REPORT ON SYSTEM DESIGN OPTIONS AND 5G/6G SETUP FOR TRACKING, MONITORING, AND INLINE QUALITY ASSURANCE IN MANUFACTURING

Deliverable D2.1

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SHORT ABSTRACT	This deliverable contains a detailed description of the use cases designed and developed in the vertical manufacturing for the cloud-native production testbed in TARGET-X.

KEY WORDS	Trail sites, manufacturing, 5G, 6G, real-time, localization, smart sensors, inline process monitoring
CONTRIBUTOR(S)	Pierre Kehl (IPT), Praveen Mohanram (IPT), Roberto Padovani (MARP), Dirk Lange (MMS), Daniel Overbeck (MMS), Oliver Tamori (MEG), Karsten Kötter (MEG)

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Executive Summary

This deliverable contains a detailed description of the use cases designed and developed in the vertical manufacturing for the cloud-native production testbed in TARGET-X. In a first step the following use cases are presented:

Environmental Condition Monitoring: Wireless sensors that are integrated into workpieces or machines to monitor various parameters, such as electric power of the machine, air flow provided by the compressors or vibrations at spindle and machine structure.
Track and Tracing of Workpieces: In this manufacturing use case, the condition and location of a workpiece will be monitored and tracked throughout the manufacturing process. Parameters such as vibration, temperature, environmental conditions, and workpiece orientation are monitored using onboard sensors.
Inline Quality Assurance for Machining: By using 5G/6G and industrial Ethernet, real-time wireless sensing is enabled, allowing sensors to be connected via industrial fieldbus protocols such as CC-Link IE TSN. The data is transmitted via 5G to a PLC integrated in the machine for process control and can also be sent to a factory cloud system for optimized data usage and the creation of a digital twin.

Further, for each use case the requirements towards the communication infrastructure are defined. From these requirements, 5G/6G features that are needed to meet these requirements are derived and discussed.

In a second step the design options for all use cases are presented on the software, hardware and the factory cloud level.

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List of Acronyms and Abbreviations

AAS	Asset Administration Shell
AI	Artificial Intelligence
BLE	Bluetooth Low Energy
BLISK	Blade Integrated Disk
CAM	Computer Aided Manufacturing
CC-Link IE	Control & Communication Link Industrial Ethernet
DetNet	Deterministic networking
DT	Digital Twin
IETF	Internet Engineering Task Force
IEEE	Institute of Electrical and Electronics Engineers
IMU	Inertial Measurement Unit
LPWAN	Low-Power Wireless Area Network
LoRaWAN	Long Range Wide Area Network
LWM2M	Lightweight Machine-to-Machine
MAC	Media-Access-Control
MQTT	Message Queuing Telemetry Transport
MSP	Multi Sensor Platform
NTP	Network Time Protocol
OPC UA	Open Platform Communications Unified architecture
PLC	Programmable Logic Controller
PTP	Precision Time Protocol
RFID	Radio-Frequency Identification
TSC	Time-Sensitive Communication
TSN	Time-Sensitive Networking
URLLC	Ultra Reliable and Low Latency Communications

1 Introduction

The industrial automation is undergoing a digital transformation – also referred to as Industry 4.0. Connecting the physical production world to a digital representation can provide flexibility and efficiency gains through better observability, control and planning of the automation system. Interconnecting multiple machines, devices, the factory cloud, and people, makes information accessible from anywhere in a factory. The resulting full transparency across processes and assets transforms the production plant into a cyber-physical production system. Smart manufacturing is made possible by adopting novel paradigms such as cloud computing, embracing digital twins and applying Artificial Intelligence (AI) in the management and control of manufacturing processes.

This document aims to explore the potential of 5G/6G technology in the manufacturing industry, focusing on various use cases and design options. The document starts with a trial site description, setting the context for the subsequent discussions. It then delves into the use cases of 5G/6G technology in manufacturing, beginning with wireless production monitoring. This section includes descriptions of use cases such as Environmental Condition Monitoring and track and tracing of workpieces. Moreover, the document outlines the requirements for wireless production monitoring in manufacturing, ensuring that the implementation meets the industry's standards. It also identifies the beyond-5G features necessary to enhance the effectiveness of these use cases, taking into account the advancements in technology. Additionally, the document explores another use case: Inline Quality Assurance for Machining using 5G/6G PLC to remote station communication. It provides a detailed description of real-time condition monitoring and outlines the requirements specific to this use case. It also highlights the beyond-5G features required to maximize the benefits of condition monitoring in manufacturing processes.

Furthermore, the document presents design options for smart sensors, covering the overall architecture, hardware setup, and software setup. It explores both embedded software and cloud software solutions, providing insights into the technical aspects of implementing and integrating these systems. Lastly, the document examines the design options for condition monitoring using 5G/6G PLC to remote use case, including the field-level architecture and cloud-level architecture. These design options highlight the connectivity and communication capabilities of 5G/6G technology in the manufacturing environment.

Overall, this document serves as a comprehensive guide for organizations looking to leverage 5G/6G technology in the manufacturing industry. It explores use cases, requirements, and design options, providing valuable insights for informed decision-making and successful implementation.

