Chapter

The Impact of 5G-Enabled Edge-Cloud Services on Energy Facilities in Industry 4.0

Nikolaos Tzanis, Eleftherios Mylonas, Panagiotis Papaioannou, Christina (Tanya) Politi, Alexios Birbas, Christos Tranoris, Spyros Denazis, Ioannis Moraitis, Alex Papalexopoulos, Anna Tzanakaki and Jesús Gutiérrez Terán

Abstract

As the energy sector undergoes a profound digital transformation, demanding a fusion of resilience, efficiency, and cutting-edge technology, 5G technology emerges as a beacon, promising not just enhanced connectivity but a holistic transformation of how we conceive and manage energy infrastructure. This work aims to provide an in-depth exploration for experts in the energy domain, unraveling the innovative aspects of 5G through the demonstration of important achievements and results of the Horizon 2020 5G Infrastructure Public Private Partnership (5G-PPP) Phase-3 5G-VICTORI's Project and its trial results on the impact of 5G technology in an energy facility located in the city of Patras, Greece.

Keywords: edge-cloud continuum, industrial IoT, 5G, private networks, virtualization, geofencing, artificial intelligence

1. Introduction

The digitization of the industrial sector has led to the arrival of the first Industry 4.0 services, which resulted in enabling new markets within the sector and creating new opportunities based on modern industrial procedure paradigms. These paradigms are the basis for the so-called Smart Factory vertical industry, which integrates and benefits from emerging technologies like Internet of things (IoT), artificial intelligence (AI), edge/cloud computing, etc., and aims to bring a new era in the way the industrial sector collects, processes and utilizes data.

From a network requirement point of view, the Smart Factory vertical can be split into different services or applications, presenting different requirements. Maintenance activities require the support of low-cost, energy-efficient sensors planted in a distributed and heterogeneous infrastructure. Security and operation services ask for low latency trip signals and high bandwidth for closed circuit television (CCTV). 5G technology is expected to integrate and deliver services able to support these diverse applications simultaneously.

5G technology offers a suite of features tailored to enhance operational efficiency and data security in industrial environments [1]: *(1) Enhanced Network Performance*, offering superior network performance for different types of applications through massive machine type communication (mMTC), ultra-reliable low latency communication (URLLC) and enhanced mobile broadband (eMBB). This performance boost enables seamless connectivity crucial for industrial processes; *(2) Slicing Support for Uninterrupted Performance*, 5G's support of slicing ensures a dedicated lane for critical applications, guaranteeing they meet their key performance indicators (KPIs) consistently. This capability enables the concurrent support of diverse applications with varying requirements, ensuring operation even in the face of fluctuating background traffic. The concept of network slicing was first introduced in Release 15 of the Third Generation Partnership Project (3GPP) 5G specification [2], while Release 17 defined a mechanism in order to support multiple service level agreement (SLA) requirements and introduced energy efficiency KPIs [3]; *(3) Co-location of 5G Core (5GC) Functions and Application Functions (AFs)*, which significantly reduces latency in communication, fostering real-time responsiveness crucial for industrial processes and concurrently enhances data privacy by keeping critical functions close to the source; *(4) Secure Isolation with 5G Non-Public Network (NPN)*, 5G's support of NPNs ensures that sensitive industrial data remains safeguarded, addressing the need for secure communication within industrial ecosystems. Moreover, it enables the monitoring and configuration of the communication network internally, allowing for quick response in case of incident or demand for re-configuration due to the inability to meet specific KPIs. The concept of NPN was first introduced in Release 17 of the 3GPP 5G specification [3]; *(5) Flexible Deployment of Edge Processing Services*, 5G technology facilitates the seamless deployment of new services demanding edge processing. This agility allows industrial setups to swiftly integrate cutting-edge solutions, empowering them to adapt to evolving technological demands with ease; and, finally, *(6) Cost Reduction*, from 5G's ability to use commercial-of-the-shelf (COTS) servers rather than dedicated network equipment to execute network functions, the support of multiple services on a single infrastructure and the ability to push intelligence at the edge, contributes to significant cost savings for industrial entities. The use of wireless 5G sensors in the "last mile" of deployment also contributes to cost reduction (e.g., at substation level).

