

6G-PATH Open Experimentation Platform for B5G Enablers and Diverse Vertical Applications

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Abstract—To prepare Europe for the 6G era with an open experimentation platform, the EU 6G-PATH project aims to help foster the further development and integration of new and improved 5G/6G enablers from EU collaboration, whilst facilitating the deployment and testing of a wide spectrum of vertical applications. To this end, the project establishes a uniform experimentation platform that is able to accommodate nine highly heterogeneous and geographically distributed testbeds from the project consortium, and is leveraging this platform for 10 diverse use cases across four key verticals including Farming, Education, Health, and Smart Cities. This paper presents the architectural design and prototyping of the 6G-PATH experimentation platform, highlighting its essential building blocks and advanced features, primary workflows, and example vertical application use of the platform.

Keywords—6G, B5G, experimentation platform, essential features, advanced features, vertical use cases

I. INTRODUCTION

As wireless/mobile communications advance towards 6G, there is a critical need to consolidate architectural perspectives that will define the foundations of future networks. The transition from 5G and 5G-Advanced to 6G goes beyond incremental improvements, requiring new paradigms that embed intelligence, integrate communication and sensing, and ensure sustainability, security, and resilience by design.

Beyond-5G (B5G)/6G experimentation platforms play a pivotal role in validating these paradigms, enabling rigorous testing of enablers like AI-native networks, Integrated Sensing and Communication (ISAC), reconfigurable intelligent surfaces (RIS), and cell-free (CF) massive multiple-in, multiple-out (MIMO) radio technologies, among others.

Europe's diverse landscape of isolated testbeds- built through Horizon 2020's 5G PPP (e.g., 5G-EVE, 5GENESIS, and 5G-VINNI [1]) and now evolving under the Smart Networks and Services Joint Undertaking (SNS JU)- has driven innovation but also highlighted fragmentation challenges.

This isolation hinders large-scale, cross-domain validation, reproducible results, and efficient resource sharing across verticals such as industry, smart cities, and e-health. More uniform architectures are essential to federate these testbeds, promoting interoperability, modularity, and scalability. Current initiatives especially those in Europe [2] like 6G-PATH [3], 6G-SANDBOX [4], 6G-BRICKS [5], and SUNRISE-6G [6] exemplify this “shift” toward pan-European, sustainable federation. Such unified platforms will accelerate 6G standardisation, foster collaborative research and development, and ensure Europe's technological sovereignty in delivering future networks.

This paper focuses upon the 6G-PATH experimentation platform, which provides significant gain points to support vertical industries in allowing vertical use cases to be deployed and tested, in a number of B5G testbeds across Europe. The main innovations and capabilities include the following: (i) A common unified experimentation portal and experimentation interface to allow vertical use cases to have a homogeneous experience in conducting their experiments in heterogeneous B5G/6G testbeds with distinct features across Europe. (ii) A number of advanced networking, intelligence, security and automation/autonomy features to enable B5G/6G network service developers and vertical businesses to test B5G capabilities that may be essential to “run” their new applications with demanding requirements that may not be feasible in current commercial 5G networks. (iii)

Development of a set of experimentation tools and methodologies to allow B5G/6G experimenters measure sets of well-defined Key Performance Indicators (KPIs) and Key Value Indicators (KVI) in several application domains (Farming, Education, Health, and Smart Cities). These are the highlighted values brought by the 6G-PATH platform. The main contribution of this paper is to provide a systematic overview of the architectural design and prototyping of the 6G-PATH experimentation platform.

The remainder of the paper is structured as follows: Section II reviews the related work, as already performed in the European framework. Section III presents the overview of the 6G-PATH experimentation platform’s architecture, especially focusing on the essential building blocks. Section IV describes the primary workflows. Section V highlights the prototyping and advanced features of the platform. Section VI concludes the paper.

II. RELATED WORK

The European Union has significantly advanced 5G and 6G validation through dedicated testbeds under Horizon 2020’s 5G PPP and Horizon Europe’s Smart Networks and Services Joint Undertaking (SNS JU). Recent years have witnessed a growth of experimentation platforms focused on validating network enablers such as network slicing, AI as a Service (AIaaS) or native AI, edge-cloud continuum, and quantum computing, and/or a variety of vertical use cases such as farming, education, health and smart cities.