1.1 Objectives of the document

The purpose of this document is to analyze the requirements for 5G/6G in various applications and communication streams related to '5G for cloud native production', which can be utilized by WP1. It also aims to define the requirements associated with 5G technology and provide insights for the advancement of 5G/6G connectivity technologies, which can be used by WP6. A comprehensive range of different architecture options should be presented to stakeholders, ensuring that they have a thorough understanding of the available choices. This will enable them to make informed decisions based on their specific requirements, preferences, and constraints.

1.2 Relation to other activities

The content provided in this deliverable is closely related to other activities carried out in other WPs of the TARGET-X project. In particular, the initiatives related to establishing 5G network requirements and aligning use case requirements across TARGET-X verticals, led by WP1 (Methodological assessment framework) and WP6 (Technology evolution beyond 5G) as outlined in deliverable D1.1. Moreover, collaborative efforts between WP2 and WP6 resulted in the identification and definition of beyond 5G technologies for the specific use case outlined in WP2. These advancements are detailed in deliverables D6.1 and D6.3.

2 Trial site description

The implementation and validation of the manufacturing use cases in TARGET-X will take place in Aachen, at the Fraunhofer Institute for Production Technology IPT. In Aachen, IPT has a total area of 9000 m² at its disposal. Of this, around 5000 m² is used as laboratories and machine halls equipped with various kinds of machine tools from different vendors, thus representing a realistic shop floor environment.

- 5-axis and 3-axis milling machines (Georg Fischer Machining Solutions, Makino, Starrag, Heller, etc.).
- Combined milling and turning centers (DMG Mori).
- 5-axis and 3-axis laser structuring machines (Kern, Axis, Fraunhofer IPT, etc.).
- Injection molding machines with different sizes (Arburg).
- 400t-press for metal blanking (Schuler).
- Tool grinding machine (Walter).

Figure 1: Fraunhofer IPT shopfloor.

- Multi-tool robot cell with laser structuring, tool spindle and 3D-sensor (ABB, Scanlab, Zeiss).
- EDM and ECM machines (Georg Fischer Machining Solutions, EMAG, Makino).
- Temperature-controlled measurement laboratory with high-precision coordinate measuring machine and 3D-fringe projection system (Zeiss, Steinbichler).

The shopfloor is equipped with a 5G research network from the swedish mobile communications supplier Ericsson. Together with various partners, concepts and application-ready industrial solutions for networked, adaptive production are being developed: Research is conducted here in an ideal production environment: a landscape of sensor systems and communication technologies that enables an intensive examination of 5G technology. The versatility of the testing possibilities and the cooperation partners enable TARGET-X to investigate an industry-oriented validation of the use cases [1].

3 5G/6G use cases in manufacturing

3.1 Wireless production monitoring for manufacturing

In many manufacturing industries, it is necessary to monitor the condition of the workpiece and track it. This monitoring allows the industry to provide quality control and checks, improve efficiency, and enhance productivity using advanced techniques such as predictive maintenance, advanced control loops to avoid defects, and digital twins [2]. Since manufacturing involves many steps and various stages that require the workpiece to move from place to place, it is necessary to track the workpiece along the manufacturing line. This track and tracing allows industries to have quality assurance and process optimization.

Typically, to monitor the condition of the workpiece, the parameters that affect the workpiece are monitored using wired sensors connected to the workpiece. These sensors include vibration, strain, temperature during the process, and environmental conditions such as humidity, air quality, etc. . Although efficient, it comes with challenges and provides limited mobility. Additionally, to track the workpiece as it moves over the shopfloor, the sensor platform must be mobile, requiring them to be sent over the wireless network while providing real-time data with low latency.

To track the workpiece, traditional methods include Radio-Frequency Identification (RFID) and barcodes to track each location manually but it does not provide real-time location details. For larger outdoor areas, a GPS module could be used to tag the location as it moves through different areas. Within the shopfloor, it is either done manually or using technology such as RFID or Bluetooth beacons to estimate the location and track it. These solutions are limited in accuracy and tracking area. 5G/6G on the other hands, can offer an accurate and shopfloor wide localization.

With 5G/6G technologies supporting Massive Machine Type Communications (mMTC) and Ultra Reliable and Low Latency Communications (URLLC), new devices and mechanisms can be developed and the sensor's data acquisition can match the mandatory industrial requirements such as low latency and high reliability, making it more suitable for wireless communication for real-time applications. With the localization features, the 5G/6G features not only interconnect the devices but also offer information such as the position of the device and the machine with accurate time stamps for the fusion of sensor and network data. In combination with the Asset Administration Shell (AAS), this data can be stored and accessed efficiently in the Factory Cloud for flexible monitoring and control of production. In WP2, such a tracking device will be developed.

3.1.1 Use Case Description: Environmental Condition Monitoring

The first use case in work package 2.1 is shown in Figure 2. The goal is to have a mobile data acquisition device to monitor the condition and energy consumption of a machine tool in the IPT shop floor. The data is provided by the device using common protocols such as Message Queuing Telemetry Transport (MQTT) or Open Platform Communications Unified architecture (OPC UA) and the actual monitoring is done on a server at IPT.

