On the Performance of OPC-UA over 5G NPN with Layer 2 Communication

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2024 IEEE International Conference on Communications Workshops (ICC Workshops) | 979-8-3503-0405-3/24/$31.00 ©2024 IEEE | DOI: 10.1109/ICCWORKSHOPS59551.2024.10615711

***Abstract*—The integration of private fifth-generation (5G) networks with standardized publish-subscribe (PubSub) communication models offers clear benefits for Industry 4.0 applications. While PubSub models ensure vendor-neutral interoperability, backward compatibility, and mature information modeling, the use of 5G non-public networks (NPN) provides dedicated coverage, exclusive capacity, intrinsic controllability, and customized service and operation. In addition, the combination of PubSub protocols and 5G provides a complete communication stack for industrial automation, where PubSub protocols operate on higher OSI layers, and 5G operates on lower layers. However, the practical implications of the integration of PubSub models with 5G systems remain largely unaddressed in the existing literature. To the best of the authors' knowledge, this paper presents the first empirical evaluation of the integration of private 5G with a PubSub protocol, namely open platform communication unified architecture (OPC-UA), in a real production environment. The proposed solution for 5G and OPC-UA integration relies on layer 2 (L2) connectivity over a virtual extensible local area network (VXLAN) tunnel. Evaluation results demonstrate the feasibility of such integration in the context of a soft real-time additive manufacturing (AM) use case for laser metal deposition (LMD)-based manufacturing.**

I. Introduction

Fifth-generation (5G) wireless communication is a key enabler of Industry 4.0, as it provides enhanced flexibility to a range of applications, such as automation, robotics, remote access and maintenance, process monitoring, and so on. Industrial applications, however, have different requirements in terms of quality of service, dependability, deployment type, and interworking, among others. By providing diverse kind of services such as massive machine type communications (mMTC), ultra-reliable low latency communication (uRLLC), enhanced mobile broadband (eMBB), and so forth, 5G systems are well suited to meeting stringent industrial automation communication requirements. In this regard, the use of a 5G non-public network (non-public network (NPN) [1] empowers industrial organizations to deploy their own local networks with dedicated equipment and configurations, enhancing the flexibility of production systems. The use of 5G NPN enables dedicated coverage, exclusive capacity, intrinsic controllability, and customized service and operation [2]. In this regard, reliable wireless connectivity is a key requirement of industrial applications. These are often extremely sensitive to poor communication performance, which can potentially cause production equipment downtime. Thus, the deployment of industrial 5G NPN requires the advance testing of wireless communication performance under realistic conditions [3].

Moreover, for a functional integration of 5G in real production environments, the highly demanding communication requirements of industrial use cases must be ensured. A key enabler of industrial 5G deployments is the integration of 5G with standardized publish-subscribe (PubSub) messaging models and protocols, such as open platform communication unified architecture (OPC-UA), aiming to ensure the convergence of the information technology (IT) and operational technology (OT) domains [4]. The integration of 5G with PubSub protocols provides a complete communication stack for industrial automation, where PubSub messaging operates on the higher OSI model layers, and 5G operates on the lower layers [5]. Thus, this convergence is poised to provide robust communication and information model-based data management in Industry 4.0.

Although the integration of 5G with industrial PubSub mechanisms has initially been addressed in the literature, this has been considered mainly from a theoretical perspective. The work in [6] proposed the integration of OPC-UA with 5G through time sensitive networking (TSN), which paved the way for further investigations on the convergence of PubSub and TSN [7]. However, very few works have studied the direct integration between PubSub and 5G in Industry 4.0. The work in [4] presented a generic architecture for the direct integration of 5G and OPC-UA, and demonstrated an end-to-end delay of under fifteen milliseconds and a reliability of 99.4%. However, validations where carried out in a laboratory testbed. Additional research is required in real environments, where the complexity of practical network setups and the lack of reliable wireless connectivity are likely to impact the achievable performance.

