Public and Non-Public Network Integration for 5Growth Industry 4.0 Use Cases

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5G is playing a paramount role in the digital transformation of the industrial sector, offering high-bandwidth, reliable, and low-latency wireless connectivity to meet the stringent and critical performance requirements of manufacturing processes. The authors analyze the applicability of 5G technologies as key enablers to support, enhance, and even enable novel advances in Industry 4.0.

Abstract

5G is playing a paramount role in the digital transformation of the industrial sector, offering high-bandwidth, reliable, and low-latency wireless connectivity to meet the stringent and critical performance requirements of manufacturing processes. This work analyzes the applicability of 5G technologies as key enablers to support, enhance, and even enable novel advances in Industry 4.0. It proposes a complete 5G solution for two real-world Industry 4.0 use cases related to metrology and quality control. This solution uses 5Growth to ease and automate the management of vertical services over a software-defined network and network function virtualization based 5G mobile transport and computing infrastructure, and to aid the integration of the verticals' private 5G network with the public network. Finally, a validation campaign assesses the applicability of the proposed solution to support the performance requirements (especially latency and user data rate) of the selected use cases, and evaluates its efficiency regarding vertical service setup time across different domains in less than three minutes.

Introduction

Until the advent of 5G, commercial mobile networks followed a one-size-fits-all paradigm toward their network infrastructure, where general-purpose connectivity is provided disregarding the distinct needs of vertical industries. As such, vertical industries have been using specialized networks customized for their specific applications. With *network softwarization*, *network function virtualization* (NFV), and *network slicing* technologies embraced by 5G, a custom-fit paradigm becomes available. Different virtual and logically isolated networks (i.e., network slices) within the same and shared network infrastructure are tailored to the requirements of different vertical services [1]. In doing so, 5G raises novel opportunities for the vertical industries to introduce innovative use cases and facilitates the creation of cross-industry partnerships and fully customized digital ecosystems.

Simultaneously, the next industrial revolution is on the verge, focusing on a digital transformation supported by cyber-physical systems, the Internet of Things (IoT), and networks. Industry 4.0 [2] aims to bridge the gap between the physical and digital worlds. This digitalization of the industry sector opens the way for the factories of the future, characterized by smartness, flexibility, increasing connectivity, automated processes, and cooperation between all elements in the industrial environment. Production lines can be rapidly and autonomously (re)configured to cope with changing needs, enabling a new evolution of the manufacturing paradigm: from mass production to mass customization and personalization.

This transformation is being highly impacted by 5G and its supporting technologies, which appear as the key enablers for accomplishing and shaping the future of Industry 4.0 [3]. Although wired connectivity provides the best value in terms of bandwidth, capacity, latency, reliability, and availability, it comes at high cost and provides limited flexibility. The wireless connectivity provided by 5G fulfills the stringent and critical requirements of a vast range of applications, while bringing the benefits of increased flexibility, connection density, and global connectivity [4]. Moreover, the ubiquitous and programmable platform offered by 5G, in combination with emerging technologies like artificial intelligence (AI), opens new opportunities in the industrial processes.

This work evaluates the applicability and efficacy of 5G and supporting technologies for realizing the Industry 4.0 vision. In particular, it analyzes the real needs of an industrial vertical whose systems and solutions are related to metrology[1] and quality control processes in manufacturing, thus focusing on two paramount use cases of its product portfolio. Toward that end, 5Growth, an AI-driven automated and shareable 5G end-to-end (E2E) platform, is set out as an essential part of the proposed 5G solution to support the selected Industry 4.0 use cases. This work culminates with the proposal of a complete 5G solution to support both use cases, including a preliminary data plane validation, and an evaluation of the

[1] Metrology refers to the field of measurement and its applications.

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setup and release of the E2E vertical service. Finally, the conclusions and future work are given.

