Leveraging 5G Networks & EtherNet/IP: Unleashing the Power of TSN, Clustered Networks, and Deterministic Connectivity for Sensor-to-Cloud Architecture

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Abstract

Industrial Internet of Things (IIoT) technologies are developing rapidly, opening new avenues and revolutionizing the industrial automation landscape. This paper explores the synergistic integration of 5G networks with EtherNet/IP, emphasizing the possible advantages of real-time data communication, deterministic networks, and sensor-to-cloud architecture. With 5G integration as the backbone for Time-Sensitive Networking (TSN) in industrial applications, this paper focuses on converging 3GPP technologies, EtherNet/IP, and high-fidelity communication.

The unique characteristics of industrial Ethernet networks, including real & non-real-time, with short cycles, demand a communication infrastructure that can cater to diverse requirements. This method allows different clusters to communicate simultaneously, ensuring effective data sharing and reducing bottlenecks by using Layer-2 (L2) Tunneling for integrating automation control systems. By leveraging the power of 5G networks driving TSN, organizations can achieve the necessary balance between ultra-low latency, determinism, and high bandwidth. Such a balance also orchestrates the varying needs of diverse applications running in parallel. This paper specifies the prerequisites of the physical layers, network architectures, and other aspects to consider for a functional, safe device. Further, it explores the testbed collaboratively developed by Rockwell Automation, Ericsson, Qualcomm, and Verizon. This collaborative research examines the current state of Industrial Private 5G networks and their compatibility with EtherNet/IP.

This paper includes proposed hardware and software architecture and reference design for anyone looking to start their MVP and reference platform for further evaluation and PoC/Pilot setup. The reference design includes two hardware section, one that runs wireless encapsulation framework and the other that runs the EtherNet/IP CIP applications.

Overall, this paper describes how integrating 5G networks with EtherNet/IP offers a transformative opportunity for industrial automation. This thought paper illustrates how integration (5G+EtherNet/IP) enables real-time data communication, enhances network performance, and empowers industrial enterprises to thrive in digital transformation.

OUTLINE:

I. INTRODUCTION

Smart Manufacturing & OT-IT Convergence

Digitalization is a benchmark every industry uses to achieve greater flexibility, improved responsiveness, and enhanced performance. Industrial communication technologies act as facilitators to achieve this goal. The recent efforts towards improving communication have leaned towards integrating IT technologies with the products, systems, solutions, and services across the automation value chain. The goal is to enable secure, reliable, and seamless access to information at every level. Industrial IoT- comprises of a wide range of devices that cannot be connected over IP-based networks. While Ethernet is popular in industrial architecture, a standardized and integrated way of communication still needs to be included.

- **M2M Communication (Horizontal Communication):** M2M Communication (Horizontal Communication): Machine-to-machine communication is essential to Industrial IoT. IIoT requires transcending from the IT to the OT domain and enabling communication between sensors and actuators. Plant floor equipment/machines and field devices are expected to process data collected from other peer devices.

- **Device-to-Cloud Communication (Vertical Communication):** Vertical communication implies communication across all layers. In a network architecture, the controllers communicate to the SCADA/HMI systems, which then communicate with MES/ERP systems. Such multi-layered and complex communication calls for a seamless exchange of information among heterogeneous systems across multiple layers of the automation pyramid.

Smart manufacturing revolves around networking dissimilar systems within and outside the factory and process boundary. Modern industrial communities and consortiums have made and are making immense efforts toward addressing the horizontal and vertical communication requirements.

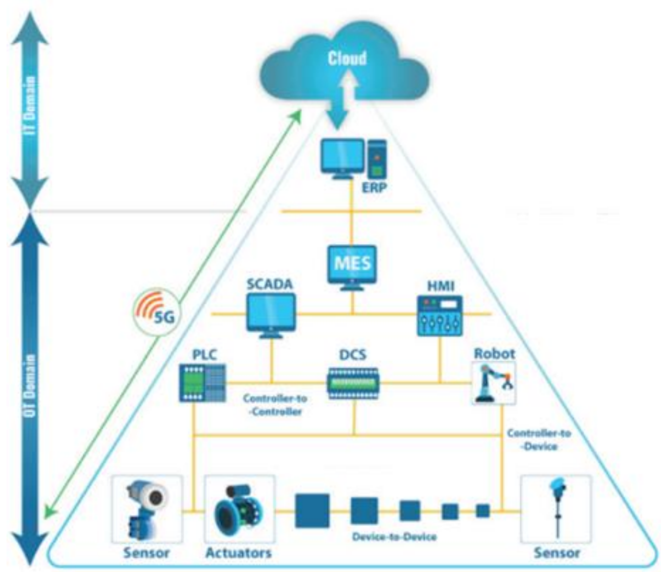


Figure 1. 5G in a Smart Manufacturing Landscape with OT-IT Integration

5G in Smart Manufacturing

Speed is also an important parameter to judge the quality of a network. While wireless networks are considered an alternative for many industrial communications, 5G is the new buzzword industrial enterprises look forward to.

