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Advanced 5G Open Testbed for Network Applications Experiments

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***Abstract*—5G Stand Alone (SA) networks are starting to be considered, designed and implemented in multiple countries in various forms (public, private, experimental). 5G SA networks mass adoption is expected to materialize by 2025. Mass deployment is anticipated at a large scale, due to the rich features and capabilities offered by 5G networks, including but not limited to slicing, service orchestration and automation, bringing the benefits of 5G among industry stakeholders and verticals. The concept of Network Applications is gaining momentum, as a way to ease the process of deploying industry-specific services and applications and to integrate them seamlessly with the new 5G networks and customer-specific application components. We target deploying and operating the novel 5G SA testbeds, Network Application and related capabilities in different T&L facilities across Europe. We envision the architectural advancement in terms of 5G features, such as orchestration, multi-slice implementation, Quality of Service (QoS)/Quality of Experience (QoE) and an innovative end-to-end monitoring framework, for network and application KPIs. In this paper, 5G open testbed advancements (3GPP Rel. 16 compliant) and readiness for Network Application experiments in real-life scenarios are presented, integrated as a unitary whole within the EU-funded VITAL-5G project.**

***Index Terms*—5G private networks, 5G-enabled, Network Applications, Experiments, VITAL-5G.**

I. INTRODUCTION

5G technology aims to support use cases that have high requirements in terms of low latency and high throughput, such as the ones falling into domains of automotive or transport & logistics (T&L) verticals. To achieve these results, the telecom operators need to upgrade the 5G Core, 5G Transport and 5G RAN as well as integrate Virtualized Edge Cloud Infrastructure resources which they are making available to customers.

Enhancing the performance of networks through (1) the use of high throughput services, i.e., deploying an enhanced Mobile Broadband (eMBB) slice, (2) extremely low latency via an Ultra-Reliable Low-Latency Communication (URLLC) slice, or (3) massive numbers of connected devices through a MachineType Communication (mMTC) slice, is discussed in [1], [2], aiming to support diverse vertical sectors such as autonomous vehicles, smart manufacturing, transport and logistics and public protection and disaster relief use cases. For instance, [3] describes the required bandwidth for automated control of vessels at 5-25Mbps in the uplink and a latency below 10 ms for an HD video camera stream. Two key enablers of these new generation networks are Software-Defined Networking (SDN) and Network Function Virtualization/Virtualized Network Functions (NFV/VNFs) as described in [4], extending this also to the Cloud-Native Network Functions (CNFs). In the European project H2020 VITAL-5G, we aim at creating an experimentation platform targeting T&L services on the three different testbeds of the project, leveraging on 5G SA technology. We are thereby building the experimentation facilities where the potential of 5G and its benefits could be validated in real-life environments (such as ports and warehouses). For efficient application development, processing and testing, dedicated environments and resources are needed to be put in place to ensure the proper Network Applications service life cycle management.This has been achieved in the VITAL–5G project [5] by setting up dedicated T&L 5G-enabled infrastructures, including virtualization and orchestration, implemented in all the three project's testbeds, as illustrated in Fig. 1.

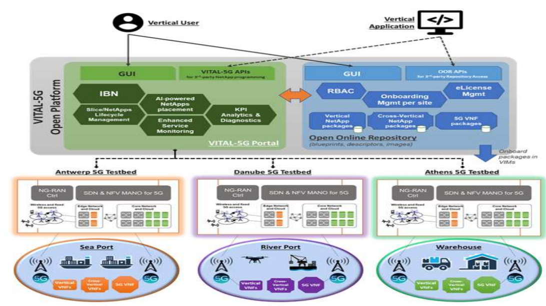


Fig. 1: The VITAL-5G Architecture and advanced testbeds for T&L.