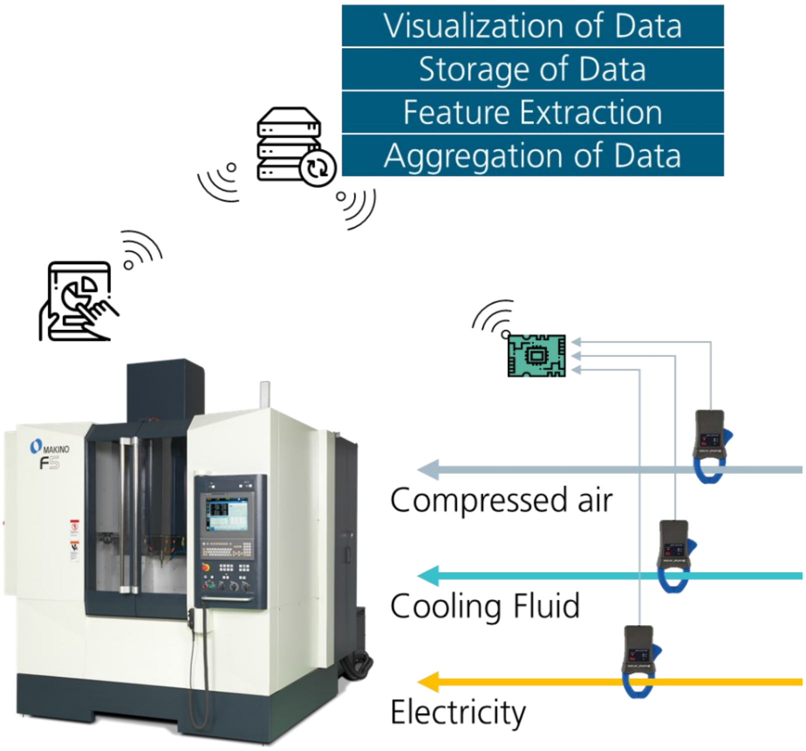

Figure 2: Use Case environmental condition monitoring.

Monitoring environmental conditions in manufacturing industries is crucial for several reasons, including regulatory compliance, sustainability, and overall operational efficiency of machines. This can be achieved by following the environmental and machine conditions in real-time and observing for anomalies. The following parameters need to be measured that are necessary for the industry:

Environmental Consumption:

- electric power of the machine
- air flow provided by the compressors
- coolant flow provided by the pumps

Condition Monitoring:

- vibrations at spindle and machine structure
- temperature of the spindle and machine
- humidty and temperature of the process
- orientation of the workpiece

The data is then transferred via 5G to the base station of the private 5G network at the Fraunhofer IPT in Aachen. The 5G modem is provided by Fivecomm and can be connected directly to a single board computer. Whether a Raspberry Pi or another device such as the Portenta X8 will be used for this purpose has yet to be determined by the project partners.

Sensors are integrated into the workpiece to monitor the parameters that affect the condition, such as vibration, temperature, orientation, humidity, etc. All this data is processed and sent to the factory cloud for applications such as condition monitoring, control, and Digital Twin. In order to optimize the process and make it more efficient, sensors are integrated directly into the machine that measures the energy consumed, CO2 and coolant flow rate, humidity, pressure, and airflow inside the machine work area. All this information is sent via 5G/6G to the factory cloud.
After the process, the workpiece, along with sensors, is moved to another process, which requires it to be tracked.

The factory cloud is connected directly to the base station and receives the information from the sensors. The machine process data is also sent to the factory cloud. The factory cloud hosts applications such as AAS, Digital Twin, and Condition monitoring, where the data streams from the sensor is analyzed and fused with process data to realize the application.

3.1.2 Use Case Description: Track and Tracing of Workpieces

In a manufacturing environment, each workpiece moves through different stages before finally being assembled into a product. The condition of the workpiece needs to be monitored and tracked along the various stages of the manufacturing process. This is done for several reasons, including quality control, process optimization, and meeting specific manufacturing requirements.

In this use case, the workpiece must be tracked and traced along its manufacturing lifecycle. For track and tracing, the following parameters must be monitored:

- Vibration on the workpiece
- Environmental conditions: humidity, pressure, temperature
- Workpiece orientation: 6 axis Inertial Measurement Unit (IMU) (accelerometer and gyroscope)

Additionally, for device power management, a fuel gauge and current sensor are attached to monitor the battery health.

To track the workpiece, the combination of 5G features and the onboard sensors are used to estimate the location of the asset. This could be using 5G cellular triangulation or sensor fusion of the onboard IMUs.

Figure 3 : Track and tracing of the assets using 5G wireless sensor platform.

All these data are sent to the factory cloud over 5G. The applications on the factory cloud receives the data, analyzes the information, and logs into the database. This information is then used to create live asset tracking, a digital map and digital twin applications to provide real-time insights about the assets.

