Next-Gen Industry 4.0 with 5G: Enabling Secure and High-Performance Services for Critical Infrastructure

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***Abstract*—The advent of Industry 4.0 heralds a new era in manufacturing, driven by advancements in automation, IoT, and AI. Integral to this shift is the deployment of robust communication networks capable of real-time data exchange. Leveraging 5G technology, with its low latency and high bandwidth, is crucial in meeting these demands. However, integrating vertical services with 5G networks poses challenges. This paper, part of the 5G-INDUCE project, focuses on deploying and validating corrosion inspection and intruder surveillance services for critical infrastructures. Trials conducted at the Greek Experimentation Facility showcased successful service deployment, configuration, and high-definition video streaming. Quantitative results exceeded expected Key Performance Indicators, demonstrating the platform's efficacy in integrating advanced network applications. This work contributes to the evolution of Industry 4.0 by harnessing the transformative potential of 5G technology.**

***Index Terms*—5G, Corrosion Detection, Intruder Detection, Artificial Intelligence, Network Application**

I. Introduction

The fourth industrial revolution, or Industry 4.0, is revolutionising manufacturing and other sectors by integrating advanced technologies like automation, the Internet of Things (IoT), and artificial intelligence (AI) [1]. This transformation hinges on robust and adaptable communication networks that can support real-time data exchange and mission-critical applications. 5G technology, with its ultra-low latency, high bandwidth, and network slicing capabilities, is ideally suited to meet these demanding communication requirements [2]–[4].

However, vertical stakeholders typically lack the fundamental understanding to leverage the capabilities of 5G networks fully. Furthermore, telecommunication providers, who possess the physical infrastructure, are often reluctant to grant third parties autonomy in orchestrating their resources. Within this landscape, the essential integration between digital systems facilitating vertical services and the network layer remains unspecified, presenting a significant challenge.

Projects such as VITAL-5G [5] aim to demonstrate the advantages of 5G-based network applications through real-world trials conducted across cutting-edge vertical facilities, including warehouses, hubs, and ports, in conjunction with advanced European 5G testbeds. Similarly, 5G-EPICENTRE [6] leverages cloud-native 5G infrastructure and network applications to enhance public protection and disaster relief efforts. The 5G-ERA [7] initiative focuses on validating use cases spanning four key vertical sectors—public protection, disaster relief, transport, healthcare, and manufacturing—through the prototyping of network application solutions utilising 5G technology. Moreover, 5G-IANA [8] endeavours to establish a 5G open experimental platform tailored for the automotive sector, comprising computer and communication infrastructure, management, orchestration components, and specialised network applications. Additionally, Smart5Grid [9] introduces a 5G solution designed to facilitate the integration, testing, and validation of both existing and emerging 5G services and network applications for future smart energy grids. The work reported in this paper corresponds to the European project 5G-INDUCE [10].

The primary objective of this project is to develop an open, European Telecommunications Standards Institute (ETSI) Network Functions Virtualisation (NFV)-compatible 5G orchestration platform designed specifically for deploying advanced

5G network applications. The platform's unique features allow network application developers to define and adjust application requirements autonomously. Meanwhile, the underlying intelligent Operation Support System (OSS) facilitates the exposure of network capabilities to end-users at the application level, safeguarding sensitive infrastructure-related information. This approach supports application-centric network management and optimisation, aligning with the operator's role as manager of its own resources. Moreover, it establishes a development framework accessible to developers and service providers, facilitating the design and deployment of tailored applications for vertical industries. This framework ensures independence from cloud providers, eliminating indirect dependencies and enhancing flexibility for all stakeholders involved [11]–[13].

This paper focuses on the use case 5 of this project. This use case focuses on inspection and surveillance services for critical infrastructures. This is important in order to prevent accidental or malicious damage. The goal of the corrosion inspection is to identify early corrosion or mistreatment signs or even critical operation levels (e.g. in storage tanks or pipelines) [14]. The goal of surveillance is to identify unwanted and potentially malicious presence of humans or even animals [15]. The AI models used are not explained in this paper as they have been already reported and published in previous ones [14], [15].

