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D1.4 Roadmap for long-term evolution of the Research Infrastructure

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

Executive Summary

The mission of SLICES is to provide the scientific community with a fully controllable, programmable virtualized digital infrastructure test platform. It aims to answer the fundamental scientific challenges regarding digital infrastructures in an evolving environment, enable new technologies to support the future Internet short and long-term vision (5G and beyond), support ICT breakthrough discoveries. SLICES is the outcome of several years of evolution of the concept of a networking test platform transformed into a scientific instrument.

To achieve this goal, the SLICES consortium has been continuously working towards designing and defining the SLICES end-to-end reference architecture that will be adopted and evaluated for the SLICES-RI. The architecture should address the needs of scientific communities and respond to the key scientific challenges identified by the SLICES-DS project within the course of its execution.

The Work Package 1 “Requirements, key technologies, roadmaps and trends” is addressing this problem by providing deep analysis of trends and technical evolution of key ICT and communication technologies. While the needs and requirements have been identified and analyzed in previous deliverables (D1.1, D1.2 and D1.3), this deliverable concentrates on the target roadmap for long-term evolution of the planned Research Infrastructure. This deliverable presents the applied methodology of the analysis, the findings – identified research priorities for the first five years of SLICES-RI operation.

The document is intended at ESFRI stakeholders, policy makers, researchers and RI managers.

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1 Vision and mission

The historic separation between the network and the compute has vanished. As defined by Sun Microsystems long time ago, “the Network is the Computer” (John Gage 1984), networks are no longer “dumb bit pipes” but Digital Infrastructures (DIs) that integrate networking, computing, storage, and analytics. These architectural innovations aim at enabling data analytics everywhere in the network, and to harvest the available computing power even at the endpoint devices. This ongoing (r)evolution of DIs is related to massive deployment of IoT devices that brings in enormous opportunities across many sectors. Designing and analysing such massively distributed and heterogeneous DIs is a challenge and a lot of research is needed to identify, build, observe, and experiment novel, disruptive networked services (also exploiting data storage and processing components) characterizing new DIs.

A research infrastructure allowing academics and industry to experiment and test future, possibly long-term and disruptive DIs is essential for European research. European economic stakeholders will gain a competitive advantage at the early stage of the development cycle. Indeed, experimentation is key to validate scientific concepts and assess and qualify diverse design assumptions and choices under realistic conditions. This critically affects the Future Internet and distributed systems roadmap concerning its fundamentals and technologies for operating reliable, secure, safe, scalable, and efficient DIs. This is our rationale for developing with SLICES a holistic and comprehensive approach whereby all computing, networking, storage, and IoT resources can be combined to continuously design, experiment, operate, and automate DIs’ full life cycle management, providing a playground for research on Future Internet and distributed systems. While several small/medium-scale monolithic testbeds that focus on individual technologies are available across EU, this is far from what is needed for realistic experimentation of future DIs.

The Future Internet and distributed systems (beyond 5G, data centres and clouds) will require well-tailored tools for testing and developing trusted services. Research platforms should be able to address end-to-end scenarios, integrating a range, if not all, of emerging technologies and components. SLICES ambition is to provide a fully programmable and virtualized, remotely accessible, European-wide research infrastructure, providing advanced computing, storage and network components, interconnected by dedicated high-speed links. SLICES will be the collaborative instrument of choice for EU researchers in Future Internet and distributed systems, to explore and push the boundaries of future DIs at the forefront of worldwide competition.

SLICES will allow researchers and engineers to tackle scientific challenges in these areas, following a European and international technology roadmap. This includes the Union’s Digital Strategy and Horizon Europe Cluster 4, future PPPs, the new 5G flagships, 6G developments and the output of many European projects (e.g,. EMPOWER). SLICES will also link to international initiatives such as US NSF PAWR and FABRIC. It will allow to experiment the concepts and support the evolution of DIs targeting short-term (e.g., new radios for beyond- 5G technologies) and long-term (e.g., new disruptive Internet paradigms integrating networking, computing, storage, and data analytics) scientific goals. This may include, in a controlled and reproducible way, experimentation of new services based on IoT generated data through 5/6G wireless networks, with distributed learning services partly executed at the edge and on micro-datacentres equipped with specific purpose processors.

2 Prioritisation of research topics

The prioritisation of SLICES research topics is an exercise the project carries 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 already to identify and refine the research topics several times, as discussed in the rest of the document.

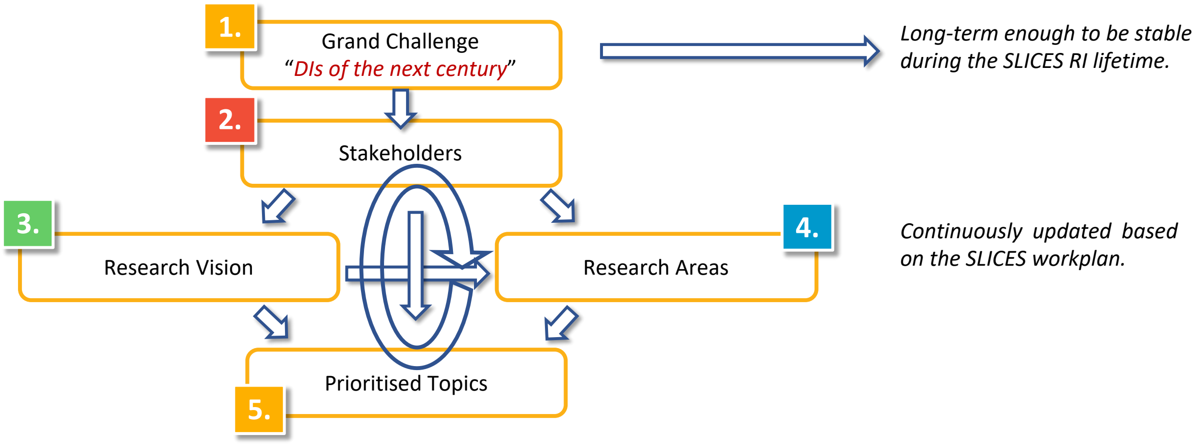


Figure 1: SLICES methodology for the prioritisation of research topics

The methodology starts with the identification of the scientific **Grand Challenge** that SLICES aims to support. This is not expected to change very often, as it corresponds to the overall vision on the evolution of research in the primary SLICES field (ICT) during the entire lifetime of the RI. From this standpoint, SLICES foresees Digital Infrastructures as the key baseline of scientific research in the digital domain during the next decades. This concept embraces DIs evolution with a very broad view, encompassing technological evolutions (currently, e.g., 6G, edge computing), novel architectural disruptions (e.g., integration of AI in the network fabric), and completely novel Internet design paradigms (e.g., quantum communications).

The rest of the methodology is an iterative process built on the identification and involvement of relevant **stakeholders**. Also in this case, SLICES has defined since the beginning its stakeholder engagement strategy. First, SLICES established several bodies and feedback channels at different levels of guidance and planning:

- *Coarse-grained/strategic*: ISAB (International Scientific Advisory Board). This is meant to provide high-level guidance, through the involvement of key representatives of the scientific community worldwide;
- *Middle-grained*: UC (User Committee). This is meant to provide feedback from communities of users (different scientific fields on the area of Digital Infrastructures), related to requirements and specific paradigms/technologies to be supported;
- *Fine-grained*: Structured Experimenters feedback. This is meant to provide very detailed feedback on the experience of using the RI during its implementation and operation.

In addition to that, SLICES partners are members of key scientific communities that are natural stakeholders for the RI, either in terms of "producers" of new ideas which generate experimental components to be integrated in the RI, or as users of the RI to test innovative research ideas. A non-exhaustive list of the communities where SLICES is present is as follows, and it is constantly growing thanks the wider and wider exposure of SLICES concepts to the reference research communities:

- **5G/6G** in EU, with strong links in US, South America, Asia: 5GPPP, Networld Europe, PAWR, CENI;
- **Next Generation Internet**: NGI in EU, POWER & FABRIC in US – example: EMPOWER;

- **AI/BigData**: BDVA, H2020 ICT-48 Flagships (HumaneAI-Net, TAILOR), CLAIRE, ELLIS, AI4EU;
- **Cloud/HPC**: EOSC, PRACE, GAIA-X;
- **Open Source communities**: OpenStack, OpenAirInterface, K8s.

The stakeholder feedback is gathered through a well-defined process, defined through T5.1 “Stakeholder continuous engagement”. Specifically

- the communities are periodically (re-)identified, updated and segmented;
- we implement a Technology Monitor through which we periodically assess and evaluate user needs and objectives.

The output of this process has been already collected several times until now, specifically:

- we have produced a first Technology roadmap description in the Design Study document submitted to the ESFRI call in 2021;
- we have run a stakeholder workshop on March 4th-5th 2021;
- we have run a community survey gathering 220+ questionnaires from relevant stakeholders.

Last but not least, it is worth mentioning that the SLICES partners are deeply rooted in the Digital Infrastructure academic environment, which allows the project to quickly “sense” new directions from cutting-edge research communities.

The output from stakeholder consultation is distilled to populate the key elements of the SLICES research vision. This is also a dynamic result, that is updated at each cycle of the iteration. The current status is depicted in Figure 2.