The technical requirements on the sensors and 5G communication link may vary widely between applications and have a close relationship with battery life. Within an application, the performances may also change during operation: as an example, during a milling operation one may want a continuous vibration monitoring, which could be turned off to save battery at other times. Workpiece orientation may be a static information during milling but be turned on in a live information during transportation between stations. Therefore, sampling frequency can range between 1000 sample/s to 1 Sample/s or less. The same is true for strain measurement. Nevertheless, given the throughput available in 5G, none of them is of any concern; on the contrary, a latency requirement may be of interest if alarm thresholds are applied to running measurements. In such case, a common requirement in the field of machining is to receive an alarm signal in less than 10ms.

3.1.3 Requirements for wireless production monitoring for manufacturing

Low latency: The use case mainly involves sending the data from the sensors from the field to the factory cloud over 5G. For condition monitoring during manufacturing, the data from sensors such as Vibration, coolant flow rate, and machine power reading are sampled at high speed. After digitalization the sensor reading results in a data package every few milliseconds. These data packages must be transmitted as quickly as possible with relatively low latency to the cloud to process, analyze, and provide accurate data feedback control and digital twin analysis.

Data bandwidth: More than one sensor is connected to a single platform for asset tracking and condition monitoring of the workpiece and machines. All the sensors acquire data simultaneously and send it to the factory cloud. After digitalization, the combined data rates from the sensors are high, with data samples aggregated and sent every few milliseconds.

Time synchronization between sensor platforms: Time synchronization is essential for maintaining the data integrity of connected sensor platforms. Synchronizing the sensor platform with the factory cloud system enables precise estimation of the generated data. This accuracy is crucial for real-time data monitoring, control, digital twin applications, and accurate analysis. Typically, services like Network Time Protocol (NTP) and Precision Time Protocol (PTP) are used.

Positioning: The 5G-enabled sensor platform is integrated into the workpiece through various manufacturing stages. To track and trace the product, the accurate positioning of the sensor platform inside the 5G Service area needs to be known. Additionally, to support the positioning, the orientation data needs to be sent to the system to fuse data with 5G and another wireless system to get better accuracy. Table 1 and Table 2 provide the technical requirements of the sensors used in both use cases.

With these different data flows in mind, the following requirements are defined for the wireless 5G/6G link:

Table 1: Sensors used for environmental condition monitoring and the resulting performance requirements.

SENSORS	SAMPLING FREQUENCY	RESOLUTION	PERIODICITY	DATA RATE	RELIABILITY
VIBRATION SENSOR	>16 KHz	>16 bit	Every 3 msec	≥256 Kbits/sec	99.999%
TEMPERATURE	> 1Hz	>16 bit	Every 1 sec	≥16 Kbits/sec	99.999%
COOLANT FLOW RATE	>1KHz	>16 bit	Every 10 msec	≥16 Kbits/sec	99.999%

AIR FLOW RATE	>100 Hz	>16 bit	Every 10 msec	≥1.6 Kbits/sec	99.999%
POWER MEASUREMENT	>16 KHz	>16 bit	Every 3 msec	≥256 Kbits/sec	99.999%

Table 2: Sensors used for track and tracing and the resulting performance requirements.

SENSORS	SAMPLING FREQUENCY	RESOLUTION	PERIODICITY	DATA RATE	RELIABILITY
DIGITAL ACCELEROMETER	2-5 KHz	10 bit	Every 1 msec	3 Kbit/sec	99.999%
TEMPERATURE	1 Hz	8 bit	Every 1 sec	8 bit/sec	999.999%
HUMIDITY / PRESUSRE	1 Hz	10 bit	Every 100 msec	8 Kbit/sec	99.999%
GYROSCOPE	100 Hz	10 bit	Every 3 msec	1 Kbit/sec	99.999%
FUEL GAUGE/ CURRENT SENSOR	100 Hz	10 bit	Every 100 msec	1 Kbit/sec	99.999%

Data is typically buffered in the micro processing module and then sent as an upstream packet of a fixed size, as data is sent every millisecond for each sensor. The sensor platform also has a downlink stream. This is used to reconfigure the sensors according to the application requirements at runtime. A summary of the data streams is given in the table below, taking into account the above considerations.

Table 3: Summary of performance requirements of the wireless production use cases.

DATA STREAMS	AVERAGE DATA RATES	DATA STREAMS PERIODICITY	RELIABILITY	PACKET SIZE

MEASUREMENT DATA (UPLINK)	1 Mbit/sec	20 msec	99.999%	500 byte – 1024 byte
CONFIGURATION AND NOTIFICATION DATA (DOWNLINK)	<1 Kbit/sec	NA	99.999%	1024 byte

3.1.4 Beyond 5G features needed for the use case

5G RedCap devices: With high performance already provided by the Rel 15 devices, the primary focus would be the energy efficiency of the sensor system. The primary power consumer in a wireless sensor platform is the 5G module, with the new Release 17 devices, called RedCap devices, offer a balance in latency, reduced bandwidth, and throughput but with much lower power consumption.— New devices such as e.g. RM255C will be evaluated along with the current Rel 15/16 devices.

