Utilizing the VITAL-5G Platform to Advance 5G Standalone Integration with Vertical Industries

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Abstract

The advent of advanced mobile communication systems like 5G and beyond holds promise for vertical sectors, particularly in Transport & Logistics (T&L), by enhancing network performance and ensuring high levels of Quality of Service (QoS), crucial for automating and optimizing T&L processes. However, assessing the impact of 5G requires investments in network infrastructure, posing time and return on investment uncertainties. To address this, the European project VITAL-5G offers an open, virtualized, and flexible experimentation platform that provides 3rd party vertical stakeholders the opportunity to test and validate 5G-enabled services under realistic conditions. This paper explores the VITAL-5G Platform's capabilities, detailing the infrastructure that supports 5G Standalone (SA) testing across multiple trial sites, including port and logistics environments. We highlight a subset of performed activities and experimentation campaigns, technical and operational challenges faced by 3rd party experimenters, and the potential business opportunities that emerge from 5G-enhanced services in the T&L sector. Finally, we present insights into future developments and opportunities for extending these capabilities to other vertical sectors.

Keywords: 5G SA, 5G trials, 3rd party experimentation, vertical industries, Business opportunities in 5G

1 Introduction

The Transport & Logistics (T&L) sector plays a pivotal role in modern production and distributed systems, significantly impacting people's lives. However, this industry segment faces challenges with low automation and process optimization, directly affecting the efficiency and safety of T&L operations. To address these issues, pilot trials utilizing 5G mobile communication systems, edge cloud, Software-Defined Networking (SDN)/Network Function Virtualization (NFV), Network Applications [1, 2], and OpenAPIs are being created in various European initiatives. These trials aim to develop and test various T&L vertical services in realistic conditions, making a substantial impact on the testing and validation of 5G-enhanced T&L applications.

To this end, one of the key strategic goals of the VITAL-5G project is the establishment of an open, virtualized, and flexible experimentation facility, as illustrated in Fig. 1. This facility comprises an intelligent virtual platform, three distributed 5G testbeds, and corresponding vertical infrastructure [1, 3]. The primary objective is to facilitate testing and validation of T&L Network Applications under authentic conditions, leveraging 5G connectivity. VITAL-5G has identified three trial sites, namely Antwerp, Galati, and Athens, strategically chosen to replicate real-life 5G-enhanced T&L experimentation environments in bustling ports (river and sea) and warehouse settings. Each trial site incorporates 5G testbeds, comprising a 5G network and virtualized and orchestrated infrastructure designed for deploying vertical services, in conjunction with T&L infrastructure.

The involvement of 3rd party experimenters who are not members of the VITAL-5G consortium (e.g., entrepreneurs, Small and Medium-sized Enterprises (SMEs), research

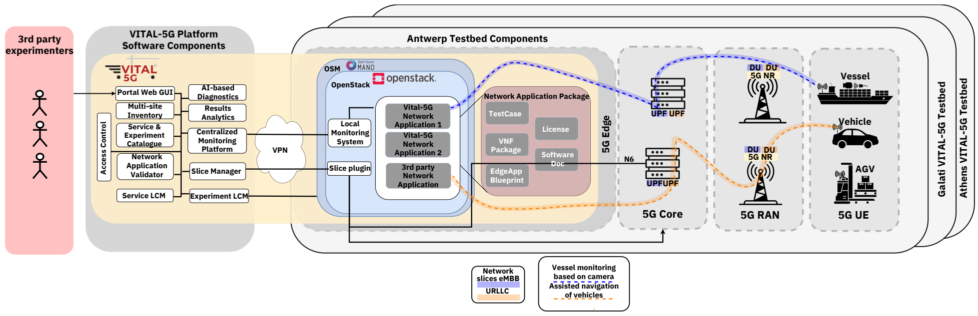

Fig. 1 VITAL-5G System consisting of the Platform and underlying network and T&L infrastructure.

centers, and larger companies) in the experimentation and/or the Network Application development, is a key aspect of the H2020 ICT-41 call [4] and hence of the VITAL-5G project. VITAL-5G has the objective of engaging with diverse stakeholders, with the main focus being SMEs and entrepreneurs, but also research centers and larger industries, interested in developing vertical services and/or Network Applications. In the context of fostering digital inclusion for entrepreneurs, SMEs, and research centers that may lack access to digital T&L services, as well as large companies, VITAL-5G offers access to diverse experimentation assets for 3rd party experimentation across its three pilot sites. This includes features of the VITAL-5G Platform provided to 3rd party experimenters, enabling them to test and validate their services straightforwardly, without necessarily understanding the network. They can utilize either the vertical services developed within the project or combine them with their own, creating more complex services. In particular, VITAL-5G offers tailored and virtualized access to the network and T&L infrastructure resources via a user-friendly interface. This enables the dynamic provisioning of customized services to 3rd party experimenters, allowing them to validate their applications over resources that would otherwise be inaccessible. This approach enhances confidence in application performance before the actual deployment of services and investments in network infrastructure.

The remainder of this paper is organized as follows: Section 3 presents the VITAL-5G system, highlighting its capabilities and how 3rd party experimenters engage with it. Section 4 covers the process of engaging 3rd party experimenters, including objectives, challenges, and technical aspects. In Section 5, we describe experimentation efforts on the Belgian 5G infrastructure, highlighting two 3rd parties that leveraged the VITAL-5G Platform to validate their services in a 5G network. Section 6 details additional 3rd experimentation activities in Romania, showcasing network assurance capabilities. Section 7 focuses on the 3rd parties performing experiments on top of the Greek 5G infrastructure, leveraging the VITAL-5G Platform to enhance transportation and logistics operations through 5G network applications. In Section 8, we discuss the adaptability of the VITAL-5G Platform to other 5G networks, extending the scope of experimentation to diverse environments, while Section 9 explores the business opportunities that emerge from the project. Finally, in Section 10, we explore future developments and potential avenues for extending these capabilities to additional vertical sectors, concluding the paper.

2 Methods/Experimental

This section outlines the methodology adopted to design, implement, and evaluate the VITAL-5G Platform and its associated experimentation activities, which involve the integration of 5G Standalone (SA) networks with T&L use cases and vertical industries. In this paper, we present two 3rd party participants at the Belgian trial site, one at the Romanian trial site, and one at the Greek trial site. Additionally, we discuss a 3rd party that utilizes components from the VITAL-5G Platform to enhance their own 5G SA infrastructure.

2.1 Study Design

The study was designed to investigate how an open, virtualized, and flexible 5G experimentation platform (the VITAL-5G Platform) can facilitate the testing and validation of T&L services under realistic operational conditions. To that end, three main pillars were established:

1. **VITAL-5G Platform**: a centrally managed system that abstracts the complexity of underlying 5G infrastructures and T&L resources and offers functionalities such as service onboarding, automated deployment, real-time monitoring, and network slicing.
2. **5G Testbeds**: three geographically distributed testbeds (Belgium, Romania, Greece) equipped with 5G SA Core networks, radio access, and edge computing resources.
3. **T&L Infrastructure**: domain-specific equipment and environments (e.g., ports, warehouses, automated guided vehicles, sensors) integrated with the 5G networks to enable operationally realistic trials.

2.2 Setting and Participants

- **Technical/Industrial Participants ("3rd party experimenters")**: These included SME, larger companies, and research centers primarily interested in validating their T&L services or network applications over 5G. Their expertise ranged from software development to robotics and sensor integration.
- **Trail Sites**: Three distinct T&L environments were used for experimentation: Port of Antwerp-Bruges (Belgium), Orange Romania's test site (Romania), and OTE/-Cosmote's pilot site (Greece). Each site offered unique operational conditions: port logistics, warehouse automation, and real-time transportation scenarios.

2.3 Materials and Infrastructure

1. **5G SA Networks**: Each trial site featured a SA 5G network (radio access and Core) capable of supporting network slicing and edge computing.

2. **Vertical Services**: Various VM-based or containerized software applications from 3rd party experimenters were onboarded to the VITAL-5G platform.
3. **Monitoring and Orchestration Tools**: Each testbed included a local instance of monitoring agents, slice agents, and NFV orchestration managers (e.g., OSM, OpenStack, Kubernetes). The VITAL-5G Platform communicated with these local agents through standardized Application Programming Interfaces (APIs) and plugins.

2.4 Description of Interventions

Each 3rd party experimenter proposed a vertical service composed out of network and vertical application(s) and then:

1. **Onboarding**: Prepared a "blueprint" describing the application's network, compute, and storage requirements, which was onboarded to the VITAL-5G Platform.
2. **Deployment**: The VITAL-5G Platform automated the placement of the vertical service components on the most suitable 5G testbed, with the possibility of leveraging distinct 5G slices.
3. **Runtime Monitoring**: The centralized monitoring system of the VITAL-5G Platform gathered Key Performance Indicators (KPIs) such as throughput, latency, and reliability.
4. **Iterative Adjustments**: Based on live metrics, experimenters fine-tuned deployment parameters (e.g., requested slice characteristics, placement on edge vs. central cloud) to meet Quality of Service (QoS) targets.

2.5 Comparisons and Validation

- **Multiple Testbeds**: Vertical services were deployed on the most suitable testbed to enable the vertical experimenter to validate their solution under real-life network conditions. For example, verticals in the warehouse business chose the warehouse testbed in Greece over the port testbed in Belgium, as the warehouse testbed provides more realistic insights into how their service will perform in a warehouse setting compared to an open port environment.
- **SA vs. Non-standalone (NSA) Networks**: In some trials, performance under 5G Standalone was compared to 5G Non-Standalone or legacy networks to quantify improvements in latency, throughput, and stability.
- **Application-Level Metrics**: For services like teleoperation and robotics, outcome metrics included Round-trip-time (RTT), object detection accuracy, or safe stopping distances for automated guided vehicles.

2.6 Analysis Approach

1. **Network Monitoring**: Time-series data (latency, bandwidth, jitter, etc. for edge nodes) were collected and analyzed using standard statistical tools within the VITAL-5G centralized monitoring framework.
2. **Application Performance**: Domain-specific metrics (e.g., robot navigation precision, object detection success rate, end-to-end delays for teleoperated tasks) were logged and cross-validated with network KPIs.

3. **Qualitative Feedback**: In addition to quantitative data, feedback from experimenters (e.g., difficulty of onboarding, ease of troubleshooting, user interface satisfaction) was gathered to refine the platform's usability.

2.7 Ethical Considerations and Power Calculations

Since this study involved the testing of software applications and network technologies rather than human subjects, no specific ethical approval was needed. No power calculation was performed, as the primary objective was technology validation rather than hypothesis testing on human participants. Nonetheless, each testbed maintained security and data protection measures (VPN-based remote access, role-based permissions) to safeguard the proprietary software of 3rd party experimenters.