5G as a Key Enabler for Industry 4.0

Industry 4.0 aims to build smart, fully connected, and automated factories, where IoT technology, cloud solutions, big data cruncher, and cyber-security components are key ingredients. This brings new challenges to deliver an industrial Internet that integrates all these components while meeting the stringent industrial requirements (e.g., <5 ms latency, >1 Gb/s data rates). This is difficult to achieve with mobile technologies such as 3G and 4G. 5G provides high-quality wireless communications, with much faster transmission rate (up to 10–20 Gb/s peak data rates) and lower latency (less than a few milliseconds), as well as a ubiquitous and programmable platform integrating various distributed networking, computing, and storage resources and interconnecting machinery, sensors, processes, products, and workers within the factory [5].

Metrology and Quality Control Use Cases

The applicability of 5G technologies for Industry 4.0 is analyzed with respect to two use cases on metrology and quality control processes. These use cases reflect the actual needs of an industrial vertical, thus shifting from a theoretical perspective to a practical and applied validation.

Connected Worker Remote Operation of Quality Equipment (INNO-UC1): Quality control is an important but expensive stage of a product's life cycle, requiring specialized personnel to configure and calibrate quality control machinery used in the process. Either specialized workers travel to the factory, or the machine is dispatched to the vertical headquarters. Enabling its remote configuration and calibration significantly reduces service response time and costs, as it alleviates the need for on-site maintenance. Therefore, this use case aims to enable the remote control of machinery that is used to measure the geometry of physical objects (coordinate-measuring machine — CMM) using a virtual joystick and high-quality live video streams that provide visual feedback of the executed actions (e.g., general view of the CMM or detailed view of the scanned surface). Since the CMM must be configured and calibrated to measure any new type of manufactured piece, rapid customization as envisioned by Industry 4.0 will significantly increase the number of times that specialized personnel need to access the CMM. Thus, this use case enables significant savings in terms of response time and cost. However, it also imposes stringent requirements in terms of latency to enable real-time control and high data rates to deliver the data generated by the CMM and the video system.

Augmented Zero Defect Manufacturing Decision Support System (INNO-UC2): Every time the model of a manufactured piece is changed, the correspondent scanning program needs to be loaded into the CMM. However, as the next piece coming out of the production lines is unknown until it arrives at the scanning station, it is not possible to trigger such operation beforehand (e.g., while the piece is being transported from the production line to the scanning station). This process takes time, which reduces the productivity and also hinders the possibility of sharing a CMM across multiple production lines. Automating the different stages of the quality control process not only optimizes the productivity of the CMM, but also increases the flexibility of the production lines. Accordingly, this use case aims to enable automated guided vehicles (AGVs), that are responsible for carrying manufactured pieces from the production line to a CMM for quality control, to preemptively notify the object identifier, triggering the corresponding scanning program to be loaded into the CMM. Measurements are then sent to the quality control system. As an example, whenever a new batch of automotive pieces is produced, different types are randomly selected for inspection; therefore, they need to be transported by AGVs to the scanning stations. Thus, this use case allows a single CMM to be shared by multiple production lines and to reduce the scanning time for different reference pieces, increasing flexibility and efficiency of the quality control process. However, the automation of this process imposes stringent requirements in terms of latency to enable remote driving of AGVs, machine-to-machine (M2M) communication between the AGVs and the CMM, and high data rates to download the scanning programs and retrieve the results to the quality control system.

Keeping Industrial Networks Private

5G will accelerate the digital transformation of industrial environments by enabling private 5G networks, known as 5G non-public networks (NPNs) [6]. A standalone NPN (SNPN) constitutes a fully operational 5G network deployed at the factory premises. It is a totally isolated network without any interaction or dependency from a public network (PN) operated by a mobile network operator (MNO), running on separate infrastructure. Furthermore, public network integrated-non-public networks (PNI-NPNs) leverage on capabilities available at the PN to complement the NPN counterpart, thus being completely or partially dependent on the infrastructure and the functions (e.g., packet core functions) of the MNO. Different degrees of integration are foreseen, namely sharing the radio access network (RAN), sharing both the RAN and 5G Core (5GC) control planes, or having the NPN fully hosted and delivered by the PN [7]. Several attributes are considered for the selection of a deployment options [8].