The main objective of this paper is to report the results obtained on the validation trials of this use case. Thus, the experimental setup is explained, describing the experimentation facilities and how the developed network applications, such as the corrosion and intruder detection algorithms, are deployed in the 5G-INDUCE platform. Then, the results are reported. These include service deployment, application configuration and Machine Learning (ML) pipeline execution times or user-perceived latency.

The remainder of this paper is organised as follows: Section II describes the experimental setup such as the testing facilities or the use case architecture. Section III shows the qualitative and quantitative results obtained. Finally, Section IV concludes this paper.

II. Experimental Setup

A. Testing facilities

The experiments were carried out in the Greek Experimentation Facility (GR-ExFa) of the 5G-INDUCE project. The GR-ExFa trial site is at Public Power Corporation (PPC) Innovation Hub in Lavrio, Greece. To cover the trial site a radio access network has been installed by Hellenic Telecommunications Organisation (OTE) covering the required multi-floor area. The radio is based on New Radio (NR) technology, and it is connected to a 5GC that is located on OTE premises. NR is integrated with the SA Rel. 16 architecture.

The two main sites of the implementation are the Core site, where the packet core is installed, and the RAN site, where the access part of the network is installed. The distance between the two sites is about 15km. In between, there is the packet optical transport network (POTP), which includes the transport network and network elements, such as servers and switches. OTE switches are interconnected to the OTE IP Core, using a 10 Gbps capacity line, to interconnect the infrastructure located at OTE Labs (Core site) with the RAN site in PPC.

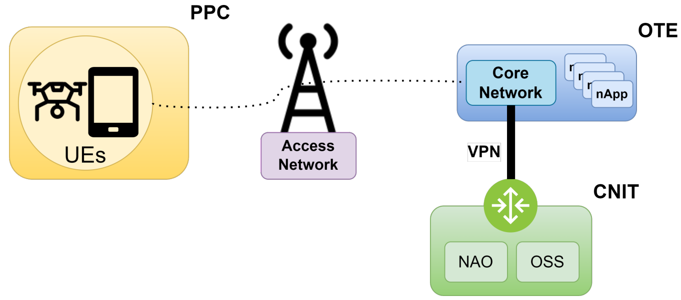

Fig. 1. High-level architecture of the GR-ExFa testbed.

Figure 1 shows a high-level architecture of the previously explained GR-ExFa. The User Equipment (UE), which for this use case will be a tablet connected to a drone, will be on PPC premises, that will be connected to the Core network in OTE via the access network. At the same time, the core network will be connected to CNIT where the DevOps testbed is located, hosting the 5G-INDUCE platform, including the Network Application Orchestrator (NAO) and the OSS. The prototyping of the orchestration platform is partially based on MATILDA [16]. The network applications (nApp) will be deployed on OTE premises, where GPU capabilities are required.

B. Use case architecture

Figure 2 illustrates a general architecture overview of this use case in the format of a graph for both network applications including all the essential components, communication flows, and key players and stakeholders. During the operation, the pilot will transmit video footage from the Unmanned Aerial Vehicle (UAV) to the network applications, which will identify corroded areas and intruders. The pilot will receive this information and it will be shown on top of the tablet screen along with the video footage. On the other side, a Commander entity supervises the video streamed from the UAV and the corresponding detections.

This use case is composed of four different components to be deployed by the 5G-INDUCE platform. An external component has been added in order to provide security and licensing to the network application. A license key will be given to every user who will be able to use an Intruder/Corrosion Detection network application. These network applications will ask the License Server component for permission to perform computationally expensive AI algorithms to detect corrosion or intruders.