3 VITAL-5G system

By providing end-to-end latencies as low as 5 ms, achieving data rates of up to 20 Gbps, and ensuring ultra-high reliability of 99.999%, 5G is enhancing the capabilities of various industry sectors, including the T&L sector, as highlighted in our previous work [1]. 5G technology is expected to significantly enhance efficiency and safety in T&L operations, thus positively impacting modern production and distribution systems. This improvement will be realized through the automation and optimization of processes and resource utilization. However, for optimal benefits from 5G, it is imperative that the design, development, and management of T&L services explicitly incorporate 5G connectivity requirements and features tailored to the specific use cases within the T&L industry.

To this end, the VITAL-5G project utilizes the concept of Network Applications as the foundational elements of 5G-enabled T&L services. These Network Applications serve to simplify the complex vertical services by abstracting the inherent network complexity, thereby bridging the knowledge gap among vertical stakeholders, network experts, and application/service providers. Additionally, these Network Applications specify service-level information unique to the vertical sectors and articulate 5G requirements, encompassing both 5G slices and 5G Core services. The concept of Network Applications stands as a pivotal component of VITAL-5G, as we envision them as the fundamental units composing T&L service chains atop 5G-enabled infrastructures.

Therefore, in this section, we provide more details on the technical aspects of the experimentation, showcasing the elements of the overall VITAL-5G system that encompasses an overarching Platform, 5G testbeds, and underlying T&L infrastructure. In particular, Fig. 1 illustrates the integration of all VITAL-5G elements into a comprehensive system that allows 3rd party experimenters to create and deploy their Network Applications, which will, depending on a testing scenario, interact with T&L infrastructure and User Equipment (UE) such as vessels, vehicles, Automated Guided Vehicles (AGVs), equipped with heterogeneous devices and Internet of Things (IoT) Platforms.

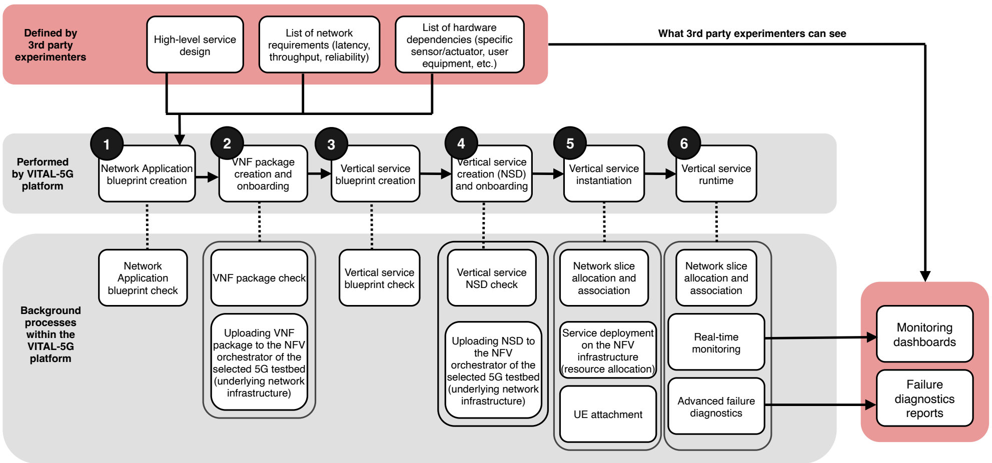

Fig. 2 Simplified VITAL-5G schema.

3.1 System components

The high-level architecture of the VITAL-5G system is shown in Fig. 1, and it consists of three main pillars:

- **VITAL-5G Platform**, which is used by all VITAL-5G users, including the 3rd party experimenters, to access the testbed resources, design Network Applications, and deploy them in different environments. It provides the various users with unified access to all the VITAL-5G experimentation services. More details are presented in Section 3.2.
- **5G testbeds**, which deliver a 5G network infrastructure with virtual computing capabilities and SDN/NFV technologies in three different types of T&L facilities. Using the testbeds, VITAL-5G users can run their experiments and trials in realistic environments and interact with real equipment.
- **T&L infrastructure**, which combines T&L equipment from the shipping and warehouse verticals, such as vessels in the case of Antwerp and Galati trial sites, AGVs in the case of the Athens trial site, along with onboard sensors, cameras, and 5G communication setups that enable connectivity between T&L infrastructure and Network Applications running on the 5G testbeds. In addition, VITAL-5G provides i) the availability of emulators specialized for the T&L sector to enable more scalable system validation mixing real and emulated data, and ii) the availability of open datasets from T&L environments, for both network and application data, to facilitate Machine Learning (ML) models training for Artificial Intelligence (AI) applications.

Table 1 VITAL-5G Platform capabilities offered to 3rd party experimenters.

Capability	Description
Facilitation of the deployment of a vertical service in the 5G network	To deploy their vertical services on the 5G SA infrastructure and start experimenting, 3rd party experimenters only need to be aware of their network requirements and hardware dependency.
Multi-platform edge computing for scalable and secure vertical services	The 3rd parties can deploy their Network Applications and vertical services over multi-platform edge environments, embedding security, high availability, and autoscaling functionalities, with support for VM and container-based applications while offering specialized hardware capabilities.
Full orchestration across IoT, mobile network & edge domains	The 3rd parties can focus on their software (SW) application logic, with the VITAL-5G Platform handling the complexity of orchestrating together network and edge resources and enabling secure and unified access to IoT devices on the field.
Open catalogue of re-usable Network Applications to act as building blocks for new services development	Open and documented interfaces, extreme modularity, common design patterns, and usage of open-source SW tools. Relying on these design principles, VITAL-5G Network Applications can be easily re-used, extended, customized, and combined together to build new services.
Network Application blueprints, templates, open datasets, and SW libraries to enable the development of new applications	The VITAL-5G catalogue is open to hosting new Network Applications to be shared with the community. Our asset comprises blueprints, templates, atomic SW components, and libraries, T&L datasets, and AI/ML tools, and thus provides a comprehensive starting kit for developing new 5G applications both for T&L and also for diverse vertical sectors.
Enhanced network performance by utilizing network slicing	3rd party experimenters can utilize the available slices available in the three VITAL-5G testbeds when deploying their vertical services. In particular, the VITAL-5G Platform analyses the minimum network performance requirements specified, and it accommodates the requested service with the required network and service quality.
Real-time monitoring of the network and service performance	As soon as the service is deployed and initiated, experimenters can start collecting performance metrics, such as network, service, infrastructure, and platform, in real-time.
Advanced failure diagnostics	The VITAL-5G Platform incorporates advanced Artificial Intelligence (AI)/Machine Learning (ML) processes to diagnose failures that happen at service runtime. The output of such services provides more insights into how the vertical service performed and what are the reasons for service termination.

3.2 VITAL-5G Platform

The VITAL-5G Platform facilitates the management of network and computing resources, which are available at any network infrastructure, i.e., a 5G testbed connected to it via southbound interfaces. Through the management of those resources, the VITAL-5G Platform is in charge of the deployment and management of vertical services (and constituting Network Applications), allowing 3rd party experimenters to install their vertical services in the 5G network and connect them with the T&L facilities of interest. In this section, we briefly discuss the subset of platform components that altogether create a set of capabilities and offerings to 3rd party experimenters, as listed in Table 1.

When a 3rd party experimenter requests deployment of a certain Network Application, **Service Lifecycle Manager** (see Fig. 1) is activated. This is a platform module responsible for processing this incoming service creation and deployment request. To perform the task, this module mainly interacts with the i) Network Function Virtualization Orchestrator (NFVO) on a selected 5G testbed, which further executes the orchestration operations on the actual NFV resources, ii) **5G Slice Manager and Inventory**, to allocate or create the 5G slice by interacting with the 5G Core and associate it to the service, and iii) **Centralized Monitoring Platform**, which performs real-time monitoring of the infrastructure, network, and service, metrics during the experiment runtime. Every 5G testbed has a local monitoring agent and a local slice agent. The monitoring agent is responsible for collecting all the metrics (such as latency, throughput, reliability, etc.) from the testbed and pushing them toward the southbound interface, which connects to the centralized monitor on the VITAL-5G Platform. The slice agent translates requests from the slice manager to the telco network. For a more comprehensive understanding of the Slice Manager and Inventory and Centralised Monitoring platform, an in-depth discussion can be found in its dedicated paper [5] and in its public deliverable [6].

Furthermore, **Multi-site inventory** module is used for determining the capabilities of the underlying network and T&L infrastructure when deciding where and how to deploy a new Network Application and vertical service. This module is a centralized repository that contains information about all testbeds connected with the VITAL-5G Platform via southbound interfaces. This information includes details about T&L devices available at the pilot site (e.g., sensors, cameras, localization modules, and AGVs), endpoints of NFVO, and slicing capabilities of testbeds (whether they support dynamic or static slice configuration).

Finally, the **Portal Web GUI** is a graphical user interface that allows users to access experimentation facilities and spawn vertical services. The 3rd party experimenters use this interface to design experiments, choose existing Network Applications from the VITAL-5G catalogue, create descriptors, and monitor network/infrastructure/service performance.

In this way, the VITAL-5G Platform is designed with a flexible and scalable deployment architecture to enhance trial facilities' capabilities, such as the onboarding and management of vertical services. The platform components, largely open-source[1], are centrally deployed (e.g., in the cloud) and interact with the 5G edge of each testbed via southbound interfaces, without requiring direct integration into the testbed's Core or Radio Access Network (RAN) [6]. Each edge environment adheres to European Telecommunications Standards Institute (ETSI) Multi-access Edge Computing (MEC) standards while maintaining 3rd Generation Partnership Project (3GPP) compliance, ensuring interoperability and adaptability across diverse network setups. This enables the VITAL-5G Platform to interact with its southbound interfaces to the edge NFVO (e.g., Open Source MANO (OSM)) to orchestrate vertical service deployments and Kubernetes/OpenStack as Virtualized Infrastructure Manager (VIM) to manage the lifecycle of these services [3]. Together, these architectural elements enable the seamless deployment of complex vertical services, simplify the integration of T&L facilities, and empower 3rd party experimenters with intuitive tools for service lifecycle management, real-time monitoring, and experiment validation through the Portal Web GUI [6].

4 3rd party experimentation

All 3rd party experimenters are provided with secure access to the VITAL-5G Platform and its entire set of experimentation tools and functionalities. This includes the VITAL-5G catalogue of available Network Applications, tools for onboarding and validation of new Network Applications, automated service provisioning, management and monitoring, test execution, results analysis, and diagnostics, which are enabled by the VITAL-5G Platform components briefly described in the previous section. All these features have been designed to facilitate experimentation activities, without requiring prior knowledge of 5G technologies. This is expected to promote engagement for application developers and service providers.

