the most prominent and important for SLICES and its future evolution. The list of topics includes the following:

1. PATHWAYS TOWARDS 6G
2. CLOUD EDGE
3. INTEGRATED SENSING COMMUNICATION
4. SECURITY
5. SUSTAINABILITY AND GREENING THE RESEARCH INFRASTRUCTURES
6. EXPERIMENT REPRODUCIBILITY
7. ARTIFICIAL INTELLIGENCE
8. METADATA AND DATA MANAGEMENT
9. INTERNET OF THINGS
10. QUANTUM COMPUTING

Each topic has been carefully examined, taking into account the following:

[1] Deliverable D1.4 Roadmap for long-term evolution of the Research Infrastructure, available at: https://www.slices-ds.eu/wp-content/uploads/2022/12/SLICES-DS_D1.4_approval_disclaimer.pdf [Last accessed 25 June 2024]

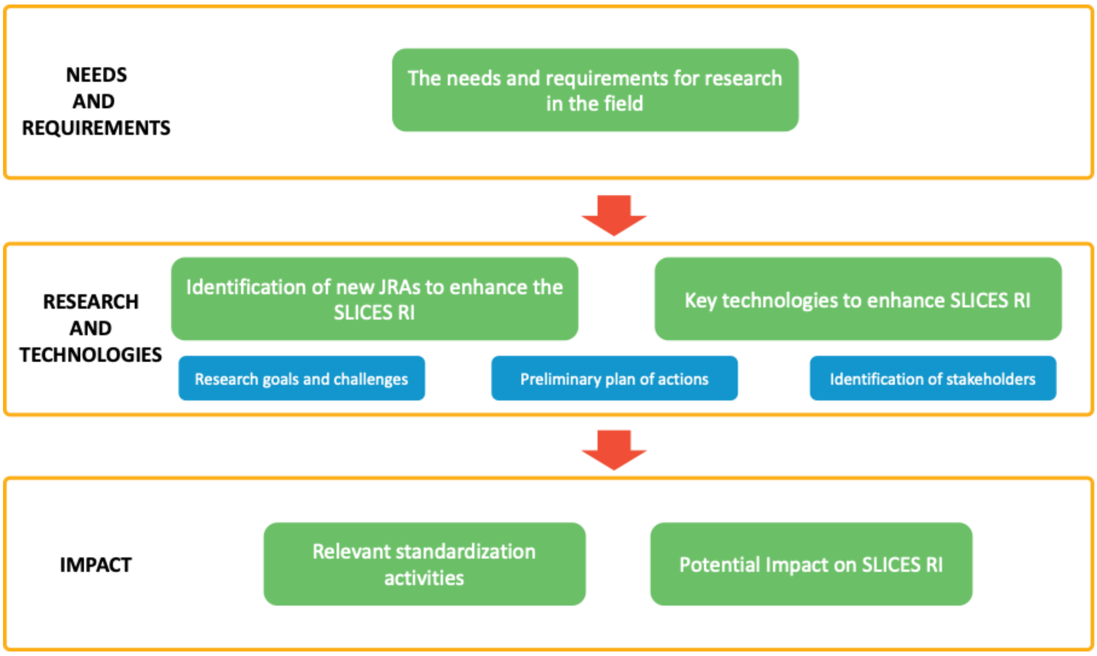

Figure 2. SLICES methodology for the analysis of potential evolution of the Research Infrastructure

The results of the analysis are presented in the following chapters.

3. Pathways towards 6G

3.1. The needs and requirements for research in the field

The development of mobile cellular technology has been incredibly fast and immense new opportunities are arising. Where 1G/2G offered speech services, 3G/4G brought broadband Internet to our pockets. 5G/6G technological and architectural features that will shape the new access, networking, and management domains in mobile communications promise countless opportunities for service innovation and business efficiencies, creating an unprecedented impact on multiple vertical sectors. The role of 5G/6G is to connect intelligently every feasible device, process, and human to a global information grid. We are therefore only now at the brink of an information revolution, and new digitalization markets will offer significant revenue expansion possibilities for those who react fastest to new opportunities. 5G, Post5G and 6G network technology offers numerous opportunities for various verticals, and new value chains and business models are introducing a paradigm shift to the old communications service provider market in transforming toward digital services. However, important efforts are still required prior to making 5G/6G a success and growth story for the industries developed around the 5G/6G-beneficial vertical sectors. Considering the different development cycles of each vertical too, a full trolley of the potential advances and vertical transformations will also continue to be deployed in the 6G era.

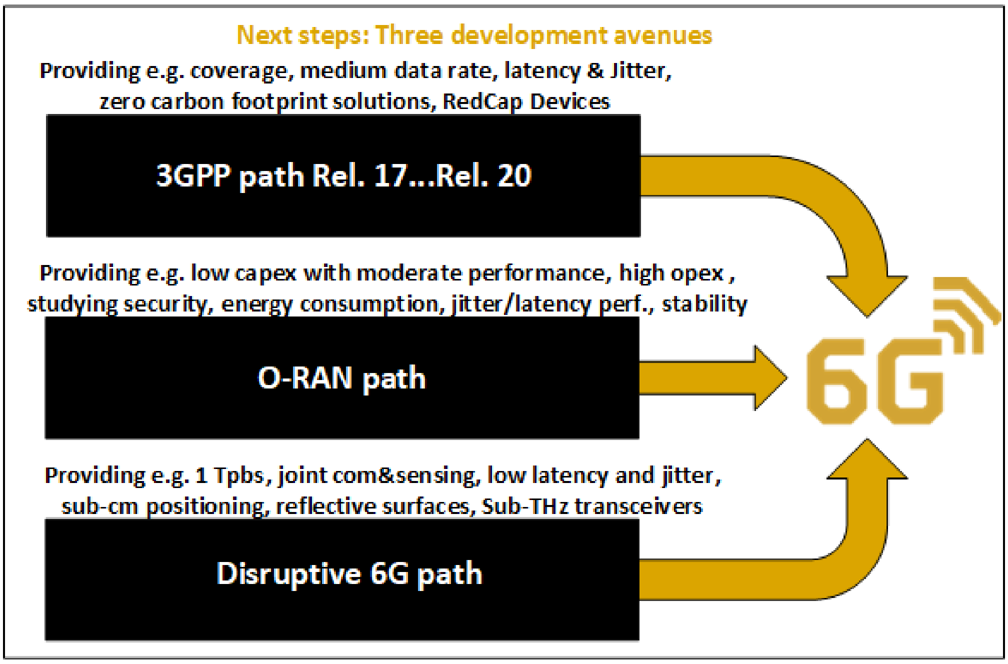

Figure 3. The foreseen three development avenues towards 6G

The verticals, however, are quite different by nature in terms of required coverage, latency performance, expected data rates, device density, energy consumption, security and, e.g., capital expenditure (CAPEX) expected. Therefore, we envisage that high-end test infrastructures should follow three development avenues or paths that are becoming relevant in terms of their capabilities in offering connectivity to differing purposes among a wide variety of vertical players.

Vertical	Link DataRate	Latency	LinkBudget	Jitter	Density	Energy Efficiency	Reliability	Capacity	Mobility
Industry mMTC	< 1 Mbps	< 100ms	+ 10 dB	100 µs	100/m³	High	$1\text{-}10^{-6}$	< 10 Gbps	240 km/h
Industry eURLLC	< 5 Mbps	< 100 µs	+ 20 dB	< 1 µs	10/m³	Nominal	$1\text{-}10^{-9}$	< 100 Mbps	240 km/h
Mobility	<10 Gbps	< 100 µs	+ 20 dB	100 µs	100/m³	Nominal	$1\text{-}10^{-7}$	1 Tbps	1200 km/h
eHealth	< 1 Gbps	< 1 ms	+ 10 dB	100 µs	1/m³	High	$1\text{-}10^{-9}$	< 10 Gbps	240 km/h
Energy	<1 Mbps	< 500 µs	+ 40 dB	< 1 µs	10/m³	Nominal	$1\text{-}10^{-6}$	< 100 Mbps	N/A
Finance	< 1 Gbps	< 10 ms	varies	N/A	1/m³	High	$1\text{-}10^{-9}$	< 10 Gbps	Low
Public Safety	<1 Gbps	< 1 ms	+ 20 dB	100 µs	1/m³	Nominal	$1\text{-}10^{-7}$	< 10 Gbps	240 km/h
Agri-business	100 Mbps	< 10 ms	+ 40 dB	100 µs	100/km²	Nominal	$1\text{-}10^{-7}$	1 Gbps	240 km/h

Figure 4. Estimated key performance indicators of some verticals

The three paths are: 1) 3GPP path, 2) O-RAN path, and 3) Disruptive 6G path as depicted in Figure 3. Combined, following these three paths will offer research, testing, and validation capabilities now, in mid-term and in long-term generating thus maximum value that a research infrastructure can offer.

The 3GPP path will offer capabilities, such as, e.g., coverage, medium data rate, medium latency & jitter, zero carbon footprint solutions, and RedCap Devices and with current estimation adopts the so-called mid-band frequencies at 6-15 GHz and will use OFDM type waveforms. The O-RAN path on the other hand offers the possibility to build networks with low capex with moderate performance and reasonable opex as well as bringing in research opportunities in areas such security, energy consumption, jitter/latency performance, stability, and RAN slicing in fully softwarized networks. Thirdly, the 6G disruptive path will provide avenues towards, e.g., 1 Tbps, joint communications and sensing, extremely low latency and jitter, sub-cm positioning, reflective surfaces, and sub-THz transceivers.

One example of the differences in Key Performance Indicators (KPIs) is depicted in Figure 4. The versatility of the requirements in different verticals stemming from differing use cases shall require a spectrum of capabilities that can be satisfactorily addressed with this three-avenue approach.