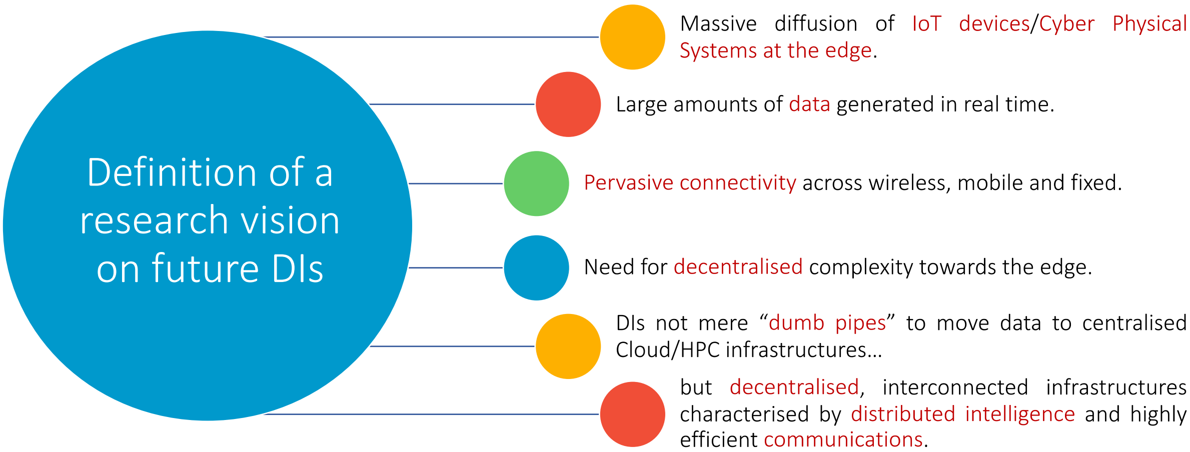


Figure 2: 2022 status of the SLICES research vision

This vision reflects the main current trends in the evolution of the research on the future Internet. Specifically, it gives significant emphasis to the decentralisation of complexity towards the edge of the network also due to the pervasive diffusion of smart devices (personal devices and IoT), to the evolution of the DIs from “dumb pipes” towards intelligent means for advanced service provisioning, to the integration of (distributed) AI as a key network component, to the seamless integration of the cloud-to-edge continuum in the SLICES fabric.

This vision is an intermediate step between the Grand Challenge and the detailed research topics. To identify the latter, the methodology considers the distillation of a set of priority areas. The current version, still based on the outcome of the extended consultation with the stakeholders, is presented in Figure 3.

Identification of **priority areas**

- 6G;
- Human-centric Dis;
- "Cloud-to-edge" scalable Dis;
- AI-centric Dis;
- Industrial/verticals demand;
- Cross-properties.

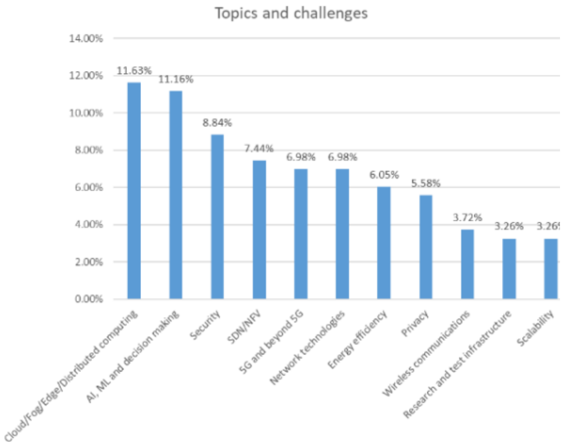
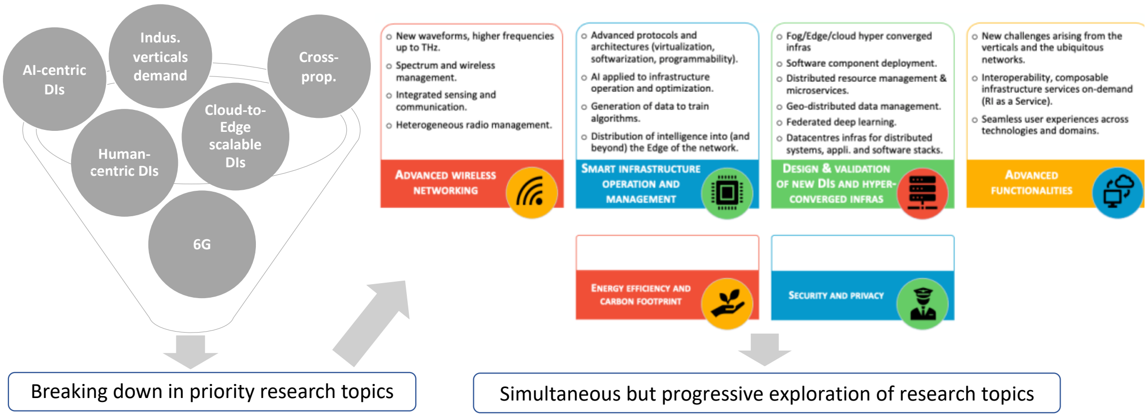


Figure 3: 2022 status of the SLICES research vision

The priority areas are finally broken down in specific research topics, which are grouped as shown in Figure 4.



- New waveforms, higher frequencies up to THz.
- Spectrum and wireless management.
- Integrated sensing and communication.
- Heterogeneous radio management.

- Advanced protocols and architectures (virtualization, softwarization, programmability).
- AI applied to infrastructure operation and optimization.
- Generation of data to train algorithms.
- Distribution of intelligence into (and beyond) the Edge of the network.

- Fog/Edge/cloud hyper converged infras
- Software component deployment.
- Distributed resource management & microservices.
- Geo-distributed data management.
- Federated deep learning.
- Datacentres infras for distributed systems, appli. and software stacks.

- New challenges arising from the verticals and the ubiquitous networks.
- Interoperability, composable infrastructure services on-demand (RI as a Service).
- Seamless user experiences across technologies and domains.

Figure 4: SLICES priority topics (status in 2022)

3 Strategic research priorities

This section provides a precise description of the thematic research priorities shown in Figure 4, and corresponding Research Priorities, derived according to the methodology described in Section 3. Within each Thematic Area specific Research Priorities have been identified, provided with relevant descriptions and guiding questions and/or challenges.

3.1 Thematic area 1 – Cloud, Fog, Edge Computing

"Cloud Computing" is defined as "access to remote computing services (servers, storage, networking, applications) via the Internet from a provider", which is the user's vision of the Cloud. Cloud computing has recently evolved toward a more distributed version of datacenters and we see the convergence between data centers, the network and the Internet of Things. This digital transition requires the deployment of new, more decentralized IT infrastructures to meet the needs of the many applications envisaged to improve our daily lives (e-health, smart cities, autonomous vehicles, industry of the future, etc.). Known today as "Edge Computing" (but also with variations under the terms "swarm", "Fog", "federated", etc.), this new paradigm of on-demand computing consists in maintaining a continuum between Clouds (hosted in datacenters) and IoT devices thanks to a massively geo-distributed federation of small datacenters placed at the edge of the network.

Research in the field of the Cloud is articulated around three main axes.

- **Infrastructure**: The first one focuses on the deployment and management of the infrastructure, in other words, all the hardware and software elements required to implement the Cloud, which includes computing power, network, storage, as well as the access interface to virtualized resources and services for users. This is a "supplier" oriented vision;
- **Programming**: The second axis is the tools, methods and programming models for managing the execution of applications on these infrastructures, and more specifically the life cycle of these applications. This is a "DevOps" oriented vision;
- **Services**: The third axis concerns the high-level services offered to end users. It includes, for example, issues related to confidentiality and data protection. This is the "user" vision. In addition to these three areas, there are also crosscutting dimensions such as security and energy.

The management of these highly distributed platforms, the orchestration of the proposed services, integrating controlled sensors/actuators, and their use in complex control systems raise many scientific and technical hurdles to achieve the goal of large-scale distributed systems that are maintainable, efficient, easy to use, and secure and to minimize energy and environmental impact.

3.1.1 Research Priority 1.1: Infrastructure management

Around infrastructure management, work has to be done around delivering appropriate system abstractions and open-source software stacks to operate and use massively geo-distributed ICT infrastructures, from the lowest (system) levels to the highest (application development) ones. Building blocks that should compose such a software stack have to be designed (i.e., from the internal algorithms to the APIs they should expose) and finally understand how they should interact with each other. The challenge consists in abstracting the description of the whole application structure in order to be able to globally optimize the resources used with respect to multi-criteria objectives (price, deadline, performance, energy, etc.). Given the complexity of the choice, it seems important to decouple as much as possible the description of the application structure from the infrastructure in order to use external services to adapt the application.

3.1.2 Research Priority 1.2: Resource management

Resource management is of course one important issue and it includes researches around geo-distributed resource and storage management, capacity planning and placement, performance characterization, self-management and self-adaptation for resiliency and fault tolerance. Heterogeneity of hardware is also an important issue, both from the resource management side and the software and application abstraction side. From the numerous approaches studied to tackle this issue, Machine Learning (ML) is a particular interesting approach as it is described in Thematic Area 2.

3.1.3 Research Priority 1.3: Virtualization

Virtualization is the cornerstone of cloud infrastructures. Virtualization is about exposing a unified, standard interface to applications in order to facilitate their design and deployment. However, it has to be taken to the next level, being able to cope with computing nodes built as Lego made up of a myriad of heterogeneous hardware components that can be dynamically added or removed. The first challenge is to hide the distribution of resources to virtual machines and to be able to run legacy codes. Secondly, virtualization systems must be able to scale up to several hundreds of components and at each level of the hardware (CPU, memory, storage, network). Managing these complex architectures comes with its own set of challenges: complexity, heterogeneity, dynamicity, scaling and locality

3.1.4 Research Priority 1.4: Data Management

Data management of such platforms is also very important. The deluge of data anticipated with the advent of IoT and CPS requires new approaches where data will naturally be geo-distributed (or even geo-replicated) using the latest storage media. These evolutions require a complete rethinking of the traditional architecture because moving data between the storage and computation tiers has become too costly or even impossible for certain application domains (e.g. medical). Today, we have also to find a compromise between moving computation vs. data. Current data storage and processing techniques have to be revisited to cope with the volatile requirements of data-intensive applications on large-scale dynamic clouds and geo-distributed infrastructures in a cost and energy-efficient way.

3.1.5 Research Priority 1.5: Energy consumption

As the energy consumption and environmental impacts of digital technology continue to grow, its impact has to be taken into account as one important target performance metrics. Energy efficiency of large datacenters as well as micro-datacenters at the edge of the network is studied at different level, from the end-to-end energy monitoring of large-scale platforms, use of different energy sources, resource management using energy metrics, and the design of future datacenters. Systems capable of virtualizing complex and dynamic infrastructures into virtual machines in which legacy software could run without requiring modifications

3.1.6 Research Priority 1.6: Security

Security is an important issue of such massively distributed infrastructures. The Cloud, like any information system, requires the implementation of classic mechanisms to ensure the confidentiality, integrity and availability of data, applications and services. Similarly, the principles of "*privacy*" and "*security by design*" must be applied, as the increased complexity of the architecture would make it almost impossible to add security functions later. Full-stack security and per-layer security issues have to be investigated with some specific encryptions methods and privacy issues have to be carefully handled. Homomorphic encryption is currently investigated, as it could be one of the cornerstones of cloud sovereignty. Thematic area 3 about Security describes it in more detail.