Localization: The feature of 5G will further be extended to provide an indoor cellular location to enable tracking of the assets where the 5G sensors are integrated. To support the positioning for better accuracy, other technologies, such as IMU sensor fusion and Bluetooth Low Energy (BLE) or Long-Range Wide Area Network (LoRaWAN), will be used with 5G to provide a tracking feature.

Time synchronization: Time synchronization is critical for sensor applications to ensure that different sensor systems within the network work in perfect coordination. By synchronizing time across the network, accurate time information can be shared. This enables the factory cloud system to know the date of the data generated. This is critical for applications such as real-time digital twin and process control.

Asset Administration Shell (AAS): The adoption of AAS in industrial production ensures compatibility and interoperability with different standards and technologies. This facilitates a large-scale data exchange on the shopfloor, but also with the factory cloud and the 5G network. Network resources can be requested on demand, prioritizing safety critical applications for example. The integration of the AAS in the industrial 5G network is one main goal of TARGET-X.

3.2 Inline Quality Assurance for Machining

3.2.1 Use Case Description: Inline Quality Assurance for Machining

Figure 4: Milling of a BLISK with integrated 5G-Sensor for wireless monitoring of the workpiece.

Machine tool processes such as milling and turning are very complex to be handled especially for high quality workpieces such as Blade Integrated Disks (BLISK) [3], see Figure 4. Small changes in the parameters or wear of the work-tool can cause a high decrease in workpiece quality and can cause rejects. Therefore, the workpiece needs to be verified frequently at a metrology laboratory for quality assurance of the product. This is costly in terms of measuring machines, the time of the measuring expert and the time that the process needs to stop for quality assurance. An alternative is an inline quality control and assurance system inside the machine. The data of the workpiece, work tool and the machine itself can be monitored and used to determine if the process is running as planned. First industrial sectors are testing the capabilities of 5G for the monitoring of manufacturing processes, showing great potential for ubiquitous connectivity [4]. State-of-the-art monitoring systems are connected with specific field-bus systems such as PROFINET, PROFIBUS or CC-Link IE [5]. These systems use a wired connection and are mostly vendor specific, decreasing the interconnectivity of the 18olutionn and the flexibility of the process itself. For milling or turning processes, a cable reduces the degree of freedom of the machine, making the Computer Aided Manufacturing (CAM)-planning more complex. Thereby, such wired systems have no sensors directly connected to the workpiece and measure only the machine behavior.

In the last years, deterministic communication services such as Time-Sensitive Networking (TSN) or Deterministic Networking (DetNet) are slowly establishing themselves in the industrial domain for wired communication. They offer more flexibility and interoperability due to the compliance to the OSI Reference Model, and with 5G/6G. Using 5G/6G as wireless bridge in such a real-time capable network, enables placing sensors inside the machine directly on the workpiece, monitoring the process behavior, without interfering with the degrees of freedom needed for the process. The goal of the condition monitoring using 5G/6G PLC to remote communication use case is to validate if 5G and Ethernet can be used for wireless real-time sensing during machining processes.

The high-level architecture proposed in TARGET-X is shown in Figure 5. Different sensors are connected directly to the workpiece inside the machine, gathering live data from the process to enable an optimized process control and design. The data is then sent to a remote station connected via 5G to the PLC integrated in the machine. For an optimized usage of the data besides process control, a connection to a factory cloud system is established. The factory cloud hosts the digital twin (DT) of the process, product and the machine used to optimize the planning and execution and subsequent tracing of the workpiece.

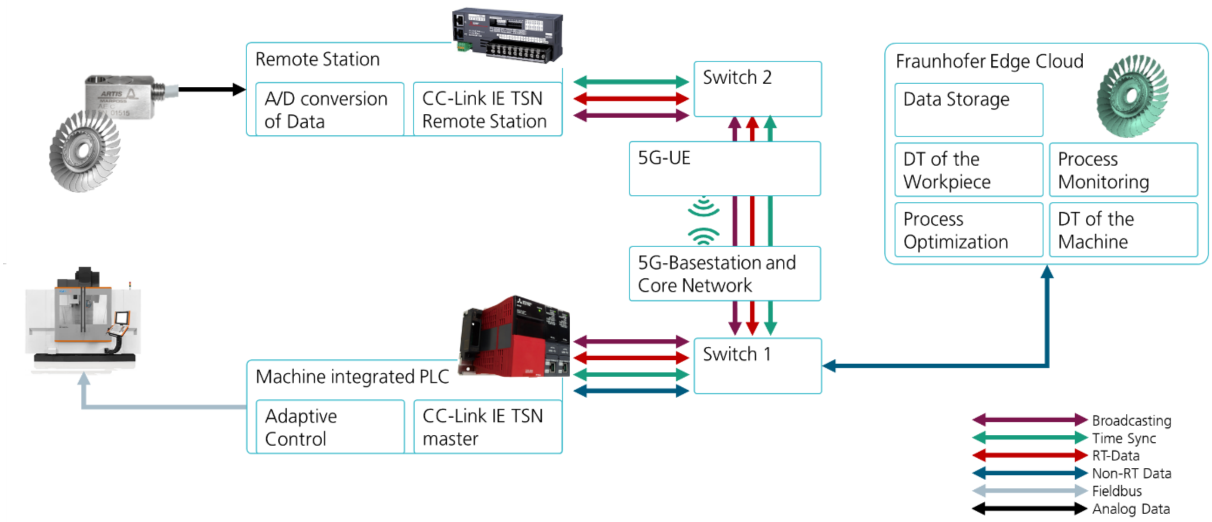

Figure 5: High level architecture of the use case Inline Quality Assurance for Machining.