This work aims to present an in-depth exploration designed for experts in the energy field. It delves into the innovative dimensions of 5G, illustrating notable accomplishments and findings within the context of the Factories of the Future use case in the 5G-VICTORI project [4]. 5G-VICTORI is a Horizon 2020 5G-PPP Phase-3 project whose main goal is to showcase large-scale field trials for advanced use case verification in commercial environments deploying 5G infrastructures in support of a number of vertical industries, specifically the Factories of the Future, Transportation, Energy, Media verticals.

The objective of the 5G-VICTORI Factories of the Future use case is to demonstrate that, by leveraging the unique features of 5G technology and 5G-VICTORI architecture [5–7], novel Industry 4.0 applications with different requirements can be sufficiently supported in a private 5G network deployment. This use case intends to demonstrate two different scenarios:

- The application of mMTC-banded IoT architectures for preventive maintenance and monitoring of the factory assets.

- The support of uRLLC and eMBB applications for real-time monitoring, security, and automation in an industrial environment.

This chapter is structured as follows: Section 2 introduces the Factories of the Future use case and the three different services it comprises namely the Operation, Maintenance, and Facilities Security service. Section 3 describes the Operation service's details and results. In Section 4, the Maintenance service's details are analyzed, whereas Section 5 deals with the Facilities Security service. In Section 6, we present the challenges we faced during the 5G-VICTORI project. Lastly, we conclude our work in Section 7, where the outcomes of the Factories of the Future use case are summarized.

2. Use case details and architecture

The trial takes place at the Independent Power Transmission Operator (IPTO or ADMIE in greek) facilities located in Patras, Greece, which consist of two sites, separated by 4 km of sea, and are electrically interconnected via a high-voltage (HV) 150 kV submarine power cable. Each site serves as termination point for the submarine HV power cable and comprises one control room and several sensors for the monitoring of the termination equipment status at this site. The facilities are interconnected with the Patras5G testbed [8], located at the University of Patras (UoP), via millimeter-wave (mmWave) links provisioned by Intracom Telecom.

Patras5G offers a cloud platform that can host core network components and mobile edge computing (MEC) deployments. By leveraging the 5G-VICTORI architecture, 5GC functions can be co-located with AFs at an edge datacenter (e.g., Autonomous Edge—located at the ADMIE site) or the cloud according to the requirements of the service. **Figure 1** depicts the architecture of this use case