3.2. Identification of new JRAs to enhance the SLICES RI

The long-term roadmap for the infrastructure development is illustrated in Figure 5, with its first phases following the progress of the standardization and regulation & legislation activities on cellular, other wireless access technologies as well as IoT. This roadmap proposal is reflecting the investment needs coming from the execution of this roadmap covering the end-user devices, sensors, radio access, core network, network management and service creation needs. Keeping the pace of constant investment is critical due to immature technology and still relatively early phase of the 5G standardization and eventually the transformation towards and to support 6G research. Specifically, to stay relevant for Horizon Europe and other funding instruments and partner needs as well as the research trends currently appearing, **we foresee three avenues (sandboxes)** that need to be followed forming the basis for this applied project:

1) **Provide 3GPP 5G long term evolution (5G-LTE) compliant infrastructure elements to the test network as they are provided by infrastructure vendors,**
2) **Provide open radio access network (O-RAN) capable devices and software to the test networks, and**
3) **Provide 6G technology enablers to the test network.**

Avenue 1) will allow research for vertical network optimization in 5G-LTE domain supporting the on-going digitalization of vertical businesses and societal services. Avenue 2) will allow to study the challenges related to fully softwarized networks. Avenue 3) will allow the experimentation of the 6G technology enablers foreseen in the next 5-10 years.

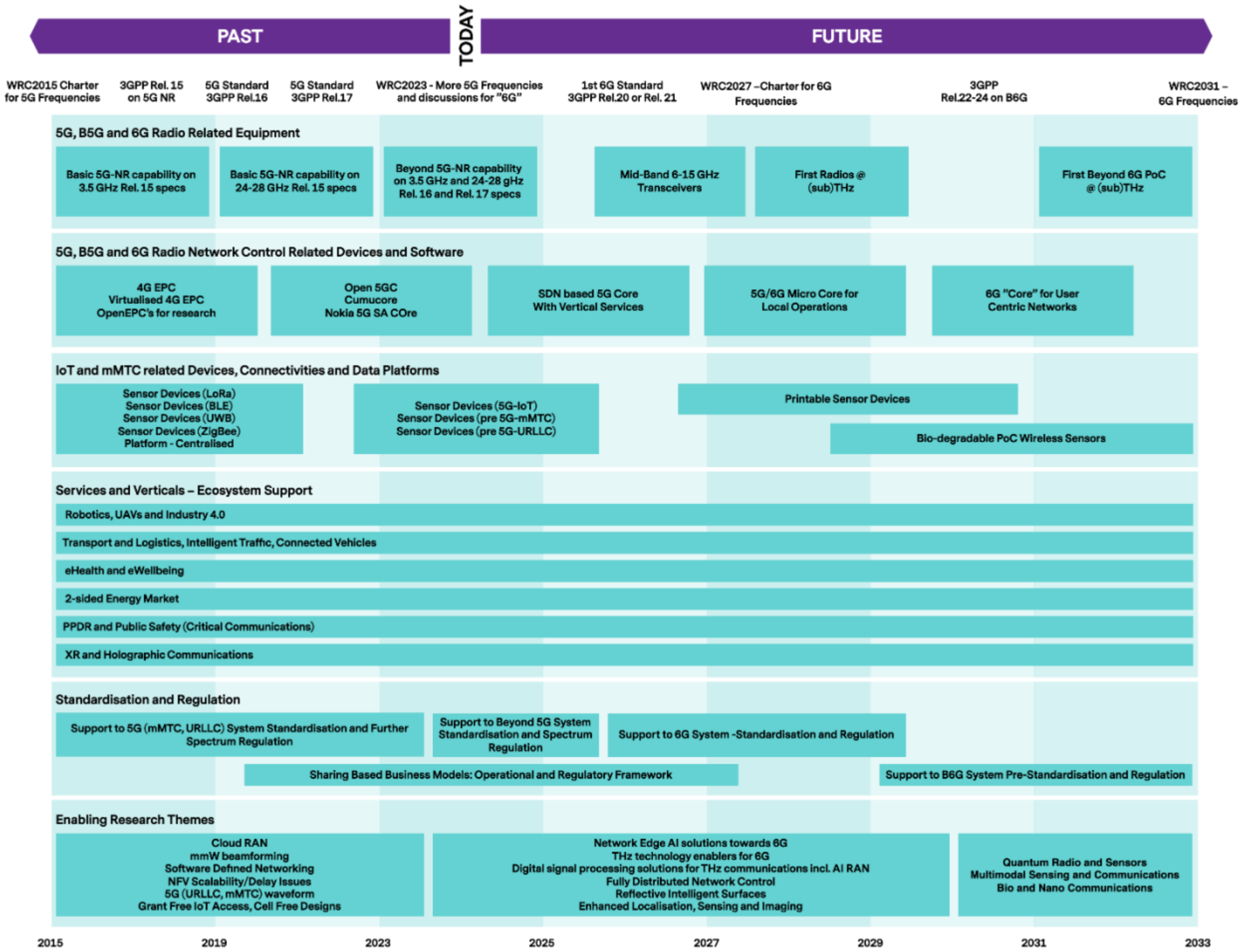

Figure 5. The overall roadmap of the 5G/6G development

Within the overall ICT ecosystem, this includes the following:

1) **Future Radio**. Current pioneering research continues during the following years targeting to real pre-commercial 5G long term evolution and 6G prototype radios with 1-10 Gbps links (later towards 1 Tbps) and up to a few hundreds of meters coverage using high-order modulation, adaptive hybrid beamforming, and 1-10 GHz instantaneous bandwidth, multi-user massive MMO transmitter/receiver solutions assuming 5G and 6G radio access networks. On one hand, it means gradually climbing up to higher frequencies and bandwidth, and on the other hand towards IoT optimized interfaces, and interworking with WLAN.
2) **Radio and core network & control**. HW centric network is shifting towards full use of virtualization and cloud technology. In upcoming years, this is utilized also in radio access functions as part of mobile network research. The network evolves to become extra-secure and elastic with QoS and scalable resource pools for services designed to allow high-availability, high bandwidth and low latency for services. The network is developed to be sliced with dynamic resource allocation according to use. This requires plenty of research and working infrastructure for algorithm validation and to ensure network performance in all scenarios.
3) **IoT & sensor devices**. As wireless communication will shift from user-centric communication towards M2M with potentially hundreds of thousands or even a million of sensors per km^2 connected. There is no winner for a single air-interface for IoT use, and plenty of research is still expected to support standardization to define a working solution assuming interworking

with existing solutions, massive number of devices, optimal energy consumption, and special security needs from critical systems such as vehicles, industrial applications or hospitals.

4) **Digital services and business verticals**. As the promise of 5G and more so of 6G is to provide services for business verticals, developing and testing wireless solutions suitable to different verticals is essential. In the 5G and beyond era, *one size fits all* is no longer valid, but diverging needs of different verticals need to be addressed. Such verticals include but are not limited to Industry 4.0, transport, eHealth, energy, and public safety.
5) **Standardization and Regulation**. Testing these new co-operation possibilities is critical to see the impact to current society and legislation to allow flexible use of available spectrum. Trialing 5G and beyond in real but safe network environment with business horizontals will reveal the obstacles that need to be removed from regulation and legislation. Furthermore, through the massive project portfolio associated with the infrastructure, a large impact in standardization contributions is evident through project partners.

3.3. Key technologies to enhance SLICES-RI

Some examples of typical research actions where wireless RIs are of benefit is described below:

Radio technology - The evolution of 5G New Radio (NR) as well as fundamental research towards 6G radio technology form the main research umbrella. Good examples of recent research in this area covers new physical layer waveform solutions, novel multi-connectivity radio technology solutions, and ultra-reliable low-latency communications solutions. Another major theme is related to the radio technologies for and through aerial vehicles. Furthermore, high-accuracy radio positioning, radio-based sensing & mapping, and the timely notion of integrated sensing and communications in Post5G/6G context form an area where large scientific impact has been achieved. Additionally, there is large amount of more implementation-oriented radio research, covering, e.g., novel and flexible duplexing methods and novel RF impairment linearization methods.

Networking - The RI has directly enabled and facilitated the design and development of novel disruptive networking solutions in mobile networks. The current mobile networks were designed for consumer applications and focus on elastic transport where best-effort networking has been enough. However, 5G and future 6G mobile networks are targeting different market segments such as industrial, machine type communications. Therefore, existing networking solutions must be adapted and enhanced to support the new demands of those areas. The usage of NFV and SDN have been the primary technologies to optimize the existing networking solutions. Moreover, future evolution of SDN (one avenue being O-RAN) for managing both network and radio equipment is proposed for 6G. We need to go beyond and aim at new networking paradigms to deliver end-to-end communications infrastructure where machines connected through 5G and future 6G will be seamlessly integrated with fixed devices connected to local industrial networks. Thus, network slicing, time sensitive networking (TSN) and 5GLAN integration are the research areas where research using RIs are creating high impact solutions. Time synchronization is key enabler for wireless technologies and GPS has been used as reliable time source. However, latest developments showed that it can be jammed thus interfering guiding and mobile networks. We need to also look at other time reference sources required to reliably deliver time synchronization over mobile networks using TSN.

Verticals – Existing wireless RIs already provide unique platforms for other projects focusing on vertical applications such as industry 4.0, energy, critical communications, health, multimedia and automotive. SLICES will facilitate also remote sites to access the infrastructure and having own dedicated network slices for their experiment. SLICES-RI will optimize and expand the usage of the resources towards other partners that do not have to invest in replicating similar infrastructure. Instead, SLICES-RI provides access to external application developers, data scientists, etc. for developing and testing new disruptive services and concepts for the digital society, enabled by future wireless technologies. The researchers will be able to remotely access their own slices of SLICES-RI. 5G system development is expected to revolutionize everything seen so far in wireless-enabled vertical applications. The key enabler in near term for future digitized societies will be 5G, making everyday lives smoother and safer as well as drastically improving the efficiency of businesses. The first 5G standard version was ready in June 2018. The requirements for 5G vary by application but will include data rates ranging from very-low-rate sensor data to very-high-quality video content delivery, low delay/latency requirements, low energy consumption, and high reliability. All of these should be achieved at the same or lower cost than with today's technologies. The application scenarios range from typical mobile broadband to machine-to-machine communication, real-time positioning of user devices, real-time control with low latency, and low-data-rate, massive-sensor networks with many nodes, to name just a few. The 5G/Post5G capability is very important to industrial partners of SLICES-RI. To boost the forerunner position, the SLICES wireless RIs will be enhanced with capabilities that enable research towards 6G.