In 5G PPP Phase 3, three flagship infrastructure projects built end-to-end facilities [1]: 5G-EVE created a multi-site European validation platform (France, Spain, Italy, Greece) for extensive trials and interoperability; 5GENESIS developed open, coordinated 5G platforms across five sites (Malaga, Athens, Limassol, Surrey, Berlin) emphasizing KPIs and automation; 5G-VINNI delivered advanced facilities for verticals innovation (Norway, UK, Spain, Greece, Portugal), supporting zero-touch orchestration and service validation.

These interconnected testbeds enabled large-scale pilots for vertical projects like 5G-VICTORI [7] and 5G-HEART [8].

Towards 6G, SNS JU initiatives build on this legacy with federated, AI-driven platforms. Flagships Hexa-X [9] and Hexa-X-II [10] defined 6G blueprints for sustainable, trustworthy networks. In addition, several key B5G experimentation projects are underway. 6G-SANDBOX is a modular pan-European testbed integrating digital twins and sites for advanced validation. 6G-BRICKS is focusing on reusable innovations like cell-free massive MIMO and RIS. SUNRISE-6G is inspired by the “network of networks” concept of 6G, aiming to integrate all private and public infrastructures under a massively scalable internet-like architecture. These efforts emphasize federation, sustainability, and vertical integration, paving the way for 6G deployment in Europe. In this paper, we focus on the 6G-PATH experimentation platform. 6G-PATH is establishing pan-European pilots and trials for both B5G enablers and vertical applications.

III. 6G-PATH EXPERIMENTATION PLATFORM - ARCHITECTURE OVERVIEW

A. Platform Architecture Overview

Fig. 1 shows the overall architecture overview of the 6G-PATH experimentation platform. The lower part of Fig. 1 represents nine different 6G testbeds. Every testbed has achieved at least three interfaces to enable it to be plugged into the 6G-PATH experimentation framework. Firstly, the Infrastructure Manager/Orchestrator API/Dashboard allows local resource management within the scope of every testbed. Secondly, the Service Manager/Orchestration API/Dashboard allows local service management in the scope of every testbed. Thirdly, the Monitoring Northbound API/Dashboard allows monitoring of both services and resources in the testbed. These are the preconditions in the participating testbeds.

Furthermore, there are several essential building blocks, as shown in the upper layers (on top of the testbeds) in Fig. 1 to