Every network application component was dockerised and stored in the internal container library of the project in GitLab. Besides a YAML (docker-compose) file that specifies the correct deployment information is shared. The 5G-INDUCE platform will download and deploy each of the components

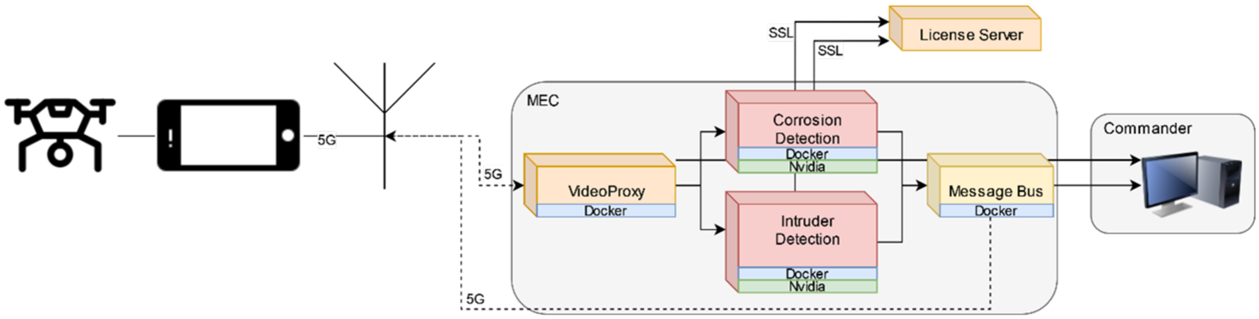

Fig. 2. General network application architecture overview.

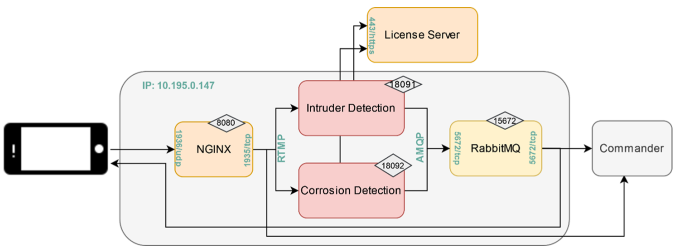

Fig. 3. Architecture deployed in the ExFa.

dockerised in the corresponding machine. Figure 3 presents the final system's architecture deployed with the protocols and interfaces mapping of each component when it was tested in the Greek Experimentation Facility. Standard interfaces for protocols such as AMQP (Port: 5672/tcp) or RTMP (Port: 1935/tcp) will be mapped to the ones available (decided by the 5G-INDUCE platform). Moreover, each component deployed in the system will have an accessible port exclusively reserved for the 5G-INDUCE platform. These ports function as health checks or heartbeats, enabling the platform to ascertain the operational status of the components—whether they are still active or have undergone termination.

After successfully deploying each component, the platform allows the pilot to connect to the services. Initially, the UE verifies the deployment and functionality of all components. Subsequently, it establishes a connection with the UAV and transmits the video stream from the UE to the network application. Figure 3 presents the use case deployed in the trial.

III. Experiments and Results

A. Testbed setup

The trials were carried out in PPC Innovation Hub, where a scenario was set up with different pipes corroded and not corroded and multiple people acting as intruders. A 5G gNB was connected to the 5G core (with GPU capability) located in OTE premises, allowing the pilot to connect to the network application deployed in the core. Before any test, a remote onboarding and deployment of the network applications was carried out. The drone used for the trials was a DJI Spark equipped with a Full High Definition (HD) camera (1920×1080px) at 30 fps. It was connected to an Android tablet Samsung Galaxy Tab S7+ with 5G connectivity.

B. Trial procedure

Sequential steps were defined for the trials to have valid results values. The steps followed were the following:

- **Step 1:** Preinstalled Android APP in pilot's tablet. Preconfigured VNFs ready to be deployed (Video Proxy (NGINX), Corrosion and Intruder detection and Message Bus).
- **Step 2:** Connect the UAV pilot's tablet to control the drone via a 5G mobile router using 5G SA.
- **Step 3:** Deploy the network applications by the OSS/NAO.
- **Step 4:** Secure communication with an external license server. (Security Extension).
- **Step 5:** Successful heartbeats checking carried out for each VNF by the OSS/NAO.
- **Step 6:** Tablet validates the connection to the VideoProxy (NGINX) and MessageBus VNFs.
- **Step 7:** The tablet starts the streaming of a video from the drone to the tablet.
- **Step 8:** Pilot starts seeing detections in the tablet.
- **Step 9:** KPI metrics are collected.