SLICES RIs have and shall further define and offer a set of open APIs in several network layers and common computing resources to deploy network slicing/spectrum manager to support further usage of the facility by not only SLICES partners but also projects and customers coming outside the 6G-SNS realm. Furthermore, the Open RAN (O-RAN) based servers and software shall be deployed to study fully softwarized networks running on general purpose computing platforms.

3.4. Potential Impact on SLICES-RI

The research themes for 5G evolution and 6G include topics, which are not yet standardized including solutions for 6G-HRLLC and 6G-massive communications as defined in ITU-R usage scenarios. Vertical specific C-RAN and O-RAN concepts are also of great interest. The disruptive 6G enablers are related to THz range solutions may they be materials, devices, waveforms, signal processing or distributed data driven network control paradigms as well as immersive usage of AI in ICT systems. Further down the road, we expect to see quantum radios and sensors, multimodal joint sensing and communications, and Bio/Nano communications emerging.

4. Cloud EDGE

4.1. The needs and requirements for research in the field

SLICES-RI has the ambition to serve and onboard a wide range of communities in conducting research in the IoT/Edge/Cloud domains, while serving specific needs of verticals in terms of security/privacy, experiment reproducibility and more. To this end, SLICES-RI needs to provide configuration and management tools that can allow experimenters to operate and control a sophisticated computing infrastructure that spans multiple operators, domains, clouds, devices, and physical locations supporting diverse applications, services and heterogeneous compute resources. In the following, we refer to such multi-site, cross-domain, multi-operator, heterogeneous compute environment as Cloud Continuum (CC), and we discuss the key research challenges that SLICES aims to support in this area, as well as the preliminary set of actions that we have delineated to develop the tools necessary for facilitating experiments across the CC.

4.2. Identification of new JRAs to enhance the SLICES RI

4.2.1. Research goals and challenges

Effective and efficient **service provisioning at the edge** poses numerous technical challenges that are unique to distributed edge-cloud environments. Firstly, in contrast to traditional cloud deployment environments, edge clouds have **limited resources** and may not be able to satisfy all application demands. Efficient and trustworthy **cross-domain** and **cross-provider resource sharing**, while adhering to a plethora of technical and high-level requirements, remains an important open problem. Secondly, applications in this environment will have overlapping needs in terms of resources. This is further exacerbated by the convergence trends meant to make sure an end-user can access the services whether the user is in motion or not. Although the problem of coordination and orchestration has been extensively studied within cloud computing (resource-rich and homogeneous environments), **service provisioning on distributed and heterogeneous cloud-edge resources** while satisfying Quality of Service/Experience (QoS/QoE) constraints r**emains a challenging problem**. Thirdly, the design and development of these systems should not only focus on performance, which is an essential functional requirement, but also on the **privacy/security of cooperative services**. Edge and cloud resources can be collectively leveraged to create novel and disruptive data-oriented applications that are distributed such that they execute parts of their logic across the continuum. Practical large-scale deployments for data-oriented applications are limited as there is inadequate support to achieve this. Finally, currently, the most advanced interoperability model (e.g., GAIA-X interoperability model) is based on the definition of basic standard blocks: Container-as-a-Service for computing, file system access, identity management and other services. However, an effective unifying abstraction is required and essential to go beyond these basic blocks and pursue a **multi-level interoperability model** - hardware/software, compute/data, and business - gluing together the disparate resource islands into the umbrella of a single distributed system that supports flexible instantiation and adaptive and elastic execution of services.

From this basis, we can identify the following set of near-to-mid-term research challenges that the SLICES RI should aim to provide support to:

- **Uniform control plane solution over heterogeneous resources**: a central feature, especially if the controller has to work in a distributed way, including edge nodes and distributed virtualized compute/networking resources. The objective is to adopt and extend current frameworks to easily support service (resource) management over heterogeneous cloud-edge providers. The point is also to support this at a sufficiently high level of abstraction that is not too hard for experimenters to describe the distributed deployment and its requirements for the controller;
- **Inter-cluster coordination mechanisms**: aimed at providing (secure) communication support for cooperative services, e.g., decentralized & distributed AI workloads, deployed over geographically distributed resources, demanding efficient and flexible solutions for data path (re)configuration;
- **Data management**: supporting efficient handling of data (with different volumes, with different read/write requirements, with distributed caches, ...) by considering virtualized storage resources exactly as the other compute/network resources.

4.2.2. Preliminary plan of actions

The SLICES RI has established a dedicated Cloud Continuum working group (CC WG) to define a unified reference architecture for the CC component of the RI and a prototype implementation of such reference architecture using a subset of the technologies described in Section 4.3. The short-term goal of the CC WG will be to provide reference solutions to support a range of different development/deployment configurations, as it is crucial for the variety of scenarios of interest for the cloud-to-edge continuum community. We start considering simple scenarios with a single remote cloud-based cluster of virtualized resources hosting all the experiment components except for data fusion components deployed locally to sensors/actuators, but also more articulated ones where multiple cloud providers (public and private) host more computing/storage-intensive tasks, while others are more distributed over multiple MEC nodes and edge gateways, possibly by supporting the dynamic migration of experiment components in the cloud-to-edge continuum. In the mid-term we want to allow experimenters to instantiate experiment components over remote clusters of virtualized resources on different cloud providers and intermediary nodes in the cloud-to-edge continuum. Inter-cluster orchestration will be developed as the federation and extension of existing state-of-the-art orchestrators in order to maximize code re-usability and to minimize the experimenters' efforts towards new tools and coordination tools.

4.2.3. Identification of stakeholders

The CC component of the SLICES RI targets primarily the needs of the research communities working on virtualized networking/storage/computing resources on multiple heterogeneous clouds, on hybrid public/private clouds, on intermediary nodes, on Multi-access Edge Computing (MEC) nodes, and on on-premise gateways, e.g., for IoT sensors/actuators integration in Cyber Physical Systems experimentation.

4.3. Key technologies to enhance SLICES-RI

To enable experiments in the Cloud Continuum, methodologies for infrastructure/experiment provisioning and control via Infrastructure as a Code (IaaC) tools and distributed control of resources and data are paramount. In addition, coordination and communication in scenarios where collaborative applications, spanning multiple SLICES nodes, are present, demand the presence of tailored communication endpoints (L3-L7 agents) which can be set up and configured dynamically. As such, we deem the following technological pillars to be key to its success:

- **IaaC tools**: The SLICES RI software solutions that enable the management and provisioning of infrastructure resources using code and automation techniques. They allow developers to define, deploy, and manage infrastructure configurations programmatically, rather than manually configuring individual components. Thus, IaaC tools support the cloud continuum by providing consistent, repeatable, and scalable infrastructure deployments across different cloud environments and infrastructure platforms. Two popular Infrastructure IaaC tools are MaaS (Metal as a Service) and Terraform. The former is specifically designed for the provisioning and management of physical servers or bare-metal infrastructure, while the latter has a broader scope and supports the provisioning and management of various infrastructure resources, including virtual machines, containers, storage volumes, networking components, and cloud services.
- **Control plane** for compute/network/storage and application layer: The SLICES RI needs a unified control plane for managing infrastructure and services across hybrid and multi-cloud environments. Crossplane is a candidate technology for implementing such control plane as it allows users to define infrastructure requirements using declarative configuration files, which are then translated into API calls to provision and manage infrastructure resources across different cloud providers and platforms.
- **Coordination and communication**: The SLICES RI needs technologies and solutions providing capabilities for handling service-to-service communication within a distributed application architecture and for managing, and securing distributed applications and services across multiple cloud environments. Various technologies and approaches can be supported. For

instance, Submariner provides cross-cluster network connectivity and service discovery for Kubernetes clusters. It focuses specifically on enabling communication between pods and services deployed across different Kubernetes clusters, allowing them to seamlessly interact with each other as if they were part of the same cluster.

- **Multi-faceted interoperability model**: The SLICES RI needs to adopt to interoperability modes at all layers and domains of the CC. For instance, compatibility between data formats and standards across different cloud platforms enables seamless data exchange and integration. SLICES-RI must promote the adoption of open standards and specifications to be vendor-agnostic and facilitate interoperability.

4.4. Relevant standardization activities

There are several relevant standardization activities for cloud and edge computing, aimed at defining common frameworks, protocols, and specifications to ensure interoperability, portability, and security across cloud and edge environments. For instance, the Cloud Native Computing Foundation (CNCF) hosts several projects that provide standardization for container orchestration, service discovery, and monitoring in both cloud and edge environments.

The SLICES RI intends to adopt open-source standards solutions for the above-described technologies and tools. For this reason, the CC WG closely monitors the outcomes of these standardization activities to ensure continuous alignment.

4.5. Potential Impact on SLICES-RI

The inclusion of a cloud continuum experimentation component in the SLICES RI enables researchers to address emerging challenges and opportunities in cloud computing and edge computing domains. Furthermore, existing SLICES nodes already have deployed a wide range of diverse cloud technologies, from OpenStack clouds to Kubernetes clusters, from MEC-based mobile edge clouds to Stack4Things systems that allow to integrate IoT devices and data into cloud environments. Therefore, the establishment of a JRA to define a unified reference architecture for a multi-site, multi-cloud platform will be essential to combine together these heterogeneous resources and platform and allow researchers to explore new architectural paradigms, evaluate emerging technologies, and investigate novel solutions to future problems in the CC field.