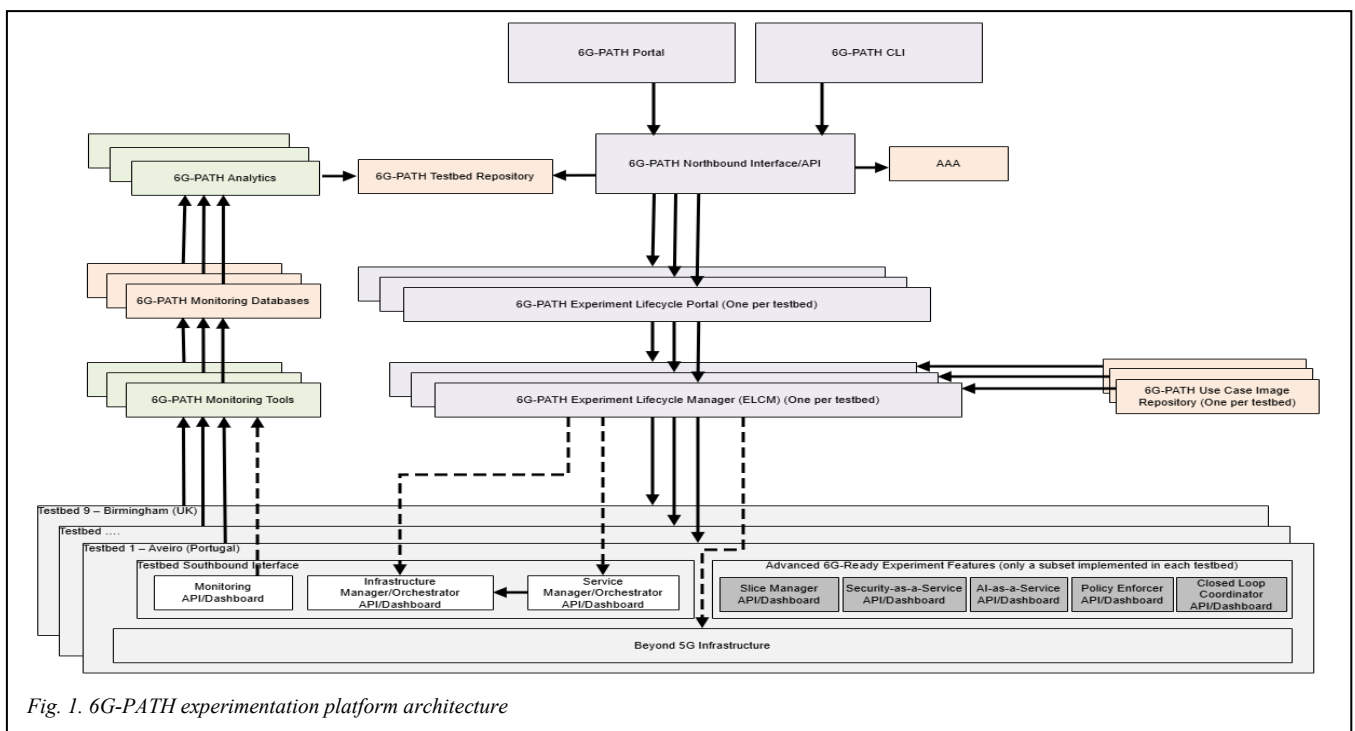


Fig. 1. 6G-PATH experimentation platform architecture

facilitate the execution of experiments. Moreover, every testbed is expected to provide advanced 6G-ready experiment features. They are depicted in the right-lower part of Fig. 1, in darker grey. It is noted that not every testbed will have every advanced functionality. The planned advanced 6G-ready functionalities and their availability in the individual testbeds are presented in more detail later.

B. Essential Building Blocks

In the following, the essential functionalities in the 6G-PATH architecture are introduced in the context of the overall operation of the system.

The 6G-PATH Portal and Northbound Interfaces/API is the entry point for users intending to experiment in any among the available 6G-PATH testbeds. User authentication and authorisation is performed first to ensure that only authorised users can access the system. To this end, it interacts with the AAA (Authentication, Authorisation and Accounting) component of the 6G-PATH architecture. Authenticated and authorised users is then provided with the set of available (registered) testbeds in the 6G-PATH Testbed Repository, from which the user can access to the 6G-PATH Experiment Lifecycle Portal via the respective links. The 6G-PATH Experiment Lifecycle Portal enables the users of an individual testbed to onboard their experiments especially those measuring KPIs and/or KVIs. Thus, the 6G-PATH Northbound API can be seen as a proxy to allow users to interact graphically with the system.

After a user gains access to a testbed, the 6G-PATH Experiment Lifecycle Manager (ELCM) manages the execution of experiments. The ELCM is a core component of the 6G-PATH experimentation framework, based on ETSI TR 103 761 [11]. Therefore, experiments are formalised in a test, which ELCM will execute. If a testbed-specific solution is required as part of an experiment, a task for launching and configuring that solution must be included in the experiment executed by the ELCM.

As the central point for experimentation, the ELCM is responsible for coordinating the complete lifecycle of a 6G-PATH experiment. The 6G-PATH Experiment Lifecycle Portal contains an interface (frontend) to allow configuring the ELCM (backend). When the ELCM receives a request to perform the execution of an experiment, it interacts with other components to carry out its task. Firstly, it retrieves the services/images of the use case from the 6G-PATH Use Case Image Repository and triggers the deployment of the use case in the indicated testbed, if the experiment requires the deployment of the services and they are not pre-deployed. Then, the 6G-PATH ELCM interacts with the corresponding testbed to execute the use case images. Consequently, it executes of the different experiment tools in order to conduct a concrete evaluation of the performance within the infrastructure, e.g., using a 6G-PATH Monitoring Tool such as a common monitoring tool like iPerf or a testbed or use case specific tool.