[1]VITAL-5G Platform components (GitLab): https://gitlab.com/vital-5g/VITAL-5G_Platform

The provision of simplified mechanisms for results analysis will facilitate the extraction of useful insights regarding service and/or Network Applications when deployed in operational 5G environments.

4.1 Objectives of 3rd party experimentation

The main objectives of 3rd party experimentation are:

- To facilitate the availability of 5G experimental infrastructures across Europe, promoting not only their concept but also the business offerings of 5G Testing-as-a-Service. This will lower the barriers to introducing new services and new technologies, making it more affordable for stakeholders who have difficulties in building their own 5G testing infrastructure.
- To support research advancements, making them more sustainable in the long term, by facilitating the efficient replication of similar initiatives in geographically distributed environments, and enabling more scalable testing infrastructures, through the creation of compatible sites with unified interfaces and common experimentation methodologies that facilitate multi-site federation.

To deploy their vertical services on the 5G SA infrastructure and start with experimentation, 3rd party experimenters need to define their network requirements and hardware dependency. As shown in Figure 2, this initial step involves, i) The Creation of the OpenStack/container image, ii) Defining the minimum network performance of their Network Application, and iii) Defining the hardware requirements of their Network Application. After this, all the next steps will be taken care of by the VITAL-5G Platform itself, thereby hiding the complexity, through the provision of an abstraction layer for the experimenters. The onboarding package consists of the Network Application blueprint containing the software image of the Network Application that the VITAL-5G Platform leverages to define the intrinsic logic of the Network Application itself.

After successfully onboarding the individual Network Applications that constitute the vertical service to be deployed, 3rd party experimenters with the support provided by the VITAL-5G project partners, can initiate the onboarding process for the composed vertical service. Once the vertical service is up and running, the experiment is initiated, and 3rd party experimenters can monitor network and service performance in real time, as well as get insights into advanced diagnostics in case of service or network failure. All aforementioned benefits for 3rd party experimenters are summarized and described in Table 1.

4.2 Technical and Operational Challenges of Hosting 3rd Party Experimenters

Despite the benefits of advanced experimentation capabilities described in the previous section, the process of successfully engaging 3rd party vertical industries in 5G experimentation imposes several technical and operational challenges. The first challenge to address is the *training* of the 3rd parties focusing on i) the capabilities and advantages introduced by 5G, and ii) the services offered by the VITAL-5G Platform and the capabilities and T&L infrastructure of each testbed. It is worth highlighting the activities in i) are usually a complex challenge since the knowledge required is outside the area of expertise of the verticals, which are more knowledgeable on the specifics of the service and less so on the capabilities of 5G. Therefore, more support is needed from the experts (e.g., VITAL-5G representatives) in the form of informative sessions and tutorials, which describe what 5G can do for the 3rd parties, so they make the most of 5G network performance when using their applications.

Once the 3rd parties acquire the required knowledge regarding 5G capabilities and services, the VITAL-5G team can better communicate with the 3rd parties regarding the *finalized technical solution*. The VITAL-5G team can then address the technical challenges associated with i) the functional blocks and software assets of the 3rd party Network Applications to be onboarded into the VITAL-5G Platform, ii) interfaces of the 3rd party Network Applications towards VITAL-5G provided Network Applications, T&L infrastructure, and 5G networks, and iii) services of the VITAL-5G Platform to be used. This is a challenge that is addressed in close coordination between the project representatives and each of the 3rd parties, to assess the technical feasibility and to align with possible business scenarios of the involved parties. Moreover, possible extensions to the VITAL-5G Platform may be proposed to overcome some specific technical limitations for a 3rd party/vertical.

The engaging of 3rd parties for experimentation activities also imposes a set of operational challenges to be addressed after overcoming the technical difficulties related to the trial design. First of all, secure channels and credentials need to be created for each 3rd party to access the VITAL-5G Platform and the underlying testbed facilities to enable the onboarding of the software images into the testbed and the correspondent descriptors into the Platform. In some cases, a 3rd party may require some physical equipment to be deployed at the infrastructure, which requires coordination with the trial site representatives. Finally, the overall planning and coordination of the 3rd party requires a tight synchronization of the 3rd party, the project contact, the trial site owners, and the VITAL-5G Platform maintainers.

4.3 Overview of 3rd party profiles

In the VITAL-5G project, a total of 60 3rd party experimenters have been engaged from the beginning until the end of the project. The engagement refers to a vast range of activities, such as participation in bilateral exploratory meetings with the project consortium, initial testing of VITAL-5G capabilities, and exploring open-source Network Applications offered in the project catalogue. Among these 3rd party experimenters, 20 have been successfully onboarded, actively contributing to the project's initiatives. Additionally, 24 entities are in ongoing discussions, signaling a robust interest and the potential for future collaboration. VITAL-5G has brought together a diverse mix of 3rd party experimenters including SMEs, larger companies, and academia, spanning diverse vertical sectors. Out of the contacted 3rd parties, 23 are SMEs, 16 are coming from larger companies, 14 of them are from academia, one is a Non-Governmental Organization (NGO), four represent Associations, and two research projects. These collaborators have been established through a variety of channels, including direct contacts, industrial conferences, webinars, etc. It should be noted that the underlying T&L infrastructure is not restrictive in the type of 3rd party experimenters or the services that can be deployed.

Each 3rd party has the flexibility to utilize the full suite of the VITAL-5G Platform's capabilities or select specific features tailored to their unique requirements (e.g., application catalogue, service lifecycle manager, slice inventory, or monitoring platform). Based on the experimentation from 3rd parties, it can be deduced that most of the entities have used the Service Lifecycle Manager and the VITAL-5G Monitoring Platform for their experimentation. Such statistics are being obtained by the VITAL-5G consortium offering useful insights into which functionalities provided by the platform are most integral to 3rd party experimentation. This has proved useful in the exploitation and commercialization plans of the platform to be put into effect after the end of the project. The following sections dive deeper into some specific 3rd party experimentation examples, performed using the VITAL-5G Platform and the network infrastructure deployed in three project pilot sites (Belgian, Romanian, and Greek network infrastructure).

5 3rd Party Experimentation on the Belgian 5G Infrastructure

In this section, we present two 3rd party experimenters (i.e., ININ and Zettascale) who utilized the Belgian 5G infrastructure located at the Port of Antwerp-Bruges [3, 7]. This 5G infrastructure is connected to the centralized VITAL-5G Platform.

5.1 Leveraging the VITAL-5G Platform for Enhanced Network Monitoring: The ININ QMON Experiment

The VITAL-5G Platform, in conjunction with the Antwerp port testbed, is utilized by the Internet INSTITUTE (ININ)[2], to deploy their quality monitoring network application, QMON[3]. This deployment involves the automated installation of the virtualized components of the QMON application through the VITAL-5G Platform on the underlying 5G testbed.

5.1.1 ININ Network Application deployment, instantiation, and assessment

The primary advantages of utilizing the VITAL-5G Platform and the testbed shown in Fig. 2 for this experiment are as follows: i) the ININ QMON network application can be seamlessly deployed within a 5G ecosystem, ii) the platform autonomously configures VITAL-5G agents on the Antwerp testbed to collect specific metrics here, end-to-end latency and uplink/downlink data rates as defined in the network application blueprint, iii) the QMON network application can subscribe to the VITAL-5G monitoring platform to retrieve these metrics, and iv) through intents issued by the VITAL-5G Platform, agents on the testbed dynamically attach the experiment (in this case, the QMON application) to the designated network slice. In this way,

[2] ININ: https://www.qmon.eu/
[3] QMON network application: https://www.qmon.eu/#qmon

Fig. 3 ININ 5G gateway incorporated into Antwerp testbed network monitoring agent.

this experiment leveraged a subset of VITAL-5G capabilities as outlined in Table 1: namely, enabling the deployment of a vertical service within the 5G network, providing multi-platform edge computing for scalable and secure vertical services, achieving full orchestration across IoT, enhancing network performance through network slicing, and supporting real-time monitoring of network and service performance.

The experiment's main objective is to showcase the QMON network application running on the 5G edge in a port environment and provide proof of the accuracy of the metrics retrieved from the VITAL-5G Platform (Fig. 3). That is why the QMON application is configured to retrieve network metrics (i.e., data rate and latency) to: validate the accuracy of the application reports in port environments, and cross-check and compare with the data retrieved through the VITAL-5G Platform (Fig. 3). The QMON network application leverages a UE side application responsible for generating and gathering the metrics from the UE site. Therefore, ININ provided a dedicated 5G gateway that collects the metrics for the QMON network application. Thus, the gateway also needed to be deployed in the Antwerp testbed.

Once everything (i.e., QMON network application and 5G gateway) is instantiated through the VITAL-5G Platform on the Antwerp testbed we observe that the metrics retrieved from the QMON network application are consistent with the ones extracted from the VITAL-5G Platform as depicted in Fig. 3.

5.1.2 ININ 5G gateway

The main purpose of the 5G gateway provided by ININ is to generate and gather the respective metrics for their QMON network application running on the Antwerp testbed. Furthermore, the gateway has been further utilized by other 3rd party experimenters to support additional experimentation activities due to the comprehensive set of metrics it can produce. This is mainly because the gateway can collect more radio

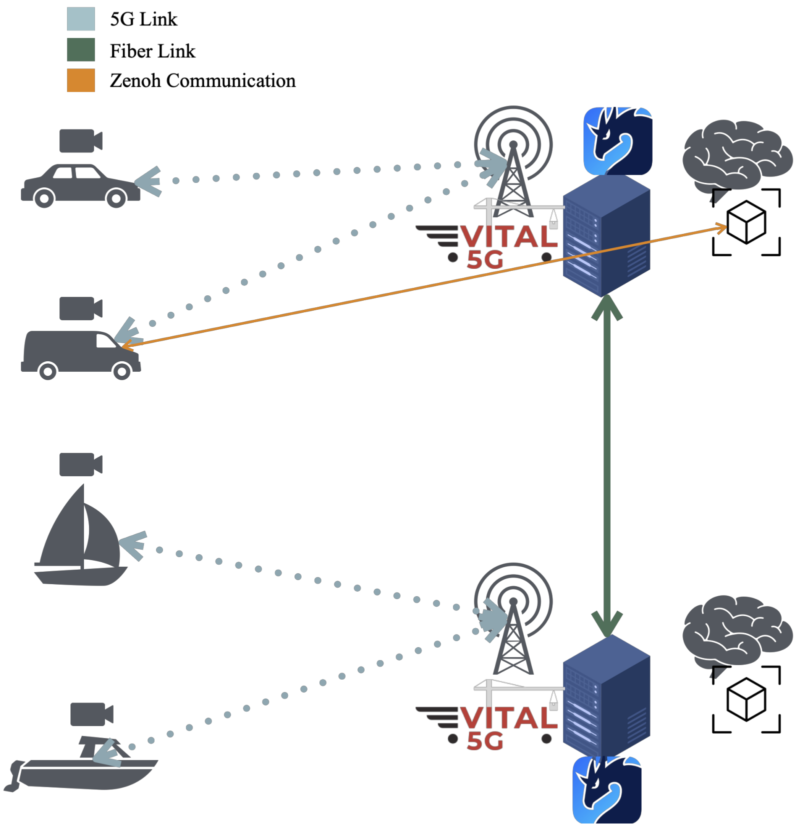

Fig. 4 ZettaScale V2X application schema.

network data (e.g., the UE its received signal strength) than the agent running on the Antwerp testbed, which is responsible for collecting network metrics. Therefore, the gateway provided by ININ is integrated into the agent, enriching the VITAL-5G monitoring platform with more detailed network metrics from the Antwerp testbed. This advancement has also enabled the provision of more detailed network metrics to the network applications and 3rd party experimenters running on the Antwerp testbed. As a result, the modem is being used by other 3rd party experimenters in the Antwerp testbed, such as Zettascale (Section 5.2), among others.