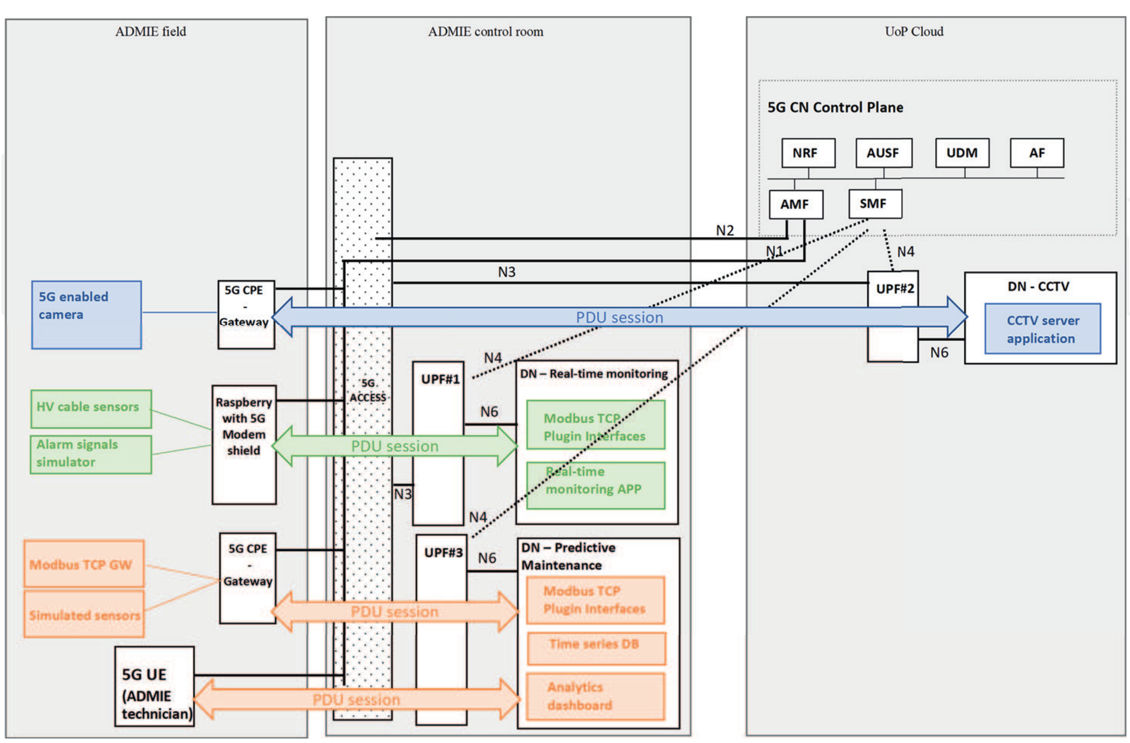

Figure 1.
High-level architecture of the factories of the future use case.

and highlights the placement of application functions and 5GC functions to support its applications. More details of the architecture description can be found in 5G-VICTORI's deliverable D3.6 [9].

The applications that are demonstrated refer to operation, maintenance, and facilities security domains [9, 10]. The following sections describe the objective of each application and the high-level deployment methodology, focusing on 5G innovative aspects, and present results and valuable findings for the energy operator.

3. Operation: real-time monitoring of HV power cable

Operation-related applications refer to applications involved in the real-time monitoring of the system and are characterized by guaranteed low latency and high-reliability requirements. In the Real-Time Monitoring of HV Power Cable, measurements of active power (MW), reactive power (MVar), and current (A) from the primary and secondary windings of the transformer at each site are collected and compared in real time. Frequency (Hz) measurements are also collected on one side of the cable via a high-frequency measurement device.

3.1 Methodology

Measurements collection is performed through Modbus transmission control protocol (TCP) clients developed for the project. Legacy sensors are connected to the private 5G network via 5G customer premises equipment (CPE) gateways. By combining voltage, current and frequency measurements, we can classify power events in the area to automate control system events and faults. This is feasible by utilizing wavelet signal processing to capture abrupt changes in the grid's voltage, current and frequency signals. Since only frequency measurements are time-stamped, to provide valid results, the latency difference of the measurements must be maintained below a specific threshold. Traditionally, this is accomplished by providing dedicated fiber connections, leading to expensive and inflexible legacy solutions. For this trial, legacy sensors are enhanced with 5G capabilities and are connected to a wireless NPN, which can meet the specified KPIs imposed by the real-time monitoring application, while providing a more economical and easily expandable/maintainable solution. To maintain measurements of latency difference below a specific value, network latency and network jitter (variation in network latency) should meet specific upper bound values.

Collected measurements during the trials are visualized on an online dashboard, which is depicted in **Figure 2**.

The future objective for this application is to be able to feed an automated controller with timely results. Toward this objective, processing must be performed as close to the sensors as possible.

3.2 Innovative aspects/results

3.2.1 User plane at premises (low latency, increased privacy)

To support the above requirements, the real-time monitoring application—and supporting 5GC functions are hosted at the ADMIE site. This choice leads to a significant reduction in end-to-end (E2E) latency and increases privacy as measurements never leave ADMIE premises.