In the context of unitary Network Applications onboarding steps, the VITAL-5G Platform has been implemented as a flexible platform, which can be adapted to serve the specific needs of the T&L sector focused on the creation, deployment,

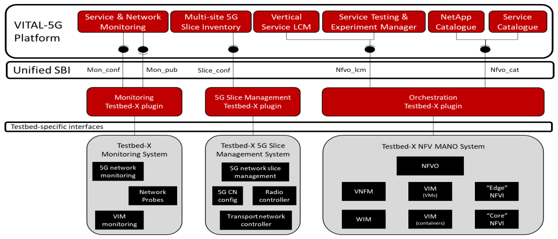


Fig. 2: VITAL-5G Platform and testbeds integration.

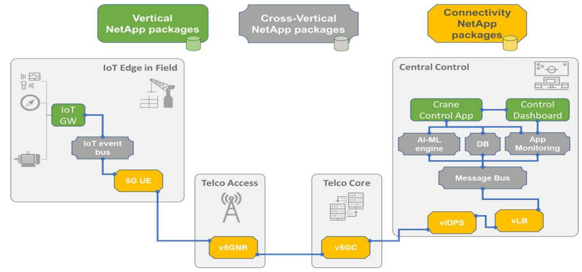


Fig. 3: VITAL-5G Network Application concept.

management and validation of applications, including service & network monitoring, slice inventories, service and testing capabilities and orchestration.

By setting up an integrated web portal, where the Network Application developers can select the needed resources from the service catalogue, we aim to ease the integration applications that require novel 5G services. The platform also helps with vertical service life cycle management, blueprint validation, service testing and monitoring, results analysis, AI-based diagnosis, and multi-slice inventory management.

The paper is including the architecture of 5G SA testbeds that are tailored to Network Application experimentation and offer possibilities for an intuitive usage of 5G resources by third-party experimenters, covering all three testbeds concepts, detailing the network and orchestration capabilities, including the 5G network slice and application performance evaluation, as presented in later sections.

II. VITAL-5G End-to-End (E2E) Reference Architecture

The key element of VITAL-5G is the Platform that provides a rich set of flexible and intuitive tools and Application Programming Interfaces (APIs) to facilitate the design, management, orchestration and validation of the services for various vertical sectors in the pan-European T&L eco-system. The platform facilitates production-ready Network Applications, made available to multiple providers by an open repository, to build end-to-end T&L services for trials. The validation is executed over 5G network slices, deployed in the three testbeds, as seen in Fig. 2.

A. VITAL-5G Concept: an integrated open platform for provisioning and validation of T&L services

VITAL-5G offers the open framework for end-to-end 5G testing and validation, as the services are offered through a centralized and integrated platform, leveraging unified interfaces towards the testbed facilities. The virtualized 5G infrastructures with embedded resources control and management offer the possibility to deploy complex services in short time. The latest virtualization techniques are applied, allocating resources and mobile connectivity based on the specific T&L service's requirements. Trials run over dedicated and custom network slices, in secure and trusted environments, validating T&L Network Applications in a variety of operational contexts, by tuning the application's services parameters.

B. VITAL-5G facility: distributed testbeds and open platform

The VITAL-5G architecture, shown in Fig. 2, consists of two major layers: the 5G-enabled T&L testbeds distributed in Greece, Belgium and Romania and the cross-facility VITAL-5G open platform for services design, onboarding and deployment, validation and diagnostics applied to T&L vertical services. Any third-party experimenter(e.g. software developers, networks engineers, researchers) can design their own virtual applications and onboard their packages and images in the VITAL-5G Repository, making them available as software blocks for complex T&L services. The Network Applications are validated in different target environments, easily composing them into T&L service blueprints for verticals and third-party service providers. The VITAL-5G Portal offers programmable REST APIs to manage the creation, instantiation, life-cycle management and monitoring of T&L services and related 5G network slices. The Portal interacts with the local Management, Orchestration and slice control systems, the actions of network slice creation, resource instantiation and monitoring data, executed in a unified manner.