In addition, the dominant networking model in current factories is based on Ethernet. Thus, to ease the introduction of 5G NPN in factory environments it is key that the 5G NPN can natively transport Ethernet frames. 3GPP has standardized the support of Ethernet access points [8]. However, this feature is not yet supported by commercial 5G modems. The authors in [9] suggest to use virtual extensible local area network

(VXLAN) over 5G to enable native transport of Ethernet frames, and evaluated the resulting end-to-end latency in a laboratory environment. We extend this work by providing a full evaluation of a real industrial PubSub protocol over a VXLAN enabled 5G NPN system.

To the best of the authors' knowledge, this paper presents the first empirical evaluation of the integration of a 5G NPN with OPC-UA in a real production environment. The proposed solution for 5G-OPC-UA integration relies on layer 2 (L2) connectivity over a VXLAN tunnel. The 5G NPN system acts as a L2 switch, so that Ethernet frames generated by OT devices can reach all the other OT devices in the same virtual local area network (VLAN). Evaluation results demonstrate the feasibility of such integration in an additive manufacturing (AM) laser metal deposition (LMD) use case, in a real factory floor.

The remainder of this paper is organized as follows. Section II presents an overview of the industrial use case of interest and its main connectivity requirements. Section III describes the 5G NPN architecture and deployment model. Section IV presents a performance evaluation of the 5G NPN and of the LMD use case of interest. Section V concludes the paper.

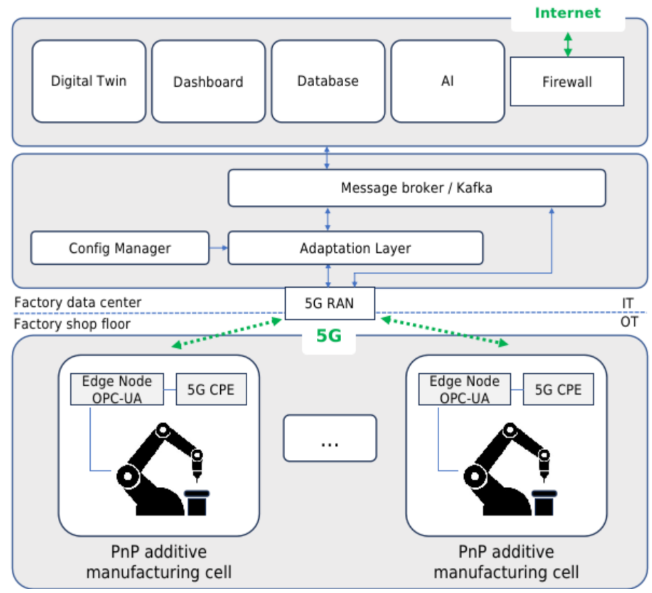

Fig. 1. 5G-enabled factory services.

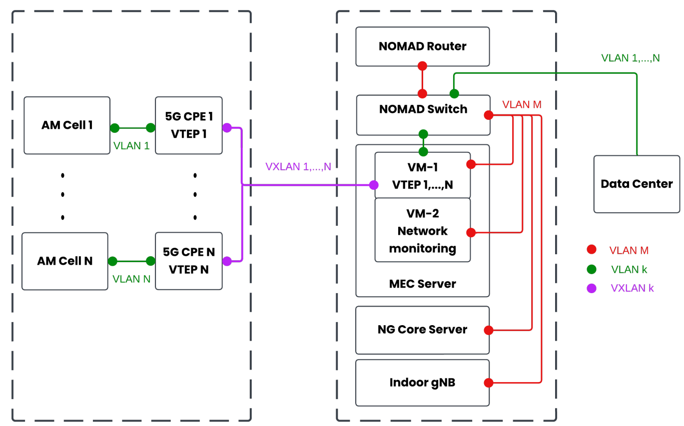

Fig. 2. Network diagram of the proposed 5G NPN deployment.

II. Reference Industrial Use Case

As test case, we consider a scenario in an advanced manufacturing facility comprised by plug-and-produce (PnP) automated AM cells for prototyping, repairing and machining metal parts. Each cell utilizes LMD to build three-dimensional components, layer by layer. The AM cells are equipped with a laser source, robot, a precise wire or powder feeder to add material to the process, a camera for online process monitoring system, and an edge-node for control. LMD enhances design flexibility and fabrication of intricate parts, but the complexity of the process due to the influence and interaction of various parameters (laser power, feed rates, material composition, environment, etc.) requires optimization and precise control to achieve the desired structural integrity and surface finish. The achievement of the vision of zero-defect manufacturing relies on online monitoring and control, as well as data-driven tools. These tools encompass digital twins, which leverage simulation and process data to enhance understanding and optimize future iterations. Additionally, AI services are employed for defect prediction.