Quality of Service (QoS) Customization: While the SNPN offers full customization, the more the PNI-NPN solution relies on the PN, the more the capability to customize QoS is diluted, up to the point where the QoS is configured by the PN (no customization).

Autonomy and Entry Barriers: The SNPN grants total autonomy, ensuring full network management but increasing the entry barrier. The vertical builds, runs, and troubleshoots the entire solution. In a PNI-NPN solution, the NPN depends partially or completely on the PN (up to the point that failures in the PN affect the NPN), including authorized management capabilities exposed by the PN. The greater the dependency, the lower the entry barrier for the vertical.

Security: In a similar fashion, a tighter PNI-NPN integration increases the dependency on the security mechanisms implemented by the PN.

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E2E orchestration of network slices with substantially different requirements over a shared heterogeneous network infrastructure that belongs to multiple organizations and features edge, cloud, and transport is a complex task. Furthermore, making an efficient use of resources when service demands and network conditions continuously change adds extra complexity.

Isolation: In the SNPN all the information is confined internally to the premises of the vertical. In less dependent PNI-NPN integration, only part of the information and control is moved to the PN domain. When fully hosted by the PN, all the information crosses the PN domain. Nevertheless, network slicing enforces any isolation requirement.

Service Continuity: In the SNPN, service continuity is not guaranteed across the PN unless specific agreements are in place. In the case of a PNI-NPN, continuity is easily guaranteed, for example, through a national roaming agreement.

Due to the nature of the selected use cases, a PNI-NPN approach that eases mobility and inter-site deployments is preferable, since the vertical services span across facilities in different geographic locations. In particular, RAN and 5GC control plane sharing is employed, as it provides the required performance to support the stringent and controlled latency and user data rate requirements, increased security, and isolation of the data traffic. Moreover, it reduces the costs of deployment and spectrum usage, and the need for dedicated personnel to manage the 5G infrastructure.

Opportunities and Challenges

Next, the main business and technical opportunities introduced by 5G in the selected use cases are identified, as well as the associated architectural and operational challenges.

Business Opportunities: The 5G promise of ultra-reliable low-latency communications (URLLC) is a clear enabler for the remote operation of factory machinery (e.g., INNO-UC1, INNO-UC2). Enabling such innovative services for factories not only leads to new business models, but also comes with significant maintenance cost savings for both the factory and the maintenance partner. Furthermore, 5G appears as a key enabler to support critical in-factory Machine-Type Communications (MTC) to expedite quality assurance processes, hence increasing factory productivity (e.g., INNO-UC2), as well as to support enhance Mobile BroadBand (eMBB) capabilities required to transmit the huge amount of data produced by industrial processes (e.g., INNO-UC1, INNO-UC2). Finally, NPNs also present interesting business opportunities to MNOs, which have to decide their role in the value chain (spectrum and infrastructure providers, value-added service providers, etc.).

Technical Opportunities: 5G softwarization, virtualization, and slicing capabilities contribute to the software-defined factories vision, bringing dynamicity to vertical applications and network deployments. Reconfiguration of factory processes, including efficient quality assurance where multiple production lines share a single CMM (e.g., INNO-UC2), is a tangible example. Tight coordination of edge, transport, and cloud domains must be orchestrated E2E while fulfilling the application requirements. Moreover, the network slicing concept allows industrial processes with distinct requirements to coexist over a shared network infrastructure, enabling performance isolation between them. For instance, in the selected use cases, response times are expected to be on the order of milliseconds when remotely operating machines or a few tenths of a second when transmitting a high-volume of measurement data for human operator decision making.

Fully exploiting these opportunities entails solving architectural and operational challenges, as summarized next.