C. VITAL-5G Network Application concept

As explained in [6], Network Applications are defined as one of the key pillars of VITAL-5G since they are the building blocks of the T&L service chains on top of 5G-enabled infrastructures. The Network Applications aim to abstract the complexity of 5G systems and assist in building complex T&L services that leverage on 5G. The VITAL-5G Platform is facilitating the creation of such applications, thereby abstracting the complexity of service descriptors for application developers. In particular, they simplify the service deployment for the T&L sector, as the Network Applications are built and distributed through self-contained packages comprising (1) application-level software images and orchestration; (2) required 5G slice profile characteristics; (3) exposed and required interfaces to simplify service composition; and (iv) metrics and KPIs to be extracted and validated, as depicted in Fig. 2.

The VITAL-5G Network Applications are divided into two categories, as seen in Fig. 3, vertical-agnostic (grey) and vertical-specific (green), which can be combined together with generalized network functions in the form of VNF or Physical Network Function (PNF - yellow) to deliver end-to-end T&L services. Vertical agnostic Network Applications usually implement core primitives for data processing at the

5G testbeds features	RAN SA	5GCN SA	IaaS VM/CN	MANO OSM	MEC	Plugins	Monitoring	Slicing
	✓	✓	✓	✓	✓	✓	✓	✓

Fig. 4: VITAL-5G testbeds features and capabilities.

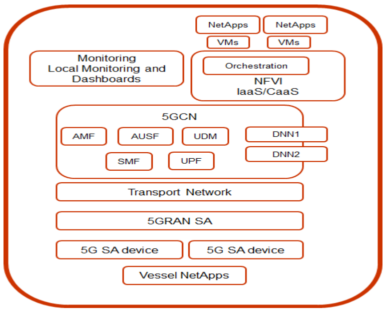


Fig. 5: VITAL-5G testbeds features 3GPP Rel.16.

Fig. 6: Galati Site Coverage.

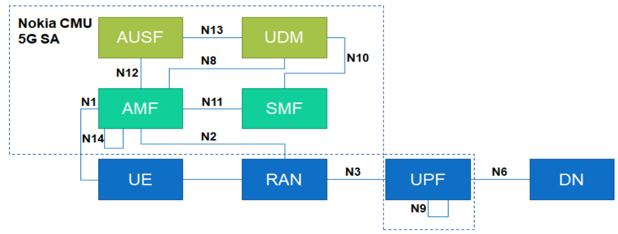


Fig. 7: Nokia 5G SA CN Service Based Architecture.

application layer, including functionalities that can be used in a variety of vertical applications and T&L services, whereas the Vertical specific ones address specific industry challenges for the T&L sector.

III. 5G Testbeds Implementation and 5G Capabilities: Cloud Native Approach

The VITAL-5G testbeds are deployed as 5G SA Option 2 networks, Rel. 16 compliant, and they encompass the key network components such as RAN, Core, Transport, Virtualization, Orchestration, and developed interfaces, as shown in Fig. 4.

5G SA network slicing is available in all three testbeds, offering broadband or ultra-low-latency communication services to the end-users. Functions such as performance monitoring of networks or services, slice provisioning, and dynamic configuration are embedded in VITAL-5G.

A. 5G SA testbed cloud-native implementation

The Romanian testbed implements services over a 5G SA network, Core Network (CN) integrated into the Bucharest facility and it is 3GPP [7] compliant, as shown in Fig. 5. The CN adopts a Cloud Native approach, involving NF based on technologies like microservices, containers, communicating over the HTTP2 protocol, while the 5G SA RAN equipment is deployed in the Bucharest lab and is also extended to the Galati port area for intensive field trials using several NetApps.

*1) **5G SA RAN Implementation**:* Radio N78 band (100MHz) has been selected for the deployment of the 5G SA gNodeBs (gNBs). The Bucharest site consists of indoor NR cells, one of them being placed in a semi-anechoic chamber for advanced experiments. The Galati site was integrated with the 5G SA CN and consists of two 5G sectors that cover the partner's (NAVROM)[1] headquarters and ships position, as shown in the Fig. 6, the radio coverage simulation. The DL/UL slot assignment has been set to 4:1 (DDDSU with 2.5 ms repetition).