3.2 Thematic area 2 – Artificial Intelligence and Machine Learning

Machine learning is a field that automates data processing, analysis and decision making. It can be used on many levels of building and managing a network. The use of ML in the network infrastructure can support the selection of optimal architectures, connections, predict future traffic, make decisions about resource allocation, detect attacks, anomalies and undesirable actions, minimize energy consumption, resources and delays. It enables automatic and immediate reaction to everything that is happening in the system. However, there are many challenges that need to be overcome when implementing AI-based methods.

3.2.1 Research Priority 2.1: Lack of data

One of the main challenges is the problem of access to data, in many cases we need large amounts of both historical and current data to solve a problem. Unfortunately, it often happens that such information does not exist because it was not collected before. It is also possible that other organizations have such data, but they cannot share such data, it may be mainly due to security and the desire to maintain competitiveness. The data may contain confidential or protected information, such as personal data, or directly describe the key elements of the system along with their advantages and vulnerabilities. Data anonymization is in many cases impossible or causes the loss of key information. The lack of an appropriate sample of data makes it impossible to train an effective and reliable AI solution that can be used in production systems.

3.2.2 Research Priority 2.2: Extreme data

On the other hand, the challenge is also to have extreme data, i.e., data that is generated in huge amounts. The challenge is to store such data itself, because in many cases such data is not stored at all or is only kept for a limited time, e.g., several weeks or months. This makes it a challenge to draw conclusions over a longer period of time. Another aspect is the identification of key features and the quality of the collected data. Often, measurement tools or data collection systems have a certain degree of error and noise. In addition, the processing time of extreme data can be so long that the conclusions drawn have already expired. Therefore, the challenge is to build such an infrastructure that allows flexible storage and processing of extreme data at such a time that they provide as much value as possible.

3.2.3 Research Priority 2.3: Dynamic and complex systems

Another challenge is building an artificial intelligence model in dynamic heterogeneous systems where the behavior of one element of the system depends on many factors that are often not directly monitored. Prediction in environments where the distribution and structure of data changes over time causes that machine learning algorithms have low efficiency and predictive capabilities. Complex systems need dedicated solutions that must be constantly monitored, improved and deployed.

3.2.4 Research Priority 2.4: Interpretability and explainability of AI methods

Most of the currently used machine learning techniques work like a black box, which means we do not know what is going on inside the method. These methods achieve high efficiency in typical conditions, however, in boundary or unusual cases, they could provide illogical solutions. In the case of applying

ML methods to all kinds of system, one should take into account their imperfections and the need to monitor their decisions, interpret them appropriately and explain why the algorithm has done so in order to prevent accidents that may happen in the future. Providing more training data does not solve this problem, but only postpones the moment when the system stops working properly once again. The challenge is to build methods and models that are interpretable by a human operator and provide an explanation of the decisions made.

3.2.5 Research Priority 2.5: Federated Analytics

The most common strategy for inferring knowledge from distributed data is to transport the data to centralized target site for further processing and analysis. However, this is not always feasible, either due to data privacy violations (e.g., sensitive data cannot be moved from their physical site because of GDPR) or due to computational burdens which arise during the analysis of big data. A solution to this is to deploy distributed environments, where the big data are split into batches and then distributed into nodes. Batch processing methods, such as online learning and meta-learning, are then used to train AI/ML algorithms across the distributed nodes, using techniques, such as stochastic optimization to update an existing estimator on a series of upcoming training instances and aggregation of the prediction outcomes from AI models that are trained on each distributed node. Meta-learning methods, however, limit the “horizon” of the training process since the individual models are trained on individual subsets whereas online learning is restricted to the additive update of the weights of an AI model on new “online” training instances. A solution to this is to use federated analytics where an incremental learning approach is used to train an AI algorithm on an initial batch of data, and then incrementally adjusts the weights of the model on the rest of the distributed batches to produce the final predictions. Towards this direction, various incremental learning algorithms have been proposed such as the multiple additive regression trees (MART), the Support Vector Machines (SVM), and the Multinomial Naïve Bayes (MNB), among others.

Several implementations of federated algorithms have been proposed but they have been tested in high performance cloud computing environments to evaluate their execution time across big data structures which are stored in federated research infrastructures that nor have been assessed in terms of their resilience against overfitting effects during the federated learning process. SLICES aims to facilitate seamless federated learning experimentation over federated data where algorithms will be trained on batches of available data across the federated databases and the orchestration of the training/testing process will be conducted by edge, fog or the central node.

3.3 Thematic area 3 – Security

Few trends in the modern digital technologies development define the growing importance of security in its multiple application domains: the growing complexity of systems which become distributed and multi-domain with multi-vendor hardware and software, shift to data centric and data driven applications where data become a critical value for research, business and society, while a growing number of security attacks that target all elements of modern digital ecosystems from infrastructure to data to humans. Security, in its wide scope, must deliver its expected effect to protect the normal operation of systems, infrastructure, processes and human activity only if all security measures are consistently applied and all elements of digital ecosystems are protected with reliable security policies, services and mechanisms. Growing systems complexity is demanding addressing security aspects during the whole applications and infrastructure lifecycle by implementing practices called "security by design", "data security by design", "privacy by design" what require full integration of the security technologies and tools with the development and operation process and people (as developers, operators, and actors).

SLICES research on security will be directed on two tasks:

(1) **Security research**: Providing infrastructure and testbeds for advanced security research conducted by the SLICES members and wider research community;
(2) **Infrastructure security**: Ensuring the security of the SLICES infrastructure and services, including all aspects of the SLICES design, implementation and operation

Security research is relevant and linked to all priority research topics for SLICES described in section 4 (refer to Figure 4). The following security research topics are identified based on security trends analysis and partners' expertise and ongoing research:

3.3.1 Research Priority 3.1: Security Technologies

Security technologies research includes research on new and prospective research with a high potential of delivering effective solutions for future digital technologies

- Confidential Computing is a new computational paradigm built on leveraging Trusted Computing Platform Architecture and using special trusted execution architecture and mode in modern CPU, in particular, SGX in the Intel architecture and TrustZone in ARM architecture. Confidential computing provides a solution for a multiparty computation model which is important for ensuring privacy and confidentiality of the data processing and IPR protection of algorithms. Confidential Computing experimentation will require a specially designed infrastructure that includes both actual CC unit and firmware to support the setup and monitoring of the secure and trusted environment both for data exchange and for key management and secure attestation procedures execution;
- Cryptographic research: The importance of cryptographic research, such as homomorphic encryption and blockchain applications, are commonly recognized. At the infrastructure level, they need to be supported with experimental and testbed facilities that can be easily configured for different experiments while protecting the IPR of algorithms. Such facilities typically comprise high performance GPU clusters and virtualized environment for sandboxing of the tested applications;
- Blockchain and NFT, besides that they have already found wide implementation and well-established business domain/ecosystem, have not yet exhausted their transformative potential on different digital infrastructure aspects. Similar to cryptographic research, blockchain and NFT research and experimentation will require a powerful computation facility and well-developed software defined networking infrastructure;
- Post-quantum security that is focusing on technologies related to quantum key exchange and new cryptographic algorithms. Despite foreseeing a long time before quantum computing will become a production technology, research on this topic attracts wide interest and attention, and practical preparation will require special infrastructure for experimentation.

3.3.2 Research Priority 3.2: Application Security

Applications security research includes new architectural solutions for the design, development and testing security applications that target to solve the challenge of building secure and resilient infrastructure, services and applications.

- "Security by design" and "data security by design" are two concepts and development models that support the whole software/application lifecycle and include new architectural methods, solutions and design templates for building/creating complex applications of multivendor components with potentially undiscovered vulnerabilities and exposures;

- Privacy enhancing research leveraging Privacy Enhanced Technologies (PET), Privacy Enhancing Computation (PEC), and differential privacy – all together targeting "privacy by design" that include multiple security areas and technologies to protect "by design" personally identifiable information in applications and systems;
- Cloud and Big Data security research for a new generation of data driven and data centric applications to ensure secure and trusted data handling in emerging domains such as Industrial Data Spaces, Virtual Reality, and Metaverse where data protection is a critical issue. This research area requires secure and trusted infrastructure for data exchange, sharing, and eventually trading digital goods;
- New security models, mechanisms and policies for distributed/decentralised Access Control, Identity Management, Trust Management, and Policy Management. This active application security research area continuously evolves with the infrastructure services evolution extending "vertically" (from hardware and network to data/semantic and normative/legal layer) and "horizontally" (from single application stack to multi-domain and heterogeneous federated environment);
- Combined security modelling and DevSecOps (ModDevSecOps): This security research area will focus on extending widely accepted DevSecOps practice with advanced security modelling of the intended infrastructure or application that would support the whole application lifecycle. It will be built on the strong standardization base and rich DevOps practice to deliver and test new solutions for large scale infrastructures. ModDevSecOps will require virtualized Infrastructure as Service (IaS) environment for such tasks as applications development, integration, deployment, and security testing. The such experimental facility can be built using existing open-source cloud platforms and major public cloud providers with extended facilities for security testing, monitoring and attack simulation. Testing facilities should be supported with the industry-maintained registries for security vulnerabilities, exposures and weaknesses;
- Secure Software Lifecycle Management: This security research area extends from the application security to the operational stage by applying AI based application monitoring that can help identify new security threats and undiscoverable vulnerabilities based on the monitoring application security model created at the development stage and adjusted at the integration and deployment stages.

3.3.3 Research Priority 3.3: Operational Security

Operational security research is focused on technologies that improve the security and resiliency of systems or infrastructure by ensuring their normal operation and protecting from security attacks and misconfiguration.