5. Integrated sensing communication

5.1. The needs and requirements for research in the field

The vision of 6G is to integrate sensing with communication in a single system, which will serve as a distributed neural network (NN) for the future Intelligence of Everything. Network sensing and native Artificial Intelligence (AI) operations are the two key aspects to build the connected intelligence in 6G. For network sensing, the use of higher frequency bands – from millimeter wave (mmWave) up to THz, wider bandwidth, and massive antenna arrays will enable high-accuracy and high-resolution sensing, which can help implement the ISAC in a single system for mutual benefit. First, the entire communication network can serve as a sensor. The radio signals transmitted and received by network elements and the radio wave transmissions, reflections, and scattering can be used to sense and better perceive the physical world. The capabilities to obtain range, velocity, and angle information from the radio signals can enable a broad range of new services, such as high accuracy localization, gesture capturing and activity recognition, passive object detection and tracking, as well as imaging and environment reconstruction. This is the so-called "network as a sensor" paradigm. Second, the sensed information provided by these new services on the localization, detected objects, and environment knowledge via network sensing can help improve communication such as more accurate beamforming, faster beam failure recovery, and less overhead when tracking the channel state information (CSI). This is the so-called "sensing-assisted communication".

Last, but not least, sensing will be served as a "new channel" that observes, samples, and connects the physical world to the cyber world. Real-time (RT) sensing will become an essential enabler to make the concept of the digital twin (DT) — a true and RT replica of the physical world — a reality in the future.

Based on the former, there is currently a huge momentum related to the ISAC topic (it is for example the second most popular topic, after AI, in 3GPP), which is only expected to grow in the next years.

5.2. Identification of new JRAs to enhance the SLICES RI

5.2.1. Research goals and challenges

The capabilities of ISAC and relevant technologies are currently being explored in a broad range of studies, including channel modeling and co-design of the hardware by sharing the spectrum for both communication and sensing, research on different waveform and signal processing design or a joint design of both, and some early work on exploring multi-band and multi-static ISAC. But most of the current state-of-the-art (SotA) ISAC solutions primarily focus on a single wireless technology domain; i.e., researchers are mostly focused to work in either 3GPP or non-3GPP (like IEEE 802.11) environments, without a real integration of both worlds and, especially, without any coordination of multi-technologies in the RAN domain. However, the future 6G-RAN systems will not only work across multi-band (e.g., mmWave, sub-6 GHz, THz, new frequency ranges), multi-radio interface (e.g., OTFS or OFDM cellular radio interface) and multi-static (multiple non-collocated transmitters and receivers), but also needs to work across multi-RAN technologies (3GPP, non-3GPP including different Wi-Fi versions). Besides, in addition to the network sensing, there are also many other diverse sensor technologies such as LiDAR, cameras, radars, which have already been widely used for traditional sensing applications and services. To this end, a huge variety of heterogeneous sensing and network technologies will all coexist in the future 6G RAN systems.

The biggest challenge is how to manage such heterogeneity and fully integrate various sensing sources and ISAC technologies throughout the RAN up to the User Equipment (UE) across different layers of the RAN stack and thus explore the full potential of each sensor, each node, each band, each technology as well as their combination to achieve the maximum spectrum and system efficiency, energy efficiency and resource usage across the entire RAN system.

5.2.2. Preliminary plan of actions

SLICES-RI has identified ISAC as a key topic for future research in 6G, that could heavily benefit from experimental platforms.

The first action would be to conduct a first deployment of a set of sensing tools and equipment. SLICES-RI requires to extend its current capabilities to offer hardware (and software tools) capable of performing joint sensing and communication. The Post5G BluePrint can be used as starting point, while this will require significant work to be extended and/or maybe alternative approaches would have to be considered. Note that this might also involve adding to the existing hardware platforms, radio access with higher frequency bands, such as mmWave.

5.2.3. Identification of stakeholders

SLICES-RI targets primarily the needs of the research communities working on integrated sensing and communication, which encompasses main telco vendors and operators, as well as the research and innovation communities.

5.3. Key technologies to enhance SLICES-RI

SLICES-RI, after deploying a first platform capable of performing some simple integrated communication and sensing, will have to work on additional extensions to address relevant research and innovation problems in the area. Some non-limiting examples, currently identified by the research community as hot topics, are the following:

- Aggregation of perception data from multi-technologies and sensors. Recent advancements in AI, particularly Federated Learning (FL), promise to address the challenges of aggregating perception data from multi-technologies and sensors.
- Synchronization algorithms of multi-static systems and fusion of distributed raw sensing data. The use of monostatic ISAC transceivers in various applications demonstrated their effectiveness in radar applications, achieving obstacle detection at distances of over 100m. The implementation of bi-static and multi-static ISAC systems in scenarios where base stations (BS) communicate with one or multiple users has been explored in various studies.
- Data management of multi-sensorial sensing data and secure exposure to third parties. Privacy-conscious data management from a wide range of sensors is discussed in several works, which focus only on individual challenges. Data aggregation facilitating both structured and unstructured data execution would enable the direct execution of AI functions on stored data. Emphasizing privacy and trust, mechanisms are needed to incorporate privacy-preserving protocols and interfaces, including opt-in/opt-out mechanisms and user-triggered data access controls. Additionally, a holistic framework for secure, private, and trustworthy collection, processing, and exposure of sensing data, complemented by network functions, is also needed.
- Communication and sensing approaches using multi-band, OTFS-based, programmable environments and disaggregated architectures. A range of studies have explored the potential of Multi-band ISAC, leveraging the diverse physical properties of different frequency bands for more accurate and reliable sensing.
- Perception-driven handovers (HOs) and network selection. HO management and network selection can be significantly enhanced by integrating perception elements and exploring novel connectivity options.

5.4. Relevant standardization activities

There are two main SDOs heavily working on this area: the recently created ETSI ISAC ISG, and the 3GPP. It is expected that both SDOs would significantly benefit from having an infrastructure for experimental prototyping and validation.

5.5. Potential Impact on SLICES-RI

The inclusion of an integrated sensing and communication experimentation component in the SLICES RI enables researchers to address emerging and very timely challenges and opportunities in the area of using the network as a perception sensor that can work as a whole to perform sensing of devices and objects.

The Post5G BluePrint already uses hardware and software components that could eventually extended to investigate on ISAC. However, this needs to be further analyzed and might potentially need of additional, ISAC-centric, hardware for more complex testing. There is therefore the need to coordinate among the interested partners and sites to facilitate and speed up the potential enhancement of SLICES-RI to support experimentation on ISAC.

6. Security

6.1. The needs and requirements for research in the field

Security aspects have not been yet sufficiently covered by SLICES. However, SLICES partners recognize the importance of security in modern communication and computing systems. Several aspects of security have been investigated, including security of Open RAN, inclusion of Artificial Intelligence (AI) into 5G/6G networks, potential integration of quantum communication in 5G/6G networks, as well as distributed ledger technology as a means to achieve transactions in communication and computing platforms.

The following section details some initial investigations and results of potential R&D activities as part of SLICES, including impact of these activities on the SLICES infrastructure. The list of initial findings is narrowed down to specific actions, which can be undertaken by SLICES partners, but it can be further extended, as security as such covers wide range of ICT activities.

6.2. Identification of new JRAs to enhance the SLICES RI

6.2.1. Research goals and challenges

The O-RAN ALLIANCE organization started work on the **security of the Open RAN** solution some time ago. The security aspects of Open RAN concern both the security of the Open RAN infrastructure itself (DU, CU, RIC) as well as the use of Ne-ar-RIC mechanisms to detect and eliminate threats. In March 2023, the O-RAN ALLIANCE WG11 published specifications, which can be divided into four groups: i) security threat models, ii) security requirements, iii) security protocol recommendations and iv) security tests. The listed specifications cover issues such as O-RAN security requirements, O-Cloud security, service management and orchestration security, shared O-RU security, and Near Real-Time RIC and xApps security. The new architecture proposed under Open RAN, despite new capabilities offering greater flexibility and efficiency, has also created new security challenges in the network.

In the context of **security of data processing at the network edge using Artificial Intelligence and Machine Learning** the main research objective would be to develop systems, algorithms and Machine Learning models to analyze network traffic between end devices, the edge cloud and the central cloud in order to identify and combat potential attacks and threats. Data security at the network edge is particularly important in the context of federated learning. In federated learning, sensitive customer data is stored on devices and used to teach the model, while not being shared with third parties. Therefore, data transmitted over a Post5G/6G network will be particularly vulnerable to attacks. The integration of Artificial Intelligence (AI) and Machine Learning to detect potential attacks and threats to a user’s or service provider’s sensitive data is already being used in similar tasks, such as detecting payment irregularities. AI algorithms are able to analyze network traffic in real time and detect all events that do not conform to learned patterns, while being able to take appropriate steps, such as blocking an intrusion or informing about a potential attack.

Post5G and future 6G networks are planned as the backbone of wireless networks and related services for a wide range of users. An important element of these networks will be the development and application of advanced technologies related to data security such as **quantum key distribution** (QKD). This technology allows the generation, transmission and management of keys, which can then be used to encrypt transmitted user data or other services related to user authentication. The 6G network is also intended to support quantum communication networks for distributed quantum computing infrastructures. An important aspect is also the use of quantum computing and quantum machine learning technologies to optimize the operation and configuration of Post5G and 6G networks. The topics of security and data privacy are central to the design and development of Post5G and 6G networks. Computing and, in particular, quantum communication technologies offering a new approach to ensuring the security of the communication channel using principles described by quantum mechanics are part of this element. The security and energy efficiency of quantum networks are superior to current solutions because quantum networks, theoretically, can work with single photons whose quantum states remain undisclosed in the transmission from source to destination.

Post5G/6G technology aims to revolutionize network communications, offering extremely high speeds, extremely low latency and security and reliability. It is a natural evolutionary step after 5G technology with the promise of even greater possibilities. In a world where data plays a central role in decision-making and value creation, maintaining its integrity, privacy and security is an overriding priority. With the potential for cloud-based computing and distributed data processing at the edge of the network, Post5G/6G technology has the potential to transform many industry sectors. Furthermore, the evolution of communication technologies such as Post5G/6G implies the need for new data management models. Thus, providing efficient verification methods and avoiding centralization is key. The use of **blockchain technology** can address these challenges by creating a secure and transpacific environment for data and transactions in Post5G/6G networks. In an era of digitalization and automation, research into the **integration of smart contracts in a Post5G/6G environment** is key. Smart contracts can enable automated transaction processing, reducing delays and costs. They can make business processes more seamless and automated. By using blockchain technology to manage these contracts, greater transparency and resilience to network manipulation can be provided.