In this regard, the full integration and interoperability of the AM cells, including the robot controller, sensors, and field devices, with IT factory services is achieved through the combination of two PubSub protocols, namely OPC-UA and Kafka. While OPC-UA ensures standardized communication and data exchange in the industrial automation domain, Kafka, as a distributed streaming platform, facilitates seamless communication between various IT services on the manufacturing ecosystem and enhances data stream processing capabilities.

The use of 5G NPN in this case aims to facilitate remote monitoring and control of AM cells, achieving full integration with private services in the factory data center. Fig. 1 illustrates the proposed integration between 5G NPN and factory services. Combining PnP manufacturing modules (AM cells) with 5G on the factory floor allows rapid production line reconfiguration. This enables dynamic adjustments to manufacturing setups, fostering a highly flexible and adaptive production environment that efficiently responds to changing demands and accommodates diverse products.

The target industrial application requires 5G connectivity to all the AM cells on the factory shop floor, ensuring high bandwidth, low latency and jitter. Each AM cell produces a continuous data stream, combining time series data (e.g., robot position, feeder rate, laser power) and a video stream from the monitoring system. The data is primarily streamed via OPC-UA using the client-server mechanism over transmission control protocol (TCP). Typically, an OPC-UA connector running in the adaptation layer (see Fig. 1) is responsible for retrieving the data from the OPC-UA server on the edge node and sending it to a Kafka cluster at a constant rate of 15 Hz. The average data rate per cell is around 4 Mbps, considering video graphics array (VGA) image resolution. Processed data is used offline to generate a digital twin of the manufactured component for analyzing and optimizing future iterations. The use case under study is soft real time, and thus it requires lower than 100 ms latency. Another main requirement is the ability to provide 5G connectivity to several AM cells simultaneously.

The use of OPC-UA services is required in the factory data center with the capability to initiate and establish communication with the OPC-UA servers in the edge nodes, to enable support for a variety of industrial services. The OT network management model is based on a firewall with dedicated VLANs for every AM. 5G connectivity to the customer premises equipment (CPE)s is provided through L2 in order to maintain the previous centralized network management model. Since the OPC-UA client at each AM cell initiates a TCP connection, the use of L2 connectivity would require network address translation, which would disrupt the connectivity.

III. Network Architecture and Deployment Model

5G mobile network architectures comprise three main functional entities: core network, radio access network (RAN), and user equipments. In public 5G networks, communication is achieved at the IP protocol layer. However, the introduction of new use cases, particularly in the industrial domain, requires an evolution not only of the network architecture but also from the connectivity perspective. In this sense, the integration of 5G NPN and mobile edge computing (MEC) in the industrial domain are considered as key enablers of new industrial use cases. 5G NPNs provide a number of advantages to industrial settings [2], such as dedicated coverage and capacity. However, there are multiple challenges in the deployment of 5G NPNs in industrial settings. Specifically, the deployment and integration of the 5G NPN must be adapted to the specific use case and existing network configuration to achieve strict industrial reliability requirements.

In the reference use case presented in Section II, an isolated 5G NPN deployment [2] must provide connectivity between a factory OT domain to a on-premise data center. 5G connectivity is intended to replace the current wired Ethernet based connection and support different industrial protocols such as OPC-UA, thus enabling re-configurability of the AM cells. Fig. 2 represents the network diagram of the proposed 5G NPN deployment to provide L2 network connectivity between the AM cells and the factory data center, through a dedicated VLAN per AM cell. The AM cells contain the functionalities of the industrial edge node, and are located in the factory shop floor, as represented in Fig. 1. Since the AM cells do not have wireless connectivity capabilities, a CPE is employed to provide 5G connectivity to the 5G NPN placed in the factory data center. It is worth mentioning that the right dotted block in Fig. 2 represents the 5G block that connects OT and IT domains in Fig. 1 which, in our deployment, is a Nomad 5G [10] all-in-one NPN 5G solution. This solution includes networking devices such as a NOMAD router and switch. The router is used for remote network management through VLAN M, while the switch interconnects the rest of the components in the Nomad 5G. In this particular deployment, two servers are considered. One of the servers implements the 5G core network. The second is employed as a MEC server with multiple functionalities such as network monitoring and VXLAN configuration to support L2 communications. The end to end L2 communication between the AM cells and the data center is established by the combination of VXLANs and VLANs, where the CPEs and a virtual machine in the MEC server act as the VXLAN tunnel end points (VTEPs).