Figure 2.
Operation: online dashboard for visualization of critical information.

E2E latency	13.7 ms (min)	38.5 ms (average)	86.8 ms (max)
Network latency difference	0.0002 ms (min)	0.7516 ms (average)	2.085 ms (max)
Jitter	< 0.0001 ms (min)	0.272 ms (average)	0.3 ms (max)
Sensor datarate	54 Kbps		
Measurements requests (transactions)	1000 requests		

Table 1.
Operation: field results.

HV monitoring application presents 38.5 ms (mean) end-to-end latency. The latency difference between the two sites has a mean value of 0.75 ms and a max of 2.08 ms. This means that the service can estimate adequately the steady state and dynamic state of the network (dynamic phenomena of 10^{-2} s).

3.2.2 Specific slice (guaranteed low latency, increased reliability)

As it is shown in **Figure 1**, the application uses a dedicated slice for its data network, meaning that the performance of this critical application is ensured and independent of background traffic produced by other services. This increases application reliability. Network delay and delay variation (jitter) are minimized, leading to better synchronization of packets between the sites and a lower rate of obsolete packets.

The results of the operation service are summarized in **Table 1**.

4. Maintenance: sensor data collection for preventive maintenance

This application uses a large number of measurements originating from different types of sensors to monitor the health of the actual HV power cable. The submarine cable is impregnated with a low-viscosity insulation fluid (oil) to increase its operating dielectric stress, working temperature and current carrying capacity. Oil pressure, oil temperature and other relevant measurements are continuously collected and processed to estimate the health of the cable.

4.1 Methodology

The application uses at its core the Unified IoT Orchestration Platform (UiTOP) (see **Figure 3**), which is an industrial IoT platform offered by Intracom Telecom [11]. This application is compatible with many industrial protocols, provides rich dashboards and customizable alarms, and follows a microservices architectural approach. The application does not have strict latency requirements, as it is used for predictive maintenance analytics. On the contrary, it must be able to handle, store and analyze vast amounts of data originating from different types of sensors. Moreover, it should be accessed only by the maintenance crew inside the facilities. This is accomplished through the geofencing (-or location-based service provisioning) feature.

4.2 Innovative aspects/results

4.2.1 Virtualization, standard APIs support

Both network function and IoT platform follow a containerized approach, thus increasing scalability—it is easy to go from 10 sensors to 1000 sensors—and portability. Moreover, the adoption of microservices architectural approach and the use of REST APIs