- AI-powered intrusion protection and deep defence mechanisms caused by the attack surface expansion: This active research area requires a complex multi-task environment to support attack simulation, advanced and security logs collections, AI-powered processes monitoring and logs analysis to discover attacks, irregularities, and new behavioural patterns;
- Digital/Software Supply Chain Security protected with advanced protection against supply chain attacks and dynamic security testing for third party components. The first task will require advanced AI-powered processes and activity monitoring and analysis, the second task will require secure trusted "sandboxed" testing environment that can use VM or container-based virtualization and system security models created at the ModDevSecOps stage;
- Formalisation of the certification and compliance for complex infrastructures and continuous risk assessment is an important area to achieve reliability and resilience of complex infrastructure, by leveraging Site Reliability Engineering (SRE) and cybersecurity mesh architecture.

3.3.4 Research Priority 3.4: SLICES Infrastructure Security

SLICES Infrastructure security will include research and development to ensure security and resiliency of the SLICES infrastructure and services, including all aspects of the SLICES infrastructure design, implementation and operation. The following security challenges must be addressed and supported by SLICES infrastructure security research:

- Security of the infrastructure continuum, including Radio Access Network, 5G infrastructure, IoT and sensor network, far edge, edge, and cloud supporting data collection, transfer, storage, processing, and sharing (or publication). This practical security area will benefit from the security research discussed above in application and operational security areas;
- Access Control and Identity Management (AIM), including Federated AIM that can leverage existing Federated AAI operated by GEANT and implemented among EOSC community members. Implementing existing solutions will require additional research to adopt them to the specifics of the SLICES infrastructure;
- SLICES Data Infrastructure security will be focused on ensuring secure and trusted data sharing inside SLICES-RI and outside. This should include data and metadata security, including confidentiality, authenticity, integrity (both data and referral), availability, IPR, and privacy, as well as ensuring FAIR data principles and supporting data management and governance policies.

3.3.5 Human Factor in Security – Security Awareness and Security Training

In addition to security research and (technical) infrastructure security, SLICES will invest in extending the traditional compliance-based security training with the behavior and culture training to motivate behavioral security awareness to address human factor in security. The experience of the academic partners will create novel training methodology and training courses that can also be offered to the European research community.

3.4 Thematic area 4 – SDN/NFV

SDN and NFV are two major components with a transformative impact on the design of future research infrastructures. SDN supports the separation of the control and data plane, adding programmability and policy-based management to the control plane. It is used in enterprise networks, cloud and wide area networks (SD-WAN). NFV proposes a paradigm shift by considering that all network functions can be viewed as applications stored in the cloud. This pushes a very strong software dimension to the infrastructure, changing the way they are designed, deployed and operated.

3.4.1 Research Priority 4.1: SDN and advanced programmability

As SDN is maturing and being more broadly deployed, research is still needed in its programmability capability, for instance using P4, as well as scaling up the concept, ranging from data-centers to wide area networks. Likewise, this concept has been originally used in enterprise networks and thus also considered in very different technologies like wireless. This is necessary in modern digital infrastructures involving network/cloud/sensing systems. In particular, the concern of verification and the ability to demonstrate that what has been programmed for an SDN controller is going to produce the appropriate outcome is of utmost importance.

3.4.2 Research Priority 4.2: NFV and function optimization

NFV is still at its infancy, even if some functions are now pushed into production. This is become it drastically transform the infrastructure design and operation, questioning the right level of abstraction that should be used in this context. It raises a lot of hope but also triggers concern about efficient and secured deployment. A lot of work has been done on NFV and service chains provisioning, deployment and adaptation but a lot of practical issues are still pending, and will be better understood as more operational data is collected.

3.4.3 Research Priority 4.3: Orchestration

The network being seen as a programmable virtualized platform, a lot of the "intelligence" is dependent of the ability to orchestrate the resources and enforce the appropriate and efficient matching of the functions and the substrate in a dynamic and agile manner. This comes even harder in a context where one has to deal with multi-tenant, multi-stakeholder, multi-technology environments where the orchestration of services becomes a challenge. Besides the technical dimension, other important considerations need to be on boarded like energy consumption, business models or resilience and self-management.

3.5 Thematic area 5 – Beyond 5G and 6G

The 6th generation mobile systems (6G). and the current deployments of 5G and Beyond 5G, will play a prominent role in the future digital world and nowadays in the RI for experimentation. It calls for advanced new principles and solutions to support the future needs, i.e., new kinds of on-line and real-time services and applications. It offers important Key Value Indicators (KVIs), such as trustworthiness, inclusiveness and sustainability supported by advanced Key Performance Indicators (KPIs), among all, predictive guarantees, seamless mobility over flexible and dynamic network slices, ultra-reliable connectivity in densely populated and triphibian1 environment, time-engineered networking, data rates per area unit (bps/km2) up to 10 times higher than 5G, AI enabled proactive behavior in RAN and unified Core Network (CN), and cloud-edge-IoT continuum.

Fifth-generation new radio (5G-NR) systems are now a commercial reality. Third generation partnership project (3GPP) Releases 16 and 17 aim to serve as key enablers for the evolution of 5G-NR, capturing the inter-working capabilities of enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable low-latency communication (uRLLC). The 6th generation of mobile systems (6G) envision disruptive technologies in response to lifestyle/societal changes, which include: (1) A holographic society where holograms/immersive reality will form a preferred means of communications; (2) Connectivity for all things much higher than with 5G; and Time-sensitive communications where sensors form the end-points of communication. SLICES-DS has analyzed the current state of the art on vision, architecture, applications and technology breakthroughs and, with the SLICES-RI objective of building and providing resources for experimentation in 6G technologies, we have identified the following fundamental research priorities: (i) 6G Architecture, (ii) Technological features for time engineering 6G applications and services, (iii) 6G RAN, (iv) 6G Mobile Core and (v) 6G Orchestration.

3.5.1 Research Priority 5.1: 6G Architecture

6G architectural proposals are appearing in the literature with the evolution of mobile networks, promoting the provisioning of consecutive traffic steering, new IP layer design, extension of Service Based Architecture (SBA), etc. They assume new ideas where compute/storage/networking are flattened; the transport network is "shortcuted" with a sliced local breakout to enable much lower latency between the networks of multiple operators, an AI-Plane (A-Plane) in addition to a user-plane (U-Plane) and control-plane (C-Plane), etc. Although there are many research activities ongoing about the 6G mobile communication systems, there official standardization is an ongoing work among the research, technical and industrial communities. The 6G functional architecture requires: 1) *the* *emergence of new verticals powered by autonomously operating machinery in the industry and by near-real-time experiences in personal communication using holograms as new fundamental media-objects; 2) the development of new communication services, where will be a model to offer new types of in-network services that enable applications to interact with networks more intelligently and with high-precision.*

Today, the network resource demand is of basic connectivity and capacity. For emerging applications this, alone, is not sufficient: the network needs to be concerned with time as well because the success of several new verticals will depend of timeless data arrival.

3.5.2 Research Priority 5.2: Technological features for time engineering 6G applications and services

In short, humans and machines are both sensitive to delays in the delivery of information (albeit to varying degrees). Timeliness of information delivery will be critical for the vastly interconnected society of the future. New applications that intelligently interact with the network will demand guaranteed capacity and timeliness of arrivals. As we incorporate gadgets in our life, quick responses and real-time experiences are going to be increasingly relevant. In a network of a massive number of connected sensors that are the endpoints of communication, timeliness becomes critical and late arrival of information may even be catastrophic. We have identified as critical for the research community to work on technologies and tools in an end-to-end fashion, introducing novel solutions at RAN, Core, Near/Far Edge and Management levels, to enable deterministic networking, native integration of AI for telecommunications, and new data transfer paradigms with deep edge integration to improve the current situation towards 6G.

3.5.3 Research Priority 5.3: 6G RAN

Some important questions have to be answered in order to build up a 6G RAN system ready for 2030, that includes: what novel L1/L2 designs and protocols as well as advanced RAN control and management plane capabilities together with the interfaces needed for the operation of these functions should be devised in the 6G network for supporting a time engineered and deterministic behaviour? How can the resulting 6G network autonomously and proactively address virtually all of the challenging situations such as anticipate and resolve a coverage whole or an obstacle blockage that otherwise could ruin any attempt to achieve high reliability/low latency at a very short time scale, cope with high mobility users, etc.? How will evolve the current virtualized RAN architecture towards a fully cloud native SBA-based RAN, that supports the provision of highly customised network slices tailored to specific services requiring time sensitive and deterministic networking?

3.5.4 Research Priority 5.4: 6G Mobile Core

The 5G Core Network (CN) supports native Ethernet PDU sessions. For user plane redundancy which secures high availability and reliability on the 5G system, it supports the establishment of redundant user plane paths through the 5G system including RAN, CN and the transport network. Such redundant paths are possible by using a single UE with the RAN dual connectivity feature in the end device or by using multiple UEs in the end device. Also, 5G can provide virtual networks (5G-VN) and LAN groups, which can be used for allocating resources to the members of a particular group. It provides a solid ground for using 5G in deterministic scenarios. Also, 5G URLLC capabilities provide a good match to IEEE 802.1 TSN and IETF Deterministic Networking (DetNet) features. These technologies are integrated to provide time engineered connectivity end-to-end, i.e., between input/output (I/O) devices with their controller, for example, residing in an edge cloud providing network management. The integration already includes data plane support for both the necessary base bridging/routing features and the TSN/DetNet add-ons, however the control and management plane need further research as today only first steps in a software-defined networking-based approach (the fully centralized model of TSN) has been taken. This should be done in the light of not making the network more complex and energy hungry.

From the SLICES perspective the main challenges are the following:

- Unified 6G core with a modular and extensible fabric on a trusted new ecosystem;
- Guarantee simultaneous flexibility and scalability for ultra-reliability and low latency;
- Next generation network data analytics;
- AI as native feature for proactive networking;
- Data models, new exposure solutions, core info integration into the vertical domains layout and enabling mobile network digital twin.