6.2.2. Preliminary plan of actions

Security in Open RAN networks

The research work related to the research objectives will be carried out as a programme of successive research activities. As a first step, activities will be undertaken related to the analysis of studies and guidelines provided by O-RAN ALIANCE, in particular by O-RAN WG11. The work of this group focuses on the analysis and definition of threat models for Open RAN, as well as the definition of security measures and policies in the zero-trust model. Based on the analysis of the available material, new threats to the Open RAN system and their impact on the system could be developed. The work envisaged in this part also includes an attempt to simulate new threats to the infrastructure of the Open RAN system. The next stage of the planned work envisages the use of RICs to implement critical security functions that can be used to create more complex services in a programmable manner. At this stage, it will be important to determine the vulnerability of elements of the Open RAN architecture and implanted xApps and rApps using data to train Machine Learning models. An important research objective is to develop models for detecting and preventing attacks on the O-Cloud infra-structure. The research programme may envisage the development of methods, based on research on real infrastructure, to prevent attacks that violate the functions of the virtual network during the creation of their image or snapshots, and to detect the misuse of containers or virtual machines for attacks on other entities in the network.

Security of data processing at the network edge using Artificial Intelligence and Machine Learning

The first stage of the research should be an extensive analysis of the available literature on possible attack vectors over the network, with a particular focus on Post5G/6G networks. This will identify the requirements for the next stages. The next stage of the research programme will be the collection of relevant training data. For this purpose, a test suite should be developed, taking into account the edge cloud and reflecting communication scenarios in future Post5G/6G networks. The next item on the agenda will be to simulate attacks on the network and collect the necessary data to develop a benchmark. Based on the collected data, a deep neural network architecture can be developed. In this step, special attention should be paid to high imbalanced data, as there will be far fewer instances of potential attacks than instances of normal operation, which may lead the algorithm to desist from indicating a fragment as an attack. The final stage will be to implement the system, followed by detailed monitoring of its performance and analysis of the model's decisions with conclusions. The data collected will be used again in training the same model so as to improve its effectiveness (model fine-tuning). The process will be repeated several times, depending on the volume of data collected and the needs of the system.

Quantum Key Distribution

The development and deployment of quantum technology solutions for Post5G and 6G networks presents a number of challenges, which are indicated as research areas:

- Integration of Software-Defined Networking solutions with QKD and their deployment in Post5G and 6G networks for control and monitoring of key management infrastructures,
- Adoption of DV-QKD and CV-QKD solutions for different types of backbone links in Post5G/6G networks tailored to different types of topologies and link coverage.
- Integration of solutions developed in QCI networks, such as EuroQCI, into Post5G/6G networks – standards, architecture, operating procedures.
- Implementation of quantum wireless communication solutions (also QKD) in Post5G, 6G networks.
- Integration of satellite-based QKD solutions planned for infrastructures such as EuroQCI into Post5G/6G networks.
- Implementation of post-quantum encryption algorithm solutions (based on current standardization plans) in Post5G, 6G networks.
- Development and implementation of solutions for QKD key generation and management for IoT scenarios in Post5G and 6G networks.
- Development and implementation of Authenticated Quantum Direction Communication solutions for Device-to-Device communication scenarios.
- Broad synergies between quantum communication system and classical telecommunication technologies.

Blockchain technologies

In the context of increasing digitalization and the potential of Post5G/6G and blockchain technologies, it is necessary to define clear research directions. With the goals and challenges of future networks in mind, the research programme takes a comprehensive approach to the topic. The programme is geared towards identifying and exploring key areas of interaction between the two technologies. The following are the key elements of our programme that mark the path of our future research.

- **In-depth analysis of the current situation**

  An in-depth analysis of the current guidance for Post5G/6G and blockchain technologies will identify key gaps and needs in both technologies and enable the identification of new research areas. Based on the analysis, further research directions will be identified.

- **Investigating attacks and threats**

  Detailed analysis of potential attacks on Post5G/6G – blockchain interfaces is necessary. Understanding these threats will enable the development of more resilient and secure defense mechanisms against attacks. Digital security is one of the highest priority aspects in modern networks.

- **Development and optimization of smart contracts**

  The research programme could focus on the development of smart contracts tailored to the demands of Post5G/6G networks. Appropriate contracts can provide greater efficiency and security in Post5G/6G networks. These technologies could become the norm in future communication networks.

- **Privacy protection**

  Develop advanced privacy protection mechanisms using the latest technologies and methods. Privacy is key to enhancing user trust, and ensuring it in a Post5G/6G environment is essential. The research programme is behind the use of modern cryptographic methods and blockchain technology to develop privacy protection methods.

6.2.3. Identification of stakeholders

Potential stakeholders of R&D activities may include (but not limited to) researchers from industry and academia, specialized in security. Moreover, key partners from Horizon Europe projects from the track of 5G/6G networks and Security are potential candidates for future collaboration with SLICES partners.

At the same time, SLICES partners, who already work in the security area (including quantum) can be interested in further development of these technologies to increase capabilities of the SLICES Research Infrastructure and develop the RI in compliance with recent security standards and recommendations.

6.3. Key technologies to enhance SLICES-RI

6.3.1. Quantum communication

Communication using quantum technologies is attracting a great deal of interest in current research and development. Recently, quantum computing (Quantum Computing) has become a reality and is envisaged as one of the paradigms of 6G networks and planned for deployment within the next decade. The 6G network is expected to meet even more stringent requirements, such as much higher data transmission and processing speeds as well as improved security and quality assurance mechanisms. These assumptions are driving the potential use of quantum techniques currently under development. The driving force behind quantum techniques is the use of traditional physics concepts, i.e., photons to process calculations on quantum qubits. The qubits are then sent from a transmitting (or emitting) machine to a receiving machine. The use of qubits in communication brings enormous benefits, such as faster computation and communication, quantum teleportation, security of communication and low transmission loss in communication.

6.3.2. Blockchain

Blockchain is a type of distributed ledger, which is maintained in a decentralized manner by the underlying P2P network of nodes. As the name implies, blockchain comprises of series of blocks of transactions that are logically chained or linked together to form a digital ledger. Blockchain promises to solve the issues such as exclusive peer-to-peer transactions without centralized third parties, fraudulent replication of digital asset/value or transaction, establishing trust with pseudonymity, transparent yet immutable record-keeping, provenance and auditable enabled distributed ledger, and digital signing and execution of legal agreements (between parties) in the form of softwarized contracts.

6.4. Relevant standardization activities

There are several standardization organizations for mobile networks:

- **3GPP**. Security in particular is addressed in the 3GPP security group SA3. This group is responsible for definition of the security architecture as well identification of requirements and protocols for security and privacy in 3GPP systems.
- In turn, **IETF** concentrates on security protocols (e.g., IPsec, EAP, TLS), which have been incorporated in the 5G security architecture.
- Additionally, **ETSI** ISG NFV defines security for network virtualization.

6.5. Potential Impact on SLICES-RI

Several partners of SLICES-RI already invested in testbed equipment and research activities in the area of network/compute security. Better coordination of joint research activities may result in new services for the community of researchers and scientists.

7. Sustainability and Greening the Research Infrastructures

7.1. The needs and requirements for research in the field

The growing threats posed by global warming make it critical to reduce the carbon footprint of human activities. While many experts believe that we are not only in the 24th hour, but that the rise in temperature above the critical level is irreversible, we have a duty to do all we can to slow the process as much as possible, buying time for societies to better prepare for living conditions that are radically different from today's. In particular, reducing the environmental impact of digital infrastructures must be a priority, as they now account for 3-4% of total global greenhouse gas emissions and are estimated to triple between 2020 and 2050, making them a very significant part of the total environmental burden.

The main (but not the only) cause of environmental pressures, including greenhouse gas emissions, is the energy consumption needed to run infrastructure.

The operation of digital research infrastructures such as SLICES can sometimes be very energy-intensive (e.g. HPC, HTC, high-capacity cloud-based, GPU-accelerated infrastructures, distributed systems with a large number of endpoints and nodes, etc.) It is therefore of particular importance to design, build and operate these infrastructures with energy efficiency in mind, and even to support their use by ensuring that experiments are carried out in an optimal way in terms of energy consumption and that users make a conscious effort to minimize the carbon footprint of their research infrastructure related activities.

This calls for an energy assessment of the SLICES infrastructure. Methodologies must be developed to ensure that energy efficiency aspects are taken into account at the design stage of the infrastructure and, of course, during its operation.

7.2. Identification of new JRAs to enhance the SLICES RI

7.2.1. Research goals and challenges

The aim of the research is to develop methods to apply energy efficiency aspects in the design and operation of the infrastructure. It includes the identification of the parameters that can be measured and continuously monitored to follow the energy consumption (GHG emissions) of the infrastructure in real time and the optimization of the operation according to energy efficiency aspects. Using the metrics developed, algorithms can be implemented that automatically take into account energy efficiency aspects, e.g., in resource allocation, load balancing, task scheduling, communication, etc.

Of course, it is not only data from the IT components of the infrastructure that is needed, but also environmental parameters, data center parameters and even information from energy suppliers regarding the actual energy mix, etc.

In processing the monitored data, the use of machine learning and artificial intelligence algorithms should also be explored.

7.2.2. Preliminary plan of actions

In greening SLICES, three major factors should be addressed that define and influence the SLICES environmental and climate impact. This includes 1) physical digital infrastructure including the involved datacenters and computer networks, which are the main factor of energy consumption, 2) provider tools that allow for energy and efficiency monitoring, 3) user tools and individual research environment that can be a strong factor of reducing energy consumption by optimal design of the scientific workflows and minimizing resources usage by supporting research reproducibility and optimizing research data management with impact awareness.

The first step is to investigate what kind of data the SLICES nodes (important SLICES infrastructure elements) can provide on energy consumption, energy efficiency, environmental parameters, load, available energy mix, etc., and what common metrics can be developed to provide information for decision making and reporting that can be managed, processed and archived in a uniform way.

The next step is to investigate what interventions and decisions can be made using these parameters in order to reduce the environmental impact via improving the energy efficiency in resource allocation, load sharing, scheduling, execution, data staging and communication.

