Deploying an End-to-End CAN–TSN–5G Industrial Network: Practical Insights and Lessons Learned

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***Abstract*—The rapid evolution of modern vehicle architectures driven by automation and the shift toward software-defined vehicles increasingly drives the need for deterministic, low-latency communication capable of connecting legacy in-vehicle networks with emerging high-bandwidth Ethernet and wireless technologies. A heterogeneous wired-wireless communication has the potential to significantly enhance flexibility and scalability in automotive networks by supporting advanced functions such as distributed control, over-the-air updates, and cooperative driving. Nevertheless, contemporary automotive systems demand highly predictable and deterministic data-packet transmission to ensure reliable and time-critical operation. This paper presents practical experiences and lessons learned from deploying an end-to-end Controller Area Network (CAN) – Time-Sensitive Networking (TSN) – 5G cellular network in an industrial operational environment. The system was designed, integrated, and validated in an operational environment where both legacy nodes and new networked controllers co-existed. We highlight the challenges encountered at all system layers, including interface issues, configuration complexity, gateway implementation and system-level behavior, and provide insights into the future industrial deployments aiming to bridge deterministic wired and wireless domains.**

I. Introduction

Modern vehicle architectures are undergoing significant evolution driven by vehicle automation, data-driven operations, cooperative driving, and software-defined vehicle functionalities, among others. These emerging trends demand communication infrastructures that can support deterministic, low-latency and highly reliable data transmission. Such requirements arise in a wide range of time-critical applications, including autonomous construction vehicles, collaborating robots, customized manufacturing systems, and real-time monitoring of industrial connected machines, to mention a few [1]. As a result, traditional industrial fieldbuses, while widely deployed and trusted for their robustness, are progressively being complemented, and in some cases even replaced by modern deterministic Ethernet technologies such as Time-Sensitive Networking (TSN) [2] and next-generation wireless solutions including 5G [3].

Despite these technological advancements, many operational environments continue to rely on heterogeneous communication landscapes where legacy fieldbus systems coexist with newly deployed network controllers and wireless devices [4]. This coexistence poses significant challenges, particularly in ensuring end-to-end deterministic behavior across fundamentally different communication domains. Achieving predictable communication, and guaranteeing reliable data transmission becomes increasingly complex when bridging wired and wireless segments [5], each with distinct protocols, timing characteristics, and configuration constraints. Nevertheless, enabling seamless integration across such heterogeneous networks is crucial for enhancing system scalability, enabling flexibility, and supporting mobile and distributed assets.

To better understand these challenges in real operational settings, this paper investigates an end-to-end communication architecture that interconnects a Controller Area Network (CAN) fieldbus with a TSN-enabled backbone and a 5G wireless network. The system was deployed, integrated and validated in an operational industrial use-case in which legacy nodes and modern networked controllers had to operate concurrently. Through this deployment, we observed a wide range of practical issues spanning multiple system layers, including physical interface interoperability, protocol translation, network configuration complexity, time synchronization, gateway implementation, and emergent system-level behavior. This paper presents the practical challenges and lessons learned from the deployment process to provide insights that can inform future deployments seeking to combine deterministic wired and wireless technologies. Our findings aim to support researchers, system integrators, and industry practitioners in designing predictable, interoperable, and scalable communication architectures capable of meeting the stringent demands of next-generation industrial systems.

II. Industrial Use Case Description

The use case originates from the automotive domain where a private 5G network is deployed on a construction site to support the remote operation of truck-mounted construction crane, as shown in Fig. 1. This use case incorporates tightly constrained control loops and and relies on real-time sensor data transmitted over a legacy CAN network. The transition towards remote monitoring, digital twins, and data-driven operations motivated the need to incorporate TSN and 5G networks, with the goal of achieving deterministic end-to-end communication across wired and wireless segments.

In this use case, the operator is located in a remote control room and performs various operations such as steering the truck and controlling the crane via a dedicated controller. The corresponding control data is first transmitted to the TSN switch, then to the TSN/5G gateway that forwards the data

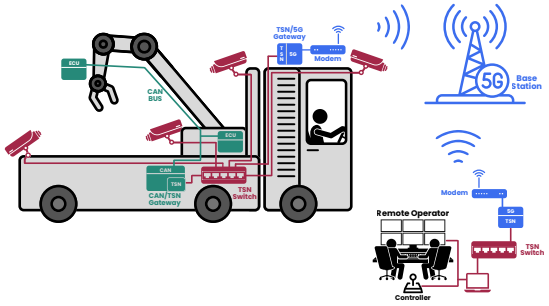

Fig. 1: End-to-end industrial use-case.