Additionally, the RAN of the proposed solution is composed by an indoor next generation node B (gNB). In this case, a gNB from the Node-H provider was selected due to its trade-off among performance, management features, and cost [11]. The Node-H cell integrates an Askey radio unit [12].

IV. Performance Evaluation

This section provides a performance evaluation of the proposed architecture. The implemented network elements and their parameters are described, and the performance evaluation is presented in terms of network and service performance. From the network perspective, a detailed analysis of the performance is introduced considering coverage, latency and throughput. These measurements were executed at the CPE and at various locations inside and outside of the factory floor, over one AM cell (see Fig. 2.) Additional evaluations of the industrial service performance over 5G are also provided. Results demonstrate that the proposed architecture meets the requirements of the use case, in terms soft real-time latency (below 100 ms for 95% of the time), and number of AM cells supported (up to twenty-two).

A. *Description of the network parameters and factory floor*

The integration of 5G networks in industrial settings is a complex endeavor, which must guarantee a seamless integration of multiple features such as: network monitoring, L2 communication through VXLAN configuration, resource allocation, coverage planning, interference management, and isolation. This subsection describes the fundamental configuration and measurement parameters of the considered setup.

1) RAN: Most of the traffic generated in the AM cell is sent to the on-premise data center through the uplink channel of the 5G NPN, in order to generate a digital twin of the manufacturing process. For this reason, the uplink was prioritized in the selection of the time division duplexing (TDD) pattern. Table I shows the fundamental parameters in the configuration of the radio access network, in which U, D, and F in the TDD pattern stand for uplink, downlink and flexible slots.

2) 5G core network: The 5G core provides advanced networking capabilities and efficient service delivery. The 5G core architecture was designed to be highly flexible, scalable, and capable of handling diverse requirements. In our implementation, an open-source 5G core, namely Open5Gs [13] was selected, as it supports 5G standalone configurations.

TABLE I
RAN CONFIGURATION

Parameters	Value
Standard	3GPP 5G Rel 16 SA mode
Frequency Band	N77 (3900MHz)
Duplex	TDD
TDD Pattern	DFUU
Bandwidth	40MHz
Subcarrier spacing	30kHz
Tx Power	18dBm

3) MEC: MEC takes a significant role to satisfy network requirements in the industrial domain. In the considered 5G NPN deployment, a MEC server was deployed. Storage and processing capacity were allocated on-premise in order to provide additional features to the 5G deployment and especially to support L2 communication between the manufacturing floor and the on-premise data center. Openstack was used as the server's virtual infrastructure manager to enable the execution of multiple and isolated functionalities. Specifically, two virtual machines were instantiated: VM-1 for the VTEP of the VXLAN configuration, and VM-2 for network monitoring purposes (see Fig. 2). A Prometheus server [14] was also deployed with the following targets: three node exporters for the CPE, the core and the MEC servers, a proprietary exporter of the gNB for the radio access network monitoring, and the Open5Gs exporter. The Prometheus server stores the metrics previously pulled from each exporter. Once the data is stored in the Prometheus server database, Grafana [15] is used for data visualization.

4) CPE: Based on the industrial board Gateworks GW7300 [16] with a 1.6 GHz ARM processor, 4 GB DDR4 RAM, and 64 GB of eMMC storage. It has two Gigabit Ethernet ports, one of these ports connects the CPE with the industrial edge node in Fig. 1. Additionally, the Gateworks board has three miniPCIe ports for connecting external devices. In one of these ports, the Quectel RM500Q-GL 5G module [17] is connected via a miniPCIe to M.2 adapter. This module implements NSA/SA modes up to 3rd generation partnership project (3GPP) Release 15 for Sub-6 GHz frequency band.