Finally, reporting and feedback mechanisms should be developed to inform both infrastructure managers and users about the environmental burden of the scientific workflows and to support their efforts in optimization.

7.2.3. Identification of stakeholders

The main stakeholders are 1) the HW and SW operators of the SLICES nodes (including the data center operators) who are responsible for the efficient, environmentally friendly operation of the infrastructure, and 2) the users of the SLICES infrastructure, who are expected to use the infrastructure in a conscious and responsible way, providing them with all the necessary information and support.

7.3. Key technologies to enhance SLICES-RI

Key technologies to enhance the sustainability of SLICES-RI are new **supporting tools** for the operators of the SLICES nodes and users of the infrastructure to continuously **monitor** their **energy consumption** and implied **environmental impact**, as well as automated and **energy-aware orchestration** of complex service meshes across the RI to reduce the resource usage footprint and induced energy consumption. This is supported by the development of **common metrics for environmental impact monitoring** the hardware components (e.g., computing resources, storage, network devices, 5G functions etc.) complemented by **energy-aware resource allocation** and task scheduling systems for lower and greener energy consumption. It may also involve **tasks/workflow and storage optimization** on the RI and adaptive data preprocessing/caching and tasks offloading mechanisms controlled from scientific applications. It is also necessary to provide **tools and methodology for the evaluation, assessment and reporting** of the environmental impact according to ISO 14000 standards.

7.4. Relevant standardization activities

The importance of energy efficiency and environmental awareness of digital infrastructures is reflected in the number of standards, standardization efforts and standardization organizations that deal with it. A few of the most relevant are highlighted: Global Reporting Initiative (GRI), EU Eco-Management and Audit Scheme (EMAS), ISO 14000 family of standards related to environmental management, the European Committee for Electrotechnical Standardization (CENELEC), EU Code of Conduct for Energy Efficiency in Data Centers (EU DC CoC)

7.5. Potential Impact on SLICES-RI

The greening of SLICES-RI with all available tools and technologies leads to two important results. On the one hand, the infrastructure itself and its operation will become greener and more sustainable, and on the other hand, the new digital applications and technologies experimented with using the infrastructure will become more energy efficient, reducing the environmental footprint of all the solutions and products that will incorporate them. This will help to meet global climate change targets and can also make the applications developed more cost-effective and competitive.

8. Experiment reproducibility

8.1. The needs and requirements for research in the field

Reproducibility is an important topic for scientific research, acknowledged by different organizations such as the IEEE[2] or ACM[3]. Multiple measures are currently being implemented by these organizations to foster the creation of reproducible research.

Such initiatives include badges that can be awarded to authors of papers that publish and document their experiments. The awarding process is typically managed through Artifact Evaluation Committees where committee members check the provided artifacts, evaluate their quality and award badges. US-based testbeds such as CloudLab.us[4] or Chameleon[5] started to prepare their platforms for hosting reproducible experiments to simplify the artifact evaluation process.

Despite the awareness and the conviction of the community that reproducibility is a highly valuable goal, creating reproducible experiments still is a time-consuming process. Reproducing experiments also remains an effortful process.

[2] https://journals.ieeeauthorcenter.ieee.org/create-your-ieee-journal-article/research-reproducibility/ [Last accessed 25 June 2024]
[3] https://www.acm.org/publications/policies/artifact-review-and-badging-current [Last accessed 25 June 2024]
[4] https://docs.cloudlab.us/repeatable-research.html [Last accessed 25 June 2024]
[5] https://chameleoncloud.readthedocs.io/en/latest/technical/daypass.html [Last accessed 25 June 2024]

8.2. Identification of new JRAs to enhance the SLICES-RI

8.2.1. Research goals and challenges

The efforts of the computer science community at large shown by the ACM and IEEE-driven initiatives towards reproducibility show the high value that is associated with reproducibility. However, the effort to create reproducible experiments is high and therefore often neglected, despite the previously mentioned efforts.

We address this issue through the creation of a framework that lowers the effort to create reproducible experiments for experimenters. We called this framework the plain orchestrating service (pos)[6]. This framework supports the experimenter by providing a specific template to create reproducible experiments. This well-defined template specifies a fully reproducible experiment workflow that can be executed using the pos framework. This means that all the steps of the experiment are fully automated and the framework takes care of the execution without requiring the experimenter to perform specific steps.

8.2.2. Preliminary plan of actions

For SLICES-RI we plan to implement the pos framework to provide this reproducibility-by-design feature for SLICES experiments forming the SLICES/pos framework. Reproducibility is a feature that is fundamental and should be available for all experiments. The integration of the SLICES/pos framework ensures that reproducibility is a feature that is provided from the beginning, i.e., it becomes an integral part of the SLICES/pos experiments rather than an optional feature that may or may not be added at a later point in time.

We already demonstrated that the portability of the SLICES/pos workflow[7]. We adapted the SLICES/pos framework to run on frameworks that drive the CloudLab and Chameleon testbeds. Using this approach, SLICES/pos experiments could be executed on these testbeds without the need to adapt the original experiment code. This means that experiments can be reproduced across different platforms without manually adapting the original experiments. This feature also ensures that SLICES/pos experiments can be executed on a set of diverse, already-existing platform and still maintain its reproducibility property.

8.2.3. Identification of stakeholders

Reproducibility is relevant for all stakeholders of SLICES. Scientific users profit from a platform that supports and simplifies the creation of reproducible experiments. The scientific community profits as experiments can be easily reproduced by re-executing the automated SLICES/pos experiment.

The SLICES testbed and framework will also be available for students. This raises the awareness for reproducible research in the future generation of scientists and software engineers. The release of experiments and experimental results helps bring state-of-the-art environments, such as the SLICES Post5G BluePrint, into the hands of students. The Post5G BluePrint can be (re-)created reproducibly creating a consistent foundation for experiments.

The SLICES pos experiment workflow can be used to create specific configurations, such as known error states, reproducibly. This feature can be used for recreating real-world environments and debug the error states without impacting the production environment. This consistent reproduction of well-

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[6] Sebastian Gallenmüller*, Dominik Scholz*, Henning Stubbe, Georg Carle, "The posFramework: A Methodology and Toolchain for Reproducible Network Experiments," in The 17th International Conference on emerging Networking EXperiments and Technologies (CoNEXT '21), Munich, Germany (Virtual Event), Dec. 2021.

[7] Henning Stubbe, Sebastian Gallenmüller, Georg Carle, "The pos Experiment Controller: Reproducible & Portable Network Experiments," in 2024 19th Wireless On-Demand Network Systems and Services Conference (WONS), 2024, pp. 1–8.

defined configurations, across different nodes in a network will help establish SLICES testbeds as a powerful tool for debugging or prototyping for industrial users.

8.3. Key technologies to enhance SLICES-RI

Reproducibility is a key feature of experimental research that can be achieved through a time-consuming process. The SLICES pos framework establishes a well-defined workflow that, if experimenters adhere to the template, creates reproducible experiments by design. This is a significant benefit over other testbeds and testbed frameworks that put the burden of creating reproducible experiments on the experimenter. We plan to further develop the pos framework and offer it as a key service in the future SLICES-RI platform.

To ensure fully reproducible experiments additional services are required. For instance, a monitoring and logging of specific features of the testbed at the time the experiment was executed, e.g., the network or specific hardware configurations. Netbox is a tool that provides such a database. Experiments can query this database and save the configurations as part of the experiment results for later analysis.

An additional related service records metadata and provides data management services, which will be explained later in this document.

8.4. Relevant standardization activities

To the best of our knowledge, there is currently no standard or a standardized approach that provides the features of the pos controller: the specification of experiments to ensure reproducibility by design. However, we are aware of existing testbeds and tools that testbed users are used to. Therefore, we created the SLICES pos framework to incorporate existing tools and testbeds.

The SLICES pos framework is designed to keep the self-developed tools and APIs to a minimum and use established tools where it is possible. The experimental workflow was also designed with this philosophy in mind. This led to a flexible workflow that can be programmed in any programming language that the experimenter prefers. A few notable tools that we suggest to use are:

- Ansible, to describe and deploy system configurations
- git to maintain code and for tracking different versions of experimental code
- Jupyter notebook to define and perform the evaluation of measurement results
- zenodo and Github to release and publish experimental workflows

Other testbeds, such as CloudLab and Chameleon use specific APIs to define experiment workflows. The SLICES pos framework defines another API. However, we demonstrated that the experiment controller of the framework can be adapted to run on other testbeds. Through this adaptation of the framework, the same experiments can run on different testbeds without the need to change the experiments themselves. Through this feature, we can reproduce experiments across different testbeds. For the future, we plan to keep the set of recommended tools up-to-date. The SLICES/pos workflow is also flexible enough to incorporate new tools if needed.

8.5. Potential Impact on SLICES-RI

Defining and making reproducibility one of the key properties of SLICES experiments creates a feature that differentiates the future SLICES-RI platform from any other available platform. While these platforms may be used for reproducible research, it is neither easy nor guaranteed to be achieved.

Through the specific design of the SLICES/pos experiment workflow, the reproducibility becomes an integral part of experiments from the begin. Reproducibility will become a native feature of each experiment on the SLICES-RI platform creating a significant scientific benefit for all its users, academic or industrial users alike. Despite this structured approach, the workflow is flexibly designed to allow the inclusion of various widely-accepted and widely-used tools and services, such as Ansible, Git, Jupyter, or Zenodo. This lowers the entry barriers for new users through the integration of well-known interfaces and toolchains supporting the usage of the SLICES-RI platform.

9. Artificial Intelligence

9.1. The needs and requirements for research in the field

Providing access to research focused on the intersection between distributed systems and AI is a must for SLICES. The original angle we consider necessary for SLICES is to support research in the emerging field of pervasive AI. Many factors are nowadays pushing for combining conventional approaches to AI (based on advanced algorithms run in data centers on very large-scale datasets) to more decentralized forms of AI. This is a requirement put forth by the pervasiveness of data generation at the edge of the network, real-time requirements, data privacy, confidentiality and sovereignty. Pervasive Artificial Intelligence (PAI) integrates centralized and decentralized computational resources, focusing on various forms of federated learning technologies. This approach allows for collaborative AI model training and inference tasks across multiple devices, allowing users to control data distribution, access patterns, and ownership constraints. Foreseen technological innovations include transitioning from centralized AI solutions to decentralized forms, designing support tools for network data transfer and computational optimization supporting a functions-as-a-service (FaaS) paradigm. The innovations also include extensive monitoring systems for the training phase and the deployment of AI models in real-time.