3.5.5 Research Priority 5.5: 6G Orchestration

Since 5G network slicing became the default technology to satisfy the requirements of mobile communications network consumers. Slicing in the 6G network will be as commonplace as VPNs in today’s IP networks, and the value propositions are similar to today’s VPNs, i.e., isolation of users to enforce security; isolation of users to avoid influence between customers; providing specific SLA per customer; abstracting the underlying network from the customer. Network slicing will remain a key enabler for multi-tenant networks. Network slicing will simultaneously provide tailored communications service to satisfy the individual tenants, and also provide means of isolation between the tenants.

Automation and orchestration are essential to reduce operation costs, because a 6G network will have multiple layers of virtualization that need to be managed as part of a complex dynamic entity. AI&ML mechanisms will become crucial components in the envisioned 6G networks to enable concepts and technologies such as deterministic networking and deep edge integration. The complexity of such novel approaches, which will comprehend, among others, the support of diverse physical devices and communications links, multiple virtualization technologies, novel service and network slice architectures, cloud-edge-IoT continuum, etc., will require to automate decision-making processes towards accomplishing the closed-loop zero-touch paradigm.

Network management will become very similar to the management of cloud. All resources are virtualized and automatically managed. The goal of network management is to constantly adapt an ever-changing network to satisfy the dynamic requirements. The network infrastructure will be treated as a large resource pool which is shared by tenants. All mapping from services to network slices and then to virtual resources will be completely elastic and flexible. There will be no direct relationship between the lifecycle of a service and the lifecycle of the assigned virtual resources. Similar to the cloud paradigm, virtual resources will be created and destroyed at high speed. Closed-loop automation depends heavily on artificial intelligence. AI is used to evaluate the current resource status and current service status, and more importantly, to predict any future problems.

From the SLICES perspective the main challenges are the following:

- A comprehensive zero-touch open end-to-end resource management system with drastic OPEX reduction and innovation support;
- The intelligent coordination among clouds, edges, devices, and networks will enable adaptation of resources such as spectrum, computing, and storage;
- AI-based network operations for operators, intent-based programmability with well-defined return values, novel interfaces for easy extensions of the running system through user-owned functions, at least at the user plane level;
- Control of compute, tasks and allocation of data injected in the AI models.

3.6 Thematic area 6 – Network technologies

The DIs of the future will not be only "dumb pipes" connecting end-points. This was one of the key cornerstones of the Internet design, which will not be entirely replaced, rather it will be augmented to address the emerging needs of the current and future scientific and industrial directions of Internet services. This also means that network technologies become a broader concept, which includes low-level technological components, but also moves progressively to architectures that allow to efficiently manage the increased complexity of DIs of the future. According to this vision, SLICES identifies three specific Research Priorities, namely (i) advanced protocols and architectures; (ii) distributed resource management and microservices, and (iii) quantum communication.

3.6.1 Research Priority 6.1: Advanced protocols and architectures

From a network technology standpoint, future DIs will be extremely heterogeneous both in terms of enabling technologies (including optical, mmWave, conventional RF, quantum technologies) and in terms of functionalities. A key research question is what is (or, are) the best architectural paradigms to support this trend. From the SLICES perspective, we need to make sure the RI is flexible enough to accommodate a full range of architectural innovations, ranging from incremental research approaches improving existing protocols, up to completely disruptive architectures breaking the conventional layered structure of the Internet and its division of responsibilities across nodes.

Guiding questions and challenges

- What is the right balance between centralised and decentralised functionalities, and what are the architectural implications of decentralising functionalities in future network technologies;
- How can we architecturally combine heterogenous network architectures (optical, wireless, quantum) across different logical layers in a seamless way;
- How can we support the full range of architectural innovations with an experimental RI, from incremental innovations to radically new network architectures;
- How can we leverage new virtualisation and softwarisation technologies for the creation, operation and management of an experimental RI that will serve a wide variety of heterogenous (and not yet entirely consolidated) use case.

3.6.2 Research Priority 6.2: Distributed resource management and microservices

Future network technologies will support a continuum between cloud, edge and users' devices. This requires services and applications to migrate across different platforms to be processed on runtime in different locations wherever required by the end user. Serverless approaches can help achieve this goal, by allowing user applications to be decomposed into processes that run without any dependency and can be globally accessible. Serverless computing adopts a programming model called Function-as-a-Service (FaaS), where applications are realized as a composition of short-lived and stateless function calls (also called lambda functions). Due to the absence of local state and in combination with a flexible virtualization infrastructure, typically based on containers, it is possible to up-/down-scale services in a fast and easy manner, also achieving fine-grained billing granularity. However, significant research efforts will be required to unlock the full serverless benefits, especially in combination with edge computing and NFV, due to a high data-plane latency and inefficient handling or transfer of the application state. From the SLICES perspective, the key challenges are the following

- How to support a serverless approach in the design and experimentation of new network functions and the related protocols;
- How to cater for management of "dispersed" resources ranging from the cloud to the edge and beyond, where new approaches like serverless are massively used;

- How to make sure that also devices under partial control of the network owners (e.g., end user mobile devices) can be exploited in this new paradigm, and approaches like this are validated in a repeatable and trusted way

3.6.3 Research Priority 6.3: Quantum communications (towards the Quantum Internet)

Quantum technologies exploit fundamental properties of matter at exceedingly small scales to perform tasks that would be too complicated or simply not possible with conventional computing and communication paradigms. Examples include unconditionally securing communications, solving problems of practical prohibitive computational complexity in a matter of seconds (the so-called *quantum advantage*), deepening the understanding of complex physical systems, improving measurements by orders of magnitude. While stand-alone quantum systems will be useful for some uses of practical interest, interconnecting them so that they can perform non-local computations on shared quantum states will reveal the true potential of quantum information technologies and accelerate the speed of their evolution, thanks to more science areas being covered and a broader audience of public and private investors reached. A whole new ecosystem of communication technologies, network architectures, protocols, and software interfaces need to be defined to materialise the upcoming Quantum Internet, which in its final form will allow quantum systems all over the world to exchange *flying qubits* much like today's computers exchange classical information (in bits) via the Internet.

The road ahead towards the Quantum Internet is still very long, and SLICES can play a fundamental role in providing a trusted playground to move from currently established technologies – mainly providing isolated technology components for quantum communications – to a full-fledged Internet system where quantum technologies become a key component.

Main research questions and challenges are as follows

- How can we support integration of existing quantum-based technologies that are ready for deployment in experimentation of novel, incremental Internet solutions, for example towards the large-scale adoption of QKD as an Internet primitive;
- How can we support intermediate goals in the road towards a Quantum Internet, for example, paradigms where HPC and Quantum Computers work in hybrid settings supporting networking tasks such as network planning and optimisation;
- How can we support long-term research towards the Quantum Internet, such as for example experimenting with networks of Quantum Computers performing collaborative Quantum Computing tasks (exploiting the *quantum advantage*) through exchanging of qubits instead of classical bits?

3.7 Thematic area 7 – Energy efficiency

The energy efficiency is an important topic highlighted in the deliverable D1.2 "Requirements and needs of scientific communities from ICT-based Research Infrastructures". Indeed, the intended SLICES Research Infrastructure is expected to be green and energy efficient. At the same time, this Research Infrastructure should permit to the researcher to develop and test through experimentations new solutions improving the energy efficiency in the ICT sector. On a generic manner, the SLICES Research Infrastructure will contribute to the implementation of actions enforcing the United Nations Sustainable Development Goals. In particular, the SDG 7 "Energy" is handling the energy efficiency: for instance, the Target 7.3 explicitly mentions that by 2030, we should double the global rate of improvement in energy efficiency.

3.7.1 Research Priority 7.1: Green and energy efficient Research Infrastructure

The creation of a green and energy efficient Research Infrastructure such as SLICES is in fact a challenge per se. The SLICES Research Infrastructure will be composed by green and energy efficient ICT components in terms of hardware and software. The objective is to reduce the environmental footprint of the research infrastructure without endangering the performance of the research infrastructure. In the SLICES-PP project, corresponding to the next preparation phase, a dedicated task "Environment, climate and sustainable development impact assessment and optimization" has been elaborated. This task will investigate the means to improve the environmental impact of SLICES to align with the SDGs, and the Green Deal objectives, including in terms of climate neutrality. It will start by assessing the impact of SLICES on the various SDGs and elaborate mitigation measures to optimize the environmental footprint of the infrastructure. It will then monitor the implementation of the identified measures.

3.7.2 Research Priority 7.2: Evaluation of energy efficiency

The SLICES Research Infrastructure should address the questions and challenges associated to the monitoring of the energy consumption and the assessment of the energy efficiency. It will permit to determine the CO2 reduction of the solution under test. Indeed, new developments are currently done in different domains of research concerning ICT in general. Typical concrete areas are hardware and wireless communications. For instance, new chips using magnetoresistive random-access memory (MRAM) are currently developed by several semi-conductor manufacturers. The main advantage of this new type of memory is the power consumption which is slightly decreased as illustrated in the following figure:

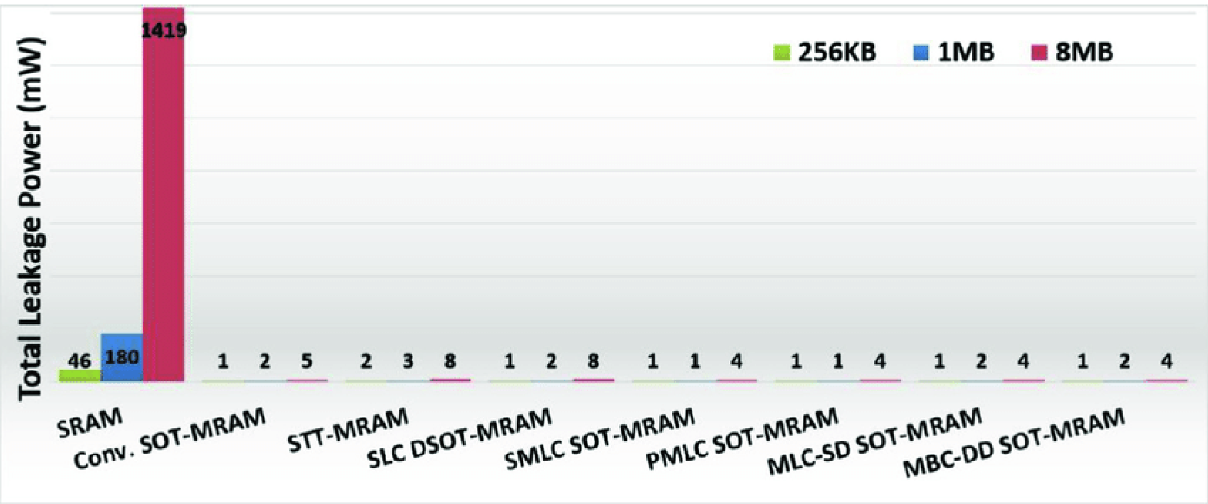


Figure 5: Comparison of total leakage power consumption between SRAM and MRAM memories[1]