3.2.2 Requirements of the use case condition monitoring

To feed-back the sensor data to the PLC, controlling the machine and to optimize the process, the requirements towards the communication are in terms of real-time, availability and reliability very high [6]. If the communication does not suit the requirements, damage of the workpiece the machine or the worker are the consequences. Thus, industrial protocols such as CC-Link IE TSN [7] have high requirements on the communication infrastructure and check regularly if these are met. If the protocol detects irregularities, the communication is shut down and the process is being stopped. Commercial of the shelf monitoring systems for tool breakage, anomalies or collision detection, are capable of sending the stop signal within 1 ms to the machine PLC. As shown in Figure 5 five different communication streams need to be considered when defining the requirements:

Analog Data: The Analog data from the sensor provides a continuous and precise representation of real-world measurements, allowing for accurate monitoring and control of industrial processes. The analog to digital conversion takes place on the remote station.

Fieldbus: A significant number of machines in production offer only interfaces for fieldbus protocols in industrial settings. This is because fieldbus protocols offer a proven and widely adopted communication standard that allows for seamless integration of diverse devices, simplifies wiring, and provides real-time control capabilities, making them a preferred choice in many industrial applications. In TARGET-X, the connection between machine and PLC will also be fieldbus based, enabling other companies to use the solution for retrofitting their machines.

Non-RT-Data: The integration and interaction with the factory cloud takes place with non-real-time communication. The factory cloud is utilized for tasks such as historical analysis, predictive maintenance, process configuration and hosting the digital twin. These tasks can be performed with soft- or non-real-time.

RT-Data: The control data for the closed-loop application needs to be transmitted in real-time. It is essential to ensures precise and timely adjustments to maintain stability, accuracy, and responsiveness in critical industrial processes. Further for safety reasons a high reliability and availability is needed.

Time Sync: Time synchronization is crucial for closed-loop applications to ensure that different devices and components within the system operate in perfect coordination. By synchronizing time across the network, precise timing information can be shared, enabling accurate sequencing of events, coordination of actions, and synchronization of data acquisition, which is vital for achieving optimal performance and reliability in closed-loop control systems.

Broadcasting: Broadcasting is used in industrial communication to efficiently connect devices with each other by allowing a single message to be simultaneously transmitted to multiple recipients on the network. This enables devices to receive important updates, commands, or status information. In CC-Link IE TSN, a layer 2 broadcast by the PLC is used to find all the remote stations in the network. Only if this message is transmitted correctly, the devices find each other and can start to communicate.

With these different data flows in mind, the following requirements are defined for the wireless 5G/6G link:

Table 4: Performance requirements for the wireless communication of the use case condition monitoring.

DATA STREAMS	AVERAGE DATA RATES	DATA STREAMS	AVERAGE DATA RATES	DATA STREAMS
MEASUREMENT DATA (UPLINK)	< 1 Mbit/sec	< 7 ms	99.999%	99.999%
CONFIGURATION AND NOTIFICATION DATA (DOWNLINK)	<1 Kbit/sec	NA	99.99%	99.99%

Table 5: Complementary requirements for the wireless communication of the use case condition monitoring.

DATA STREAMS	MESSAGE SIZE	TRANSFER INTERVAL	END DEVICES	VELOCITY	MESSAGE SIZE	TRANSFER INTERVAL
MEASUREMENT DATA (UPLINK)	908 bytes	7 ms	mobile	1-x m/s	50	Periodic
CONFIGURATION AND NOTIFICATION DATA (DOWNLINK)	512 bytes	Aperiodic	mobile	1 m/s	50	Aperiodic

3.2.3 Beyond 5G features needed for the use case

To match the requirements defined for the use case, different technologies need to be tested and validated. In TARGET-X the following technologies will be used for the use case:

Time-Sensitive Communication: Time-sensitive communication (TSC) is critical for PLC to remote station communication in industry because it ensures that data and control commands are transmitted with precise timing and deterministic latency. Especially in the context of coordinating complex industrial processes, enabling reliable automation, safety and high quality processes, real-time is a crucial requirement. In TARGET-X two technologies for TSC will be investigated: Time-Sensitive Networking (TSN) and Deterministic Networking (DetNet). TSN is a set of Institute of Electrical and Electronics Engineers (IEEE) standards that provide deterministic and low-latency communication over Ethernet networks on layer 2 of the OSI model, making it ideal for real-time and critical applications in various industries. Deterministic Networking (DetNet) is an emerging set of networking technologies that is being defined in the Internet Engineering Task Force (IETF) aiming at improving the real-time capability on Layer 3. Using TSN or DetNet on the wireline side and 5G/6G on the wireless side creates a converged communication network capable of real-time communication. With standardization ongoing, TARGET-X will explore the available features in the trial networks to test how these features can be used to achieve deterministic latency and packet delay variations. The execution of several measurement series with different feature sets will provide the needed insights to progress towards full determinist communication in future 6G networks. First trials for TSN switch integrated wireless communication via 5G have been done and show the great potential for industrial manufacturing [4].