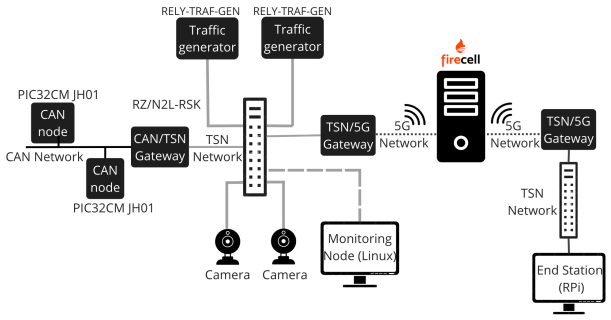

Fig. 2: End-to-end CAN-TSN-5G prototype design.

wirelessly over 5G. Inside the crane, three cameras connected to a TSN switch continuously stream frames required for the remote operation. Two Electronic Control Units (ECUs) generate and transmit the CAN frames on the CAN bus, which are forwarded to the CAN/TSN gateway for protocol translation. The CAN/TSN gateway, in turn, interfaces with the TSN switch, which directs all aggregated traffic towards the controller via the TSN/5G gateway. The main performance requirements of the system include:

- Low and bounded latency, especially for control-critical traffic. The initial requirement was an end-to-end delay that does not exceed 20 ms.
- Interoperability across heterogeneous network segments.
- Time synchronization to support coordinated operations.

III. End-to-End System Architecture

The end-to-end system integrates three major subsystem layers: 1) Legacy CAN bus for local sensing and actuation, 2) TSN backbone providing deterministic wired Ethernet connectivity, and 3) 5G private network enabling wireless data transmission to remote controllers. In between those subsystems, there is a CAN/TSN Gateway and a TSN/5G Gateway that serve as interfaces to support the end-to-end communication, as shown in Fig 2.

A. Subsystem Employing Controller Area Network

The Controller Area Network (CAN) [6] is a widely used protocol for onboard real-time communication, particularly in the vehicular domain. It enables multiple ECUs to communicate via a shared serial bus that employs fixed-priority non-preemptive scheduling. It allows the highest priority frame to be transmitted first and once a CAN frame begins the transmission, it cannot be interrupted.

The CAN network in the use case consists of two ECUs. Each ECU uses a Microchip PIC32CMJH01 device that features a 48 MHz Arm Cortex M0+ Core microcontroller with 512 KB Flash memory, 64 KB SRAM, and two CAN controllers that support classical CAN. The microcontroller runs FreeRTOS real-time operating system.

B. Subsystem Employing Time-Sensitive Networking

Time-Sensitive Networking (TSN) is a set of standards designed to support reliable and deterministic delivery of time-sensitive data over switched Ethernet [2]. TSN prioritizes the transmission of time-sensitive data over less-critical traffic by using the concept of VLAN tagging, which include a Priority Code Point (PCP) field to classify incoming frames and apply QoS mechanisms such as, traffic shaping and priorities to make sure data is delivered with a guaranteed level of reliability. The PCP value defines eight FIFO queues for a port in the TSN switch with priorities of 0–7, from low to high.

The network includes various TSN endpoints, including two camera nodes that send TSN traffic. These endpoints are connected to an industry-grade TSN switch that supports various TSN features, inlcuding the IEEE 802.1Q VLAN tagging, QoS-es to prioritize critical traffic, guard bands for efficient scheduling, frame preemptions, and has a set of scheduling options including strict priority, Weighted Round Robin (WRR) and Time-Aware Shaper (TAS). The switch can be configured via the Cisco-style command line interface with plain text commands.

C. Subsystem Employing Private 5G Network

A private 5G network is a dedicated network tailored specifically for the unique requirements of an organization. It consists of several 5G endpoints or User Equipments (UEs) that are connected to the private 5G network via the 5G modems. The Radio Access Network (RAN) handles the wireless communication between the UEs and the core network. A Universal Software Radio Peripheral (USRP) is used to facilitate the development and implementation of the 5G RAN using software.