New devices like wireless sensors are expected to be built around these new chips and integrated in global software solutions deployed in the edge, fog or cloud. The SLICES Research Infrastructure should provide some tools to monitor and measure the energy consumption of such solutions in real deployments made in the testbeds, taken into account the latest progress in terms of hardware. The

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[1] Area-Efficient Spin-Orbit Torque Magnetic Random-Access Memory - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/Total-leakage-power-consumption-of-SRAM-STT-MRAM-conventional-SLC-DSOT-MRAM-S-MLC_fig3_340943673 [accessed 17 Jun, 2022]

results of these measurements could be used to evaluate it the Sustainable Development Goals (SDGs), in particular the Goal 7 on energy, are reached by the solutions under test. They also allow the optimisation of such solutions on the energy consumption.

3.7.3 Research Priority 7.3: Needs of ICT in the context of energy efficiency

The development of clean and sustainable energy involves a better management of smart grids, a distributed generation of energy and the apparition of new energy storage. For example, Energy Vault[2] is developing a gravity energy storage which permits to produce electricity by stacking blocks of concrete with a crane, but requires information provided by the stakeholders of the smart grid to run in an optimal fashion. The common point between the energy generation, storage and distribution is the need of communications based on ICT. Indeed, to successfully manage a smart grid based on clean and sustainable energy, synchronisation and coordination among the different components of the smart grid are required and the exchanges of information through reliable and scalable communication channels are essential. The SLICES Research Infrastructure will address the challenges related to ICT involved in the management of clean and sustainable energy.

3.8 Thematic area 8 – Privacy

Privacy is a key requirement for any data-driven architecture, so much that privacy-centric techniques should be at the core of such architecture, such as for example the use of anonymization techniques to support data sharing. Privacy preserving techniques are essential moving towards a hyper-connected world, especially with key enabling technologies, such as 6G, providing ubiquitous connectivity for billions of IoT devices. Data sharing between different stakeholders, such as individuals, organizations and machines, will rely on efficient and effective privacy preservation mechanisms to share personal data.

3.8.1 Research Priority 8.1: Privacy in infrastructure design

Privacy cannot be supported without sufficient security in place. The security, however, is becoming more and more challenging with the increasing use of emerging technologies based on virtualization and distributed computing, like the Internet of Things and Cloud Infrastructures. The challenges for guaranteeing privacy in such technologies must be investigated from different perspectives. Firstly, we must look into the security of the technology, especially with regards to the confidentiality mechanisms in place and to the availability and integrity of the data. Aside from the security though, the idea of privacy has to do with specific policies and processes that can ensure that the level of privacy required is supported. Security and privacy are intertwined concepts, and both must be considered as requirements in virtual, distributed digital environments.

Security and privacy objectives must be set from the design phase. In order to establish security, one must first examine the technology, e.g., whether virtualization is used, or whether web services are active, and apply mechanisms that can support enhanced security like encryption. For privacy, the technologies are still important but as they relate to specific policies, e.g., whether virtualization can be used under a specific legal framework, or the extent that confidentiality can be guaranteed when webservices are used. Trust can be established once security and privacy are established.

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[2] Energy Vault website: https://www.energyvault.com/gravity, [accessed 30 September 2022]

3.8.2 Research Priority 8.2: Ethics in infrastructure design

Ethical requirements for a secure and private system must go one step further and consider the human element and the perception of trust, i.e., that the expected behaviour will happen. Expectations of trust can be different between different populations, different ages, genders, cultures, professional expertise. This is not the case when it comes to security and privacy because these requirements must follow a more universally acceptable set of guidelines and thresholds. Given the consideration for trust can be translated into different requirements for different populations, it is important to consider the idea of situational scenarios, in addition to technologies and legal frameworks.

Summarizing, in order to consider privacy for data, it is essential that also the dimensions of security and of trust are considered. The consideration of security deals more with the technology itself and the specific system safeguarding mechanisms that can be employed to ensure there is no security breach. The consideration of privacy deals with the legal frameworks and the framework of standards that the provider entity must align with, especially in having specific policies and processes in place to ensure the private (and sensitive) data is kept private. Finally, the element of trust is the consideration of the human expectation and to achieve that, a culture or an environment of trust must be cultivated because there is much more variety in experiencing trust than experiencing security and privacy. Therefore, ideally, a privacy plan would consider different scenarios where situations and populations would be allowed to vary.

Therefore, organizations should aim for a “privacy framework” in which a variety of tools can be engaged to deal with the considerations of the different technologies and the considerations of the specific legal framework, e.g., GDPR. – At the same time a privacy framework can employ scheduled risk assessments and impact analyses to adjust the policies and processes to the evolving organizational environment, thus aiming to install the element of trust to the framework as well.

3.9 Thematic area 9 – Wireless communications

Wireless communications play a key role in today’s communications, and through their evolution are expected to provide the communication substrate for a multitude of advanced services, for enhancing the everyday living of the future citizens. For example, emerging technologies within the next decade such as robots, drones, self-driving vehicles, AR/VR applications and new medical devices are expected to highly rely on wireless networking for their intercommunication with the edge and the core network. As such, research on wireless communications for producing new waveforms, including the use of higher frequencies up to the THz frequency bands, spectrum and ultra-dense wireless network management, integrated sensing and communication and multiple heterogeneous radio technology management are key towards the success of the SLICES initiative. In this section, in line with this vision, we detail the SLICES research priorities for the domain of wireless communications (excluding 5G/6G which has been described in a previous thematic area). As such, we organize the priorities in the following: (1) New waveforms and massive MIMO systems, (2) Software Defined Radios, (3) Heterogeneous Network/Multi-RAT Management.

3.9.1 Research Priority 9.1: New waveforms and massive MIMO systems

Millimetre wave wireless technology operates at frequencies in the range of 30 to 300 gigahertz, with wavelengths in the range of 1 to 10 millimetres. The technology can be used by wireless systems such as Wi-Fi and 5G for short-range, high-bandwidth communications (for example, 4K and 8K video streaming). Networks beyond 5G are envisioned to provide unprecedented performance excellence, not only by targeting data rates in the Terabit-per-second regime but also by inherently supporting a large dynamic range of novel usage scenarios and applications that combine these extreme data rates with agility, reliability, zero response time and artificial intelligence. Terahertz (THz) Wireless Communication is one of those technologies. In the future, the users in rural or remote regions, which are difficult to access should be connected with high data rates up to 10 Gbit/s per user. This is either infeasible or very costly when using solely optical fibre solutions. Terahertz transmission as a wireless backhaul extension of the optical fibres will be an important building block to face this challenge and guarantee high-speed internet access everywhere beyond 5G.

Complementary to these, Massive multiple input, multiple output (MIMO) antennas will be an important technology for enabling 5G and eventually 6G networks. Instead of having just a few antennas at each end of a link, a Massive MIMO system has a much larger number of antennas, organized in a phased array fashion. This enables multiple signals to travel over the same radio channel at the same time, meaning that the capacity of the system is much higher. With Massive MIMO, the system can be scaled theoretically as large as it needs to be Massive MIMO is already live in some areas and is used in Japan and China for 4G LTE technology. It’s expected to play an important role in the future of wireless network infrastructure, as 5G and 6G are rolled out.

Main research questions and challenges are:

- How can we support experimentation in the field of massive MIMO and THz communications with an experimental RI;
- How can other fields of research (e.g., Machine Learning) be applied for optimizing the performance of such systems;
- How can such resources be effectively integrated in an ever-expanding ecosystem of services and technologies for fast wireless communications.

3.9.2 Research Priority 9.2: Software Defined Radios

Software Defined Radios (SDR) have shifted the majority of the signal processing in wireless communication radio systems away from the RF chipsets, and enabled its execution as a software function. This enables the radio to support more frequency bands, and through the software that is running on top support different protocols. The technology has been available for many years, but has never been widely adopted in COTS vendor solutions as it is more expensive than using dedicated chips. However, SDR devices are expected to grow in popularity as new protocols emerge, and are the key vehicle for evaluating and prototyping new candidate wireless protocols. As older protocols are rarely retired, SDR will enable a device to support legacy protocols, with new protocols simply being enabled via software upgrade.

To this aim, SLICES will closely monitor and integrate latest high-end SDR devices offered for experimentation with emerging protocols and waveforms. The guiding questions and challenges for this thematic area are the following:

- How can SDR devices be integrated in the SLICES resource offering;
- How can such devices be managed from both the experimenter and the platform provider view;
- How can repeatable and reproducible experiments be performed with the use of Software Defined Radios.

3.9.3 Research Priority 9.3: Heterogeneous Network/Multi-RAT Management

Heterogeneous network deployment represents an important solution for decreasing congestion on mobile networks, by sharing traffic with other wireless access technologies with higher flows. Because of their fast and significant deployment, and the availability of several technologies (e.g., WiFi, legacy

LTE, etc.), future mobile communication networks will consist of a set of heterogeneous systems, managed by different operators and formed of distinct access networks. In this context, mobile terminals will be network multi-interfaces, which enables them to move from one system to another transparently during communication, supporting global mobility and vertical handovers. All the user connections with this heterogeneous network should occur transparently: without interruption and without degradation in service when the user changes from one network to another. To do this, networks should be based on existing infrastructure, by interconnecting networks already deployed.