3GPP (3rd Generation Partnership Project) is a standard that creates specifications for mobile networks. 5G is the 5th generation cellular network, up to 100 times faster than the 4th generation 4G network. This modern technology promises to deliver a unified connectivity fabric that will take industrial automation to a new level. The 5G specifications defined by 3GPP include the following elements that make it the next big thing for intelligent factories:

- **QoS (Quality of Service)**: 3GPP has defined four parameters for 5G based on the types of traffic, i.e.,
  - **Periodic Deterministic Traffic**: Stringent requirements are defined.
  - **Aperiodic Deterministic Traffic**: No pre-set sending time, but stringent requirements in terms of timeliness and availability are defined.
  - **Non-Deterministic Traffic**: Specifying lesser stringent requirements.
  - **Mixed Traffic**: Minimum stringent requirements.

- **End-to-End Latency**: As less as 0.5 milli second that goes up to 500 milli seconds
- **Data Rate**: Up to Gbits/second
- **Communication Service Availability**: 99.9% to 99.999999%
- Seamless integration with wired technologies on the same machines

Faster speed, ultra-low latency, and increased bandwidth are some of the highlighting features of 5G. What makes 5G stand out is its capability of network slicing. Being capable of slicing the network, 5G allocates different speed segments to different network slices, thereby defining dedicated bandwidth and network modes. Such features allow 5G to achieve highly improved performance - something that previous cellular network generations could not achieve.

High-band or millimeter wave (mmWave) 5G: High speed but short range. High band 5G frequencies range from 24 GHz to 100 GHz, making it incredibly fast - enabling multi-gigabit per second speeds. But these high frequencies cause trouble going through buildings and walls, making it useful only for short distances.

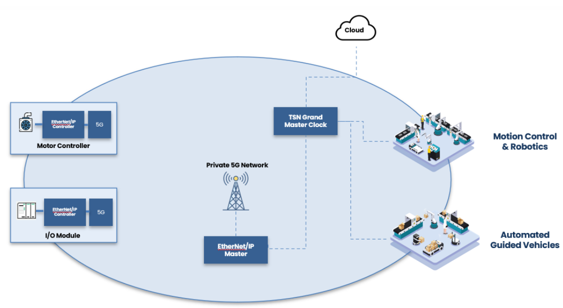


Figure 2.a 5G mmWave Spectrum
Figure 2.b Typical Use Cases of 5G in Smart Manufacturing

5G & Purdue Model for Industrial Automation

Typically, OT environments follow the Purdue model. This model allows robust control and security by building on traffic choke points defined by the mode. Hence, traffic can be easily controlled and secured between the layers. All traffic inside a layer can communicate with other devices in the same layer, but inter-layer traffic is access controlled. Private 5G can easily break this model as it can leapfrog layers, ensuring clean deployment to create the Purdue model or integrate with it.

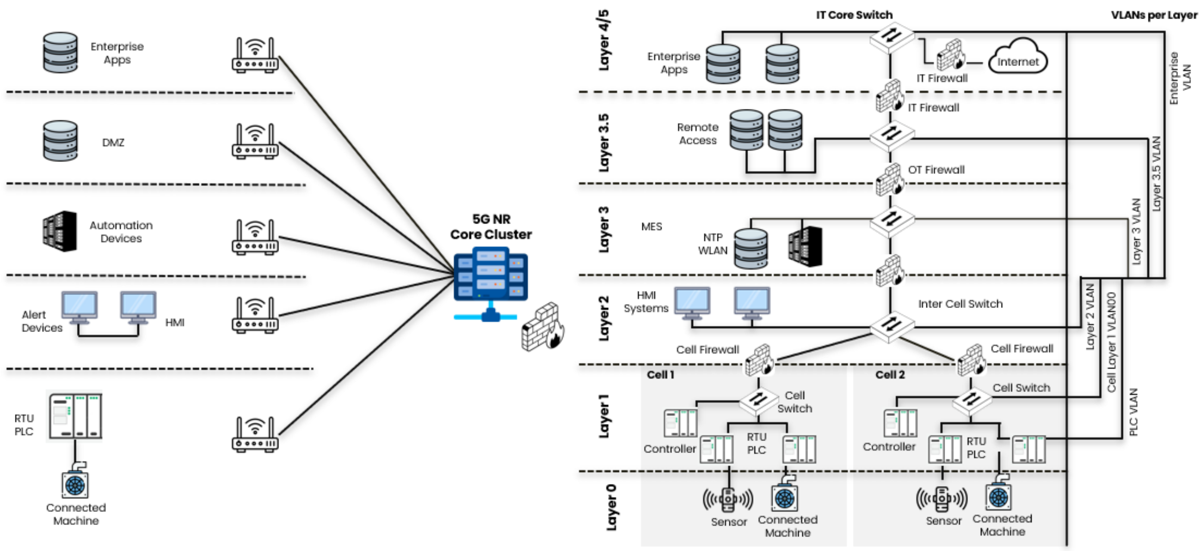


Figure 3. 5G Integration with an OT Environment as per the Purdue Model

EtherNet/IP with 5G Networks

The Industrial Internet of Things (IIoT) is altering the industrial automation environment and opening new opportunities for productivity, efficiency, and creativity. It is crucial to investigate cutting-edge strategies that may fully utilize the potential of IIoT technologies as they develop rapidly. One such strategy is the combination of EtherNet/IP, a widely used industrial communication protocol, and 5G networks to produce a potent synergy that elevates industrial connectivity to new levels.

For real-time data communication, 5G network integration with EtherNet/IP has enormous promise. Such integration allows businesses to transmit crucial data in real-time, enabling quick decisions and prompt solutions to tackle operational difficulties. It also enables a new age of real-time communication, allowing transmission of sensor data from far places, control of machines, and seamless collaboration across various components of an industrial ecosystem.