In this work, the complete setup of the private 5G network is part of the Firecell Solutions[1]. This private 5G setup is less complex and offers full control over managing 5G radio resources compared to many other commercial systems, rendering it suitable for experimental evaluation and testing of industrial prototypes. The hardware consists of a Software Defined Radio (SDR) with two antennas (the USRP B210 module developed by the Ettus Research), a server running the 5G Core, and the 5G UEs. The USRP supports frequencies in the range of 70 MHz to 6 GHz with a maximum transmit power of 10 dBM. The system achieves a maximum downlink throughput of 131 Mbps and a maximum uplink throughput of 21 Mbps. The RAN software supports bandwidth up to 40 MHz.

[1]Firecell Solutions - https://firecell.io/

D. CAN/TSN Gateway

Communication between CAN and TSN networks is enabled through a gateway node that interfaces both domains. In this work, we consider a CAN-to-TSN gateway based on the architecture proposed in [7]. In this design, incoming CAN frames are encapsulated and forwarded into the TSN network. The number of CAN frames that can be carried within a single TSN frame is constrained by the TSN maximum payload size of 1500 bytes, whereas a classical CAN frame has a maximum size of 17 bytes (considering maximum payload of 64 bits and overhead of 71 bits). While CAN traffic is event-driven and dynamically scheduled, the gateway transmits encapsulated frames periodically, without requiring strict offline scheduling. This periodic forwarding mechanism provides bounded latency without explicit synchronization with a global schedule.

In this work, the gateway implements a one-to-one mapping strategy, where each incoming CAN frame is immediately encapsulated into an individual TSN frame. While this leads to underutilization of the TSN frame payload, it minimizes gateway-induced latency by avoiding the queuing of multiple CAN frames for aggregated transmission of multiple CAN frames in a single TSN frame. This design choice is driven by the stringent end-to-end latency requirements, and aligns with prior observations that CAN-to-TSN communication delay is minimized when the gateway employs a one-to-one mapping strategy, as reported in [8].

E. TSN/5G Gateway

The TSN-5G gateway acts as an interface to support the protocol translation and maintain QoS between both networks.

1) Protocol Translation: Priority fields, such as PCP in the TSN frame and Differentiated Services Code Point (DSCP) in the IP frame, are defined at different layers of the OSI model, natively making them incompatible without translation. To ensure compatibility within the TSN-5G network, a gateway is needed for translating communication protocols. This guarantees seamless interoperability between the networks.

Within the TSN framework, PCP values ranging from 0 to 7 were successfully mapped to a format recognized by the 5G network, as shown in Algorithm 1. By converting the PCP value to DSCP in the IPv4 header and removing the VLAN tag before the packet is sent to the 5G network, we enabled the packet to be processed correctly by the 5G core network. Algorithm 1 defines a function *handle_packet* that checks if a packet contains an IEEE 802.1Q standard VLAN tag, therefore being a TSN packet. It retrieves the PCP value from the VLAN tag, converts it to DSCP using a predefined mapping, creates a new packet without the VLAN tag, sets the destination MAC and the IP type of service (ToS) field to the new DSCP value, and forwards the packet to the egress port of the gateway. Similarly, Algorithm 2 is used to process and forward network packets from the 5G UEs to the TSN endpoints. Further details regarding the proposed TSN/5G Gateway can be found in [9].

2) QoS Mapping: To ensure deterministic communication across both networks, the TSN/5G gateway must also account for the QoS requirements associated with each traffic flow.

Algorithm 1 Gateway Implementation: TSN to 5G.

```
begin
 1: define handle_packet function with parameter packet
 2: if packet contains 802.1Q VLAN tag then
 3:     retrieve PCP value from VLAN tag
 4:     convert PCP to DSCP using a predefined mapping
 5:     create a new packet without VLAN tag
 6:     set destination MAC to 5G UE MAC address
 7:     set IP ToS field to new DSCP value
 8:     forward the new packet towards the gateway
 9: end if
end
```

Algorithm 2 Gateway Implementation: 5G to TSN.

```
begin
 1: define handle_packet function with parameter packet
 2: if packet is a returning package then
 3:     retrieve DSCP value from IP ToS field
 4:     convert DSCP to PCP using a predefined mapping
 5:     create a new packet with VLAN tag
 6:     set destination MAC to TSN endpoint MAC address
 7:     forward the new packet towards the gateway
 8: end if
end
```

In 5G systems, every uplink or downlink packet or flow is assigned to a specific QoS flow. The 5G standard distinguishes between two main QoS categories: (i) Non Guaranteed Bit Rate (Non-GBR) flows, and (ii) Guaranteed Bit Rate (GBR) which provide reserved resources for traffic with bounded latency or throughput requirements. In contrast, TSN organizes traffic into three principal classes: (i) Scheduled Traffic (ST), (ii) Audio-Video Bridging (AVB) traffic, and (iii) Best-Effort (BE) traffic. When forwarding packets from a TSN domain toward a 5G network, an appropriate mapping between TSN traffic and 5G QoS flows is therefore required. In this work, we adopt the rule-based mapping approach introduced in [10], which provides deterministic handling of TSN traffic while ensuring alignment with the 5G QoS profiles.