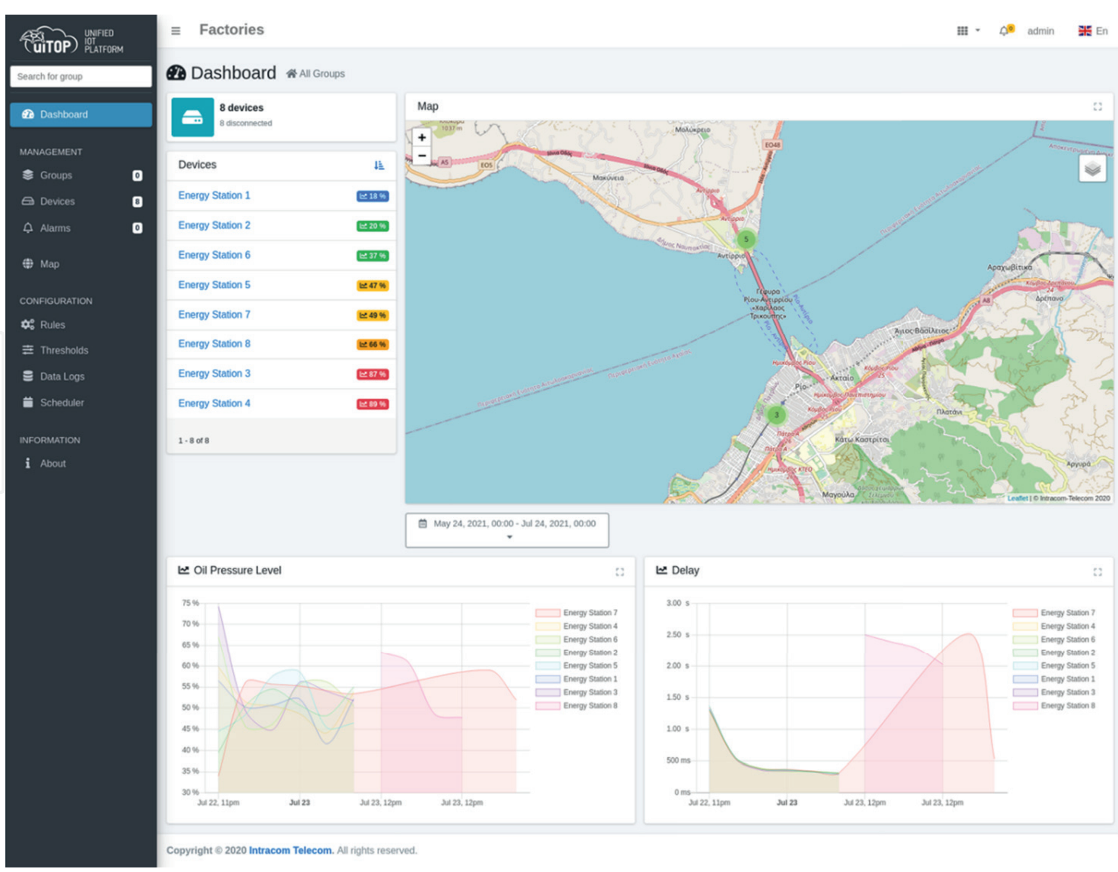

Figure 3.
Maintenance: UiTOP dashboard also shows live measurements collection delay.

for information exchange facilitates the integration of third-party tools for advanced analytics not supported by the platform (e.g., machine learning to predict equipment aging).

4.2.2 Geofencing

Geofencing is a virtual boundary that, in our case, is accomplished through the 5G radio domain. More precisely, the network can be configured to provide different access levels to the same application, according to the base station that the user is registered. This means that a user with 5G user equipment (UE) can access the application (or specific features of an application) only when he is inside the facilities served by the specified base station.

Geofencing offers two valuable features to the preventive maintenance solution:

1. *Enhanced privacy*: Even if an intruder finds credentials for the application, he will not be able to access specific information if he is not physically inside the facilities.

2. *Information presented on the application's dashboard is facilities-specific*: This facilitates the inspection process. Inspector crews, who often travel to remote locations, do not have to search for equipment codes in long lists, but measurements of interest are automatically shown according to their location.

To showcase the advantages of the proposed 5G-VICTORI architecture, two identical gNodeBs (gNBs) are deployed at the Patras5G cloud facility (emulating the Central Offices of ADMIE) and at the ADMIE Rion facility (facility environment), which are featured in **Figure 1**.

Location-based service provisioning is realized via the selection of different data networks according to the gNB in which the UE is registered. **Figure 4** depicts the UiTOP dashboard accessed from a UE connected to gNB2 at ADMIE premises. Since UE is connected to gNB2 it uses Data Network $\#2$ ($DN\#2$) that has access to UiTOP service running on Autonomous Edge. On the contrary, when the UE is registered to the NPN through gNB1 at the University campus, it uses $DN\#1$, and cannot access the specific service.

Figure 4.
UiTOP dashboard accessed by UE only at ADMIE premises (right), custom dashboard created for a specific type of measurements (left).

Sensor datarate	~0 Kbps (min)	11 Kbps (average)	54 Kbps (max)
Total datarate	~0 Mbps (min)	1.07 Mbps (average)	5.40 Mbps (max)
Packet loss ratio	~0		
# of sensors	100 sensors		
Measurements requests (transactions)	6000 requests		

Table 2.
Maintenance: field results.