Deterministic connectivity is possible by combining 5G networks, EtherNet/IP, and TSN. Such a combination enables mission-critical communication and makes it easier to coordinate an organization's entire landscape of time-sensitive processes.

In addition to real-time communication and deterministic networks, the sensor-to-cloud architecture has tremendous potential when a 5G network is combined with EtherNet/IP. Organizations can fully utilize the possibilities of sensor networks to gather enormous amounts of data - thanks to 5G's fast speeds, low latency, and abundant bandwidth. Once the data is processed and examined in real-time, it can be utilized to generate insightful decisions and operational improvements. Organizations can achieve seamless communication, data aggregation, and analysis using 5G networks and EtherNet/IP capabilities.

As organizations embark on their digital transformation journey, integrating 5G networks with EtherNet/IP emerges as a critical enabler. This convergence offers unparalleled opportunities for real-time data communication, deterministic networks, and sensor-to-cloud architecture in the IIoT landscape. By leveraging both technologies' strengths, organizations can overcome existing limitations, optimize operational efficiency, and unlock new avenues for growth and innovation.

This paper explores the synergistic integration of EtherNet/IP and 5G networks, highlighting its many benefits for sensor-to-cloud architecture, deterministic networks, and real-time data transfer. Organizations can overcome conventional constraints, improve connection, and unlock the full potential of the IIoT ecosystem by seamlessly integrating various technologies.

II. SYNERGISTIC INTEGRATION OF ETHERNET/IP WITH 5G NETWORKS

Blended Architecture Mapping to OSI Layer

The need of accurate timing and synchronization are essential to networks' deterministic properties. Due to EtherNet/IP's strong and tested capabilities, deterministic communication is available in industrial applications. Organizations may create deterministic networks that guarantee predictable and consistent performance by integrating 5G networks as the foundation for EtherNet/IP. EtherNet/IP generally has two kind of communication, implicit and explicit.

i. **Explicit Communication:**

Under this type of information exchange, each device communication is a unique 'query-response' pair. Originating from a source as an 'information request', the receiving device or node decodes the query and returns the response to the device/note requesting the query.

Such communication is generally used for non-critical messaging, such as data diagnosis for maintenance purposes. This paper explores the use cases associated with explicit communication.

ii. **Implicit Communication:**

Using EtherNet/IP, such communication between the source and the destination/s is used for time-critical communication. Implicit communication transmission is real-time and is used for high-speed and low-latency applications.

Typically, scheduled exchange of information or notifications between controllers uses an implicit form of information communication.

EtherNet/IP is built upon the foundation of the Common Industrial Protocol (CIP), which follows an object-oriented approach to handle data presentation, connection management, and message exchange across the various layers of the OSI model. By adopting CIP, EtherNet/IP enables seamless integration of automation services and applications like control, synchronization, motion, and safety. A generic OSI layer of Ethernet is described in the figure below:

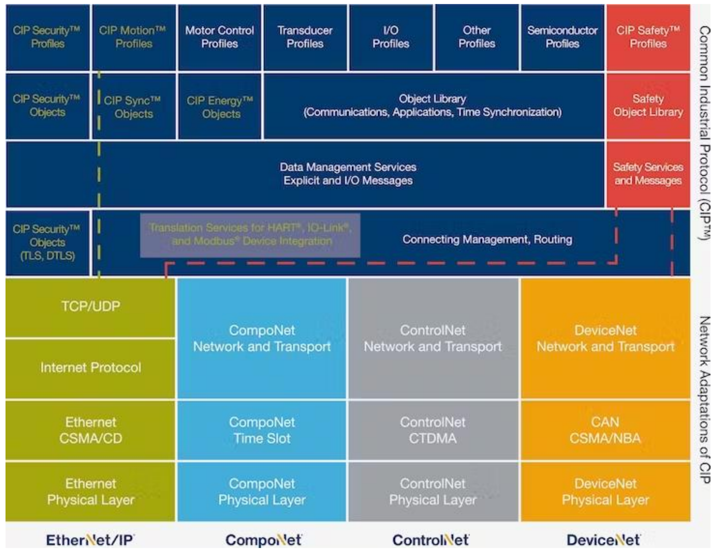
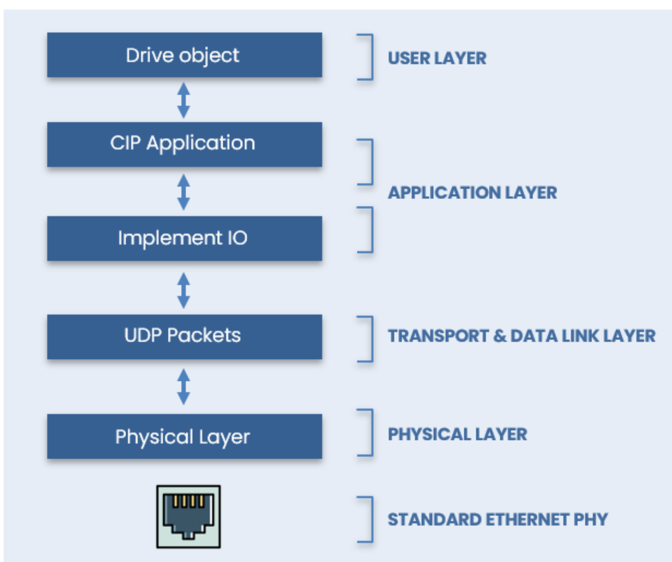


Figure 4. EtherNet/IP as per the typical OSI Layer

The Common Industrial Protocol (CIP) layer is the application layer, with UDP as the underlying transport layer protocol and the physical layer typically based on EtherNet/IP integrated with 5G technology. One of the key advantages of EtherNet/IP is its flexibility in selecting the physical communication medium due to its reliance on CIP and IEEE standards at the application layer. This adaptability allows for a variety of communication setups to suit different requirements.