After executing both use case images and test case tools, the results generated from the experiment are stored in the 6G-PATH Monitoring Databases such as InfluxDB. In the test cases, each testbed will include the task of injecting the result data into the Monitoring Databases through a messaging/data streaming mechanism. In the current release of the 6G-PATH framework, Kafka is employed in several testbeds as a messaging backbone for data exchange, while others rely on

alternative mechanisms for data collection and communication, depending on their specific infrastructure and requirements. Each testbed implements and configures its own data management setup, accordingly. Monitoring is performed at the testbed level using a combination of common, as well as testbed- or use case-specific, monitoring tools. To ensure interoperability, the Monitoring Tools enable conversion between the native data formats of each testbed and the unified 6G-PATH monitoring format shared across the various testbeds in the framework.

Furthermore, the 6G-PATH Analytics component provides graphical visualisation of monitoring metrics collected during experiment execution, with results displayed through a dedicated dashboard. This dashboard leverages the 6G-PATH Testbed Repository to determine how to access the various Monitoring Databases associated with each testbed, and interacts with the 6G-PATH Northbound Interfaces/API for user authentication and authorisation, ensuring that users can only view results from their own experiments.

It is noted that the 6G-PATH ELCM is instantiated multiple times, one per testbed, to provide experimentation capabilities within the context of the testbed. Moreover, there will be multiple instantiations of the 6G-PATH Monitoring Databases to “keep” the information related to each testbed collected in the same database. Meanwhile, all these databases will have the same data model to allow reusing the same 6G-PATH Experiment Lifecycle Portal dashboard for all the testbeds. Thus, the 6G-PATH Experiment Lifecycle Portal (also referred to as ELCM Portal hereafter) will also be instantiated per testbed and only the users with permission will have access the corresponding dashboard.

IV. 6G-PATH PLATFORM - PRIMARY WORKFLOWS

This section presents the main workflows in the 6G-PATH experimentation platform for deploying and testing vertical use cases.

A. Onboarding Use Case

The onboarding of the use cases can be handled as an isolated action before the experimentation or demonstration phase, or it can be included within the experiment itself. In the first case, the sequence of actions is shown in Fig. 2. The experimenter – or use case provider – briefly accesses the 6G-PATH Portal and queries the available platforms. After verifying the experimenter’s identity in the AAA module, the links to the available platforms are sent to the experimenter. The experimenter selects one of them and accesses the ELCM Portal, where the available test cases for that user will be listed. The numbers in Fig. 2 indicate this sequence.

B. Conducting Experiments

Firstly, the experimenter visits the 6G-PATH Portal and inserts a username and a password. The 6G-PATH Northbound interface receives this authentication request and redirects it to the AAA server. The authentication result indicates whether the user is authenticated and which testbed they are authorised to access. The 6G-PATH Northbound interface will retrieve from the 6G-PATH Testbed Repository all the links necessary for the user to get access to the testbed. The ELCM will retrieve all the images of the use case, if the experiment requires the dynamic deployment of the images as part of the experiment. Subsequently, the experiment will be triggered at the testbed ELCM Portal. After the experiment has begun, the metrics will flow from the testbed and then be