F. Realization on the Industrial Use Case

The proposed end-to-end architecture has been deployed and validated on the industrial use case introduced in Section II. The setup integrates heterogeneous communication technologies, namely CAN, TSN, and 5G, across the different subsystems of a truck-mounted construction crane, as shown in Fig. 3. The deployment demonstrates the complete realization of the architecture on an operational industrial platform and enables deterministic end-to-end communication across heterogeneous network segments while supporting both high-bandwidth video and low-latency control traffic.

(1) CAN subsystem is located on the crane itself, shown in the upper part of Fig. 3. It is responsible for acquiring real-time sensor data from the crane's boom, including joint positions, pressures, and actuator states. Two ECUs generate and exchange CAN frames that implement the time-critical local control loops of the crane. These frames are forwarded to the CAN/TSN gateway, which performs protocol translation

from CAN to Ethernet TSN and exposes the data to the upper network layers. *(2) TSN subsystem* resides on the truck and serves as the central aggregation and scheduling point for all wired real-time traffic. Multiple onboard cameras are connected to the TSN switch, which continuously stream video frames required for situational awareness and for updating the digital twin. The TSN switch forwards all aggregated traffic, including camera streams, control data originating from CAN, and auxiliary sensor information, to the TSN/5G gateway. *(3) 5G subsystem* consists of a private 5G base station that is deployed in close proximity to the truck as shown in the lower part of Fig. 3. The TSN/5G gateway transmits prioritized traffic over the 5G uplink toward the remote operator, who supervises and controls the crane from a dedicated control room. Operator commands, such as crane actuation and truck steering inputs, follow the reverse direction. These commands traverse the 5G link, are delivered to the TSN network, and then are forwarded to the CAN subsystem through the CAN/TSN gateway.



Fig. 3: Remote operation of a crane on a CAN-TSN-5G setup.

IV. Practical Experiences and Lessons Learned

This section discusses the challenges and lessons learned from our experience of integrating the CAN-TSN-5G communication in industrial settings.

A. CAN Layer: Challenges, Solutions and Lessons Learned

Impact of various higher-level protocols. In practical automotive systems, a CAN message may not be strictly periodic or sporadic as often assumed in academic environments. Instead, many higher-level protocols for CAN introduce mixed message semantics that differ significantly across protocol families. For example, CANopen, AUTOSAR, and HCAN each define their own mechanisms for mixed transmissions, relying on combinations of periodic and event-triggered releases and protocol-specific timing parameters such as Event Timers, Inhibit Times, and Minimum Delay Times. These mechanisms create dependencies between periodic and sporadic releases, can delay periodic transmissions, and impose constraints on when sporadic updates may be queued. While conventional analyses effectively handle purely periodic or sporadic messages, mixed semantics introduce timing behaviors that require explicit modeling of protocol rules to avoid optimistic response-time calculations. The key lesson is that higher-level protocol semantics must be incorporated directly into the timing analysis to ensure predictability and correctness of CAN messages when analyzing them at the design time.

Practical limitations in the CAN interfaces. Practical limitations in CAN interfaces have a substantial impact on message response times and jitter. Different ECUs may implement FIFO or priority-based transmit queues, support only a limited number of transmit buffers, or allow or prohibit transmission abort requests. Limited or non-abortable buffers in the CAN interfaces can cause high-priority messages to wait behind lower-priority ones, resulting in additional delays and jitter that must be accounted for in the design-time analysis of CAN messages. Even CAN interfaces that support transmission abort requests can experience priority inversion due to copying delays during the buffer swapping. These limitations highlight the need for analysis frameworks and industrial tools that explicitly incorporate queueing policies, buffer sizes, abort semantics, and message copy times, since ignoring these practical constraints leads to unsafe or underestimation of response times at the design time. The lessons learned emphasize that accurate timing analysis must reflect the real behavior of CAN interfaces rather than idealized academic assumptions.