To ensure successful integration, it is crucial to map EtherNet/IP and 5G networks synergistically onto the OSI stack, with 5G as the physical layer and EtherNet/IP as the application layer. This pairing enables efficient communication and data exchange between the two systems. By leveraging CIP's functionalities and adapting it to work seamlessly with Ethernet and Internet protocols, EtherNet/IP becomes a powerful solution for industrial automation, providing reliable and efficient communication between devices and applications in modern manufacturing environments.



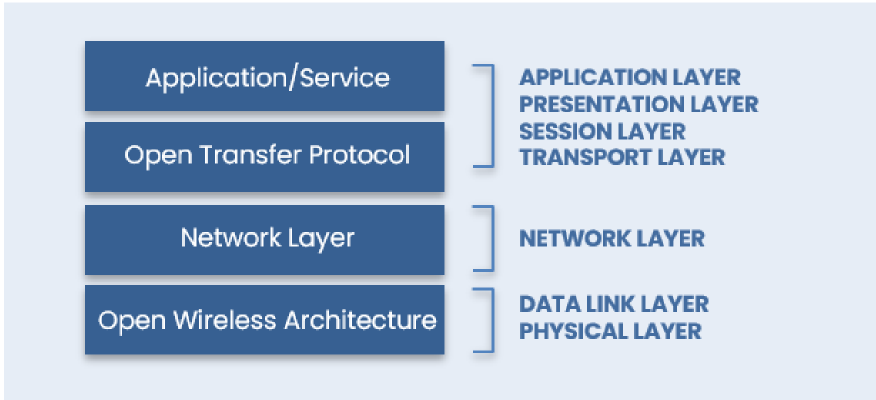


Figure 5. OSI Layer – Breakdown for EtherNet/IP & 5G Integration

The 5G network leverages on MTP – Message Transfer Part, typically used for communication in public switched telephone networks since it is reliable, unduplicated, and in sequence transport of SS7 messages between communication partners. Hence, MTP is used as the protocol for the Network Layer and Data Link Layer for seamless integration.

This paper further explores the basic modeling of EtherNet/IP over 5G and further experiments are underway using the Pilot setup described in the next section.

EtherNet/IP & 5G Test Bed by Rockwell Automation, Ericsson, Qualcomm, Verizon

To fully understand the feasibility of this synergistic integration of two technologies, it is crucial to understand the prior work and evaluation in the area. Four companies - Rockwell Automation, Ericsson, Qualcomm, and Verizon - collaborated on a unique project to test "Private 5G" in industrial settings. They found that this technology can replace wired connections in industrial networks. Designed for industrial IoT and automation, 5G offers reliable and fast connections using private networks and a "millimeter wave (mmWave) spectrum." The test used specific equipment from the companies, and the results showed that the 5G network performed even better than wired connections.

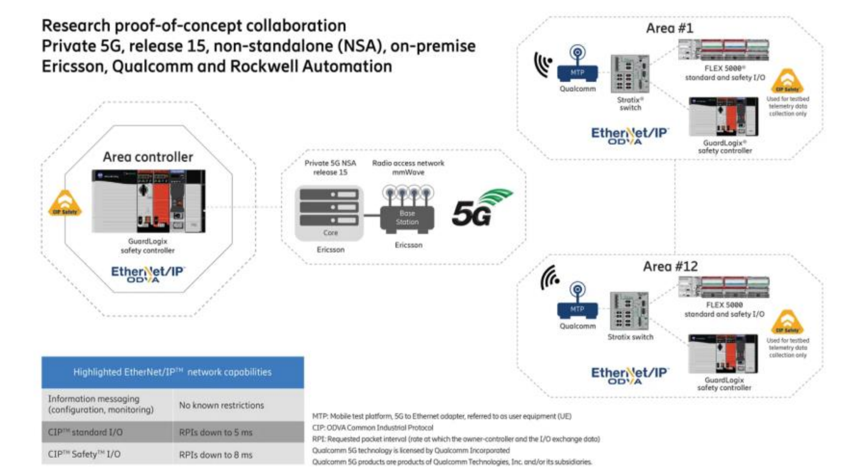


Figure 6. EtherNet/IP & 5G Test Bed
[Reference]: https://www.arcweb.com/blog/rockwell-automation-ericsson-qualcomm-verizon-successfully-test-industrial-private-5g-release

This breakthrough is significant because it eliminates industries needing expensive wired infrastructure. Instead, they can use wireless 5G, saving time, money and being more environmentally friendly. Based on these positive results, the team plans to explore more applications of 5G technology in various industrial settings.

The research proved that 5G technology works well in industries, providing reliable and fast connections without costly wired infrastructure. These benefits can revolutionize industries by saving costs, increasing flexibility, sustainability, and operational speed. The researchers are excited to explore future possibilities for this technology.