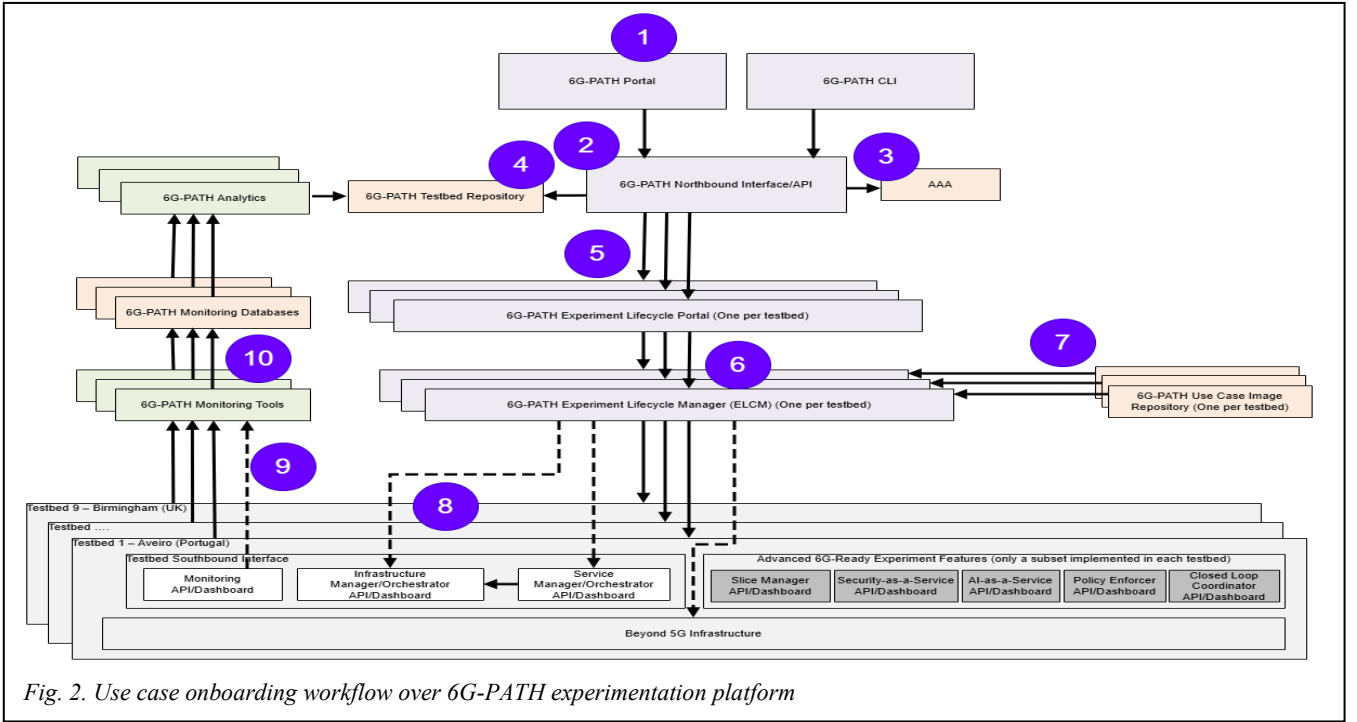


Fig. 2. Use case onboarding workflow over 6G-PATH experimentation platform

stored in the associated Monitoring Database. For brevity, the sequence figure for this workflow has been omitted.

V. 6G-PATH PLATFORM – ADVANCED FEATURES, PROTOTYPING AND USE EXAMPLE

A. Advanced Features and Technology Gaps Filled

The advanced 6G-PATH experiment features practically “reflect” several innovations deployed, including Slice Manager, Security as a Service, AI as a Service, Policy Enforcer and Closed Loop Coordinator.

For instance, the 6G-PATH platform implements advanced Slice Manager based on complementary network slicing functions spread over several testbeds, such as end-to-end 5G and beyond Radio Access Network (RAN) and core network slicing, and data plane programmability-based network slicing. Another example of innovation is the Closed Loop Coordinator, responsible for coordinating the various automated closed loops available in different testbeds for different purposes such as network slicing, backhaul monitoring and updating, service quality monitoring, and Automatic scaling of edge/cloud resources.

In the context of the 6G-PATH vertical use cases, several gaps have been identified in the current technologies and filled to support the use case deployment and experimentation by leveraging the advanced features.

Firstly, various use cases especially those demanding ones need to clearly showcase how beyond 5G experimentation platform can benefit the use cases’ performances, and offer efficient facilities to evaluate not only KPIs but also KVIs. For example, in the Education use cases, the immersive teaching and learning environments based on eXtended Reality (XR) require improvements and evaluation in both KPIs (e.g., higher bandwidth and lower latency) and KVIs (student satisfaction, etc.). To address the challenges in deriving KPIs in a more efficient manner, a new scheme called KPI2KVI is designed in 6G-PATH to provide a multi-agent workflow for calculating KVIs from service descriptions [12].

Secondly, the various use cases have divergent requirements in KPIs and KVIs, which require evaluating various network slicing solutions available in different testbeds to identify the optimal solution per use case scenario. Existing network slicing solutions such as [13-15] typically provide different interfaces/APIs for testing and managing the lifecycle of the network slices, making it difficult for use case experimenters to create, deploy and operate network slices at different experimentation platforms. In 6G-PATH, a uniform API based on ETSI OpenCAPIF [16] has been integrated over the different network slicing solutions’ northbound interfaces, thereby significantly reducing the complexities and avoiding adaption each time for use case experimenters to try different network slicing solutions.