Heterogeneous ECUs in the CAN subsystem. Automotive CAN subsystems include heterogeneous ECUs that differ in their queuing policies, buffer limitations, supported transmission modes, and overall timing capabilities. As a result, messages originating from different ECUs can experience varying delays even when their timing parameters are otherwise identical. For example, an ECU with non-abortable transmit buffers may experience significantly larger delays than one with abortable buffers, even when sending messages with identical periods and priorities. Such heterogeneous set of ECUs are found in industrial applications more than perceived. The main lesson is that the analysis tools must support heterogeneous configurations and avoid one-size-fits-all assumptions; otherwise, the design-time response-time calculations may be overly optimistic and jeopardize the system correctness.

B. TSN Layer: Configuration and Integration

Tradeoff between CAN-TSN encapsulation techniques. One of the major challenges in delivering CAN frames via the TSN switch is to encapsulate CAN frames into Ethernet frames. Although there have been several strategies for such an integration, there was no implementation to evaluate efficiency of different strategies. The work in [11] shows that in most of the cases encapsulating one CAN frame into one Ethernet

frame is a suitable solution due to the large difference in the network capacities for Ethernet and CAN. In our implementation, we implemented the one-to-one mapping of CAN frame to Ethernet frame. Selecting this strategy made the implementation simpler, but also reduced the waiting time in the gateway. For this implementation, we strictly used the AVB traffic that do not need offline scheduling. Mapping CAN frames into Scheduled Traffic is a research challenge that is still ongoing in the research community.

TSN switch configuration. TSN switches require configuration of various queues in each port which depends on the load and traffic classes. There are several existing solutions to efficiently select network bandwidth per queue per port of each switch. However, vendors have different ways for applying the configuration in the switch. Some of the vendors allow deployment of configuration via a web-based interface, while others support only Command Line Interface to enter the configuration manually. The easiest way, as only some of the vendors support, is deployment of the configuration automatically via a Centralized Network Controller (CNC) using NETCONF protocol. However, in this case, there is no unique implementation for CNC network management. In this project, we have used an in-house implementation presented in [12] while there is no standard implementation available.

Legacy nodes support. A common challenge in TSN networks is support for legacy nodes. The challenge is that the existing computing nodes, e.g., ECUs in this use case, may not support the TSN shapers that the use case requires. Therefore, the configuration is limited to the network (switches) only, that may have impact on the overall performance. Another issue is the compatibility of clock synchronization protocols. The TSN switches support gPTP according to the standards, while the nodes may only support PTP. This incompatibility can result in clock drift which can, in the worst-case, lead to packet drops. The details of such an issue is studied in our previous work [13].

C. 5G Layer: Deployment Issues and Practical Insights

Protocol Translation. Current 5G deployments introduce significant heterogeneity, largely driven by vendor-specific implementations and hardware constraints. Our experiments revealed that while some configurations preserve PCP values across the 5G transport domain, the DEI field of the TSN frame is often modified inconsistently. These observations highlighted the importance of guaranteeing the retention of the PCP values as part of the TSN/5G gateway, as it is essential for maintaining predictable transmission and supporting deterministic end-to-end communication.

QoS Profiles. In our setup, as well as in several commercially available 5G solutions, the system is built on the Open Air Interface (OAI) Software Alliance platform, an open-source project [2]. Our investigation into the QoS capabilities within the OAI platform reveals significant findings. The default UE QoS flow session for GTP-U in OAI is designated as the Non-GBR type, intended for best effort traffic. As a result, the UE must initiate a PDU Session Modification request to the Access Management Function (AMF) to apply enhanced QoS parameters for high-priority traffic. Furthermore, our analysis shows that the OAI release (v2.0.1) does not support automatic QoS mapping. Consequently, the QoS profiles for high-priority flows must be manually assigned in the database that stores the priority levels of the PDU sessions. These findings highlight the limitations of the OAI platform and emphasize the need for further development of its QoS management mechanisms to effectively manage and prioritize data traffic in practical 5G deployments. Further details can be found in our previous work presented in [9].