Managing such networks poses several challenges for both each of the providers, as well as the end users, based on the availability of their network interfaces. SLICES aspires to be able to offer a highly heterogenous experimentation environment, where such scenarios can be evaluated. The main challenges that SLICES prioritizes are the following:

- How to effectively select the access technologies to serve end users given SLAs that they have contracted with the network operator;
- How to maintain session continuity in a across several physical wireless links.

How to split the traffic among the different candidate wireless technologies available for each user.

4 Preliminary design of SLICES-RI as a response to users' needs and requirements

The SLICES consortium has been continuously working towards designing and defining the SLICES end-to-end reference architecture that will be adopted and evaluated for the SLICES-RI. The architecture should comply with the next generation digital technologies systems that will dominate the market in the next decade, as presented in Section 3. The evaluation of the candidate solutions, as defined by the consortium, will be performed during the preparation phase, in order to consider several possible scenarios and articulations of the various components to accommodate the ambitious requirements and expectations of the scientific community. In D2.1 "Initial Description of the SLICES Architecture and Services" the SLICES partnership tried to sketch out candidate solutions for the definition of a truly open end-to-end architecture for the SLICES-RI. The document emphasized the analysis of the current demand from relevant ICT stakeholders for the operation of the SLICES facility, and the foundational principles on which it will be grounded. Below, we present the major points for the architecture.

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

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

Different tools have been employed within the SLICES-DS project in order to collect feedback from the research community, towards identifying current gaps in the facility offering. These are consolidated in the below functionalities, extracted from the analysis reported in Section 3:

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

The foundation principles of SLICES provide better exchanges between the industry and the academic world through a permanent dialogue and a market-based access. The architecture of SLICES has to be designed considering the experimental environment as a fully controllable, programmable and virtualized digital global infrastructure test platform. This architecture will provide high quality experimental services using emerging technologies around the area of digital sciences. The **primary technologies and approaches** to address the requirements for SLICES testbed are the following:

- Software Defined Network (SDN) and Network Function Virtualization (NFV): SDN is a technology that separates routing control traffic from data traffic, and that allows a centralized software to dynamically control the network. In the 5G ecosystem, the SDN architecture includes 3 different layers: 1) A WAN Resource Manager (i.e., SDN application) that represents the functional element that triggers SDN control plane operations. It translates the abstracted view at orchestrator level into a network domain-specific view; 2) Two kinds of SDN controllers, one used to configure the core network domain and the other one dedicated to the configuration of the RAN domain; 3) A data-plane composed of Core NFV Infrastructure (NFVI), backhaul network, Edge NFVI, fronthaul network, WLAN Access Points and LTE small cells. NFV transforms the way network operators and providers design, manage and deploy their network infrastructure by exploiting virtualization technologies. It enhances the delivery of network services to end users while reducing CAPEX and OPEX;
- Network Slicing: Slicing which allows a single 5G physical network to be segmented into multiple isolated logical networks of varying sizes and structures dedicated to different types of services. It is a multi-tenant virtualization technique in which the various network functionalities are extracted from the hardware and/or software components and then offered in the form of slices to the different users of the infrastructure (tenants);

- Network disaggregation: Network device disaggregation is the ability to source switching hardware and network operating systems separately. This concept has been extended to the radio access network: RAN disaggregation was specified by 3GPP and detailed by the Open Networking Foundation (ONF) as an important step allowing for dynamic creation and lifecycle management of use-case optimized network slices;
- Distributed Platform: All the aforementioned techniques SDN/NFV, network slicing and disaggregation can be combined in a distributed platform to test advanced networking scenarios in realistic large-scale environments. This could be done by leveraging virtualized computing and networking resources in a flexible way to provide support for solutions based on the use-case, geography and experimenter choice;
- Control and User-plane Separation: Control and User Planes (CUPS). In fact, with the densification of the next generation radio access networks, and the availability of different spectrum bands, it is more and more difficult to optimally allocate radio resources, perform handovers, manage interfaces, and balance load between cells. It is therefore necessary to adopt centralized control of the access network in order to increase system performance;
- Configuration and Orchestration of Experiments: An experiment is composed of a list of steps that include a specific set of tuning parameters for the system components, the configuration parameters for background traffic components, and the deployment and execution of the components to the testbed nodes and network elements. Orchestration of experiments is thus the process of running the sequence of steps that define the experiment. It is a complex task due to the concurrent, heterogeneous, asynchronous, and prototype-based systems that must be integrated into realistic scenarios to conduct trustable evaluations;
- Data-Storage Design: Data storage is an important feature to support in order to understand how the execution evolves during the experiments that generate detailed log traces with multiple levels of detail. Depending on the type of experiments, logs can be huge and saved locally on the testbed nodes as well as managed by a log collector and for instance saved in a MongoDB database in different locations, e.g., at the network edge infrastructure or in the public cloud.

Based on the above foundational principles for the RI, the architecture of SLICES-RI is organized as follows in terms of hardware and software.

SLICES hardware facilities and can be categorized into four basic sub-systems:

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

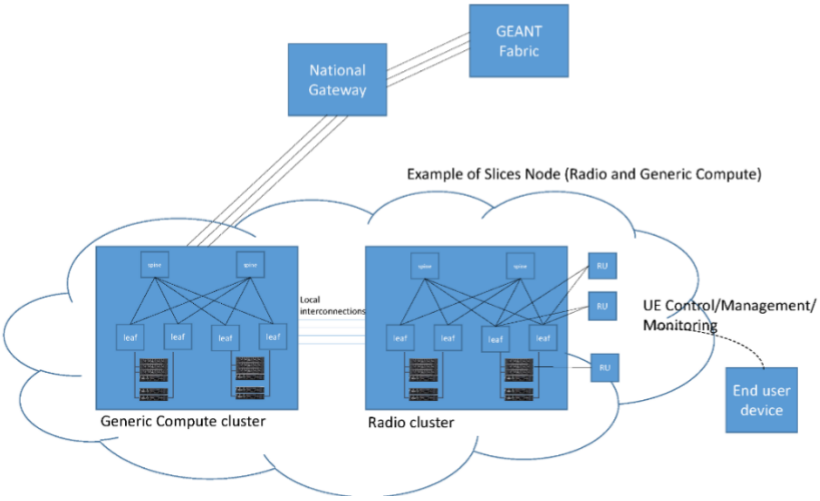

Figure 6: A high-level view of a SLICES node from an equipment standpoint

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

In turn, the software architecture of SLICES needs to organize the different geographically dispersed site facilities in a single pan-European facility, adopting common tools for managing and orchestrating experiments over the infrastructure, as well as providing a single access and credentials to users. A first attempt to sketch our reference architecture, with respect to the tools used for its management, is described in Figure 7.

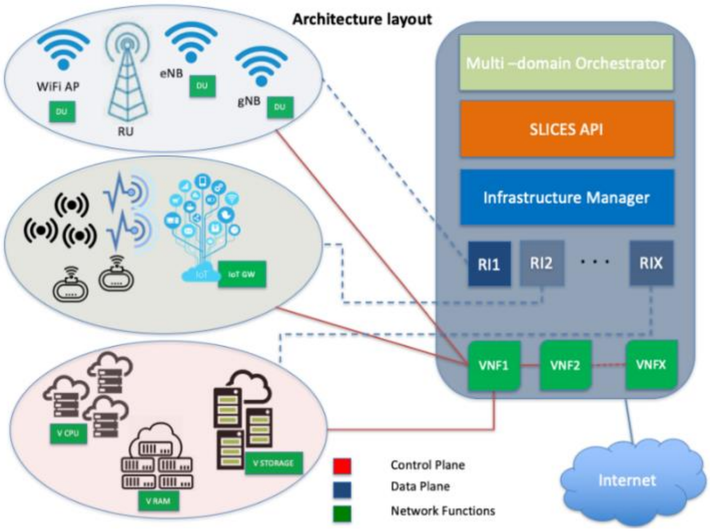

Figure 7: SLICES conceptual architecture

Towards achieving this integration, the sites will adopt network virtualization for their resources, compatible with the Management and Orchestration (MANO) architecture[3] for managing and

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

deploying new services over the physical equipment. Each node will be considered as a single domain for experimentation, while the overall orchestration of experiments will be performed through a centralized infrastructure. Site and node selection frameworks will be developed in the context of SLICES, towards ensuring the optimal use of resources among the sites.

Moreover, and towards ensuring the smooth operation of the infrastructure, tools for facilitating access will be developed and deployed. Open-source software shall be employed, based on the paradigms of existing testbed access schemes, user authentication and authorization. This software will be appropriately tailored with new modules for managing the new equipment described in the previous section. Complete guidelines for the software and hardware architecture of the SLICES RI are presented in depth in D2.1 “Initial Description of the SLICES Architecture and Services”.

5 Next steps to make SLICES-RI operational

SLICES RI will span over a long period, progressing along the phases of a research infrastructure. The timeline is described in Figure 8.