Architectural Challenges: The selection of the architectural option that best suits the needs of a private 5G network [9] is a challenge, as it possibly involves multiple parties and different options on how the infrastructure is shared. This depends on whether the 5G network is perceived as part of the factory infrastructure or as a connectivity service offered by an MNO, as well as the degree of dependability from the MNO (as explained previously). Mixed PNI-NPN deployments require a number of heterogeneous resources to be configured and interoperate, involving virtual and physical network functions; RAN and mobile core elements; on-premises, edge, and cloud computing; and off-premise, metro, and core transport resources. Dynamically sharing, connecting, and coordinating all these network entities and segments under the control of different administrative domains poses a remarkable architectural challenge.

Operational Challenges: E2E orchestration of network slices with substantially different requirements over a shared heterogeneous network infrastructure that belongs to multiple organizations and features edge, cloud, and transport is a complex task. Furthermore, making efficient use of resources when service demands and network conditions continuously change adds extra complexity. Beyond the logical separation of communications, inter-slice performance isolation is required given the critical nature of communications. Still, synchronizing the operation of highly different traffic flows (e.g., video and control in INNO-UC1) is required. Furthermore, closed control loops in charge of service auto-scaling, anomaly detection, root cause analysis, and fast restoration of the communication in case of failure aim to maximize production line availability.

5Growth Platform for Automated Vertical Service Provision and Management

5Growth is an AI-driven automated 5G E2E service platform [10] that integrates 5G connectivity with network slicing, virtualization, and multi-domain solutions. Custom network slices are instantiated to concurrently support the service requirements of multiple heterogeneous applications over a shared network infrastructure that not only comprises different types of resources (e.g., at the edge, cloud, and transport) but also spans across multiple administrative domains (e.g., the PNI-NPN scenario).

Building on such capabilities, 5Growth is selected as the 5G service orchestration platform to solve the above-mentioned architectural and operational challenges, and simultaneously exploit the business and technical opportunities. In summary, 5Growth brings the following benefits to the selected use cases, and Industry 4.0 in general:
- Enhanced and abstracted vertical support
- Automation, dynamicity, and scalability
- Service coexistence and performance isolation

- Multi-domain approaches to PNI-NPN integration

5Growth System Architecture

5Growth system architecture (Fig. 1) enhances the 5G-TRANSFORMER platform in the following five dimensions: usability, flexibility, automation, performance, and security. Its core building blocks, namely the vertical slicer (5Gr-VS), the service orchestrator (5Gr-SO), and the resource layer (5Gr-RL), are inherited from 5G-TRANSFORMER and complemented with two new building blocks, namely the vertical-oriented monitoring system (5Gr-VoMS) and the AI/ML platform (5Gr-AIMLP).

5Gr-VS: acts as a single entry point for verticals requesting the provisioning and management of vertical services through a simplified and vertical-oriented northbound interface with the vertical operations/business support system (OSS/BSS).

5Gr-SO: provides network service and resource orchestration capabilities to support E2E orchestration of NFV Services (NFV-NSs) and their life cycle management. NFV-NSs are provisioned in the local and/or peering administrative domains according to service requirements and available resources.

5Gr-RL: offers a customizable software-defined networking (SDN) and NFV-based transport and computing platform supporting a diverse range of computing and networking requirements. It abstracts and handles the configuration of the transport, mobile, storage, and compute resources.

5Gr-VoMS: integrates application-level monitoring probes and provides enhanced monitoring to the remaining building blocks of the 5Growth platform.

5Gr-AIMLP: supports different 5Growth layers to run AI algorithms for their decision making processes. It handles online or offline training of selected AI models using either data coming from the 5Gr-VoMS or external data.

5Growth-Based Enhancements to Selected Use Cases

The 5Growth platform implements a set of architectural, algorithmic, security, and auditability innovations designed to automate vertical service provisioning and management. These leverage mostly on the 5Gr-VoMS and 5Gr-AIMLP to provide relevant data and train the AI models, respectively, which are then executed in the 5Growth stack to enhance the selected use cases, as follows.

Vertical service monitoring offers real-time monitoring information based on metrics received from the vertical service. As such, verticals have an enhanced view of the operational status of their services. The critical environment experienced in Industry 4.0 scenarios requires services to be executed with extreme precision and must always fulfill the performance requirements. Monitoring information is also exploited to train and automate the life cycle management of the services. Production lines must stop if the conditions are not satisfactory or safe.