Thirdly, global optimisation at the platform level for the distributed testbeds is envisioned to improve the performance and efficiency, especially the different automated closed loops, for the operation of the infrastructure and the services to support the various use cases. This has motivated the design of a new Closed Loop Coordinator – MIRO [17, 18]. MIRO is a cloud-native framework for enhancing the management of the edge-to-cloud continuum. It facilitates the dynamic creation and peering of Kubernetes clusters across multiple cloud providers and automates the deployment and management of applications within these complex, multi-cluster ecosystems within an innovative solution. MIRO lays the groundwork for effective lifecycle management, including essential service migration operations, while providing comprehensive monitoring capabilities for a multi-domain Kubernetes infrastructure.

Finally, the various use cases demand more cost-efficient cybersecurity and AI services, as seen in the eHealth use cases. Thus, the different approaches in X-as-a-Service need to be tested and improved. Work is underway in 6G-PATH to enhance Security-as-a-Service based on OpenCAPIF or EU FiWARE, AI as a Service based on 3GPP Network Data Analytics Function (NWDAF) [19] and custom AI solutions for use cases’ QoS/QoE etc., and Policy Enforcer based on

ONemNEF (OneSource Microservice-based Network Exposure Function) [20] of EU FUDGE-5G [21] or 3GPP Traffic Influence API [22].

B. Prototyping

The current hardware and software deployment is underway in these testbeds. Table 1 summarises the software prototyping. For the beyond 5G infrastructure in the trial locations, the following hardware (and corresponding solution) deployment is being employed across the different network segments. For user and network equipment, the hardware includes various 5G Standalone (SA) network-validated User Equipment (UE), commercial-grade 5G SA routers, Multi-access/Mobile Edge Computing (MEC) devices, and so on. For the RAN segment, RANs of various flavours from different vendors are available, such as Huawei SingleRAN (SRAN) SA/NSA, Nokia AirScale, Ericsson DOTs SA/NSA, and OpenAirInterface (OAI). For the Core Network (CN) segment, similarly, different CNs are co-existing, such as Nokia Compact Mobility Unit (CMU), Ericsson virtual Evolved Packet Core (vEPC), 5GC, and Open5GS.

C. Platform Use Example

Fig. 3 shows an example of a test case for the deployment of a Farming use case. Once this test is selected, the ELCM will download the necessary artefacts from the use case image repository to deploy the selected testbed's infrastructure. To this end, it will communicate with the local orchestrator available in that infrastructure. The deployment will be monitored by the Monitoring Tools available on that testbed, and the obtained KPI metrics will then be stored in the

Fig. 3. Definition of a new experiment to execute the deployment of the Use Case FARM 1

Monitoring Databases with the corresponding Execution ID generated by the ELCM to identify the experiment uniquely.

The onboarding of the use cases is done through a test case executed via the ELCM. The first step is to define a new experiment in the local 6G-PATH ELCM Portal available at each testbed, and the test operator conducts this. The Portal sends an experiment descriptor to the ELCM for the test case to be executed to run the deployment.

Three tasks can be used, including the “Run.CliExecute”, “Run.DeployExperiment” and “Run.RestAPI” tasks. The “Run.CliExecute” enables the execution of an application

Table 1. Current 6G-PATH's software prototyping of essential building blocks and advanced features