*2) **5G SA CN Implementation**:* The Romanian testbed uses the 5G SA Compact Mobility Unit (CMU) CN solution, which is running on a virtualized infrastructure in the Orange Datacenter. Three main components are integrated, the Cloud Mobile Gateway (CMG), the Cloud Mobility Manager (CMM), and the Authentication and Policy Control (APC). These components implement the 5G SA 3GPP defined Network Functions (NFs) [8], represented in the Fig. 7, as follows: the Authentication and Mobility Management Function (AMF), managed by the CMM and handles UE tracking, authentication of UE inside the core; the Session Management Function (SMF), managed by the CMG and handles PDU sessions, selection of the User Plane Function (UPF) for data service based on the QoS needs and session authentication via the Unified Data Management (UDM); the UPF that handles the data sessions payload, payload prioritization, multi-access edge computing integration communications to the access domain; the Authentication Server Function (AUSF), managed by the APC and handles authorization, authentication, and accounting (AAA); the UDM acts as a subscriber management frontend for 5G SA users; finally, the Unified Data Repository (UDR) works as a subscriber profile repository.

*3) **Slicing Lifecycle and Implementation**:* The slicing concept proposes a shift from the static network model to a new model where multiple logical network partitions can be created, with specific isolation, resources, and topology characteristics, providing different service types for different verticals and applications.

As defined in the 3GPP TR 28.801 [9], these network slices require dedicated solutions for management and orchestration on the network slice instance layer and also on the resource layer. The network slice lifecycle management for a Network Slice Instance implies different phases: preparation, instantia-

[1]https://www.navrom.ro/index.php/en/

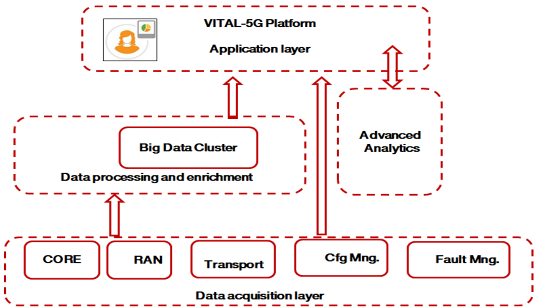


Fig. 8: Facility monitoring architecture

tion, configuration, activation, run-time, and decommissioning. The testbed facility supports different slices based on 3GPP NSSAIs parameters, for eMBB (sst=1, sd=0xABCDEF, and for URLLC (sst=2, sd=0xABCDEA). At the RAN level the slicing performance is ensured by leveraging gNB-specific QCIs functionality for proper slice implementation (Uplink Preallocation, SR Period Configuration).

*4) **Virtualized Infrastructure platform design**:* The testbed infrastructure is composed of various network and compute equipment, including open tools and technology brands like Cisco, Fortinet, HP, Nokia and Huawei ready to host and accommodate applications and services, using the following virtualization environment software tools: an Openstack Ussuri distributed cluster based on containers, an ESXi VMWare [10] cluster and a Kubernetes Container cluster. The testbed's orchestrators are based on OSMv12 [11], deployed in the infrastructure and per facility integrated with both VITAL-5G platform LCM.

B. Monitoring platform

5G networks are characterized by the ability to monitor networks and services through the collection of various metrics and KPIs (bandwidth, load, latency), using open-source tools such as Prometheus or other internal network tools. Our monitoring process is divided into two main areas: (1) monitoring of infrastructure components (RAN, Core, Transport, and Virtualization), including user's equipment, and (2) end-to-end monitoring of network and services performance, including the evaluation of network resources and service status, highlighted in Fig. 8.

5G supports performance monitoring, by actively measuring the end-to-end QoS/QoE. This includes not only traditional metrics like throughput but also key relevant metrics, such as the end-to-end slice latency, as in Fig. 9. The service-level agreements (SLAS) are ensured by monitoring the quality of services and the resources in real-time and by collecting data for analytics and by visualising them on dashboards, e.g., the end-user slice throughput, as seen in Fig. 10.