5) Factory Floor: Fig. 3 shows a simplified map of the factory floor, which includes the AM cells, the set of points where the performance was analyzed (P1 to P8), and the CPE and Node-H gNB locations. The elements were located at the same height on the ground floor, except for the Node-H and P6, which were placed on the second floor, with light-of-sight (LOS) through a window, to improve propagation conditions. During the deployment process, it was assumed that points P1, P2, P3, P4, P5 (see Fig. 3) and the CPE would enjoy better propagation conditions, as they have a LOS path. Although network performance in this dynamic environment is conditioned by different random processes, such as high interference (one of the fundamental challenges in the provisioning of 5G connectivity in industrial settings, due to electromagnetic noise introduced by industrial equipment, among other factors), we followed a simplified approach in our experimental deployment,

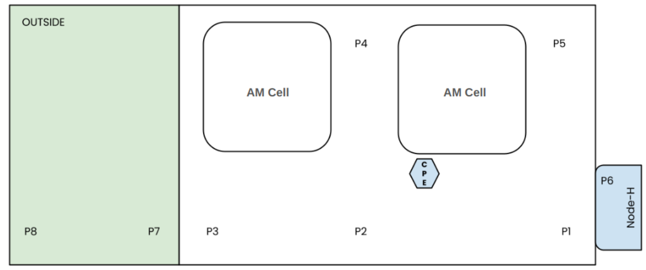

Fig. 3. General diagram of the factory floor.

TABLE II
INSTANTANEOUS COVERAGE MEASUREMENTS

	P1	P2	P3	P4	P5	P6	P7	P8
RSRP [dBm]	-82	-82	-82	-85	-83	-61	-115	-120
SINR [dB]	33	33	33	32	23	31	7	7

where the Node-H radiation pattern lobe was oriented towards the CPE to guarantee 5G connectivity to the AM cell. However, in production-level deployments, especially if more than one additive manufacturing need to be served, it is necessary to apply a gNB placement optimization strategy.

B. Network performance and validation

This subsection aims to provide a network level validation, where latency, throughput, coverage and a preliminary validation of the end-to-end service using OPC-UA protocol are considered to validate the network performance.

1) Coverage Analysis: The analysis of the network performance along the factory floor was executed from P1 to P8, using a XR20 Nokia mobile phone. Since VXLAN connectivity is not supported by this device, measurements were executed in layer 3 (L3)-based 5G communication. Note that this does not affect the generality of the measurements to provide an approximation of the signal coverage in the factory floor. Table II summarizes the instantaneous coverage measurements, namely the reference signal received power (RSRP) (in dBm) and the Signal-to-Noise-plus-Interference-Ratio (SINR), along the considered measurement points. According to the results in Table II, measurement points can roughly be classified into three coverage categories: excellent, good, and weak coverage. In P6, the mobile phone has the best signal level, namely RSRP $= -61$ dBm, since measurement point is located in the same room of the gNB cell. Measurement points inside the factory floor (P1-P5) experience a comparable RSRP. It is interesting to highlight that point P4 has 3 dB of attenuation compared to P1, P2, and P3, which is a potential consequence of the attenuation introduced by the AM cell.

Since interference is one of the most critical aspects of mobile communications, especially under indoor deployments, the signal-to-noise ratio SINR must also be considered in the coverage analysis. Table II shows the SINR measured by the Nokia XR20 at each point. Note the considerable effect of the interference at measurement points P5. Additionally, the measurement of outdoor coverage at points P7 and P8 was

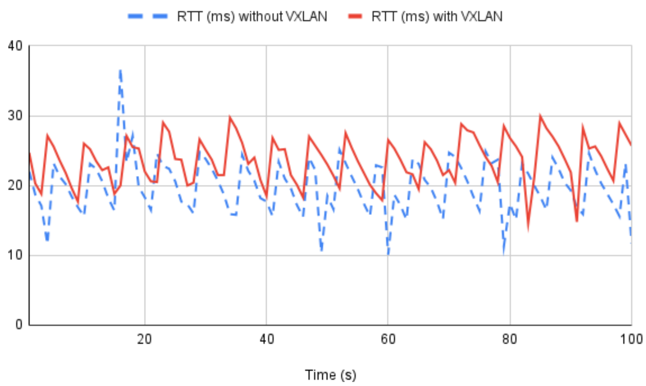

Fig. 4. Latency comparison between L2 and L3 communications.