5.2 Dynamic obstacle detection with Zenoh over 5G

Zettascale leveraged the Antwerp 5G testbed and the VITAL-5G Platform to test their in-house open-source framework, Zenoh, within the Port of Antwerp environment. This testing aims to validate Zenoh's performance in a real-life End-to-End 5G system, enabling the exploration of new use cases for Zenoh. Zenoh is a pub/sub/query communication protocol that unifies data in motion, data at rest, and computations. It is utilized for transferring data, such as video in the uplink, and disseminating notifications to relevant users based on detected obstacles in the downlink.

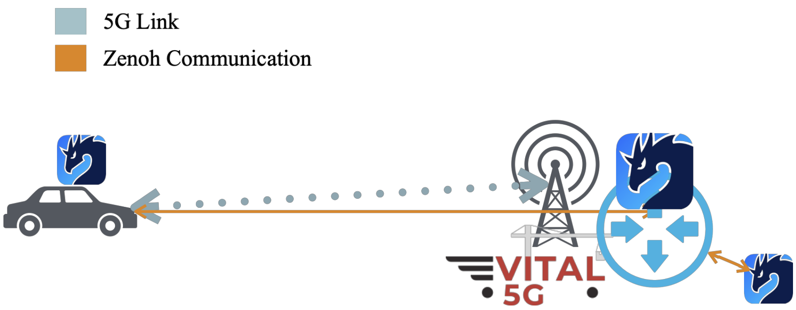

Fig. 5 ZettaScale Synthetic Tests Schema.

5.2.1 Experiment description

To validate Zenoh's performance over 5G, Zettascale completed the three steps required of a 3rd party experimenter, as outlined in Fig. 2. The VITAL-5G Platform provides a robust and flexible environment to support the validation of services within a 5G-enabled infrastructure, including tools to simulate various 5G conditions. This enables a comprehensive analysis of Zenoh's performance metrics such as latency, throughput, and reliability across different network configurations, making full use of the platform capabilities detailed in Table 1. Among these, the real-time monitoring of network and service performance was crucial for validating Zenoh's performance over 5G.

The validation of Zenoh was conducted through a combination of real-world application testing and synthetic benchmarks. In the real-world scenario, Zenoh was integrated into a vehicle-to-everything (V2X) application environment, where camera frames were streamed via Zenoh to an edge server, providing ML-based Object Detection and streamed back to the vehicle, effectively validating computation offloading. This provided insights into how Zenoh handles real-time data distribution, network dynamics, and varying traffic loads. Complementing this, synthetic tests were designed to gather metrics in both latency and throughput. Together, these approaches ensured a comprehensive validation, demonstrating Zenoh's robustness and efficiency in diverse 5G scenarios.

5.2.2 V2X Application

In the context of V2X, where vehicles are expected to communicate with another part of the infrastructure, it is crucial to leverage functionalities like Ultra-Reliable Low-Latency Communication (URLLC) and massive Machine-Type Communication (mMTC), to ensure timely communication between all participants in the system. To this extent, a YOLOv7-based Object Detection application has been developed with the idea of being used to offload the computation from multiple vehicles connected to the same Next-Generation Node B (gNodeB).

Fig. 4, illustrates the deployment of the V2X application, the aforementioned ML-based application being deployed at the Edge, giving its requirements of low-latency between the vehicles and the applications themselves. Each vehicle is equipped with a set of cameras, each streaming directly to the application. Leveraging Zenoh's location

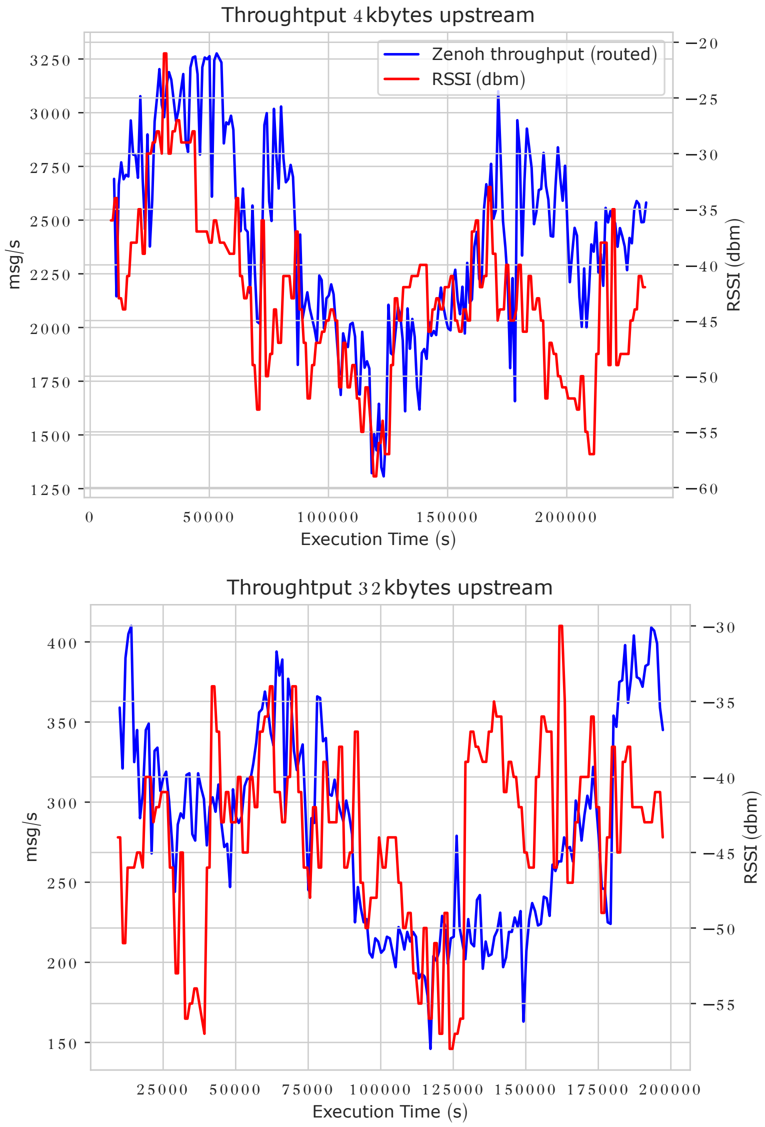

Fig. 6 ZettaScale Synthetic Tests Results.

transparency the applications do not need to know where to stream the information, it is Zenoh that automatically routes the information to the closest server. Detected objects are then streamed back to the corresponding vehicles where autonomous driving algorithms use them to make decisions.

5.2.3 Synthetic benchmarks

In the synthetic tests, Zenoh was validated in both latency and throughput, to validate its capabilities and understand how 5G metrics such as Received Signal Strength Indicator (RSSI) and Reference Signal Received Power (RSRP) can influence performance.

Fig. 5, depicts the deployment scenario for the synthetic tests. At the side of the vehicle a Zenoh application has been deployed, this application is able to perform both RTT and throughput measurements, at the Edge we find a Zenoh router and another application like the one present in the vehicle.

Such tests have been used to evaluate RTT between the vehicle and the Edge application, with different publication rates, ranging from 1 msg/s to back-to-back publications, as well as throughput in both uplink and downlink scenarios, with payloads mimicking one camera (4Kbyte) or 8 cameras streams (32Kbyte).

Fig. 6, provides a synthesized view of the throughput results. We can see that throughput follows the RSSI and RSRP curves, nevertheless, Zenoh is capable of maintaining a sustained throughput of more than 1000msg/s for 4Kbytes payload upstream, and more than 100msg/s for 32Kbytes payload upstream.

Thanks to the experiments conducted in the VITAL-5G Platform it has been possible to evaluate Zenoh performances in an End-to-End 5G system, results show that Zenoh enables new use-cases, like the V2X offloading, and while the 5G connectivity impacts its performances it is still capable of sustained throughput that allows applications to still function in a situation where network coverage is not perfect.

These experiments demonstrate the VITAL-5G Platform's capacity to enable advanced network services and validate novel technologies in real-world 5G environments. The ININ QMON experiment highlights the platform's ability to support accurate, real-time network monitoring, offering valuable insights for optimizing operations in industrial environments like the Port of Antwerp-Bruges. Similarly, Zettascale's Zenoh framework validation showcases how the platform facilitates robust testing of innovative data distribution protocols under diverse 5G scenarios. These findings emphasize the platform's pivotal role in advancing vertical services, ensuring scalability, and driving innovation in mission-critical and latency-sensitive applications such as network monitoring and V2X communication.

6 3rd Party Experimentation on the Romanian 5G Infrastructure

In contrast to the previous section, this 3rd party experiment (i.e., RWS) is conducted on the Romanian 5G infrastructure hosted by Orange Romania (ORO), which is also connected to the centralized VITAL-5G Platform.