Finally, the platform was designed to communicate with the 5G network through APIs, handling in real-time the subscriber's management, being able to provision or de-provision, configure and instantiate appropriate network slices, attach users to the slice or delete slices.

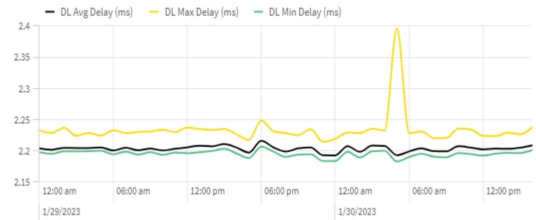


Fig. 9: E2E in-slice latency monitoring(MIN/AVG/MAX).

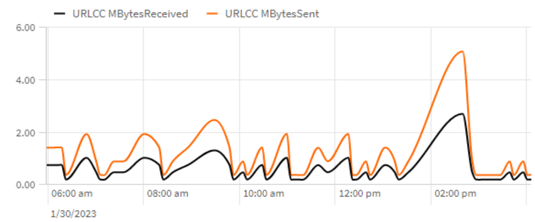


Fig. 10: URLLC slice traffic monitoring.

TABLE I: Facility Capabilities and resources.

Capabilities	VNFs	VMs	vCPUs	RAM (GB)	Slicing
Available Resources	20	200	3200	6400	eMBB URLLC

C. 5G Available resources for experiments

In VITAL-5G, the three facilities are offering a variety of resources for experimentation and prototyping, such as RAM or vCPUs, different slices implementation through the slice inventory modules, as in Table I, including E2E performance monitoring.

In VITAL-5G, the testbeds have also validated, within the scope of supporting developers and 3rd party experimenters a variety of 5G SA devices, including evaluation boards (Quectel RM500Q-GL), CPEs (Nokia, Inhand ER805, Cradlepoint R1900) or Smartphones. Based on the application requirements, we are capable to implement a multi-slice scenario for the same customer on a single device (e.g., Nokia Fastmile 5G Receiver), assuring the communication service QoS. We have implemented an Automatic Configuration Server (ACS) – TR-069 for remote control of the end devices, for provisioning and monitoring of the traffic and service performance.

IV. Examples of Network Application deployments and experimentation on the 5G testbed

In this section we present examples of Network Applications deployed in the Romanian test site, as the "Distributed sensor data ingestion, fusion & post-processing" which incorporates a series of functionalities centered mainly around the use of machine learning (ML) for analyzing data from multiple sensors and - among other services - allow for improved vessel navigation. Its functionality consists of three main steps: (1) The collection of data from multiple sensors, coming from

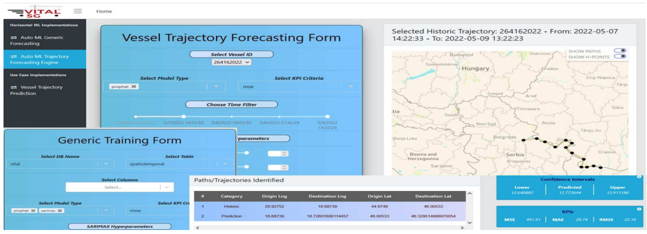


Fig. 11: Selected views of the deployed vertical agnostic Network Application

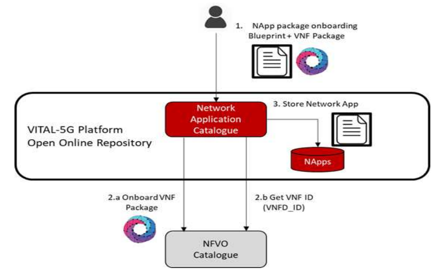
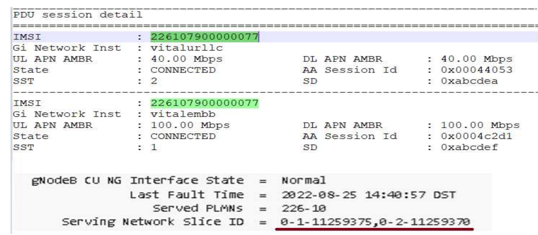