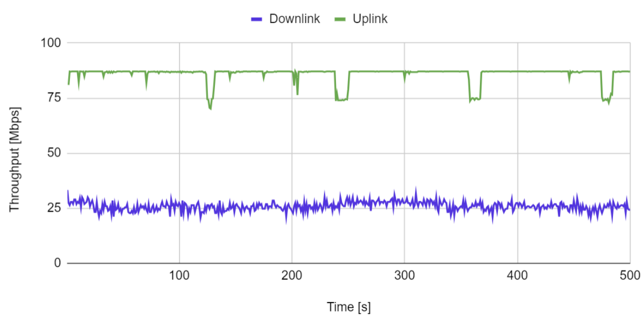

Fig. 5. Throughput of the CPE using L2 communication.

also executed to analyze possible interference generated by the indoor cell, with measurements yielding weak signal coverage.

2) Latency analysis: Latency is a key network performance parameter in manufacturing use cases. Fig. 4 shows the round trip time (RTT) during a preliminary test of 100ms with L2 (with VXLAN) and L3 (without VXLAN) communication approaches. Most of the values of RTT range from 10ms to 30ms during this test. Note that the VXLAN overhead increases the achieved latency, but this was only a moderate increase in our measurements. This analysis was based on ICMP packets, using the ping tool, which is not representative of the latency at service level. Thus, a deeper analysis on industrial service performance is presented in subsection IV-C.

3) Throughput analysis: The network throughput validation was executed with the open-source tool iperf3, a server-client application that allows to measure the network throughput using TCP and user datagram protocol (UDP). Additionally, the measurements can be executed in both directions, server to client and client to server, allowing the measurement of network throughput in the uplink and downlink. Fig. 5 shows the throughput results from the CPE to the MEC server. Based on the use case requirements and the protocols running in the industrial edge, measurements were executed with TCP protocol in the iperf3 and over L2 communications with VXLAN configuration. Results in Fig. 5 show the uplink traffic is prioritized with an available throughput around 80Mbps because of the TDD configuration, while the downlink exhibits around 25Mbps, supporting twenty-two users. This is a desirable effect, as most data traffic is generated at the AM cell.

C. Industrial Service Performance Evaluation

In this subsection, the performance of OPC-UA over the 5G NPN is analyzed in the context of a service for the monitoring of an industrial AM process. The test topology consists of two main components. The first is an industrial edge device, specifically an Nvidia Jetson with 8GB RAM and 8 cores. On this device, an OPC-UA server based on the open62541 C library is deployed. The second component is a server with 15GB RAM and 6 cores on which an OPC-UA client is launched. This client reads 16 variables from the OPC-UA server with a frequency of 15 Hz, providing dynamic monitoring of the additive manufacturing process. Connectivity is provided over a VXLAN-based L2 5G service. The performance results are evaluated in terms of bandwidth and latency.

Fig. 6 shows the network bandwidth of a single AM cell (i.e., an OPC-UA client), averaging 4 Mbps. Consequently, the system can effectively accommodate up to twenty-two AM cells, yielding an aggregated bandwidth of approximately 88 Mbps, which is the total uplink bandwidth capability. I.e., the network bandwidth allows for the monitoring of up to twenty-two AM cells simultaneously.