Use Case - Motion Control Driver

A typical EtherNet/IP device has an EtherNet/IP Slave Device; for example, Motion Control Driver, the Ethernet I/P Object will be Motor Object. The same EtherNet/IP setup is referred to for bringing in 5G Integration.

The 3GPP specification 16 & 17 Rotary [Reference] for implementation of mission control or specific I/O motor control platform taking a use case of EtherNet/IP motion object as per the above spec. For such motion control use cases, the unlicensed spectrum 17-mmWave-52.6 > 71GHz is suggested to be most suitable for implementing RTT (Round-Trip Time) based method for TSN to achieve deterministic networks.

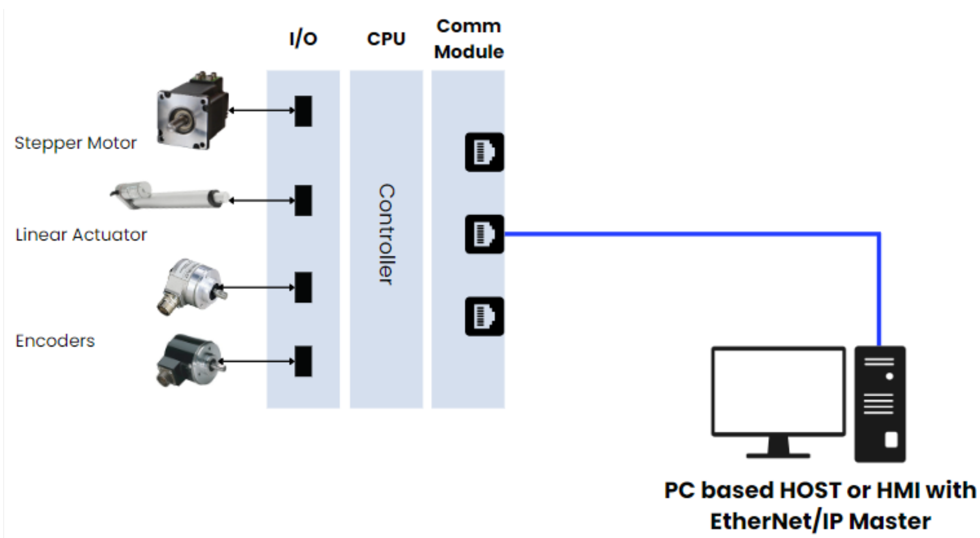


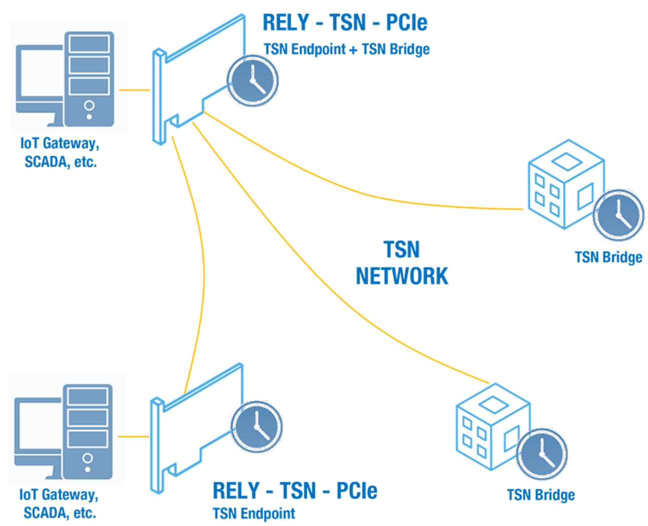
Figure 7. Typical EtherNet/IP Device Setup

Typical Applications

Following are two real-life applications of 5G in industrial automation:

- **Robotic Motion Control:**
  Controlling machine tools, assembly robots, precision AGVs (Automated Guided Vehicles), etc., are some of industrial automation's most demanding use cases of 5G communication systems. These operations require an exceptionally reliable network with high availability and low latency. However, the latency requirements make retransmission impractical with moving equipment on the plant floor. 5G URLLC can be used in this scenario to support the dual need for high availability and low latency by deploying architectures using a robotic arm or AGV.
- **Intelligent Transport**
  With an unprecedented speed, 5G URLLC allows real-time routing, spacing, and controlling trains' operations. Preventing the trains from taking colliding routes, optimizing track usage, maintaining a safe distance, etc., can be reliably carried out with minimal signal latency to optimize transport more efficiently.
- **Factory automation**
  Typical wired factory automation infrastructure can be replaced by a private 5G network with TSN Grant master connecting over the wireless 5G device will minimize the wiring the effort and cost

III. TEST SETUP



A high-level architecture of the test setup to replicate a typical EtherNet/IP-based Motion Control Driver use case is shown in Figure. The test setup to evaluate the integration of EtherNet/IP with a Private 5G Network included an I/O Device connected to an STM32 Evaluation Board with an EtherNet/IP Slave Stack. The objective was to connect the I/O Device with a PC-based Host System with an EtherNet/IP Master.