Control-loop stability, smart orchestration, and resource control aim to fully automate vertical services (network slices) life cycle management and service level agreement (SLA) enforcement.

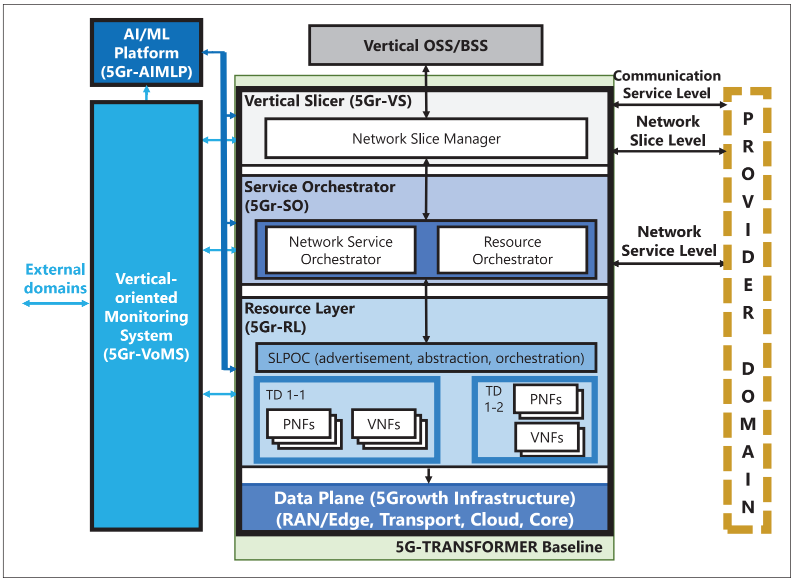

FIGURE 1. 5Growth system architecture.

In Industry 4.0 environments, different processes with distinct requirements need to coexist. Assuming that computational and networking demands change over time for one of the vertical services, the impact on the remaining services must be minimized to avoid SLA violations. For example, the slightest misbehavior during the remote calibration of the CMM results in its misconfiguration and consequently leads to incorrect measurements. Through 5Growth, optimizations are autonomously applied to ensure the fulfillment of SLAs. Dynamic scaling strategies can be enforced using AI techniques such as random trees, random forests, or reinforcement learning, trained using infrastructure context information (e.g., resource consumption and available resources), key performance indicators (KPIs) and SLAs, and application-level usage information [11].

Security, anomaly detection, and forecasting allow the detection and/or forecast security breaches, intrusions, and anomalies, but also forecasting future demands. Early detection of these events allows preventive actions to be taken to mitigate any impact on the running services, as stalling events of even seconds can incur high losses. For example, detecting the malfunction of a given infrastructure resource (e.g., compute server or gNodeB) allows preemptive service migration to a different set of resources before the running services are actually impacted. Its implementation can explore AI techniques such as principal component analysis (for security), *K*-means and hierarchical clustering (for anomaly detection), and long short-term memory (for forecasting), trained with traffic and mobility patterns, resource-level telemetry data, and application-level usage information.

Federation and multi-domain allow vertical services to be extended toward other peering providers, targeting efficient PNI-NPN integration. As depicted in Fig. 1, multiple levels of interactions are supported by 5Growth at the communication service level, network slice level, and network service level. As the radius of operation of both selected use cases spans across multiple geographic locations, vertical services extend outside