Fig. 7 presents the latency measurements obtained when transmitting OPC-UA traffic, including both the delay introduced by the network and that introduced by the data processing at the OPC-UA client side. Measurements were performed over (i) a wired connection, (ii) a 5G connection, with simulated OPC-UA data, and (iii) a 5G connection, with OPC-UA data generated during a real production process. Moreover, Table III presents the latency 95th percentile, mean, median and standard deviation, for each of the experiments performed. The experiment performed over a wired connection yields very consistent results, as expected, which are reflected in the low standard deviation achieved. Moreover, the 95% of measurements yielded values equal to or lower than 1.66 ms. Measurements of simulated OPC-UA data over the 5G network yielded a mean delay of 24.69 ms. This measurement fulfills the non real-time requirements of the AM LMD use case but, also, of typical soft real-time industrial applications such as mobile robots and remote control-to-control communication.

Measurements of real production OPC-UA data over 5G presented a more complex picture, as seen in Fig. 7 and Table III. Measurements presented a large variability in latency and jitter. This is due to two main reasons. First, production OPC-UA traffic is burstier than simulated data, which can lead to network overflow and congestion, thus resulting in frequent high latency peaks, and on an increased average latency and standard deviation. And second, during production, service processing time introduces a large latency jitter. Nevertheless, the achieved latency and jitter are acceptable in our non real-time system, and it is also sufficient to meet the latency requirement of 100 ms in typical soft real-time industrial applications [2].

V. CONCLUSIONS

This paper presented an experimental evaluation of the integration of 5G NPN with OPC-UA in a real production

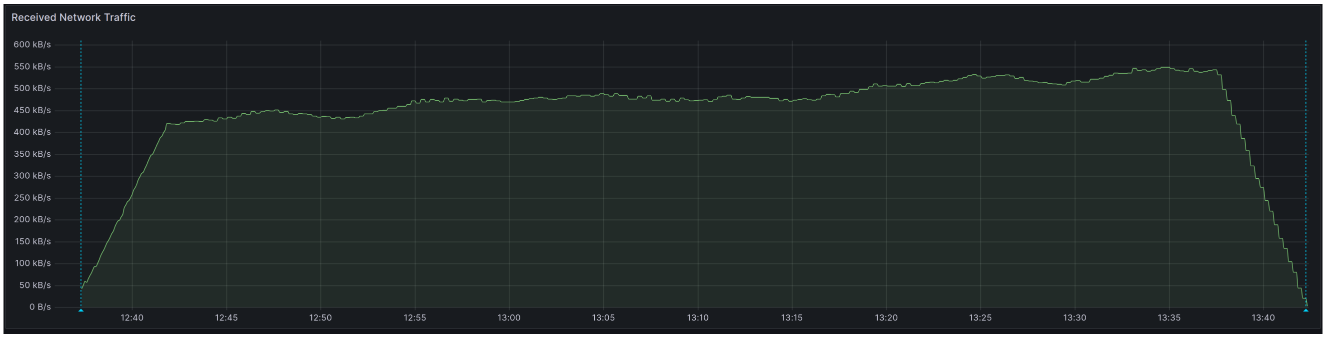

Fig. 6. OPC-UA single-client bandwidth.

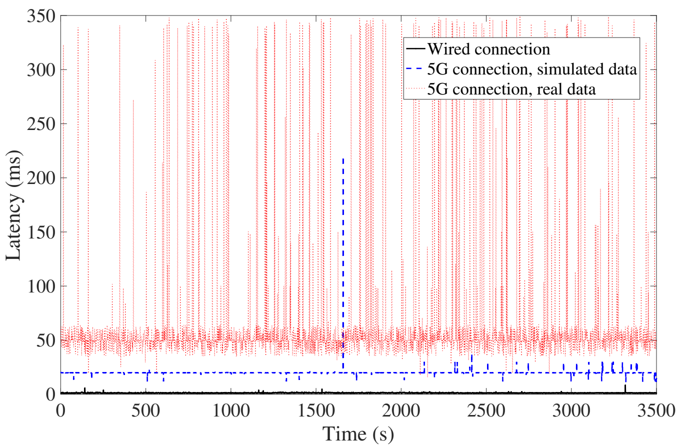

Fig. 7. OPC-UA latency measurements.