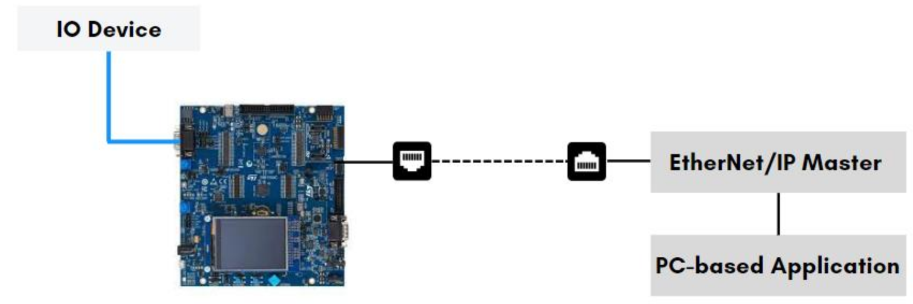


Figure 8 a. Typical EtherNet/IP Device Setup

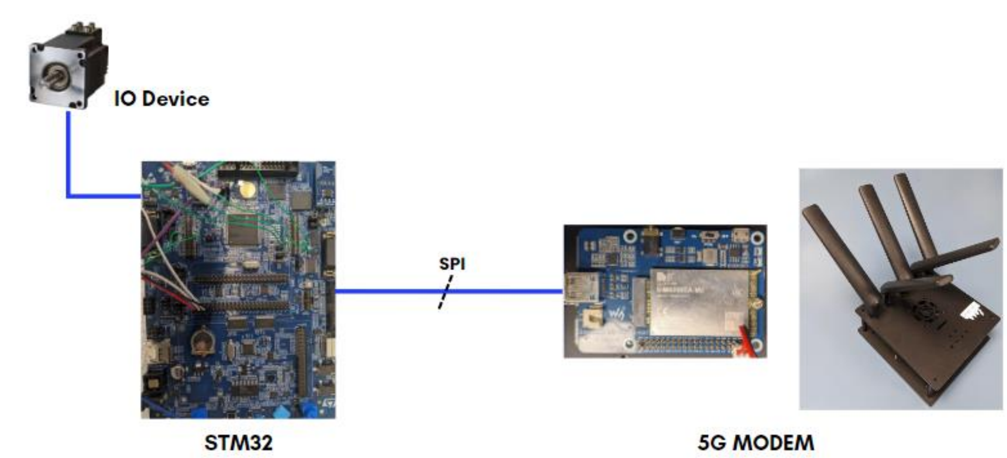


Figure 8 b. EtherNet/IP Device Integration with a 5G Modem

The physical layer between the two systems is leveraged by integrating a 5G modem. SPI communication was used in this blended system. The corresponding OSI architecture to signify this setup is shown below. The Application and Session Control is done by the STM32 Board, UDP Protocol over SPI is used as the Transport Layer, and the 5G Modem is used for the Network and Physical Layer. The mapping against the OSI Layer is shown in Figure 9 to ensure compliance with Ethernet Standards.

The SPI communication between the two hardware was configured as:

- Clock Speed: 1MHz
- Mode : Full Duplex

Figure 9. Blended Architecture - OSI Layer

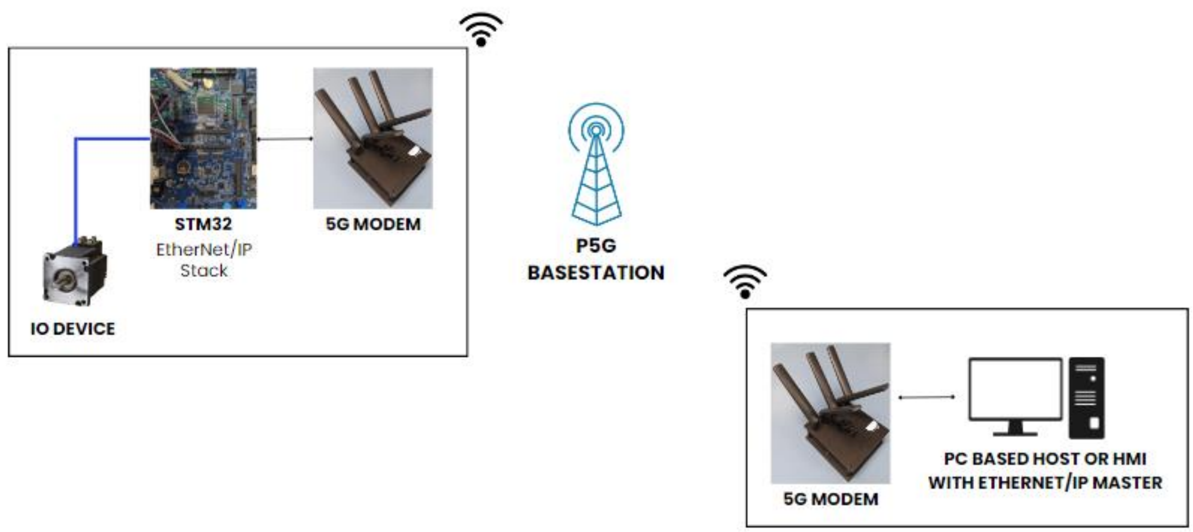


Figure 10. Connecting an IO Device to an EtherNet/IP Master using Private 5G Network

IV. CONNECTED FACTORY OF THE FUTURE

EtherNet/IP Master with I/O Scanner, along with Private 5G forms the basis for Industrial Communication for uses cases like Motion Control, Robotics, and AGVs, as highlighted in the representation below. This forms the bases for a 5G network-based protocol network for connected shopfloor or large factory.