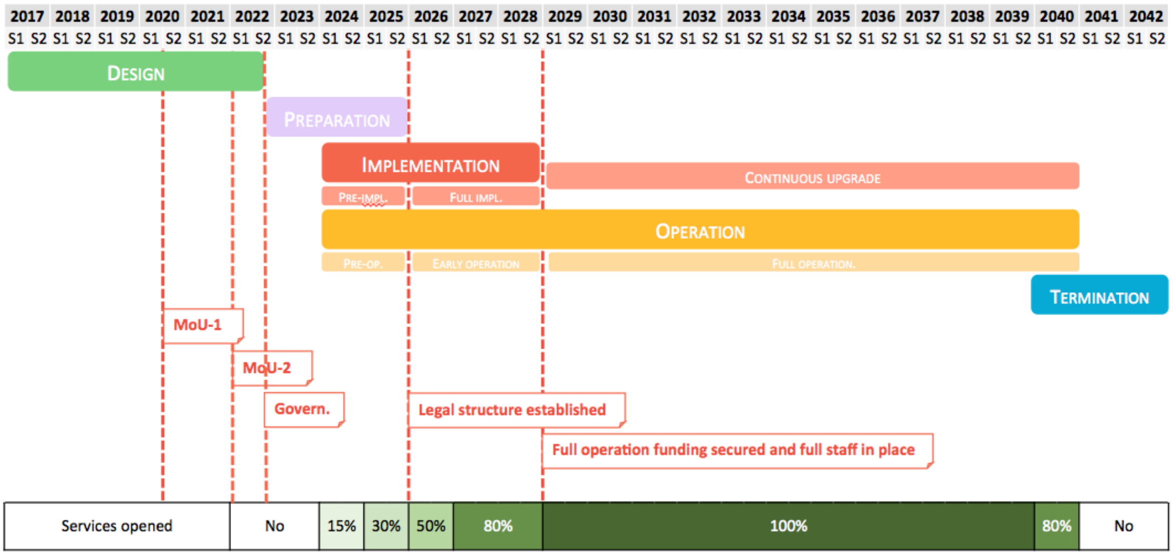


Figure 8: SLICES RI development timeline

Research infrastructures need to embrace the complexity of the world, regarding impact assessment, finding connections with the different stakeholders. In this deliverable we mostly consider the research and innovation roadmap, but we also have to onboard the expectation from industry. Fortunately, the roadmap is usually developed jointly, although with specific timescales, between academia and industry. Most importantly, the industrial expectations have to be considered upfront. As presented in our methodology, our community is strongly connected to the various stakeholders and relevant organizations.

This will be instrumental in order to develop a sustainable business model for SLICES, including market access. Not to forgot the ability to address the full research life collecting, exploiting and archiving FAIR data, in relation with EOSC.

In addition, we will continue to do our survey (D1.2) in order to collect the expectations from our community, in addition to the other tools of our methodology. In particular, key functionalities collected from workshop participants will be considered in order to discuss how to best address them:

- Support for 5G and beyond 5G;
- Large scale operational testbed;
- RI network management;
- Openness;
- Support for AI and ML;
- Support for cloud, fog and edge computing;
- RI federation;
- Real data;
- Traffic generators and simulators.

Another important point is related to the positioning of SLICES regarding other related initiatives, mostly developed by the hyper scalers and the open-source community. In particular, network disaggregation provides a unique opportunity to benefit from the strength of open-sources communities alike OAI, ONF or ONAP. SLICES is not expected to develop open-source software for the telecommunication industry, but can act as a catalyst to stimulate a tighter articulation of the roadmap of open-source solutions, mostly OAI and ONF. This is because SLICES provides a large-scale footprint enabling the deployment, testing and operation of an integrated open infrastructure, providing a preference target for the open-source software solutions. As a consequence, SLICES will work also on how we can stimulate a proper articulation among those who potentially can provide us with the software components that are needed for deployment. This will allow us to focus on what is specific, namely the control, experimental planes as well as the main APIs.

6 SLICES-RI in 2030: success measures

SLICES delivers state-of-the-art digital research infrastructure for scientists and industry to address key technological challenges in telecommunication and computing technologies. As explained in Section 5, the timeline for the implementation phase ends in 2028 and from 2029 SLICES will enter the operational phase with all infrastructure elements in place. In order to evaluate readiness of SLICES in early stage of the operational phase we have identified a set of measures of success of our initiative by 2030:

- **Established** – SLICES-RI is well positioned in the ESFRI Roadmap of Research Infrastructures, with governance bodies established and operational procedures implemented;
- **Interoperable** – policies for interoperability with relevant research infrastructures and/or EOSC services defined and executed;
- **Based on Strategic Research Priorities** – the research infrastructure reflects the needs of research communities and the state-of-the-art development in the field. Both, the needs of research communities and the state-of-the-art will be monitored by Partners and reflected in future evolution of the RI;
- **Harmonized** – the RI will be managed and orchestrated by software tools and the management platform to provide seamless access to resources and services offered by the infrastructure;
- **Easy to use** – the project will monitor satisfaction of the users of the research infrastructure and will be continuously working on improvements to provide an easy-to-use research environment to its users;
- **Supporting PhD programmes** – the RI will promote open science, and in particular establish dedicated PhD programmes to promote applied science and research among young researchers.

7 Conclusions

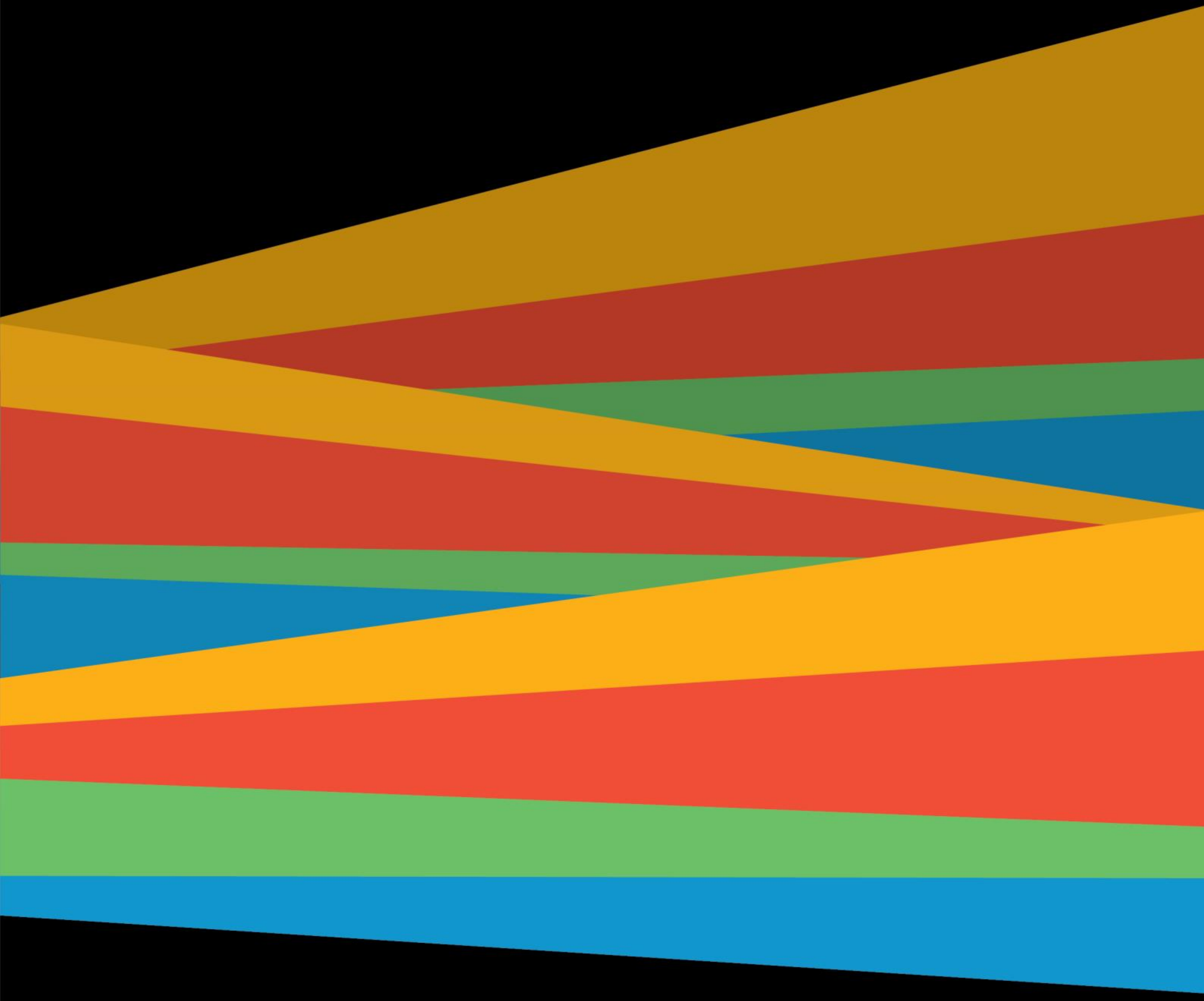
Identification and analysis of the key scientific challenges in the ICT and communication fields is a critical task for the SLICES consortium in order to properly design, implement and operate a modern, competitive digital research infrastructure. This task requires properly adopted methodology for prioritization of research topics SLICES will be built upon. This deliverable explains the selected methodology and presents the results of analysis of key scientific challenges, which will drive the evolution of the research infrastructure in the next period. The following thematic areas have been identified within the project duration for further analysis:

- Thematic area 1 – Cloud, Fog, Edge Computing;
- Thematic area 2 – Artificial Intelligence (AI) and Machine Learning (ML);
- Thematic area 3 – Security;
- Thematic area 4 – SDN/NFV;
- Thematic area 5 – Beyond 5G and 6G;
- Thematic area 6 – Network technologies;
- Thematic area 7 – Energy efficiency;
- Thematic area 8 – Privacy;
- Thematic area 9 – Wireless communications.

The topics have been selected as part of the analysis of users' needs, realized through SLICES workshops and questionnaires. The work on the analysis of users' needs have been reported in the Deliverable D1.2 "Requirements and needs of scientific communities from ICT-based Research Infrastructures".

Within each thematic area key research priorities have been identified, followed by the overall description and guiding questions and challenges related. In total, within 9 selected thematic areas 30 key research priorities have been identified. These priorities will drive the design and implementation of the SLICES RI in the upcoming years. The preliminary design and the architecture of the SLICES RI, as an outcome of the analysis of users' needs and identified research priorities is presented in Section 4. However, it is important to ensure the work initiated in SLICES-DS, and WP1 in particular, continues in follow up activities of this project. Therefore, as part of the SLICES Preparatory Phase project, SLICES-PP, the Work Package 3 "Scientific and technical strategy and specifications" will be devoted to further develop the long-term vision and evolution of the SLICES-RI along with the continuation of work on prioritisation of research topics. The SLICES-PP consortium will take appropriate actions to monitor and evaluate on the annual basis the list of research priorities for the SLICES-RI communities, and their respective time horizon for development. This will represent the prioritised set of topics that the RI should support, a key input for further technical design and operational choices.

Moreover, this report will be consulted with the SLICES Advisory Board and feedback and recommendations will be implemented in follow up activities, as part of the SLICES-PP project.



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