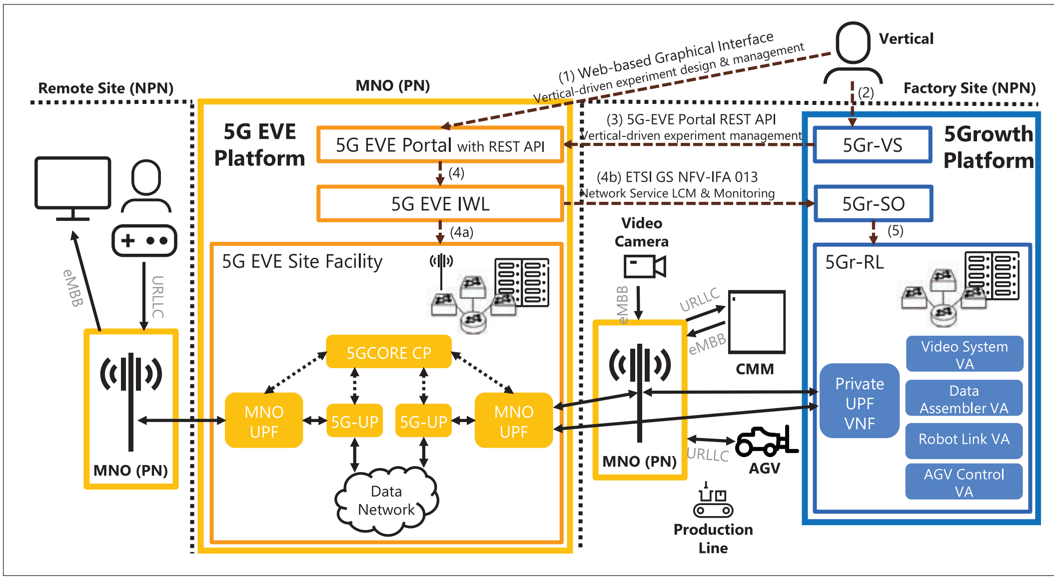

FIGURE 2. Integrated technical solution.

Virtual network functions		
Private UPF	Function of the 5G Core related to the user plane that handles the service traffic	INNO-UC1 INNO-UC2
Virtual applications		
Video system	Gathers and distributes the video streams from the cameras to the remote operator	INNO-UC1
Data assembler	Manages the sensor data from the CMM	INNO-UC1 INNO-UC2
Robot link	Manages the movements of the CMM	INNO-UC1 INNO-UC2
AGV controller	Navigates the AGV across the factory floor	INNO-UC2

TABLE 1. Virtual components for the selected use cäases.

the local domain using any of the aforementioned interactions, to achieve full connectivity that guarantees the KPIs and SLAs. Reinforcement learning, and specifically Q-learning, can be applied to achieve profit maximization for the vertical service deployment, relying on data such as the available resources in the local and peering providers, and price of a service [12].

5G-Based Technical Solution for the Selected Use Cases

The complete 5G solution for both use cases is depicted in Fig. 2. It comprises two vertical sites, namely the factory where all the machinery is installed and the headquarters where workers remotely control operations, and the PN interconnecting these sites. The 5Growth and 5G-EVE [13, 14] platforms embody the 5G service platforms for the NPN (i.e., vertical premises) and the PN, respectively. 5G-EVE is a European platform for the validation and large-scale experimentation on 5G technology, providing full sets of 5G capabilities, including 5G New Radio, backhaul, core, and service technologies, as well as slicing and orchestration.

A shared RAN and control plane deployment option is envisioned for the private 5G network deployed within the vertical premises (i.e., NPN). This is the preferable option as it reflects a realistic commercial solution for the targeted industrial vertical. It meets the low latency and privacy requirements for the NPN since a private (local) user plane function (UPF) operates in the vertical site. Data traffic between devices in the same site (i.e., NPN domain) remains inside the vertical premises, using the local UPF. In turn, data traffic destined to a geographically remote location needs to be transferred via the PN. However, the operation and subscription information of the NPN terminals is stored in the MNO's domain. Finally, an edge server located in the vertical site hosts the different virtual components, as summarized in Table 1.

5Growth–5G-EVE Approach

Figure 2 presents the high-level architectural components and interactions involved in a vertical service deployment between the 5Growth and 5G-EVE platforms. 5G-EVE provides programmatic interfaces to external platforms that enable life cycle management operations. Service definition is performed manually over the 5G-EVE Portal by the vertical, in order to onboard the virtual network function (VNF) packages and descriptors that define the service (step 1). However, in a commercial setup that involves a PNI-NPN deployment, the vertical would not directly interact with the MNO (5G-EVE in our example). Instead, the vertical would only interact with its local platform, which in turn would relay service definition, onboarding, and life cycle management operations using the interfaces provided by the MNO.