In addition, for an infrastructure like SLICES it is fundamental to support specific research on Generative AI models, which are also evolving at an incredibly fast pace. SLICES services should include AI-powered researcher assistant tools that leverage Generative AI benefits for optimizing access to the overall SLICES service ecosystem. On the other hand, it should support forthcoming generations of Generative AI approaches, not focused exclusively on Large Language Models, but integrating multimodal data sources, and supporting decentralized ways of training and using Large “Whatever” Models.

Last but not least, embedded AI is a key research topic high in the research priorities of the community. This matches the decentralization of AI implied by pervasive AI approaches. Specifically, as AI becomes more and more distributed, it runs also on edge devices, which may have less predictable behavior and significantly higher resource constraints as opposed to large data centers. SLICES should also support, therefore, research on resource efficiency in pervasive AI, both at the training and at the inference stages.

9.2. Identification of new JRAs to enhance the SLICES-RI

9.2.1. Research goals and challenges

They key challenges we aim to support in the area of AI are summarized as follows, following directly from the needs identified in Section 9.1:

- Novel forms of **federated learning**, also considering decentralized approaches where a large number of devices train models on partial data and cooperatively exchange obtained knowledge without any central controller.
- **Resource-efficient AI at the edge**, whereby AI models are trained and executed taking into account resources available at edge nodes, in terms of energy, memory, computation, storage.
- **Large "Whatever" Models**, supporting novel forms of generative AI not limited to LLM only, but trained on multimodal data, and possibly in decentralized settings.
- **Generative AI** for networking experimentations, i.e., augmenting the SLICES service offering with Generative AI tools assisting experimenters to navigate the SLICES resources and automatically configure their experiments.

9.2.2. Preliminary plan of actions

Plans are already in place for all the challenges highlighted above. The outcomes of these activities are going to be integrated into specific SLICES services. Specifically:

- **Federated learning**. SLICES (in the framework of the SLICES-PP project) has already started a Working Group on this topic. In addition, SLICES groups are working on supporting experiments in this area that require the combined integration of tools to virtualize distributed resources, connect them via appropriate network services, and host advanced AI algorithms for decentralized ML (e.g., LLMs). The service will allow researchers to configure such decentralized systems in an easy way (abstracting away many technical details) and focus on their core interest, possibly ranging from the performance of the underlying distributed system, the behavior of the network components, to the emerging behavior of decentralized AI algorithms.
- **Resource-efficient AI at the edge**. We plan to support researchers in developing algorithmic and network solutions for data-intensive platforms, especially those facing resource constraints like memory, energy consumption, time efficiency, and bandwidth utilization. It is particularly relevant for embedded AI solutions on far-edge devices and dynamic software environments where user needs, hardware availability, and workloads change over time. The service involves advanced resource virtualization at both individual node and network levels, leveraging emerging hardware accelerators for data processing and storage. Optimized AI techniques will be used to reduce model complexity, with consideration for Tiny-ML methods.
- **Large "Whatever" models**. We plan to exploit advanced network configurations and appropriate data management technologies to support research into how to develop generative AI models in decentralized settings, possibly including edge devices with limited resources. Support for multi-cluster service exposure will be provided in order to train LLMs with a subset of the data (preserving the sovereignty of the data at each site), and aggregated centrally in an overall model. Dynamic and efficient placement of the inference functions will be considered within the multi-cluster setup, in order to support low-latency prompt responses, depending on the requirements of each end-user.
- **Generative AI for networking experimentations**. A first component under development enables direct feature extraction from human-friendly logs gathered across components of the 5G network. It is tailored for the distributed operation of the 5G Core Network, designed with a service-based architecture. Utilizing LLM agents, the service parses logs from various components, conducts distributed processing, and performs feature extraction and dataset generation. By automating these tasks, it accelerates research in telecommunication networks, reducing the need for manual data labelling and lowering barriers for new researchers to understand and extract valuable insights from complex systems. The service

facilitates easier analysis of experiment logs, particularly concerning the impact of network parameters.

9.2.3. Identification of stakeholders

The main stakeholders for such extensions are identified as follows:

- Networking researchers, considering the impact of network configurations on decentralized AI;
- Complex-network researchers, focusing on the large-scale impacts of decentralization of AI algorithms;
- AI algorithm designers, focusing on testing novel algorithmic solutions for pervasive AI;
- Embedded AI researchers, focusing on the specific aspects related to resource efficiency of pervasive AI at the edge of the network;
- Networking researchers in general, exploiting GenAI tools for the automatic configuration of their experiments.

9.3. Key technologies to enhance SLICES-RI

To support these research activities, the nodes and sites of the RI need to be equipped with appropriate components to support decentralized AI. This involves, for example, resource-constrained devices of different kinds (e.g., personal devices, IoT devices, industrial IoT).

From a software standpoint, SLICES needs to integrate reference frameworks for pervasive AI, such as flower.ai, as well as tools to support GenAI research (such as APIs to Large Generative Models).

9.4. Relevant standardization activities

The emphasis on standardization for this type of activities is less strict than with respect to more "conventional" networking areas, and therefore we do not see this as a particular issue for the development of these services.

9.5. Potential Impact on SLICES-RI

Integration of these services can open up SLICES to a very significant and large community of researchers, already identified as stakeholders in Section 9.2.3. In addition, it will allow all SLICES users to benefit from advanced GenAI tools to better support their experimental needs.

10. Metadata and data management

10.1. The needs and requirements for research in the field

The storage and the publication of open-source experiment data and metadata represent for the SLICES Research Infrastructure an important service to be delivered by the SLICES partners. Indeed, this service will allow the management of the data and metadata for their whole lifecycle in the SLICES RI. Different needs were identified in particular the publication of data and related metadata in the EOSC marketplace and the implementation of the MRS (Metadata Registry System). This service should allow the importation and the exportation of datasets with the associated metadata. The data management is a research priority, taking into account the huge amount of data generated by the Internet of Things devices and other cyber-physical systems deployed in a distributed way such as the edge, at the fog and at the cloud.

The SLICES-DS D4.5 deliverable named "SLICES infrastructure and services integration with EOSC, Open Science and FAIR: Recommendations and design patterns (final report)" provides the description of the different steps included in the whole experimental research lifecycle concerning the data management. The data collection and storage are the starting point, followed by the data processing. The final steps are the lineage and provenance of the data, and of course, the data publication and archiving. Furthermore, the SLICES-DS D4.3 deliverable has already presented an initial definition of the metadata, taking into account the FAIR principles and Open Science.

A data management infrastructure (DMI) is required and its requirements have been specified as follows:

- Distributed data storage and experimental dataset repositories should support common data and metadata interoperability standards, in particular common data and metadata formats.
- SLICES DMI should support the whole data lifecycle.
- SLICES DMI shall provide persistent identifiers (PID) and FAIR Digital Object (FDO) registration and resolution services to support linked data and data discovery that should be integrated with EOSC services.
- SLICES DMI must support trusted data exchange and transfer protocols that allow policy-based access control to comply with the data protection regulations.
- SLICES DMI must enforce user and application access control and identity management policies adopted by SLICES community.
- Procedures and policies must be implemented for data curation and quality assurance.
- Certification of data and metadata repositories should be considered at some maturity level.

10.2. Identification of new JRAs to enhance the SLICES RI

10.2.1. Research goals and challenges

One of the challenges in the domain of data management is to find the right compromise between moving the data and moving the computation, in particular if the cost and the energy efficiency are considered as very important parameters.

A second objective is to ensure the correct adoption of Open Science and Open Access and also, the FAIR principles. The concept of SLICES FAIR Digital Object (S-FDO) has been presented notably in the SLICES-DS D4.5 deliverable and it should be implemented in the next phases of the SLICES RI.

10.2.2. Preliminary plan of actions

The first action to be taken is to implement the Metadata Registry System (MRS). The SLICES Research Infrastructure should store metadata from internal and external digital objects. Examples of internal digital objects are equipment, experiment nodes, projects and internal services. External digital objects are for instance open publications, datasets, services, tools, experiments and trainings. The MRS is composed of three parts: a repository containing all the data of the metadata and their models, a set of APIs enabling the discovery, the reporting and the interoperability, in particular with EOSC, and a Web portal to access this service and the related dashboards. Of course, the MRS should be fully compliant to the FAIR principles. Furthermore, the exportation of data and metadata to common formats, such as DublinCore, DataCite and RDA, should be supported by the MRS.

10.2.3. Identification of stakeholders

The stakeholders involved in the SLICES-RI initiative are the researchers using the different SLICES RI services, the testbed/research infrastructure providers and managers, and the EOSC community. The researchers can work for universities, colleges, research institutes, enterprises and SMEs. Of course, the scientific research community working with open data is also a good stakeholder, in particular in the context of research and development involving the digital science.

10.3. Key technologies to enhance SLICES-RI

A key technology to improve the SLICES Research Infrastructure is the SLICES Fair Digital Object (SFDO) already described in the SLICES-DS project. It should be compatible with EOSC. A mapping between the SLICES SFDO and other data and metadata models should be maintained during the whole duration of the SLICES RI. The structure of SFDO is very similar to the RO-Crate structure and can benefit from the developments done by the community working on RO-Crate. Then, it will be possible to export the SFDO metadata model to the RO-Crate one.

10.4. Relevant standardization activities

The standardization activities can be undertaken in relation with EOSC. Other possibilities to realize standardization contributions are the different initiatives and alliances specifying and promoting open data and metadata formats used by the research community at the European level and worldwide.