5G service assurance is a hot topic for end-to-end Telco services delivery within the agreed Service-Level Agreements (SLAs), as the service assurance can be supported by the network features and capabilities implementation, also applied to the service slices. Even though there are industry standards and approaches for automatic operations and automatic service assurance and management, there are very few solutions implemented in live environments able to support network dynamic root cause

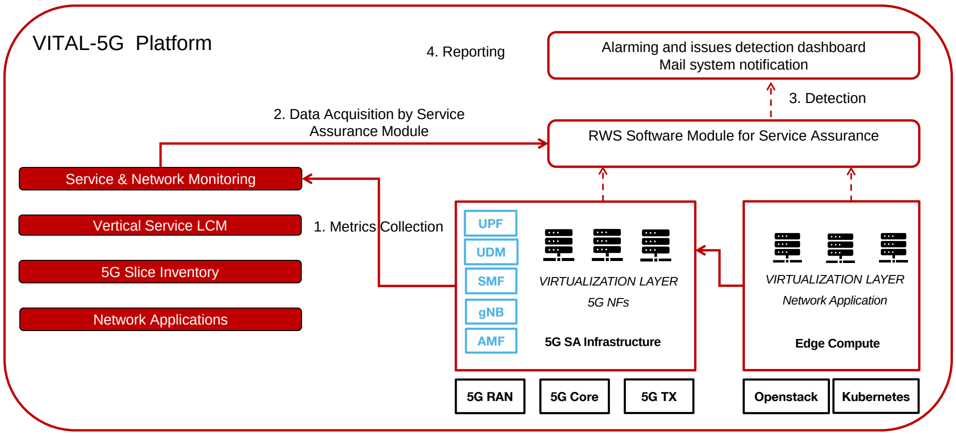

Fig. 7 RWS 5G Service Performance analytics - Romanian testbed.

analysis and services SLAs impact, capabilities enhanced with performance prediction and degradation. Within the VITAL-5G project, ORO and the SME company Realworld Eastern Europe (RWS), a software company for the Telecom and Energy Industry, have implemented an experiment focused on the 5G network, based on various 5G metrics collection, and through ML identifying possible root causes of services and network degradation. The 5G SA is a very complex technological environment, with network functions implemented in different ways, as Core Network Functions (CNFs) or Virtual Network Functions (VNFs)/CNFs, by decoupling the hardware from software through virtualization. 5G networks deliver communication services for demanding applications, satisfying requirements from different UCs and Verticals perspectives. This Proof of Concept (PoC) offers guidance for operators to understand issues and make appropriate decisions quickly.

The 3rd party trial site for this experiment is the VITAL-5G Romanian testbed, a successful collaboration between the VITAL-5G project and the RWS company to deliver 5G Network Assurance capabilities, the utilized Platform capabilities are highlighted here *recursive*. This collaboration leverages *Multi-platform edge computing for scalable and secure vertical services*, enabling RWS to deploy its network applications with security, autoscaling functionalities, and high availability over a multi-platform edge environment, as well as *Facilitation of the deployment of a vertical service in the 5G network*, which simplifies deployment by allowing the experimenters to focus on network requirements and hardware dependencies. The key result is a 5G network and system service assurance in these complex environments for RAN, Core, and Edge, supported by *Real-time monitoring of network and service performance*, where telemetry data is automatically collected, processed, and analyzed for alerting, health checks, and proactive detection of network issues. The setup is detailed in Fig. 7 and includes

VITAL-5G Platform modules, with various metrics collected from the testbed by the VITAL-5G Centralised Monitoring Platform and its agents. The data acquired from live components is then fed into the RWS software module for AI/ML service assurance, which provides incident detection, alarm generation, healing recommendations, and reporting.

As described, the test environment is based on the VITAL-5G Romanian 5G testbed located in Bucharest, composed of end-to-end network elements such as RAN, Core, IP Network, and virtualized layer infrastructure based on OpenStack and Kubernetes. The experiment is based on the automatic metrics collection from the network infrastructure; the 3rd party has implemented an algorithm for network service assurance trained to respond to critical service issues such as network port down, server failure, hypervisor issues, network element overheating, and high consumption of Central Processing Unit (CPU), Random-access memory (RAM), network bandwidth, and disk, as well as internal VNF issues. Through *Enhanced network performance by utilizing network slicing*, the VITAL-5G Platform accommodates the requested service with the required network and service quality within specific slices, which helps in quickly isolating faults and ensuring minimal impact on service-level SLAs.

Components and configuration used for this experiment:

- RWS software module for Advanced Analytics dedicated to service solution performance, VITAL-5G monitoring system, and data metrics collection acting as network sensors.
- RWS - Cross Software Module for Service and Network Assurance, VITAL-5G KPIs acquisition framework.
- VITAL-5G virtualized infrastructure, running VNFs under test, VITAL-5G Platform, Edge Cloud for 3rd party Network Application deployment.
- Secured 5G testbed connectivity for the 3rd party partner, 5G network, and services running in a normal health state at the initial step before running experiments.

The experiment steps are as follows: the 3rd party partner accesses the VITAL-5G testbed. The targeted VNF for service assurance runs in a healthy state, and the assurance software is deployed and connected to all data sources, trained for the specific network and service states. Throughout the experiment, issues are introduced into the network (e.g., server restarts, connectivity disruptions, network port downs), sometimes simulated via a soft test module. For each test, the 5G system's health is monitored in real-time, with alarms and root cause analysis generated automatically by leveraging the *Advanced failure diagnostics* capability of the VITAL-5G Platform, which uses AI/ML processes to diagnose failures during service runtime.

Supported by the methodology used during the experimentation period, extensive network and compute experiments were conducted with the 3rd party partner to train the software algorithm for the proposed service assurance solution. After the training period, the solution was activated in the VITAL-5G testbed and extended to the production environment, continuing the experiment for solution improvements and testing the speed of service assurance response to network and service issues.

In conclusion, the experiment results demonstrate the impressive capabilities of the VITAL-5G Platform in enabling advanced network assurance for complex, real-world environments. By continuously monitoring the 5G system's health and leveraging AI/ML-driven root cause analysis, the platform empowers operators to detect, diagnose, and address network issues with speed and precision. This minimizes SLA breaches and ensures high service reliability. Furthermore, the collaboration with RWS validates the platform's effectiveness in supporting dynamic network assurance and highlights its potential to enhance operational efficiency for telco services. As 5G networks become increasingly complex, the VITAL-5G Platform emerges as a comprehensive tool for service providers.

7 3rd Party Experimentation on the Greek 5G Infrastructure

Finally, this section presents a 3rd party experiment conducted on the 3rd and final 5G infrastructure of the VITAL-5G project, hosted by OTE/Cosmote5G, which is also connected to the centralized VITAL-5G Platform.

A joint collaboration between WINGS and OTE/Cosmote (part of Deutsche Telecom Group) to attract 3rd party experimenters but also potential customers has been running since September 2023. The aim was to design, develop, deploy, and demonstrate use cases that demonstrate T&L operations that benefit from 5G SA networks as compared to 5G NSA. For this partnership, Cosmote set up a private 5G SA network provided by Ericsson, while WINGS ICT Solutions employed the WINGSChariot solution to design latency-sensitive and throughput-demanding use cases, which demonstrate the capabilities of this network. WINGS utilized multiple industrial and research robots with 5G SA capable modems to demonstrate autonomous pallet transfer, teleoperation, object detection-powered product picking, and obstacle avoidance scenarios, while clearly demonstrating the effects of latency and throughput on the accuracy and velocity of logistics operations. Following an initial development period, the first integration tests were performed during November 2023 to finalize the scenarios and fine-tune the network behavior. WINGS set up the WINGSChariot backend components in an edge server directly connected to the 5G Core to achieve a truly private 5G SA network. Five different scenarios have been designed and showcased, namely:

- Effects of Network Latency on Autonomous Mobile Robot (ARM) Navigation - Private 5G SA Vs. traditional mobile networks.
- Effects of Network Latency on Coordinated Robotics tasks - Private 5G SA Vs. traditional mobile networks.
- Teleoperation under private 5G SA Vs. traditional mobile networks.
- Autonomous pallet transfer under private 5G SA.
- Object detection-powered product picking under private 5G SA.

During the preparation period and throughout the experimentation phase, network KPIs have been collected through the VITAL-5G Platform's real-time network and service performance monitoring capabilities. The aggregated results are analyzed in *Section F: Results Summary*. Furthermore, all network applications were onboarded

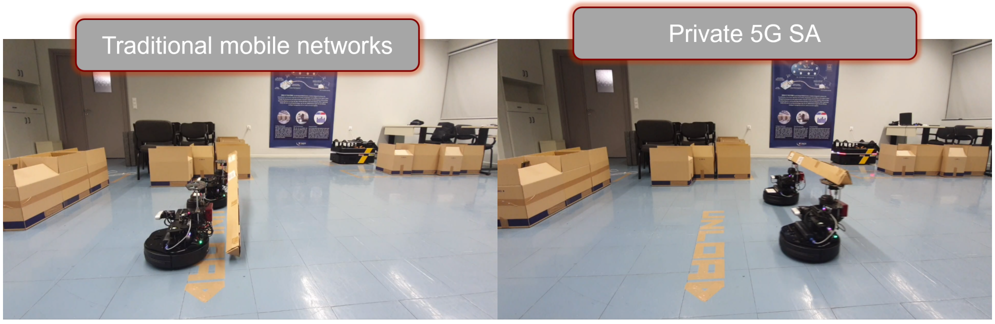

Fig. 8 Effects of Network Latency on Coordinated Robotics tasks.

through the steps depicted in Fig. 2, and all the Platform capabilities summarized in Table 1 have been utilized.

7.1 Scenario 1: Effects of Network Latency on ARM Navigation - Private 5G SA Vs. Traditional mobile networks

In this scenario, a velocity controller has been deployed as a Network Application to a remote server. The ARM is directed to move to the test area. The ARM is instructed to move with 1.4 [m/s] linear velocity. The front distance is measured using Light Detection and Ranging (LiDAR) and transmitted to the controller. Upon reaching a threshold, the controller commands the ARM to stop. In this case, it has been observed that the 5G SAs low latency allows the ARM to break and stop in time. On the other hand, when this scenario was tested using the NSA 5G network, the ARMs stop was delayed due to the higher latencies measured.

7.2 Scenario 2: Effects of Network Latency on coordinated Robotics tasks - Private 5G SA Vs. Traditional mobile networks

In this case, two robots move simultaneously with the same linear velocity and carry a load. One of the 2 ARMs detects an obstacle in front and keeps track of its distance from it. Upon reaching a threshold, it stops and also commands the other robot to stop. Due to the low latency of 5G SA, the other robot is notified in time and stops without the load falling. In the case of a higher latency network, the second robot stops a few centimeters further and the load falls. As depicted in Fig. 8.

7.3 Scenario 3: Teleoperation under private 5G SA Vs. traditional mobile networks

Teleoperation is the functionality of moving the robot from a remote location. This functionality extends the autonomous capabilities of the ARM. In this scenario, a user can manually move the robot using the WINGSChariot User Interface (UI) by viewing the camera video feed through the UI. This functionality allows for remote inspection in case of an emergency, or when something unexpected has taken place. In this scenario, low latency is essential as it allows messages to be transmitted and received faster compared to other networks. Furthermore, higher bandwidth allows video streams of greater quality to be used. Collected metrics such as Download and Upload traffic and RTT latency are calculated in real-time and provided through the UI.