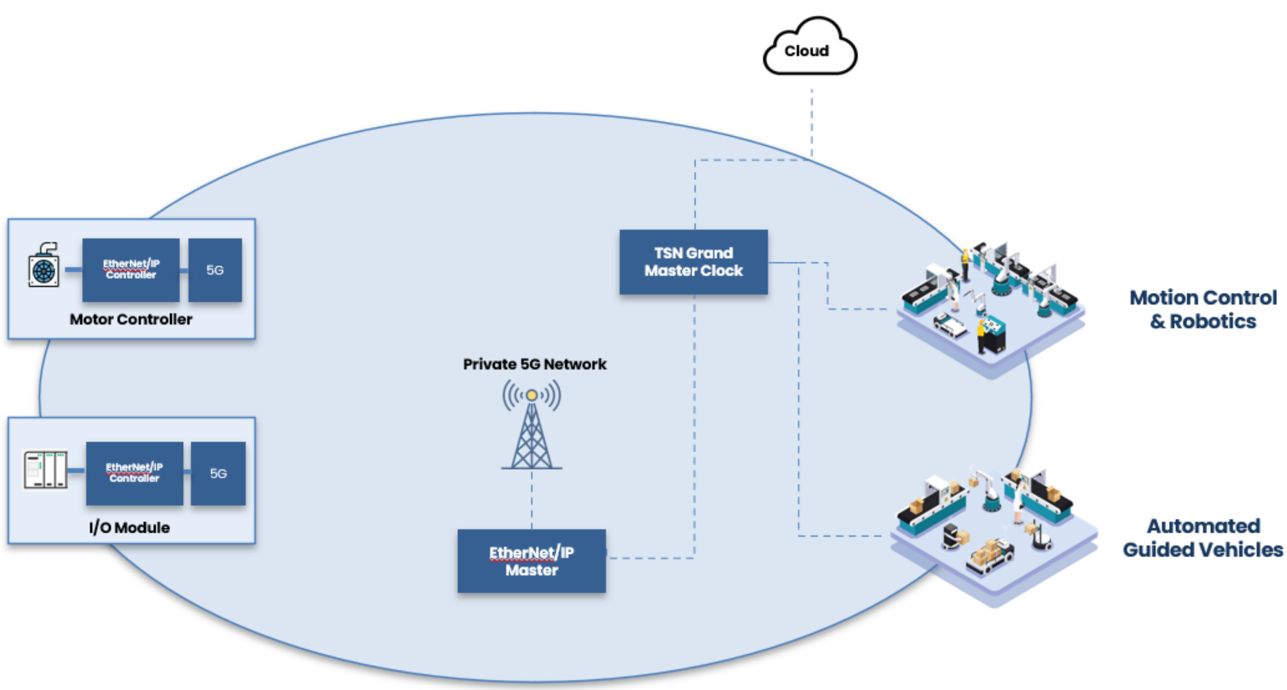


Figure 11. EtherNet/IP Scanner with Private 5G Network for Manufacturing Use Cases

The below section describes the proposed hardware and software architecture for integrating EtherNet/IP with 5G networks. It provides a design reference for anyone looking to start their MVP and a reference platform for further evaluation and PoC/Pilot setup.

Proposed Hardware Architecture

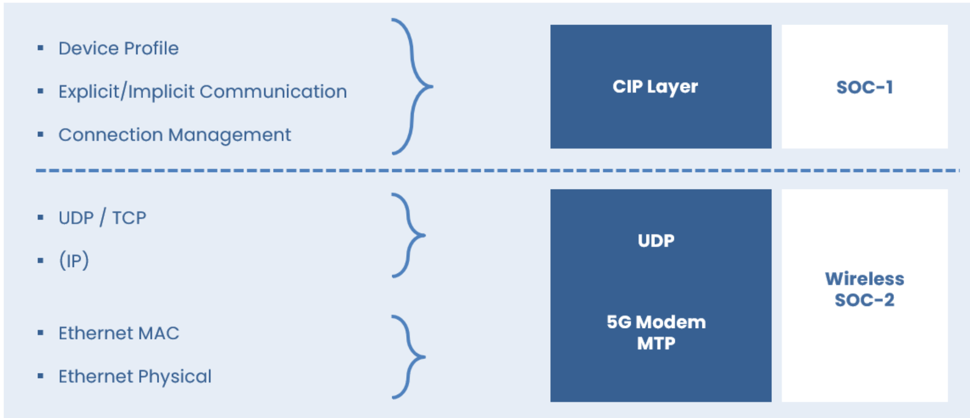


Figure 12. Proposed Hardware Architecture - SoC-1 & SoC-2 Integration & Mapping to OSI Layer

The figure shows the blended architecture for implementing 5G network layer with EtherNet/IP. In this case, two hardware components - SoC 1 & SoC 2 was be used as represented. EtherNet/IP-related implementation is done on SOC 1. The EtherNet/IP specific CIP layer implementation includes the Device Profile and Explicit/Implicit communication. The 5G implementation in SoC-2 was through UDP and MTP. This includes the complete transport to physical layer implementation.

The hardware architecture for SoC-1 & SoC-2 was implemented as per the below hardware schematics. This proposed hardware design provides a design reference for anyone looking to embark on the feasibility study for integrating EtherNet/IP with 5G Networks.