As shown in **Figure 4**, inspection workers have access to information regarding the health of the HV power cable, but they also have access to information regarding the communication network status (the dashboard also presents network latency and bandwidth). NPN deployments offer complete control to the vertical industry (in this case, the power transmission operator) to monitor and (re)configure/expand the network according to their needs without relying on external network providers.

4.2.3 NPN deployment (increased monitoring, increased flexibility)

Continuous monitoring of telecommunication networks is crucial for critical infrastructures. NPN deployments also offer complete control to the vertical industry. The ability to reconfigure/expand/maintain the telecommunication network without relying on third-party network operators increases the reliability, security and privacy of the critical infrastructure, as it is easier to identify bottlenecks, prioritize critical applications and steer traffic when application needs change.

The results of the maintenance service are summarized in **Table 2**.

5. Facilities security: smart CCTV surveillance service for industrial environments over 5G

Industrial infrastructures must be monitored, not only for the security of the facilities themselves but also for the technical personnel to ensure their physical well-being. To this end, CCTV monitoring of facilities over 5G will provide a solution to this problem by collecting and processing live video feeds when technical personnel is present or an event occurs, while not compromising other Industry 4.0 applications running in the background.

The application does not have strict latency requirements since it focuses on throughput and sending multiple, stable, high-quality video streams from the edge (ADMIE facilities at Rion) to the cloud (UoP facilities) without interruption. In order to demonstrate this and test the application in real working conditions of industrial environments over 5G and 5G NPNs, the application is deployed in parallel with the two aforementioned Factories of the Future services. Application isolation and guaranteed quality-of-service (QoS) is achieved via the network slicing feature of 5G.

5.1 Methodology

A static ultrahigh definition (UHD) CCTV camera and a 5G-enabled mobile surveillance robot (**Figure 5**) are used for collecting live video feeds from the ADMIE

DOI: http://dx.doi.org/10.5772/intechopen.1005514

Figure 5.
Facilities security: 5G-enabled mobile surveillance robot in action.

Figure 6.
Facilities security: capture from the CCTV camera and analyzed by the intruder detection service, accessed by UoP.

facilities. The CCTV camera inside the HV cable control room monitors the industrial equipment installed there while the mobile surveillance robot patrols outside and near dangerous high-voltage areas. The video streams from the CCTV camera feed an AI-empowered intruder detection algorithm running at the UoP cloud (**Figure 6**). The video collected from the robot is streamed to a web server hosted at UoP, which can be accessed as-is by the facilities' supervisor. The service runs isolated from the others while no QoS degradation is detected.

5.2 Innovative aspects

5.2.1 Network slicing

Provision of dedicated network slice for guaranteed video streaming, regardless of background traffic, for both static camera and mobile surveillance robots.

5.2.2 Support of AI

AI has become a standard tool in developing new industrial services since it offers numerous benefits. In the Factories of the Future use case, this is demonstrated via the use of an AI-powered facilities monitoring and intruder detection algorithm running in the cloud, which minimizes human intervention with regard to facility security. The inclusion of AI is crucial not only for the mitigation of work accidents in such hazardous environments but also offers an effective solution for facilities located at remote sites, since there is no need for physical presence. The AI solution presented in this scenario is based on a pre-trained region-based convolutional neural network (RCNN) in TensorFlow for human detection, which runs in the UoP cloud. The application receives live video from the interior of the HV cable control room, analyzes it, and notifies the user (facilities' supervisor) in case someone enters the facilities. The user is then able to identify if this is a scheduled visit or an intrusion incident and act accordingly. More advanced intrusion detection techniques for critical facilities monitoring—without humans in the loop—could include biometrical identification algorithms [12], which were not investigated during the 5G-VICTORI project.