Architecture Component	Main Functionality	Software Deployment
Portal & Northbound Interface/API	Access layer for users (including AAA)	Based on EU 5G-MediaHUB [14]
Experiment Lifecycle Portal	GUI for the front end of experiment management	ELCM Portal software based on EU 5GENESISM [1]
Experiment Lifecycle Manager	The backend of experiment management	ELCM software based on EU 5GENESIS [1]
Use Case Image Repository	Repository for use case components	Based on standard image repositories such as GitLab
Monitoring Tools	Common and use case-specific tools for KPI/KVI monitoring	Standard monitoring tools such as Prometheus, iPerf and Ping, and various use case monitoring tools
Monitoring Databases	Databases to store monitoring outputs	De facto industry-grade databases such as InfluxDB
Analytics	Aggregation, analytics and visualisation	De facto industry-grade solutions such as Grafana
Slice Manager	Network slice lifecycle management	Based on commercial network slicing solutions (APN-based, etc.), EU 6G BRAINS [23], etc. The northbound API is based on OpenCAPIF [16].
Security as a Service	Cybersecurity management as a cost-efficient service	Based on OpenCAPIF [16], EU FiWARE, etc.
AI as a Service	AI tools and capabilities as a cost-efficient service	Based on 3GPP Network Data Analytics Function (NWDAF) [19] and AI solutions for QoS/QoE etc.
Policy Enforcer	Policy enforcement for automated closed loops	Based on ONemNEF (OneSource Microservice-based Network Exposure Function) [20] of EU FUDGE-5G [21], 3GPP Traffic Influence API [22] etc.
Closed Loop Coordinator	Coordination of various automated closed loops across testbeds	Custom build in the format of a Multi-domain Infrastructure and Resource Orchestration (MIRO) [17, 18]

with a CLI (Command Line Interface) or the execution of different types of scripts, in which the deployment steps can be included. The “Run.RestAPI” enables direct invoking of the RESTful API exposed by the orchestrator of the testbed. The “Run.DeployExperiment” is capable of performing deployments based on Helm Charts. The test case for the deployment can include additional tasks to perform some actions such as configuration or activation of the use case or the collection of results. In the ELCM, the implementation of the deployment test case should include a task or several tasks, which incorporate the commands used for executing the deployment in the respective testbed.

Moreover, the 6G-PATH platform enables aggregating the measurements available in the testbeds in a very simple and flexible way in the Monitoring Databases such as InfluxDB (as this approach “links” all of them through the same unique Execution ID). The measurements collected by the different monitoring tools deployed in the testbeds will be collected using the definitions of specific tasks in the test case. For example, Fig. 4 shows a test case that includes a task of the type “Run.CliExecute”, which connects via an SSH (Secure Shell) transaction to a VM (Virtual Machine) located in the Edge and executes a script (pingm.sh) that contains a ping from the Edge to the IP address of the UPF (User Plane Function) and stores the results in a file called “edgeping.csv”. After this task, the test case includes a new task that retrieves the file with the results via an SSH. Finally, the test case includes a task, “Run.CsvtoInflux”, which injects results stored in the file into the Monitoring Databases with the Experiment ID of the experiment under execution.

VI. CONCLUSIONS

6G-PATH offers a new uniform experimentation platform with essential building blocks for onboarding and testing a wide range of diverse vertical applications, as well as advanced B5G/6G features to facilitate vertical use cases to conduct challenging trials towards the 6G era. The 6G-PATH platform enables heterogeneous existing 5G/B5G testbeds to be upgraded and integrated under a common experimentation architectural framework in a highly distributed manner across Europe. Prototyping has proven the usability of this platform in deploying and running applications across Health, Education, Smart Cities and Farming sectors. Work is underway in collecting KPIs of these applications, complemented by trials focused on evaluating KVI.

```

Version: 2
Name: EDGEPING
Sequence:
  - Order: 20
    Task: Run.CliExecute
    Config:
      Parameters: plink -ssh 10.11.32.XXX -l admin -pw hello -batch -t "sh pingm.sh 10.11.32.1 TESTTEST"
      CMD: C:/ELCM/Experiment
  - Order: 21
    Task: Run.CliExecute
    Config:
      Parameters: plink -ssh 10.11.32.XXX -l admin -pw hello -batch -t "cat edgeping_ping.csv" > edgeping.csv
      Parameters: 'echo'
      CMD: C:/ELCM/Experiment
  - Order: 30
    Task: Run.CsvtoInflux
    Config:
      ExecutionId: '#(ExecutionId)'
      CSV: "C:/ELCM/Experiment/TESTTESTping.csv" # Replace with the location of the file
      Measurement: '5G_Ping_Agent'
      Delimiter: ','
      Timestamp: 'Timestamp'
      Convert: True
  
```

Fig. 4. Test case example: Inject measurements in InfluxDB with the Execution ID

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