C. Quantitative results

In the context of the INDUCE-5G project, several Key Performance Indicators (KPIs) were defined for this use case. These KPIs measure the performance of the whole system including not only objective results, such as inference times or deployment times, but also subjective ones, such as the perceived latency by the users of the application. At the beginning of the project expected results were defined for each of the KPIs. Below, the definition of each of the defined KPIs is found along with the expected result and the real result obtained on the trials.

- **KPI-1 - Service deployment time:** Service deployment time at the ExFa site through the 5G-INDUCE platform. The overall duration between the time the end user issues the request for a Network Application instantiation through the NAO and the confirmation for service instantiation appears at the service management tab of

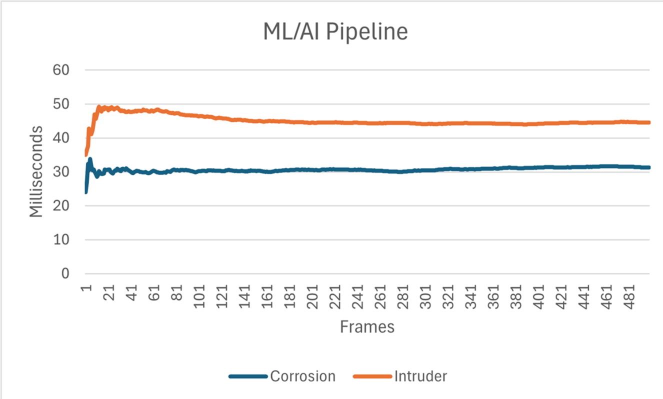

Fig. 4. Cumulative average execution speed of the frames processed over the corrosion and intruder detection components.

the NAO front-end. The KPI value was 60 seconds and a result of 33 seconds was achieved. The deployment time was taken after all container images had been already downloaded.

- **KPI-2 - Application-specific configuration time:** Application-related configuration time after a certain monitoring parameter that triggers the configuration is detected. It is the average time required by the pilot or user to configure the UE app to successfully connect to the network application. The KPI value was 60 seconds and an average result of 48 seconds was obtained.
- **KPI-3 - HD video quality (real-time operation):** High-resolution video quality is shared from the UAV to the network application. The KPI value was a bandwidth of 8Mbit/s or the transmission of HD video. In the trials, it was tested that HD video could be transmitted.
- **KPI-4 - Artificial Intelligence (AI)/ML pipeline execution time:** It is the time for the network application to execute the AI/ML pipeline. The KPI was 50 milliseconds per frame. On the corrosion algorithm (KPI-4a), a result of 23.56 ms was obtained, whereas the intruder algorithm (KPI-4b) achieved 40.53 ms. Figure 4 illustrates the cumulative average inference time for both algorithms.
- **KPI-5 - End user-perceived latency:** It is the perceived latency from the time the UE starts the streaming of video until the pilot starts seeing detections. The KPI value was a score from 0 to 5 given by the pilot. On the trials, five people who were on site voted. A score of 4.6 was obtained on the time to start detecting and a 4.8 for the video latency.

The results of the main KPIs are summarised in Table I. As can be seen, all the KPIs were achieved, improving notably the expected results. The accuracy of both the intruder and corrosion detection algorithms are not reported as it was already reported in [15] and [14] respectively.

D. Qualitative results

Figure 6 and Figure 5 show two examples of corrosion detection on pipes during the trials using the corrosion network application. For the trials, different pipes were chosen at the PPC premises, some of them corroded and others not. In the second one, some corroded pipes were put on top of not corroded pipes to simulate a pipe with a corroded section.

As can be seen in the images, the corrosion detection algorithm can correctly identify the corroded pipes.

In Figure 7 all the participants in the trials at PPC premises are shown. The intruder detection algorithm is being executed and all the people were detected, thus confirming the correct performance of the algorithm.