Fig. 12: VITAL-5G Platform onboarding service flow.



```
PDU session detail
IMSI              : 226107900000077
Gi Network Inst   : vitalurllc
UL APN AMBR       : 40.00 Mbps          DL APN AMBR      : 40.00 Mbps
State             : CONNECTED           AA Session Id    : 0x00044053
SST               : 2                   SD               : 0xabcdea
IMSI              : 226107900000077
Gi Network Inst   : vitalembb
UL APN AMBR       : 100.00 Mbps         DL APN AMBR      : 100.00 Mbps
State             : CONNECTED           AA Session Id    : 0x0004c2d1
SST               : 1                   SD               : 0xabcdef

  gNodeB CU NG Interface State  =  Normal
             Last Fault Time    =  2022-08-25 14:40:57 DST
                Served PLMNs    =  226-10
     Serving Network Slice ID   =  0-1-11259375,0-2-11259370
```

Fig. 13: E2E network slice validation.

other Vertical Specific Network Applications, indicatively vessel position at various times, static and moving sensor data, environmental measurement sensor data, and engine parameter data (2) The spatiotemporal fusion of these data, where a mechanism is employed to automatically combine data in both space and time. (3) The actual ML functionalities that include a short-term trajectory prediction that allows users to monitor future vessel positions on a map and a time-series prediction of a user-specified parameter/ sensor measurement.

The aforementioned Network Application has been successfully onboarded and deployed in Roamanian testbed, while its APIs are fully compatible with the OpenAPI specification [12]. Some APIs are available to 3rd parties, while others are indirectly accessible through a user interface (UI). Fig. 11 displays indicative views of the deployed Network Application. Another Network Application deployed in the Greek testbed is the "Indoor robot navigation & coordination with task planning", which provides the necessary functionality to allow AGVs to perform autonomous transport operations within a warehouse. The AGV connects to the 5G Network though a 5G connectivity module (Quectel RM500Q-GL) and communicates with the Network Application which is deployed at the Greek testbed. Along with the AGV, warehouse device simulators have been deployed to assist in collecting KPIs (such as bandwidth and latency). The aforementioned Network Application has been successfully onboarded through the VITAL-5G Platform deployed in the Romanian testbed. The AVG supports four different capabilities: (a) Move forward (speed up to 2m/s), (b) move backwards, (c) rotate, (d) lift. It contains also a set of sensors in order to support the Network Application functionalities, namely a Laser Scanner (LiDAR), a RGBD camera, an Inertial Measurement Unit, Motor Encoders and a Custom cart has been designed for carrying EU pallets to support the autonomous operations in the warehouse. Furthermore, a simulation platform is provided for 3rd party experimenters to be able to build their own Network Applications, thus decoupling the development of Network Applications from specific equipment.

V. Integration, Experiments results and Analysis

For the sake of brevity, in this paper we present the experiments results only from the Romanian testbed, where the 5G SA network is deployed and integrated, providing 5G services for Network Application, as described in Section IV. The same experimentation activities can be extended and validated also in the others testbeds, with similar capabilities. The 5G RAN and 5G Core are integrated and tested, from network perspective, including the 5G slicing capabilities, where multi-slice devices have been connected for experiments purpose. Network Application packages are onboarded, onboarding flow as seen in Fig. 12, the experimentation activities and tests being performed from an end-to-end perspective, from the end-user application, connected through the network slice to the edge cloud, orchestration and automation mechanisms being applied, as presented in Section III.