Time Synchronization. Time synchronization is a critical component in the integration of TSN and 5G networks. A time synchronization approach is needed to enable precise coordination of time across devices for real-time and deterministic communication. Although 3GPP classifies the Precision Time Protocol (PTP), defined by the IEEE 1588 standard [14], as the most promising solution in TSN-5G networks, an effective PTP implementation across both networks required advanced synchronization techniques and specific hardware to ensure precise time alignment for time-sensitive applications. During testing and implementation, we also uncovered interoperability issues between PTP and gPTP protocols requiring compatible network entities that support the relevant PTP profiles. Due to the hardware limitations and the aforementioned challenges, we utilize the Network Time Protocol (NTP) to support the end-to-end communication over TSN-5G networks.

Radio Resource Allocation. A significant and still open challenge for TSN–5G integration is the allocation of 5G radio resources for the transmission of TSN flows, particularly given the diverse QoS characteristics and cyclic schedules originating from the TSN domain [15]. In 5G, radio resource allocation determines how data flows are assigned slots in time and carriers in frequency. The amount of data that a UE can transmit within these allocated resources is further influenced by the channel quality, which varies due to various factors such as mobility, and interference, among others. This dynamic behavior makes the problem even more complex.

Achieving TSN traffic flows requirements in 5G necessitates aligning TSN schedules with the 5G resource allocation mechanisms. Without such coordinated mechanisms, the end-to-end deterministic behavior expected in TSN domains cannot be reliably preserved over a 5G radio interface. Due to the lack of OFDMA support in our hardware configuration, we were unable to assess the effectiveness of various radio resource allocation mechanisms as part of our practical investigation. Therefore, our results presented in [9], demonstrate that the dominant source of end-to-end latency variations comes from the radio interference.

D. System-Level Experiences and Integration Challenges

Message receiving policy implemented by ECUs. In a practical automotive system, ECUs may originate from different vendors, and each can implement a distinct policy for handling incoming messages. Some ECUs rely on a polling-

[2]OpenAirInterface Software Alliance — https://openairinterface.org/

based mechanism, where the software periodically checks the network interface to detect newly received messages. Others implement an interrupt-driven approach, in which the network interface generates an interrupt as soon as a message arrives and the ECU immediately services it. These differing policies lead to variation in message response times and jitter, since polling introduces periodic detection delays while interrupt-based reception minimizes reaction time but may introduce interrupt-handling overhead. Such differences must be considered when designing industrial systems, as they influence not only the reception time of the message at each ECU but also the end-to-end data-propagation delay along a multi-domain CAN-TSN-5G communication chain. Neglecting these vendor-specific reception policies may therefore result in optimistic timing assumptions in end-to-end system analysis.

Lack of synchronization in legacy ECUs. Practical systems may also include legacy ECUs that lack hardware or software support for the time-synchronization mechanisms mandated by TSN. Without a synchronized local clock, these ECUs may experience drift relative to the global network time, which can lead to additional delay, jitter, and misalignment between expected and actual message release times. Since TSN depends on precise timing for traffic shaping, scheduling, and latency guarantees, unsynchronized legacy nodes in the system can introduce unpredictable timing deviations that must be accounted for in system-level analysis [16]. When integrating such ECUs into a heterogeneous architecture, designers must explicitly consider clock drift, potential misalignment of transmission windows, and the resulting variability in end-to-end latencies to ensure predictable and reliable operation.

Integration with the Digital Twin. Integrating real-time data into a digital twin introduces timing and consistency challenges across the CAN–TSN–5G chain. The digital twin depends on frequent and coherent data from the physical system, yet variations in latency and jitter across heterogeneous subsystems can cause the twin to operate on delayed or misaligned data. This is critical when the twin supports the operator assistance, where outdated data reduces accuracy and responsiveness. Lessons learned indicate that reliable digital-twin integration requires accounting for end-to-end delays, compensating for jitter, and ensuring that data streams from different network domains remain temporally aligned. Without such measures, the digital twin may fail to represent the actual system state in real time.

V. Conclusions

In this paper, we investigated the end-to-end communication architecture of a heterogeneous CAN–TSN–5G network and validated its performance in a real industrial setting. The demonstrated use case consists of a private 5G network deployed on a construction site to enable remote operation of a truck-mounted construction crane and illustrated the feasibility and the practical benefits of integrating legacy and next-generation communication technologies within a unified control framework. We presented the practical challenges and lessons learned from the deployment process with the goal to support the researchers, system integrators and industry practitioners in designing heterogeneous network architectures capable of meeting the stringent demands of next-generation industrial systems. The practical challenges and lessons learned are provided per each communication layer i.e CAN, TSN, 5G, as well as for the system-level and overall integration. In addition, we also highlighted several open research challenges that remain to be addressed by the research community.

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