7.4 Scenario 4: Autonomous pallet transfer under private 5G SA

Preconfigured area coordinates can be sent using names. A single button can be used to command to move. A whole sequence of commands can be sent simultaneously. The ARMs sensor data, such as its linear, angular velocity, and current stare are transmitted alongside its position on the map in real-time. The camera video feed is always available to inspect the process and the robot's whereabouts.

7.5 Scenario 5: Object detection-powered product picking under private 5G SA

An object detection algorithm is deployed as a Network Application to a remote server. An ARM is commanded to move to the test area. The user decides which product the ARM must fetch (oranges/bananas). The ARM moves to the designated area where similar carts loaded with products are available. Video feed from the onboard camera is transmitted and processed. Each cart is scanned until the algorithm detects the product. The ARM notifies the user. Proceeds to pull the cart to the designated unloading area.

7.6 Results Summary

Various tests using different configurations were conducted in order to assess the network performance in terms of throughput and latency. The measurements were obtained using iPerf. The tests aimed to establish a baseline for network capabilities under various conditions using TCP and UDP protocols under the different scenarios presented in the previous subsections. Based on the results obtained the maximum throughput registered was 948Mbps downstream and 125Mbps upstream. The detailed throughput measurements are omitted here for brevity. Regarding latency, the 5G client-Edge server recorded a minimum of 5.6ms and a maximum of 18.4ms while the 5G client-to-client minimum latency was 14.1ms and a maximum of 40.9ms. From the results obtained, the following conclusions have been extracted:

- **Protocol Efficiency:** TCP and UDP protocols showed different performance characteristics, with UDP achieving higher throughput in specific test configurations.
- **Transmission Direction:** The direction of data flow (send/receive) had a notable impact on the throughput, necessitating further investigation into asymmetric routing or traffic management policies.

- **Routing efficiency:** Latency was notably higher in client-to-client communication compared to client-to-server, pointing towards potential improvements needed in client-to-client routing efficiency (Client-to-Server vs Client-to-Client).

Overall, based on the results presented in the previous section, the scenarios that were demonstrated were successful in demonstrating T&L operations that benefit from 5G SA networks as compared to 5G NSA. Based on the results obtained we have identified some cases where the private 5G network failed to cover the requirements set by the different scenarios, but this was related to the current network configuration. For example, for deployments with multiple robots, there is more demand for upstream than downstream throughput. However, the private 5G SA network was configured at a 10:1 downstream/upstream ratio. When stress-testing the network, the latency spiked above 40-50ms.

Although the network latency was measured as low as 6ms, the jitter caused by a combination of network and application factors forced us to develop a network controller that estimated the location of the robot at precise 5ms intervals. Without the precisely timed loop, we would not be able to guarantee a target deviation lower than 10 cm. There is some variation in the stopping distance of a robot due to variation in the floor friction which should be accounted for when targeting high cruising speeds and there is a need for high precision.

In terms of engagement, this collaboration has resulted in direct engagement with over 30 additional stakeholders from diverse verticals. The engaged stakeholder categories comprise i) manufacturing companies, ii) food production, iii) retailers, iv) logistics centres, v) professional services and, vi) pharmaceutical.

In terms of the next steps, the above setup is to be moved to a more permanent location at OTE headquarters, where the demonstration will be further extended with new features based on the feedback received by the engaged stakeholders.

The results from this experiment demonstrate the transformative potential of private 5G SA networks for latency-sensitive and throughput-demanding logistics operations. By enabling precise control, real-time communication, and effective resource allocation, the VITAL-5G Platform and the WINGSChariot solution highlight significant improvements in automation and teleoperation compared to traditional mobile networks. These findings are particularly impactful for industries such as manufacturing and logistics, where the ability to enhance operational precision and efficiency can drive substantial value. Additionally, the experiment's engagement with over 30 stakeholders underscores the practical applicability of these solutions, paving the way for broader adoption and further innovation in diverse verticals.

8 Adapting the VITAL-5G Platform to New 5G Networks for Flexible and Sustainable 5G Experimentation

In contrast to previous sections, which focus on the use of VITAL-5G's own network infrastructure, this section presents an example of a 3rd party connecting its infrastructure with the VITAL-5G Platform. This is particularly relevant, as the VITAL-5G

Platform aims at facilitating the overall process of experimentation of vertical services on top of any 5G-enabled infrastructures, easing the experiment and service design, automated service life-cycle management, metric and KPI collection, and experiment validation.

To provide these services, as explained in 3.2, the VITAL-5G Platform interfaces with different components of the testbed management system: i) NFV orchestrator for the onboarding and Lifecycle Management (LCM) of VNFs and Network Services (NSs), ii) 5G Slice Manager for the retrieval and allocation of 5G slices, and iii) Testbed monitoring platform for the creation and configuration of the monitoring jobs and retrieval of the experiment metrics. To use these interfaces, the software components and interfaces of the VITAL-5G Platform were designed to use a plugin-based approach, following a common and universal southbound interface. This approach allows the decoupling of the main logic of the Platform from the testbed-specific APIs and enables a simplified and flexible integration of the VITAL-5G Platform to the specific testbed interfaces. In particular, this enables easy customization and deployment of the VITAL-5G Platform on top of any other 5G-enabled infrastructure besides the project-specific ones (i.e., those in Belgium, Romania, and Greece) to benefit from the Platform's experimentation services and capabilities.

In VITAL-5G, we demonstrated this flexibility of the VITAL-5G Platform through one 3rd party trial and experimentation with the University of Catania. The setup of the 3rd party experiment is depicted in 9, illustrating the VITAL-5G Platform components integrated with the UniCT testbed. As shown in the figure, the setup uses a subset of the VITAL-5G Platform components (namely the Service Catalogue, Service, and Experiment LCM) deployed at Nextworks facilities in Pisa connected to the testbed via a Virtual Private Network (VPN) connection.

As shown in Fig. 9 the UniCT testing and trialing facilities network infrastructure includes:

- Cumucore 5G Core, deployed as a Physical Network Function (PNF), providing both the User Plane Function (UPF) and the Control Plane Function (CPF).
- UERANSIM based emulated RAN, enabling a scalable number of gNodeBs and UEs. In particular, two gNodeBs and UEs were used using the experimentation activities.
- multi-technology edge platform with support for the deployment of virtual edge applications based on Virtual Machines (VMs) or containers. Currently, the edge compute resources include two OpenStack computing nodes (with graphics processing unit (GPU) acceleration capabilities), and a Kubernetes working node.

The UniCT testbed includes a management system enabling deployments on top of the virtualized network infrastructure described above. This management system is composed of (i) an OSM instance acting as NFV NFVO, (ii) an OpenStack controller as VIM, (iii) a custom monitoring platform solution leveraging the state-of-the-art open source software components (e.g. Telegraf, Kafka, InfluxDB, Prometheus, and Grafana).

The integration of the VITAL-5G Platform with the UniCT testbed required the development of specific Service LCM plugins for the testbed Slice Management

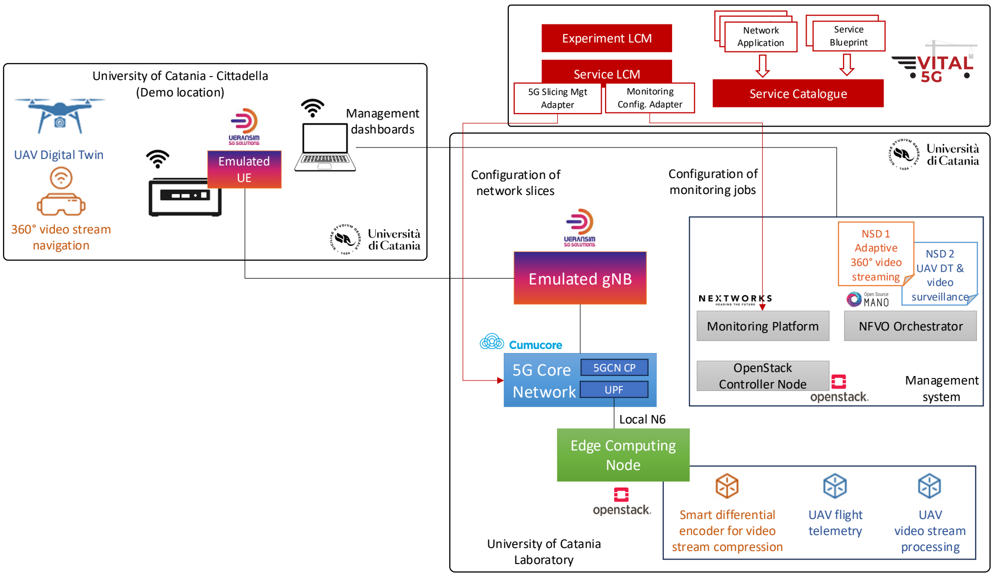

Fig. 9 UniCT 3rd party experiment setup.

and Monitoring interfaces. These are particular plugins for retrieving and allocating the network slices using the APIs exposed by the Cumucore 5G Core, and for creating and retrieving monitoring data from the testbed monitoring platform. The VITAL-5G Platform already provides support for OSM, and therefore no extension or development was required for the integration of the NFVO in this case.

The vertical service design was performed by onboarding the virtual applications and services of the targeted use cases as Network Applications and Vertical Service Blueprints into the Service Catalogue, triggering the onboarding of the associated Virtual Network Function Descriptors (VNFDs) and Network Service Descriptors (NSDs) into the UniCT NFVO. The lifecycle management of services was performed through the Service LCM, which automated the deployment of the network services, the provisioning of the network slices, and the creation of the monitoring jobs. Currently three different vertical services have been deployed at the UniCT facilities using the extended experimentation capabilities of the VITAL-5G Platform: (i) a 360° video streaming service over a 6G softwarized network, (ii) an Unmanned Aerial Vehicle (UAV) telemetry data gathering service, and (iii) an AI powered UAV camera streaming analyzer service.

The 360° video streaming service provides an immersive experience by optimizing video quality based on the user's viewport position. Each video frame is divided into tiles, with different quality levels applied according to their relevance to the user's current viewing area, which is tracked in real-time. The service is composed of two key components: 360-ST TX, which handles video compression and streaming, and 360-ST RX, which tracks the viewport position and communicates it back to the transmitter. Both components are implemented as VNFs on the VITAL-5G Platform.