All figures are screenshots from the Android application

Fig. 5. Corrosion detection of pipes during the trials at PPC premises, with corroded ones overlaps with not corroded.

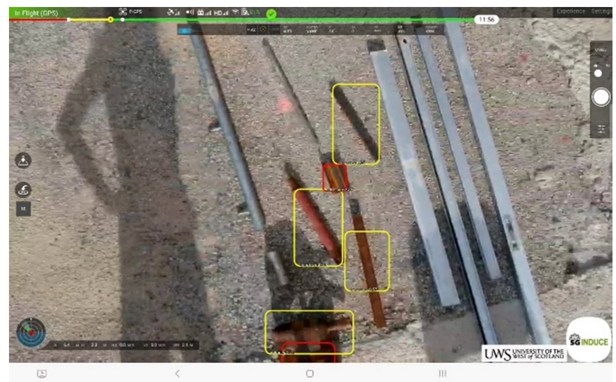

Fig. 6. Corrosion detection of pipes during the trials at PPC premises.

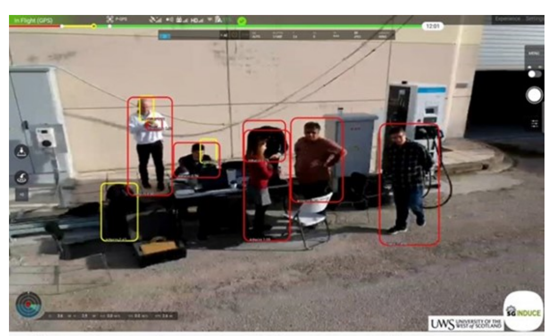

Fig. 7. Intruder detection of the participants on the trial at PPC premises.

TABLE I
RESULTS OBTAINED ON THE TRIAL FOR EACH OF THE USE CASE KPIS.

KPI	Description	Expected	Result
KPI-1	Service deployment time	60 s	33 s
KPI-2	Application-specific configuration time	60 s	48 s
KPI-3	HD video quality (real-time operation)	HD video resolution	HD video resolution
KPI-4a	Corrosion AI/ML pipeline execution time	50 ms/frame	23.56 ms/frame
KPI-4b	Intruder AI/ML pipeline execution time	50 ms/frame	40.53 ms/frame

installed in the tablet that receives from the message bus network application the detections obtained by the intruder and corrosion detection algorithms. The figures are evidence of the successful validation of the use case and the high performance of both developed algorithms.

IV. CONCLUDING REMARKS

Several conclusions can be extracted after the validation and testing trial performed for Use Case 5 in the 5G-INDUCE platform at the Greek ExFa. As can be appreciated, the fast deployment (KPI-1) is provided by the 5G-INDUCE platform allowing high scalability and orchestration when ensuring the optimal resource allocation whilst deploying the different services regarding its requirements. In computationally expensive applications such as this use case, where two instances of AI models require GPU capabilities, this resource efficiency by preventing over-provisioning can lead to cost savings.

In addition, one of the great advantages highlighted over the tests is the capability of choosing between edge computing and core computing. Using edge computing allows the users to process their video streaming close to the data source resulting in a reduction in video streaming latency. This became very useful when deploying this system in critical infrastructure such as in this validation (PPC) e.g. for intruder detection. Nevertheless, if the use case is less critical, the allocation of the AI models may be ported to the core, improving the overall system performance in terms of accuracy.

The attainment of the high-resolution video streaming (KPI-3), and optimal end-user perceived latency (KPI-5) are intricately linked to the strategic implementation of the 5G network in combination with the 5G-INDUCE platform. Particularly through the utilisation of network slicing, which plays a pivotal role in tailoring and allocating the network capabilities to meet the specific requirements of each application, enhancing the overall efficiency and performance of the network. This approach allows a more targeted and customised allocation of network resources, ensuring that the functional tests, high-resolution video streaming, and latency targets are met with precision and adaptability within the 5G framework.

Overall, the trial was a success with both network applications validated and all the target KPIs met.

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