Native Layer 2 Communication: Layer 2 communication, also known as data link layer communication, involves the exchange of data between devices on the same local network or network segment. Frames are transmitted over the physical network, and switches or bridges forward the frame based on the destination MAC address, ensuring it reaches the intended recipient. Industrial Ethernet protocols such as PROFINET and CC-LINK IE TSN [8] typically operate at Layer 2 (data link layer) of the OSI model due to the need for deterministic communication, seamless integration with existing fieldbus systems, and the simplicity and efficiency offered by Layer 2 protocols within local network segments. 5G communication operates at layer 3 in the network stack, therefore network layer 2 communications are not yet supported. TARGET-X aims at testing different mechanisms of transporting layer 2 fieldbus protocols via 5G.

Time Synchronization: Time synchronization in computer networks is achieved through protocols such as PTP and NTP. PTP (Precision Time Protocol) enables highly accurate time synchronization by exchanging timing messages between a master clock and slave devices, allowing precise adjustment of clocks to maintain alignment within sub-microsecond accuracy. This is crucial for applications like industrial automation or scientific research. NTP (Network Time Protocol) operates in a hierarchical manner, with a network of time servers that synchronize with each other, gradually aligning clocks across the network within millisecond to sub-millisecond accuracy range, making it suitable for general time synchronization needs in computer networks and internet-based applications. Different approaches for time synchronization in industrial applications will be tested in TARGET- X.

Layer 2 Broadcasting: Layer 2 broadcasting works by sending a message or data packet to all devices within a specific network segment. In this process, the source device sets the destination Media-Access-Control (MAC) address to a special value called the broadcast address. When the network switch receives a packet with the broadcast address, it forwards the packet to all devices connected to that network segment. Each device on the segment receives the broadcast packet and can process or respond to it as needed. This allows for simultaneous distribution of information to all devices within the broadcast domain, facilitating efficient communication and coordination in industrial networks. This mechanism is used to connect unknow devices within the network to the master. Layer 2 broadcasting is not yet supported by 5G, but an important asset for PLC to remote communication.

AAS: The adoption of AAS (Asset Administration Shell) in industrial production ensures compatibility and interoperability towards different standards and technologies. This facilitates a large-scale data exchange on the shopfloor, but also with the factory cloud and the 5G network. Network resources can be requested on demand, prioritizing safety critical applications for example. The integration of the AAS in the industrial 5G network is one main goal of TARGET- X.

4 Design options for the wireless smart sensor use cases

4.1 Overall architecture

One Wireless Sensor Platform (WSP) will be developed for the use cases of environmental condition monitoring, and for track and tracing. The design options are discussed in the upcoming topics. The following picture represents the overall architecture of the system used for the use case.