As the user shifts their focus within the 360° video, the RX component continuously updates the TX component through an Message Queuing Telemetry Transport (MQTT) broker, allowing the system to dynamically adjust video quality. In experiments, edge computing resource usage and video quality were evaluated across several encoding scenarios. For example, CPU usage reached 42.83% with uniform compression and increased to 45.22% with tile-based differential compression. Interestingly, maximum compression without tile division reduced CPU usage to 30.94%, while combining maximum compression with tile splitting raised it to 38.90%. RAM usage remained stable across all scenarios, ranging from 1.11GB to 1.29GB (7-8% of a 16GB total).

In terms of video quality, tile-based differential compression achieved a Peak Signal-to-Noise Ratio (PSNR) of 37.07dB, significantly higher than the 31.74dB observed with uniform compression, representing a 16.79% improvement. The highest video quality, with a PSNR of 49.24dB, was obtained in the no compression scenario.

The UAV telemetry data gathering service leverages the VITAL-5G Platform to collect and process real-time telemetry data from UAVs, specifically the DJI Matrice 350 RTK. This service operates by utilizing the DJI Cloud API to capture critical flight parameters, such as altitude, speed, GPS location, and battery status, which are continuously transmitted from the UAVs remote controller to a cloud-based broker via the MQTT protocol. The service is designed as a VNF within the VITAL-5G Platform, enabling the seamless integration and management of telemetry data streams.

This data is then utilized to construct a digital twin of the UAV, which dynamically mirrors the real-time state of the physical drone. The digital twin, a key component of the service, subscribes to all relevant MQTT topics, ensuring it receives up-to-date telemetry information for accurate replication and monitoring. By maintaining a real-time digital representation of the UAV, this service enhances operational awareness and facilitates advanced analytics, predictive maintenance, and simulation capabilities, making it a vital tool for both routine UAV operations and more complex mission scenarios.

The AI-powered UAV camera streaming analyzer service is another advanced offering within the VITAL-5G Platform, designed to process and analyze real-time video streams from UAVs. This service captures the live video feed from the UAVs onboard camera, transmitted via the Real Time Streaming Protocol (RTSP), and applies sophisticated AI algorithms to detect and track various entities within the video feed.

The Core of this service lies in the implementation of YOLOv8 (You Only Look Once, version 8), an advanced object detection model known for its high efficiency and accuracy. As the video stream is processed in real-time, YOLOv8 identifies and tracks entities such as humans, vehicles, and wildlife, providing instantaneous insights into the UAVs surroundings. Like other services on the VITAL-5G Platform, this one is also implemented as a VNF, allowing for flexible deployment and scaling across various network environments. The combination of real-time video analysis with AI enhances the UAVs capabilities, making this service particularly valuable for applications in surveillance, search and rescue, and environmental monitoring, where quick and accurate detection is critical.

These results highlight the VITAL-5G Platform's flexibility and relevance in enabling advanced 5G services across diverse infrastructures. By facilitating seamless integration with 3rd party testbeds, such as UniCT, the platform proves its adaptability and sustainability for experimentation. The successful deployment of diverse vertical services, from 360° video streaming to AI-powered UAV analysis, underscores its capacity to support cutting-edge applications in multimedia, UAV operations, and real-time analytics, making it a valuable tool for advancing 5G-enabled innovation across industries.

9 Exploring Potential for Business Opportunities

The implementation of 5G technology in the T&L sector presents significant opportunities for innovation, targeting efficiency and cost reductions in a market projected to reach €920 billion globally by 2028, with a current Compound Annual Growth Rate (CAGR) of 52.4% [8]. As a sector contributing approximately 5% of Europe's Gross Domestic Product (GDP) and accounting for 10–15% of product costs [9], optimizing operations is critical for competitiveness. Key challenges, such as reducing delivery times and addressing inefficiencies at supply chain hubs, are being addressed by VITAL-5G through the adoption of advanced 5G technologies.

VITAL-5G aims to empower T&L stakeholders with tools to digitalize operations, enhance processes, and achieve competitive advantages. By aligning project assets with market needs, including insights from use cases and interactions with stakeholders, the project ensures functionality remains relevant and impactful. This approach not only highlights the value of 5G in the T&L sector but also fosters demand for vertical-specific 5G services.

3rd party Information and Communication Technology (ICT) providers and innovative SMEs, crucial for driving digitalization in logistics, play a key role in developing solutions that boost innovation and operational efficiency within the sector.

9.1 Key Opportunities

This section focuses on how the VITAL-5G assets were leveraged during the project's market engagement activities. Therefore, the following provides an overview of how 3rd parties engaged with the project and highlights the market needs directly addressed by the project assets:

- The majority of the 3rd party experimenters were interested in testing their own applications on the 5G SA network, to understand the benefits of 5G in terms of e.g. sensor density, edge computing, and the core network metrics achievable.
- Re-use of VITAL-5G network applications was requested in order to accelerate the development of the 3rd party services.
- The VITAL-5G Platform was employed to ease the onboarding of applications on the 5G network and to conduct in-depth application performance analysis using the platform's monitoring capabilities (see Section 3.2).

In alignment with the Section 4.3, a diverse set of use cases was seen throughout this engagement, covering such areas as real-time hybrid positioning, enhanced cell

Table 2 Key business benefits enabled by the VITAL-5G Platform.

Business Opportunities enabled by VITAL-5G	**Stakeholder(s)**
Delivery of consulting services for end customers. These services include integration, onboarding, performance evaluation, and configuration of 5G-enabled vertical services.	Information and Communication Technology (ICT) Integrators
Provision of standardized tools that encourage **scaling the roll-out of increased numbers of vertical services**. The Platform facilitates rapid deployment of applications and vertical services, avoiding the need to create complete custom applications each time new services are required.	Mobile Network Operators (MNOs)
Enabling detailed understanding of application-specific performance challenges. For the emerging 5G-enabled T&L sector, detailed technical knowledge is critical for SMEs to offer customized/specialized solutions to clients to remain competitive, especially versus larger, global operators.	SME Software Developers
Development of additional / enhanced network applications that can be shared and reused through the Platform's online repository. • This enhances the demand for the VITAL-5G Platform services among application developers and vertical service providers, who could be offered a wider range of network applications through the VITAL-5G repository. • The repository facilitates business opportunities for software developers through revenue-sharing mechanisms. • Encouraging such ecosystem effects is essential for platform-based business models to thrive.	VITAL-5G Platform Operator, Network Application Developers, Vertical Service Providers

handover, V2X, water infrastructure, and tourism. This supports the project's position that the core capabilities of the VITAL-5G Platform (e.g., application onboarding, monitoring, and network slicing) can be considered *horizontal* in nature, and applicable to other sectors beyond T&L.

Those leveraging the VITAL-5G Platform's experimentation services during the project's external engagement were various stakeholders from the 5G services ecosystem, such as software developers, T&L end users, 5G infrastructure providers, ICT integrators, and research organizations. Table 2 summarizes the outcomes of the 3rd party engagement in terms of the main business benefits offered by the VITAL-5G Platform to the different stakeholders.

9.2 Business Model Development

As discussed in Section 3.2, the Platform integrates components developed by various project partners, with each component mapped to its respective owner. During the project, different business models were explored to maximize the commercial impact of the Platform, incorporating feedback from 3rd-party stakeholders as potential customers. These models ranged from a static version of the Platform, encompassing all components, to a modular approach where specific components could be integrated based on bespoke client needs.

The modular approach was particularly relevant for potential network operator clients seeking custom 5G and B5G testbeds or services. This flexibility leverages the Platforms modular design, enabling component suppliers to tailor solutions to a rapidly evolving market. Such adaptability, especially for SMEs, is a critical differentiator, aligning with their strengths in delivering versatile, client-focused solutions

9.3 Outlook

Beyond what has been found through the project activities, further investigation of the market opportunity is required to determine its scale. To facilitate further investigation of this topic, the project has made the platform assets available for the wider community[4], providing the opportunity to better understand the benefits of the assets. This helps external partners to further explore the opportunities for commercial impact that can be facilitated through the VITAL-5G Platform.

In addition, exploring business opportunities with 3rd parties has provided i) first-hand experience of service provision using the platform, allowing partners to understand the level of effort involved, the implications of this on the running costs of the platform, and ii) our 3rd party partners an understanding of the level of investment needed to engage with the VITAL-5G Platform. This information is essential to calculate the return on investment of different business models and the viability of future business endeavors.

10 Discussion lessons learned and conclusion

The comprehensive trials conducted within the VITAL-5G project, both internal and 3rd party ones, have highlighted a range of unique challenges and valuable lessons, effectively showcasing the diversity and potential of the various use cases enabled by the VITAL-5G Platform. A diverse array of Network Applications is developed and tested on top of the VITAL-5G testbeds, utilizing the monitoring platform of the project to its full capacity. These developments are not only indicative of the robustness and versatility of the VITAL-5G Platform but also highlight the innovation ecosystem that the project has fostered.

This paper outlined several relevant challenges that need to be taken into account when creating opportunities for 3rd party experimentation. Before any experimentation, it is of utmost importance to create proper training and exploration sessions for interested parties. These sessions are usually held by technical and non-technical experts (e.g., business developers) who are capable of exemplifying the benefits of using advanced network capabilities via experimentation platforms such as the VITAL-5G one, to enhance the operational efficiency of their respective industrial processes. In addition, 3rd parties coming from diverse industrial and academic environments need to sustain their privacy and secure their network and application resources during

[4] Link to the VITAL-5G Platform repository: https://gitlab.com/vital-5g/VITAL-5G_Platform/vital-5g-platform-installation/

experimentation. For that purpose, the VITAL-5G Platform offers secure channels and credentials needed for each experimenter to access any resource from the underlying network and T&L infrastructure. The modular design of the VITAL-5G Platform allows specific components to be utilized with no dependency on other components. For example, the centralized monitoring module and the LCM of the platform can operate without relying on additional components. The modular design of the VITAL-5G Platform ensures that specific components can be utilized independently, with no dependency on other modules. For instance, the centralized monitoring module and the LCM of the platform can function autonomously without requiring support from additional platform components. This design enables the platform to be deployed seamlessly on any 5G Edge or cloud environment, providing flexibility for integration with various 5G networks. Such adaptability supports trial facilities where verticals can perform experiments across different infrastructures, ensuring compatibility with heterogeneous network setups.

This flexibility makes the VITAL-5G Platform adaptable for various applications. The VITAL-5G project originates from the Horizon Europe 2020 Framework Programme and is associated with the 5G Infrastructure Public Private Partnership (5G-PPP). Although this program is concluding, the modular design of the VITAL-5G pPatform ensures its relevance in the 6G era. For instance, the 6G Smart Networks and Services Joint Undertaking (SNS JU) program, which succeeds the 5G-PPP, is already reusing and enhancing platforms developed during the 5G-PPP era. For instance, TrialsNet is part of SNS JU, and it is reusing a subset of VITAL-5G Platform components, i.e., centralized monitoring module and LCM to support large-scale trials in 6G context.