Regarding the slicing integration, Fig. 13 demonstrates the slicing configuration at the gNB and Core level, as the single-subscriber IMSI (e.g. 226107900000077) is simultaneous dual-slice connected, for broadband eMBB (100Mbps) slice and low-latency URLLC (40Mbps and 5ms one-way delay). By being able to connect the same device to two different types of slices, we prove and validate the multi-slice functionality, different communication services types implemented and used by the Network Applications. For clarity, different 5G users and services can be dynamically configured, the slices configuration being automatically propagated in the network, as a developer is able to properly connect the application to the testbed edge cloud where the back-end application is hosted, connected into a secure way.

The end-to-end performance is validated by running experiments and tests, using in the first phase a test 5G subscriber connected to the slices (e.g., eMBB slice for throughput validation and URLLC for latency validation), through a dynamic 5G multi-slice service profile configuration. Relevant output and monitoring data from the slice and service functionality in the system are collected, as described in Section III-B. We performed the end-to-end 5G network intensive tests (20 simultaneous eMBB subscribers and 10 URLLC), running experiments with the support of different tools and applica-

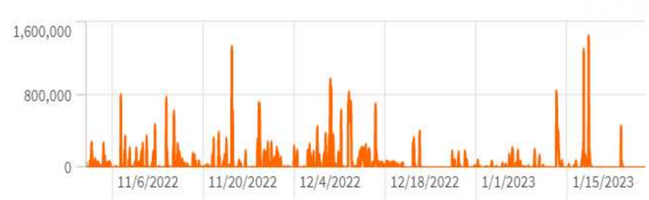


Fig. 14: eMBB(kbps) DL throughput services tests.

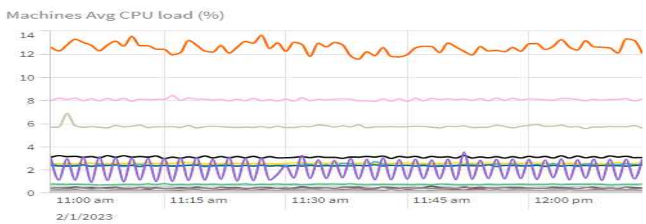


Fig. 15: Network Application virtualized resources consumption.

tions as *iperf3* for throughput, Two-Way Active Measurement Protocol (TWAMP) for latency, 4k video streaming and edge-cloud analytics and system load, experiments performed in Galati port also, as for example DL/UL throughput and latency, results values are reported in Table II.

TABLE II: Performance results.

Slice type	Downlink (Mbps)	Uplink (Mbps)	Round-trip latency (ms)
eMBB	1660	150	14 (ms)
URLLC	40	40	8 (ms)

By actively measuring the slice performance, the user's application is attached through the Slice Management Interface in the multi-slice configuration, contexts active at the same time for eMBB and URLLC slices. We concluded that, during our intensive tests, based on the real KPIs collected from the network and slices, seen in Fig. 14 (an eMBB experiment), we are proving also the high availability and reliability of the testbed infrastructure and the supported services.

We have performed a series of validation tests, from the preparation to the onboarding and automatic deployment in the virtualized infrastructure of Network Application. We demonstrate that in this case, no network issues have been faced for several months (more than 6 months). We have collected and analyzed, based on different traffic characteristics, application's network slice metrics and KPIs (throughput, latency) including the CPU usages of VNFs VMs composing the applications, as can be seen in Fig. 15.

VI. Conclusion and the Open Path to 6G

The presented 5G-enabled testbed is deployed within the targeted network architecture, including orchestration and virtualization, capable of automatic services and Network Applications instantiation through the VITAL-5G Platform, ensuring end-to-end application connectivity. The evaluated testbed was also 5G SA capable with end-devices connected to the network and an advanced end-to-end monitoring system. We evaluated the advancements in 5G capabilities and successfully demonstrated the 5G open testbed's readiness for Network Application experiments in real-life scenarios.

The services, architecture, and validation outputs shown in this paper are expected to be carried forward into 6G, as it will be necessary to support the high-bandwidth and ultra-low-latency requirements of emerging applications, within a fully novel programmable infrastructure. 5G will evolve into 6G, building upon its foundation to provide even greater connectivity and capabilities, open to 3rd party experimenters.

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