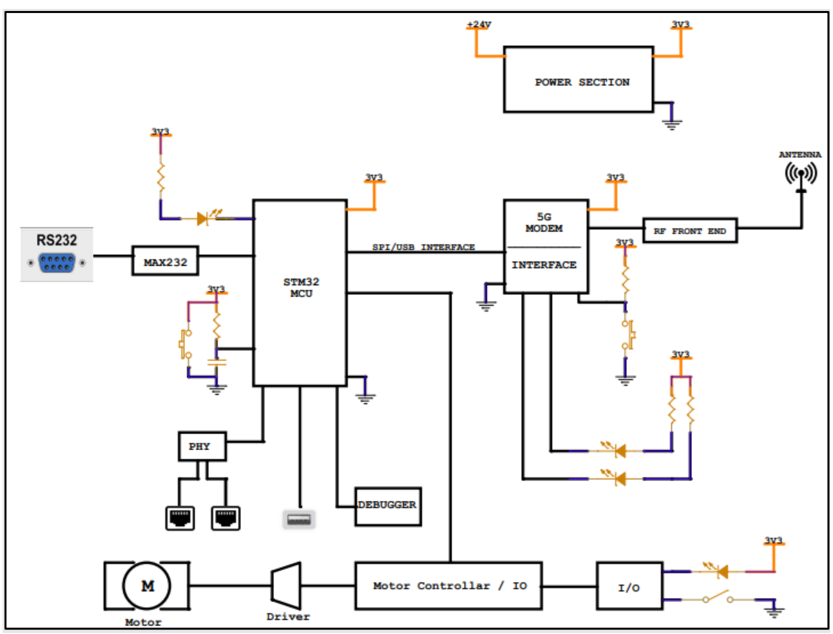


Figure 12. Proposed Hardware Architecture - Reference Design Schematics

Proposed Software & Firmware Architecture

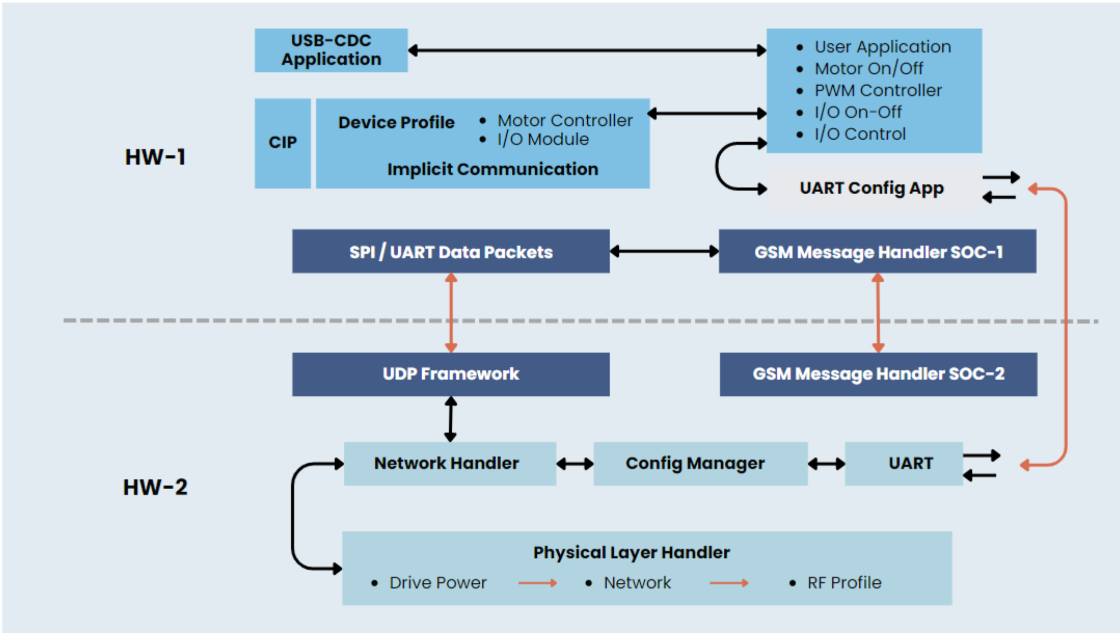


Figure 13. Proposed Software & Firmware Architecture

The above architecture describes the high-level software/firmware architecture of a 5G-based EtherNet/IP Device, which can control a DC motor's speed and handle some of the I/O functions.

- Encapsulation for EtherNet/IP to work with 5G.
- This architecture describes the message handling between the two SoCs.
- The two SoC hardware are interconnected over an SPI bus to have a maximum 10mbps connection.
- Inter-chip connection over serial (UART) interface with a USB-CDC connection device class was used to configure the SoCs.

V. CONCLUSION

The amalgamation of 5G networks with EtherNet/IP represents a pivotal advancement in industrial automation, further bolstered by the potential of Time-Sensitive Networking (TSN). This synergy promises ultra-responsive, deterministic, and broad bandwidth communication platforms uniquely suited to the multifaceted requirements of modern industrial ecosystems. Drawing upon collaborative insights from leaders like Rockwell Automation, Ericsson, Qualcomm, and Verizon, this integration crafts a foundational pathway for organizations aiming to exploit the full spectrum of real-time data communication. The outlined hardware and software architectures not only facilitate streamlined MVP developments but also position industries at the vanguard of a burgeoning digital evolution.

Keywords
EtherNet/IP, 5G, Time-Sensitive Networking (TSN), 3GPP, Deterministic Networks, Ultra-Low Latency, Functional Safety
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