The three most important capabilities of the VITAL-5G Platform utilized by 3rd parties discussed in this paper are the *facilitation of the deployment of vertical services in the 5G network*, *enhanced network performance through network slicing*, and *real-time monitoring of network and service performance*. These capabilities enable 3rd parties to deploy their services in a 5G network while leveraging slicing technology, allowing them to simultaneously monitor how their services are performing within the 5G ecosystem.

Given that the resulting efficiency gains of creating vertical services in the 5G ecosystem bring competitive advantages for the parties involved and increase profitability, it is important to highlight specific business opportunities that emerge from such activities. In particular, the 3rd party ICT providers and innovative SMEs are specifically interested when it comes to exploring potential business opportunities, as their Core business relies on developing innovative solutions for T&L companies. Some of the identified business opportunities refer to i) the delivery of consulting services for end-customers in case of ICT integrators, ii) enriching the pool of standardized services Mobile Network Operators (MNOs) offer, which can encourage increases in the number of vertical services and offer new business cases, iii) creating a knowledge-base for SMEs that are interested in application-specific performance challenges, and iv) design and development of innovative Network Applications by software developers, which will boost various vertical sectors.

The following provides an overview of how 3rd parties engaged with the project and highlights the market needs directly addressed by the project assets:

- The majority of the 3rd party experimenters were interested in testing their own applications on the 5G SA network, to understand the benefits of 5G in terms of e.g., sensor density, edge computing, and the core network metrics achievable.
- Re-use of VITAL-5G network applications was requested in order to accelerate the development of the 3rd party services.
- The VITAL-5G Platform was employed to ease the onboarding of applications on the 5G network and to conduct in-depth application performance analysis using the platform's monitoring capabilities.

The primary general challenges and lessons learned from the experiences of 3rd party experimenters, as discussed in this paper and throughout the VITAL-5G project, are:

- Installation of physical devices in the target testbed (5G gateway compatibility, blacklisted devices on target 5G network).
- Porting of network applications in the VITAL-5G environment is highly facilitated by using "standard-de-facto" tools (OSM, OpenStack).
- Network application and Service Blueprint capable of capturing all the current requirements. Extensions should be needed to support additional metrics of interest of the 3rd party experimenter.
- Engagement with 3rd parties requires several steps, from initial training and joint design of the end-to-end solution, up to continuous support during onboarding and installation of devices on the field.
- Ensuring strong security is crucial when providing 3rd parties with access to the VITAL-5G Platform and testbeds. This includes implementing measures such as per-user VPNs and credentials for platform access, as well as per-institution VPNs for secure remote connectivity to the target testbed.

11 List of Abbreviations

The list of abbreviations in the paper is listed in Table 3 at the end of the paper.

12 Declarations

12.1 Availability of data and material

Not applicable.

12.2 Competing interests

The authors declare that they have no conflict of interest.

12.3 Funding

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12.4 Authors' contributions

VC and NSK developed the idea, wrote the paper, and polished the paper. VC, LK wrote subsection 4.1. GB wrote subsection 4.2. MI and CP wrote section 5. EG and PD wrote section 6. JB, GL, AC, CG, and GS wrote section 7. RF wrote section 8. VC and NSK wrote section 9. NSK and JMB were the main advisors.

12.5 Acknowledgements

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13 Figure Title and Legend Section

Figure 1: Vital-5g-platform-testbeds, **Title**: VITAL-5G System with Platform and Underlying Network and T&L Infrastructure. **Legend**: This figure illustrates the VITAL-5G system architecture, which integrates a central platform that is connected to three 5G infrastructures (Belgium, Romania, and Greece) to facilitate the deployment and validation of 5G-enabled applications in the T&L vertical. The VITAL-5G Platform includes features for managing network applications, virtualizing network functions, and orchestrating services across various distributed testbeds. These testbeds offer realistic environments for pilot trials, leveraging resources such as edge cloud computing, SDN, and NFV. The infrastructure enables interoperability across different geographic locations, supporting diverse T&L network applications.

Figure 2: 3rd party diagram.pdf, **Title**: Simplified VITAL-5G Service Workflow., **Legend**: This figure depicts a simplified schema of all the complexities the VITAL-5G Platform extracts from the 3rd party experimenter. The workflow includes key stages for defining network and hardware requirements, creating blueprints for network applications and vertical services, and VNFs and NSDs to the NFV orchestrator. The process is divided into phases that outline activities managed by external experimenters, the VITAL-5G Platform, and background processes within the system. Key steps include network slice allocation, service deployment, real-time monitoring, and advanced diagnostics, with dashboards enabling visibility into vertical service performance and diagnostics reports. The VITAL-5G Platform facilitates seamless integration of 3rd party applications, ensuring flexible, reliable service testing in realistic 5G environments.

Figure 3: ININ_overview_figure.pdf, **Title**: ININ 5G gateway incorporated into Antwerp testbed network monitoring agent., **Legend**: The ININ 5G gateway (top left) is integrated with the VITAL-5G Belgium testbed infrastructure, enabling real-time network monitoring. Network metrics collected by the gateway (top right) are compared with those monitored through the VITAL-5G platform (bottom left and right). This comparison demonstrates metric consistency across both the gateway and platform, validating the gateway's monitoring capabilities within the testbed environment.

Figure 4: 3rd party zettascale v2x.pdf, **Title**: ZettaScale V2X application schema., **Legend**: The figure illustrates the deployment of a V2X application, with an ML-based, low-latency processing module deployed at the network edge of the Belgium testbed. Each vehicle is equipped with cameras that continuously stream data directly to the edge application. Leveraging Zenoh's location transparency, data streams are automatically routed to the nearest server without needing the application to specify a destination. Detected objects are then sent back to the corresponding vehicles, where autonomous driving algorithms utilize this data to inform decision-making.

Figure 5: 3rd party zettascale synt.pdf, **Title**: ZettaScale Synthetic Tests Schema., **Legend**: This figure depicts the deployment scenario for synthetic tests. A Zenoh application is deployed on the vehicle and is capable of performing both RTT and throughput measurements. At the network edge, a Zenoh router and a similar application are deployed to facilitate these measurements, enabling end-to-end performance assessment between the vehicle and edge of the Belgium 5G infrastructure.

Figure 6: 3rd party zettascale synt result.pdf, **Title**: ZettaScale Synthetic Tests Results., **Legend**: This figure presents a synthesized experimental results of Zettascla leveraging the Belgium VITAL-5G 5G infrastructure the throughput results. The throughput closely follows the RSSI and RSRP signal curves. Despite fluctuations, Zenoh maintains a stable upstream throughput of over 1000 messages per second for a 4 KB payload and over 100 messages per second for a 32 KB payload.

Figure 7: image1_oro.pdf, **Title**: RWS 5G Service Performance analytics - Romanian testbed., **Legend**: This figure shows the setup for 5G network of the Romanian testbed. This setup enables real-time monitoring of network and service performance, with telemetry data automatically collected, processed, and analyzed for health checks, proactive issue detection, and alerting. The figure highlights the VITAL-5G Platform modules, including the Service and Network Monitoring component, which gathers diverse metrics from the testbed. This data is fed into the RWS (3rd party experimenter on the Romanian testbed) software module for AI/ML-driven service assurance, providing incident detection, alarm generation, healing recommendations, and detailed reporting.

Figure 8: VITAL-5G-GR-3rd parties-Psalidi1.png, **Title**: Effects of Network Latency on Coordinated Robotics tasks. **Legend**: This figure is the result of 3rd party activity on the Greek 5G infrastructure. The figure illustrates the effects of network latency on coordinated robotics tasks using Private 5G SA versus traditional mobile networks. In this scenario, two ARMs move simultaneously at the same linear velocity while carrying a load. One robot detects an obstacle and monitors its distance from

it. When the distance reaches a predefined threshold, it stops and commands the second robot to halt as well. With the low latency of the 5G-SA network, the second robot receives the stop command promptly, preventing the load from falling. In contrast, with a higher latency network, the second robot reacts too late, stopping a few centimeters later, resulting in the load dropping.

Figure 9: unict-3rd-party-experiment.png, **Title**: UniCT 3rd party experiment setup. **Legend**: This figure illustrates the modularity of the VITAL-5G Platform. In this setup, the 3rd party trial conducted by the University of Catania (UniCT) within the VITAL-5G project showcases the integration of various VITAL-5G Platform components with the UniCT testbed and as such transforming their testbed capabilities. Key elements of the setup include a subset of the VITAL-5G Platform components, specifically the Service Catalogue, Service, and Experiment Lifecycle Management (LCM), deployed at Nextworks facilities in Pisa and connected to the testbed via a VPN connection.

Table 3 List of abbreviations

The technical term	**The abbreviation**
Transport & Logistics	T&L
Software-Defined Networking	SDN
Network Function Virtualization	NFV
Small and Medium-sized Enterprise	SME
Internet of Things	IoT
Automated Guided Vehicle	AGV
User Equipment	UE
Artificial Intelligence	AI
Machine Learning	ML
Standalone	SA
Non-standalone	NSA
Non-Governmental Organization	NGO
vehicle-to-everything	V2X
Ultra-Reliable Low-Latency Communication	URLLC
massive Machine-Type Communication	mMTC
Next-Generation Node B	gNodeB
Received Signal Strength Indicator	RSSI
Reference Signal Received Power	RSRP
Round-trip time	RTT
Service-Level Agreement	SLA
Core Network Function	CNF
Proof of Concept	PoC
Radio Access Network	RAN
Key Performance Indicator	KPI
Application Programming Interface	API
Lifecycle Management	LCM
Virtual Private Network	VPN
Physical Network Function	PNF
User Plane Function	UPF
Control Plane Function	CPF
Virtual Machine	VM
Open Source MANO	OSM
Network Function Virtualization	NFV
Network Function Virtualization Orchestrator	NFVO
Virtual Network Function	VNF
Virtual Network Function Descriptor	VNFD
Network Service Descriptor	NSD
Message Queuing Telemetry Transport	MQTT
Peak Signal-to-Noise Ratio	PSNR
Compound Annual Growth Rate	CAGR
Gross Domestic Product	GDP
Information and Communication Technology	ICT
5G Infrastructure Public Private Partnership	5G-PPP
Smart Networks and Services Joint Undertaking	SNS-JU
Mobile Network Operator	MNO
Autonomous Mobile Robot	ARM