5.2.3 Use of 5G-enabled surveillance robot

The use of a 5G-enabled surveillance robot gives great opportunities. 5G-enabled drones, often used in power grids, are suitable for overhead power line inspection spread at remote locations, but they suffer at identifying faults near the ground (e.g., the base of power towers) or hard-to-reach spots inside the facilities. In case of an incident, a surveillance robot can be used to identify if it is safe for the personnel to reach the area and provide a useful insight into the situation. In collaboration with swarms of drones, surveillance robots can provide a unified surveillance solution for power utilities.

The results of the Facilities Security service (as summarized in **Table 3**) prove the seamless CCTV service provisioning over 5G with full isolation from other running

Video streaming latency (plus application processing overhead)	0.9 s (min)	2.32 s (average)	5.01 s (max)
CCTV camera datarate	6.5 Mbps (min)	9.33 Mbps (average)	12.78 Mbps (max)
5G-enabled mobile surveillance robot camera datarate	0.4 Mbps (min)	1.5 Mbps (average)	2.5 Mbps (max)
Aggregated datarate	7.3 Mbps (min)	11.03 Mbps (average)	15 Mbps (max)

Table 3.
Facilities security: field results.

services and without introducing performance errors. In addition, they show smart facility monitoring services, that is, intruder detection, inside power utility facilities, which are a special case of the industrial environment due to their harsh conditions, for example, high-voltage and electromagnetic interference. Finally, the ability to stream high-quality video stream from a moving surveillance robot to a remote location improves the safety of first responders in the case of event, and the security of the overall facility.

6. Challenges raised during the project

The process of designing, developing, deploying, and validating the aforementioned services and the necessary setups for both lab and field trials during the 5G-VICTORI project was faced with a lot of hardships. One of the most critical issues

Figure 7.
Installation of mmWave antenna equipment linking ADMIE and UoP sites.

Figure 8.
Field trials for factories of the future.

during the project was the interconnection of the ADMIE facilities with the Patras5G testbed via a mmWave link (**Figure 7**). This task was essential for the development of the services as well as the preparation of the final demonstration actions, and it proved extremely difficult due to the management and orchestration issues it raised, since different teams with different expertise backgrounds had to work together. In addition to this, the hostile environment of power utilities resulted in permanent equipment damage after a thunderstorm in the vicinity of the facilities, which again demanded new installation works at the site. Furthermore, the project's great ambition to provide real network slicing for applications of diverse requirements and deployment flexibility resulted in much development work, eventually leading to a fully configurable 5G network deployment flow. Through this flow, features like geofencing were possible. Last but not least, adapting industrial protocols into a 5G environment and enabling legacy sensors to be integrated into a 5G network required the development of appropriate protocol adapters, which came to be crucial for the successful demonstration of the services (**Figure 8**).

7. Conclusions

The inclusion of 5G technology in industrial environments and more specifically critical infrastructures is a crucial step toward the realization of the Factories of the Future concept. Through 5G, flexible network architectures that satisfy both low latency and high-bandwidth application requirements are possible. In addition, thanks to the network slicing feature of 5G, complete isolation between different applications of diverse required QoS is achieved without performance penalties and regardless of background noise. These features, along with the reduction of installation costs due to the use of standard COTS equipment for private 5G network deployments, plus the wireless nature of the sensors, are especially critical from the operators' point of view since they make 5G a viable and powerful solution. Furthermore, advanced data privacy is possible through the geofencing feature, which enables location-based service provisioning and can further safeguard industries from cyber threats. Lastly, 5G networks are able to support the requirements of emerging AI technologies that will further contribute to the development of future smart services for the industry sector.

Acknowledgements

This work was supported by the H2020 European Project 5G-VICTORI under Grant 857201.