10.5. Potential Impact on SLICES-RI

Different possibilities of exploitation can be already expected. For instance, data of experiments made available directly to the relevant scientific community can be used by the researchers in their research and development. New products and ideas can emerge from post-experiment processing of the experiment data, leading the way to a commercial exploitation. Finally, open-source exploitation is of general interest for several communities.

11. Internet of Things

11.1. The needs and requirements for research in the field

The identified needs and challenges related to the Internet of Things are the interoperability and the integration through the communication protocols used by the IoT devices. An IoT experiment conducted in the SLICES Research Infrastructure could for example gather data related to IoT from various data sources like IoT sensors, legacy platforms, open data platforms. The scalability in the context of the Internet of Things is also an important requirement to take into account in the SLICES RI. Furthermore, IoT is also an important element in the network architecture encompassing the cloud, the fog and the edge computing. Indeed, the data processing can be done in these different places in function of the needs and requirements of each particular use cases involving the Internet of Things. IoT requires from the SLICES Research Infrastructure a good data storage, an efficient data management and data processing capacities.

11.2. Identification of new JRAs to enhance the SLICES-RI

11.2.1. Research goals and challenges

The SLICES Interoperability Framework (SLICES-IF) was defined in the SLICES-DS D4.2 deliverable and it should support in the SLICES-RI large-scale experiments involving IoT data which could be potentially published through EOSC for instance. Different kinds of experiments should be conducted in the SLICES RI like the testing of applications linked to IoT, ubiquitous IoT networks, the interoperability and the integration of IoT sensors into a dedicated infrastructure. A Joint Research Activity (JRA) could be potentially organized to find and develop concrete solutions to support in an efficient way these IoT experiments.

11.2.2. Preliminary plan of actions

A first action related to the Internet of Things is to study which possible IoT components could be incorporated in the SLICES-RI to ease the experiments involving IoT. A second action is to use an experiment generating IoT data to test and validate the SLICES Data Management Infrastructure (DMI). Indeed, the requirements from the IoT domain are very connected to an efficient management of the data generated by the heterogeneous IoT devices. Such an experiment can validate the whole lifecycle of the data flow in the SLICES Research Infrastructure and detects any problems associated to the data management.

11.2.3. Identification of stakeholders

The stakeholders are the researchers coming from industry and academia, working in the IoT area. This community is rather large considering the numerous verticals where IoT is employed: smart building, smart city, smart agriculture, smart water management, IIoT (Industrial IoT), etc. The testbed/research infrastructure providers and managers can also play a role in the area of Internet of Things by offering any tools or services inside the SLICES RI to ease the management of IoT data.

11.3. Key technologies to enhance SLICES-RI

The key technologies used by the Internet of Things encompass IoT components such as MQTT brokers, FIWARE NGSI-LD context brokers, OGC SensorThings API/FROST servers, AMQP brokers. All these IoT components could be provided by the IoT testbeds or research infrastructures included in the different SLICES nodes.

11.4. Relevant standardization activities

The standardization activities associated to the Internet of Things include relevant Standards Developing Organizations (SDOs) with their appropriate study or working group: ITU-T SG20 Internet of things (IoT) and smart cities and communities (SC&C) and ISO/IEC SC41 JTC1/SC1 Internet of things and digital twin. Furthermore, alliances regrouping different stakeholders involved in IoT are also a good place to collaborate with in the context of the standardization activities; for instance, AIOTI and IoT Forum are two good matches.

11.5. Potential Impact on SLICES-RI

The SLICES Research Infrastructure can offer some services and tools specifically dedicated to the Internet of Things to ease the creation of experiments involving heterogeneous IoT devices and IoT data from various sources. At the same time, the IoT domain is a good concrete example to showcase the complete lifecycle of data in the SLICES RI. A dedicated experiment could be used to validate the developments done in relation with the Data Management Infrastructure (DMI).

12. Quantum computing

12.1. The needs and requirements for research in the field

Quantum computing is a new computer technology that builds on the special phenomena of quantum physics and, in a different way from Neumann's principles, can perform very large numbers of parallel operations, exceeding the performance of conventional supercomputers by orders of magnitude. Although the theory of quantum physics and the quantum computers based on it have long been known, the technology to put them into practice is still very much at the experimental stage. However, progress has been accelerating over the last few years and the emergence of quantum computers that can be used to solve real practical problems is within reach. The quantum computers that are available on the market today still have rather limited capabilities, in particular in terms of reliability and the size and type of problems they can handle, and their use requires highly specialized knowledge. Naturally, they are also expensive and in most cases their operation requires very specific conditions. For these reasons, there are still relatively few operational quantum computers available to researchers. However, learning about quantum computers and developing quantum algorithms and applications has become extremely important, because with the expected imminent advent of practical technology, we need to be ready to apply it. We are therefore seeing an increasing number of research/development projects that seek to build on quantum computing solutions, typically in some way related to a sub-task. The need to serve these needs in the SLICES research infrastructure thus naturally arises. However, this will require the research and development necessary to integrate quantum computing tools into the SLICES ecosystem, with high abstraction-level interfaces that allow them to be successfully used by more than just those with specific quantum expertise. A promising approach from this standpoint is the integration of Quantum Computing and Quantum Internet solutions. Specifically, as already said, single Quantum Computers are very expensive and provide only a limited number of qubits due to the current technological constraints. One approach to scale-up computing capacity is to interconnect, via quantum links, different quantum computers and provide the primitives to break a quantum circuit (the way a typical quantum algorithm is implemented) into different “pieces”, each running on a single quantum computer.

12.2. Identification of new JRAs to enhance the SLICES-RI

12.2.1. Research goals and challenges

The key research goal in this area is to develop an environment and procedures that both enable the seamless integration of quantum computing resources into the SLICES ecosystem and significantly lower the entry threshold for researchers in different fields to learn and use quantum computing. It is possible to stage addressed research goals based on the current technological maturity of the involved technologies, as follows:

- short-term: integration in SLICES of specific secure quantum links via QKD. This will allow experimenters to test conventional systems distributed on the network, by exploiting intrinsic security provided by Quantum Key Distribution technologies. QKD devices are already at the commercial stage, and in fact some SLICES nodes are planning to integrate this offer in their services in the short term
- short-term: realistic quantum computing emulation. Exploiting synergies with existing projects (such as the ones of the EuroHPC initiative) it would be possible to provide hybrid computing services integrating HPC and quantum emulators, to test hybrid computing approaches based on conventional HPC and quantum technologies

- medium-term: distributed quantum computing emulation. Leveraging the previous two points, it would be possible to emulate distributed quantum computing solutions to increase the scale at which quantum algorithms can be executed
- long-term: full distributed quantum computing and quantum Internet. As soon as the technology will be mature enough, it would be possible to test distributed quantum computing, integrated with HPC, running on a quantum Internet of medium-to-large scale.

12.2.2. Preliminary plan of actions

The first step is to identify the quantum computing resources that could potentially be included in the SLICES infrastructure. Then they have to be integrated in a cloud environment. As a third action, a development of a sufficiently high level of user environment and support is needed. Specifically, the plan of SLICES follows the natural evolution of the research goals described in Section 12.2.1.

12.2.3. Identification of stakeholders

The stakeholders are scientists and researchers who work on problems that involve extremely computationally demanding subproblems and fall into the category for which quantum algorithms exist or can be created. Also of interest are experimental quantum computing institutions (in particular those hosting EuroHPC quantum resources) that make their resources available for exploration, experimentation or early adoption.

12.3. Key technologies to enhance SLICES-RI

The key technologies that emerge from the user side of quantum computing are mainly gate-based and annealing quantum computers and the quantum computer simulators that simulate them in a classical HPC environment, and the development environments (qiskit, Ocean SDK, etc.) and algorithm libraries needed to program them. With respect to quantum networking, the key technology available already now are the devices to implement QKD. The same devices, joined with quantum repeaters (which are not yet available as technological components) will enable to create a truly multi-hop quantum network, thus unleashing the potential of quantum Internet and Quantum distributed computing. These technologies need to be made available in the SLICES research infrastructure in such a way that they can be used together with the other components of the infrastructure to perform complex experiments.

12.4. Relevant standardization activities

In quantum computing, as a highly experimental and rapidly developing technology, widely accepted international standards have not yet been developed. However, some de facto standards do exist, such as the widely used development environment for gate-based quantum computers, qiskit, which is supported by most manufacturers. Its support by SLICES is also essential. In the future, when standards for quantum computing start to emerge, SLICES can make a valuable contribution to their development by using the experience gained.

12.5. Potential Impact on SLICES-RI

The emergence of quantum computing in the SLICES research infrastructure allows the use of a very advanced, new - still immature but very promising - technology and its integration into experiments and developments, which could open up new horizons in a range of applications. When integrated with the other technologies available in SLICES, an environment will be created that will offer users unique opportunities of its kind. This serves perfectly the declared EC objective of promoting the practical application of quantum technologies in European countries to enhance innovation and global competitiveness.

13. Conclusions

This deliverable follows up on well-defined thematic areas for the long-term evolution of SLICES identified in 2024 within the SLICES-DS project. It summarizes the outcome of WP7 activities, specifically concentrating on the needs and requirements stemming from scientific communities around SLICES-RI, identification of new JRAs to enhance the Research Infrastructure and roadmaps for the exploitation and deployment of the RI.
The deliverable identified key relevant topics for future SLICES-RI evolution:

1. Pathways Towards 6G
2. Cloud Edge
3. Integrated Sensing Communication
4. Security
5. Sustainability And Greening the Research Infrastructures
6. Experiment Reproducibility
7. Artificial Intelligence
8. Metadata And Data Management
9. Internet Of Things
10. Quantum Computing

and for each of those topics, the following information was collected:

- The needs and requirements for research in the field
- Identification of new JRAs to enhance the SLICES-RI
- Key technologies to enhance SLICES-RI
- Relevant standardization activities
- Potential Impact on SLICES-RI

The goal of SLICES is to build and maintain a research infrastructure to support this research. As the budget is not unlimited it is key to find common infrastructure building blocks that can serve multiple key research topics to leverage the scale of experimenting (both in size and in number of topics). This work will be followed up with activities of SLICES-PP and other future projects to further enhance SLICES-RI.

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