Following the onboarding step, the vertical requests the creation of the service from the 5Gr-VS of the local 5Growth platform (step 2). The 5Gr-VS leverages the 5G-EVE platform to deploy the vertical service using the 5G-EVE Portal application programming interface (API) (step 3). 5G-EVE decomposes the vertical service to individual functions, deploying the 5G control plane under the 5G-EVE domain (step 4a) and requesting the deployment of the private UPF and remaining VNFs from the 5Growth platform

	KPI	Expected value
Vertical service setup	Creation time	5 min
	Removal time	5 min
Video system (eMBB slice)	E2E latency	< 100 ms
	User data rate	70–100 Mb/s
	Packet loss	< 0.1%
	Availability	99.99%
Remote joystick (URLLC slice)	E2E latency	< 5 ms
	Packet loss	< 0.1%
	Availability	99.99%
AGV control (URLLC slice)	E2E latency	< 5 ms
	Packet loss	< 0.1%
	Availability	99.99%
CMM program storage (eMBB slice)	E2E latency	< 100 ms
	User data rate	100 Mb/s
	Availability	99.99%
Quality control system (eMBB slice)	E2E latency	< 100 ms
	User data rate	100 Mb/s
	Availability	99.99%

TABLE 2. Network slices and target KPIs required by the use cases.

Metric	5G NSA*	4G
E2E latency	6.56 ± 1.04 ms	23.88 ± 5.84 ms
Packet loss	0%	0%
User data rate (uplink)	96 ± 1.81 Mb/s	44 ± 0.20 Mb/s
User data rate (downlink)	600 ± 13.50 Mb/s	72 ± 1.04 Mb/s
Jitter	0.46 ± 0.18 ms	2.32 ± 0.35 ms

*5G massive MIMO radio on 3.5 GHz band; downlink: 5G bandwidth 50 MHz; uplink carrier aggregation: 5G bandwidth 50 MHz + LTE bandwidth 20 MHz; time-division duplex (TDD) pattern used is 7:3 (10:2:2).

TABLE 3. 5G NSA and 4G benchmark at 5TONIC.

(step 4b). Finally, the 5Gr-SO orchestrates the virtual resources to implement the NFV-NSs, requesting their instantiation toward the 5Gr-RL (step 5).

Preliminary KPI Validation

A preliminary validation on the applicability of 5G connectivity on supporting the selected use cases is presented in this section. In doing so, the main KPIs associated with both use cases are identified and summarized in Table 2. Note that the KPIs for each component are provided by the industrial vertical partner, which highly relies on the selected use cases for its operations. This validation is fundamental prior to any use case deployment in the operational environment of the vertical (i.e., Technology Readiness Level 6 and above), allowing the identification of potential gaps toward supporting the services' KPIs and to tune the virtual applications and 5G configurations.

Experimentation Setup: The validation experiments are performed at the 5TONIC Laboratory (https://www.5tonic.org/), located in the IMDEA Networks Institute, Spain. 5TONIC provides 5G non-standalone (5G NSA) (BB630 baseband and Advance Antenna System AIR 6488) and 4G (BBU5216 baseband and RRU 2203 with integrated antenna) networks, both by Ericsson. As the industrial equipment (e.g., CMM, video cameras and remote user device) is not 5G-enabled, the devices are connected (via Ethernet) to two 5G/4G CPEs (HUAWEI 5G CPE Pro Baloong 5000 and HUAWEI B315s-22) that provide the radio interface to the 5G NSA and 4G networks. Both 5Growth and 5G-EVE platforms are deployed in the edge data center at 5TONIC, each managing its own set of computing and networking resources. Management, control, and data plane connectivity between platforms is established through the 5TONIC network.