Abbreviations

5G-PPP	5G Infrastructure Public Private Partnership
IoT	Internet of things
AI	artificial intelligence
CCTV	closed circuit television
mMTC	massive machine type communication
uRLLC	ultra-reliable low latency communication
eMBB	enhanced mobile broadband
KPI	key performance indicator
3GPP	Third Generation Partnership Project
SLA	service level agreement
5GC	5G Core
AF	application function
NPN	non-public network
COTS	commercial-of-the-shelf
HV	high-voltage
UoP	University of Patras
mmWave	millimeter-wave
MEC	mobile edge computing
CPE	customer premises equipment
E2E	end-to-end
UE	user equipment
gNB	gNodeB
DN	data network
QoS	quality-of-service
UHD	ultrahigh definition
RCNN	region-based convolutional neural network

Author details

Nikolaos Tzanis[1,2†], Eleftherios Mylonas[1,2*†], Panagiotis Papaioannou[2†], Christina (Tanya) Politi[2†], Alexios Birbas[2†], Christos Tranoris[2†], Spyros Denazis[2†], Ioannis Moraitis[1†], Alex Papalexopoulos[3†], Anna Tzanakaki[4†] and Jesús Gutiérrez Terán[5†]

1 Department of Research, Technology and Development, Independent Power Transmission Operator (IPTO) S.A., Athens, Greece

2 Department of Electrical and Computer Engineering, University of Patras, Patras, Greece

3 Ecco International Inc., San Francisco, CA, USA

4 National and Kapodistrian University of Athens, Athens, Greece

5 IHP Leibniz-Institut Für Innovative Mikroelektronik, Frankfurt (Oder), Germany

*Address all correspondence to: e.mylonas@admie.gr

† These authors contributed equally.

References

[1] Empowering Vertical Industries through 5G Networks—Current Status and Future Trends. Available from: https://5g-ppp.eu/wp-content/uploads/2020/09/5GPPP-VerticalsWhitePaper-2020-Final.pdf [Accessed: January 23, 2024]

[2] 3GPP TS 23.501 Version 15.9.0 Release 15. Available from: https://www.etsi.org/deliver/etsi_ts/123500_123599/123501/15.09.00_60/ts_123501v150900p.pdf

[3] 3GPP TS 22.261 Version 17.11.0 Release 17. Available from: https://www.etsi.org/deliver/etsi_ts/122200_122299/122261/17.11.00_60/ts_122261v171100p.pdf

[4] 5G-VICTORI Website. Available from: https://www.5g-victori-project.eu/ [Accessed: January 23, 2024]

[5] 5G-VICTORI Deliverable D2.2. Available from: https://www.5g-victori-project.eu/wp-content/uploads/2020/05/2020-05-21-5G-VICTORI_D2.2_v1.0.pdf

[6] 5G-VICTORI Deliverable D2.3. Available from: https://www.5g-victori-project.eu/wp-content/uploads/2021/07/2021-06-11-5G-VICTORI_Deliverable_D23_v1.0_submitted_EC.pdf

[7] 5G-VICTORI Deliverable D2.4. Available from: https://www.5g-victori-project.eu/wp-content/uploads/2022/05/2022-04-11-D2.4-5G-VICTORI-end-to-end-reference-architecture.pdf

[8] Patras5G. Available from: https://wiki.patras5g.eu/ [Accessed: January 23, 2024]

[9] 5G-VICTORI Deliverable D3.6. Available from: https://www.5g-victori-project.eu/wp-content/uploads/2023/02/2022-06-17-5G-VICTORI_D3.6-Final-Test-Cases-for-Energy-and-Factories-of-the-Future_v1.0.pdf

[10] 5G-VICTORI Deliverable D3.5. Available from: https://www.5g-victori-project.eu/wp-content/uploads/2022/05/2021-07-31-5G-VICTORI-D3.5-Prel-Test-Cases-for-Energy-and-Factories.pdf

[11] Unified IoT Orchestration Platform. Available from: https://www.intracom-telecom.com/en/products/telco_software/IoT/IoT_orchestration_Platform.htm [Accessed: January 23, 2024]

[12] Minaee S, Abdolrashidi A, Su H, et al. Biometrics recognition using deep learning: A survey. Artificial Intelligence Review. 2023;**56**:8647-8695. DOI: 10.1007/s10462-022-10237-x