TABLE III
SUMMARY STATISTICS FOR EXPERIMENTS

	Wired connection	5G connection, simulated data	5G connection, real production data
Percentile 95	1.66ms	28.96ms	99.82ms
Mean	1.25ms	24.69ms	61.16ms
Median	1.17ms	17.82ms	49.96ms
Std. Deviation	0.33ms	44.41ms	53.33ms

environment, namely an AM use case for LMD manufacturing. 5G connectivity was established through L2 over a VXLAN tunnel. A performance evaluation of the proposed deployment was executed to validate the integration of the 5G NPN into the existing OT network, as well as the network performance and the target industry service performance. Evaluation results demonstrate that our approach can simultaneously serve a large number of AM cells. Additionally, our VXLAN-based approach was validated, yielding an increased RTT of only a few milliseconds. Moreover, the OPC-UA latency measurements over a real production process produced a large jitter which, however, is acceptable in non and soft real-time industrial applications.

ACKNOWLEDGMENT

This work was supported by the European Union's Horizon Europe Innovation Actions under grant agreement no. 101057083 (Zero-SWARM), and by the Spanish Ministry of Economic Affairs and Digital Transformation and the European Union – NextGeneration EU, in the framework of the Recovery Plan, Transformation and Resilience (PRTR) (Call UNICO I+D 5G 2021, ref. number TSI-063000-2021-9-6GSMART-ICC and TSI-063000-2021-15-6GSMART-EZ).

REFERENCES

[1] A. Aijaz, "Private 5G: The future of industrial wireless," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 136–145, 2020.

[2] 5G Alliance for Connected Industries and Automation (5G-ACIA), "5G non-public networks for industrial scenarios," White Paper, Frankfurt, Germany, Jul. 2019.

[3] ——, "Performance testing of 5G systems for industrial automation," White Paper, Frankfurt, Germany, Feb. 2021.

[4] X. Zhang, S. Lim, C. Lee *et al.*, "Integration of 5G and OPC-UA for smart manufacturing of the future," in *2023 IEEE/SICE International Symposium on System Integration (SII)*, 2023, pp. 1–6.

[5] R. Muzaffar, M. Ahmed, E. Sisinni *et al.*, "5G deployment models and configuration choices for industrial cyber-physical systems – a state of art overview," *IEEE Transactions on Industrial Cyber-Physical Systems*, vol. 1, pp. 236–256, 2023.

[6] D. Bruckner, M.-P. Stănică, R. Blair *et al.*, "An introduction to OPC-UA TSN for industrial communication systems," *Proceedings of the IEEE*, vol. 107, no. 6, pp. 1121–1131, 2019.

[7] G. P. Reddy, Y. V. P. Kumar, Y. J. Reddy *et al.*, "OPC-UA implementation for industrial automation - part 2: Integrating PubSub model with TSN," in *2023 1st International Conference on Circuits, Power and Intelligent Systems (CCPIS)*, 2023, pp. 1–6.

[8] 3rd Generation Partnership Project (3GPP), "Technical specification group services and system aspects; system architecture for the 5G system; stage 2," Technical Specification TS 23.501, 2022.

[9] N. Ambrosy and L. Underberg, "5G packet delay considerations for different 5G-TSN communication scenarios," in *2023 IEEE 21st International Conference on Industrial Informatics (INDIN)*, Lemgo, Germany, 2023.

[10] N. T. S.L., "Nomad 5G." [Online]. Available: https://www.neutroon.com/nomad5g

[11] Node-H, "5G RAN Software." [Online]. Available: http://node-h.com/en/solutions/5g_ran_software.php

[12] ——, "5G Enterprise cell." [Online]. Available: http://node-h.com/en/solutions/5g_enterprise_cell.php

[13] "https://open5gs.org/." [Online]. Available: https://open5gs.org/

[14] Prometheus, "Overview | Prometheus." [Online]. Available: https://prometheus.io/docs/introduction/overview/

[15] "Grafana: The open observability platform." [Online]. Available: https://grafana.com/

[16] "Industrial single board computer - dual Ethernet." [Online]. Available: https://www.gateworks.com/products/industrial-single-board-computers/imx8-single-board-computers-gateworks-venice/gw7300-single-board-computer/

[17] "5G RM50xQ series." [Online]. Available: https://www.quectel.com/product/5g-rm50xq-series