Benchmark Results: Benchmark results for 5G NSA and 4G are presented in Table 3. The results reflect an exemplary data flow between the infrastructure in the factory (e.g., CMM or video camera) and the remote operator device. The data flow path includes *CMM or Video Camera → Private UPF → Data Assembler and Robot Link VAs or Video System VA → MNO UPF → 5G-User Plane (5G-UP) → MNO UPF → Operator Device*.

Results presented in Table 3 show that 4G is unable to meet the target KPIs of the required network slices, as defined in Table 2, namely in terms of latency and user data rate. In turn, 5G provides an important enhancement on these two metrics and also in terms of jitter, performing close to the required levels. Nevertheless, with the implementation of 5G SA, further enhancements on latency and user data rate are expected. The availability KPI is not assessed, since a good estimation requires the system to run for long periods and preferably on its final deployment location.

In terms of vertical service setup, Fig. 3 presents experimental results regarding the instantiation and termination times of the INNO-UC1 vertical service. Whenever the vertical service is deployed across both PN and NPN domains (i.e., 5G-EVE and 5Growth, respectively), some extra time is required to complete operations. The main reason for this overhead is that both platforms follow a pooling mechanism (instead of an event-based approach) to check the status of operations on their counterparts. Complementary to the above-mentioned results, 5G-TRANSFORMER, the parent platform of 5Growth, deploys federated services, featuring virtual mobile core entities and applications, in $\approx$ 270 s [15].

Conclusions and Future Work

This work analyzes the merits of 5G technologies as key enablers to support, enhance, and even enable novel advances in the Industry 4.0 landscape, focusing on two use cases relevant to metrology and quality control. A complete 5G solution is proposed, which includes not only 5G connectivity on the last networking hop but also exploiting the 5Growth platform to ease and automate the creation and management of vertical services following a PNI-NPN approach. The validation campaign shows that 5G performance is close to the required KPIs (especially in terms

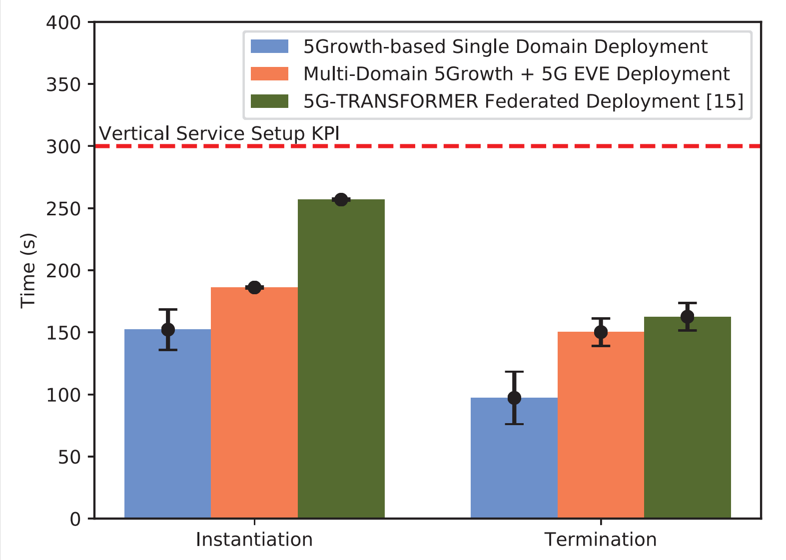

FIGURE 3. Average vertical service setup time with standard deviation.

of latency and user data rate), while the use of the 5Growth platform keeps the service instantiation and termination time low (less than 3 min). In the next set of validation campaigns, 5G SA is going to be assessed in both the mid-band (3.5Ghz) and high-band spectrum (millimeter-wave), including a full deployment of both use cases in the vertical premises.

Finally, complete automation of industrial processes, using AI-powered operators that autonomously perform any task, will not only increase the amount of generated data, but also impose more stringent latency requirements, since machines are not limited by the human capability to perceive the environment and operate faster.

Acknowledgments

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