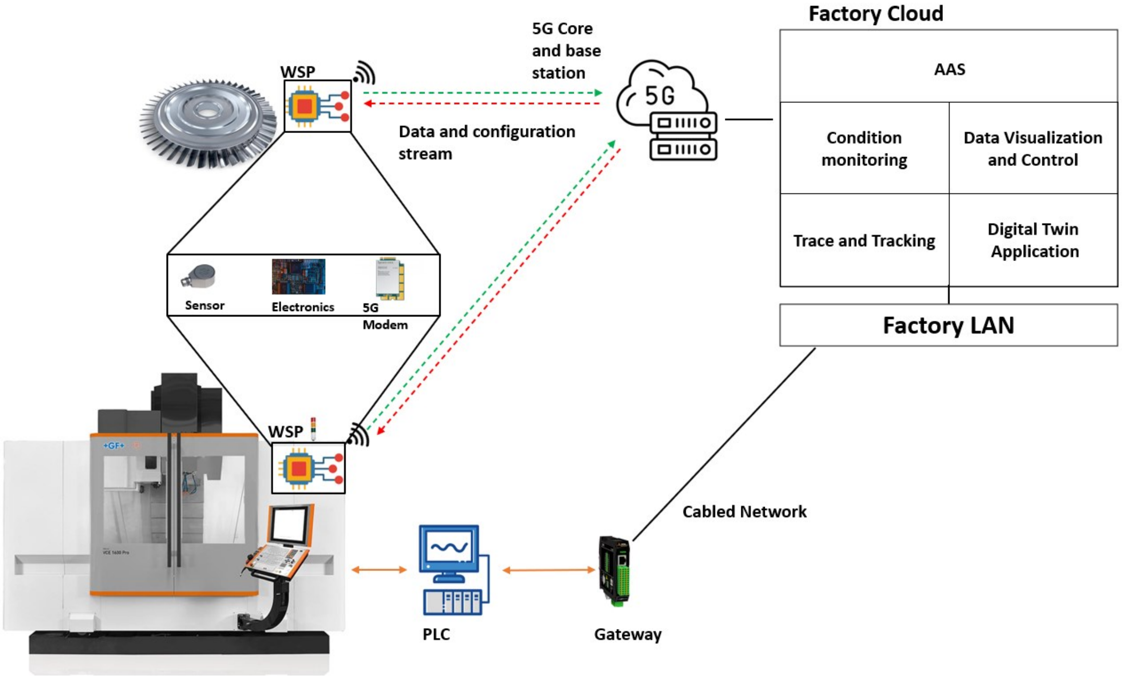

Figure 6 : Overall architecture of the wireless smart sensor use cases.

To monitor the condition of the machine and the process, 5G wireless smart sensor platforms with energy meters are integrated into the machines. They are in the work area, close to the spindle and the coolant and air flow. These sensor platforms collect data on spindle vibration and air/coolant flow. They also measure the energy consumed by the machine. Another 5G-WSP is mounted at the workpiece. This monitors the condition of the workpiece. This sensor platform monitors the vibration, the orientation, the temperature, and the environmental conditions such as the humidity and the pressure. All this data is sent as data packets via 5G to the factory cloud using OPC UA or TCP/IP protocols such as UDP. In the factory cloud, protocols such as Lightweight Machine-to-Machine (LWM2M) and the Asset Administration Shell are used to onboard and configure the sensor platform. The AAS store the configuration list of the sensor platform, the communication configuration and also the structure of the application. Based on this information, the servers accept the data streams, extract and store the data in the AAS database. These extracted data is then analyzed for applications such as Condition Monitoring, Tracking, visualizing data and creating digital twins. Due to application requirement demands, the sensors must be reconfigured during run time. To help this, the application uses the AAS system to identify the sensor platform and its possible configurations and trigger its configuration.

4.2 Field level Architecture setup

One of the objectives of the project is to explore the possibility to design and employ a small, low power device; nevertheless, some level of flexibility is required due to the early stage of the technology and of its implementation; a compromise of performances and design is required.

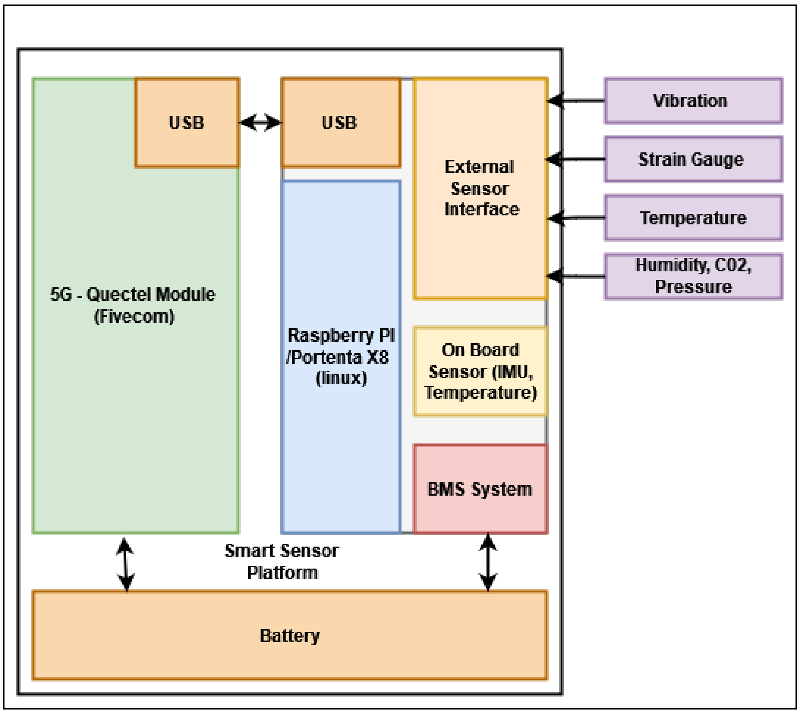

Figure 7 : Hardware architecture of the wireless smart sensor platform.

The wireless smart sensor platform is therefore based on a modular design, with four components:

- 5G radio module
- Microprocessor module for example Raspberry Pi or Potenta X8
- External sensor interface
- Battery

For the 5G radio module, a first option is the new Fivecomm module, which integrates a Quectel R500. Alternatively, we may include an M.2 connector for other expansion cards.

The microprocessor module is going to be in the range of a Raspberry PI 4 or Arduino Portenta series, dependent from the balance of energy consumption, peripherals and flexibility. What is more, developing in such environments let us explore different details of design choice, so that the best solution can be identified and tested before the actual, real-world implementation.

Consequently, the specific sensors and interfaces are implemented in a custom board which is the supporting unit to the other modules. The battery is connected to this board, which also includes its power and recharge management.

4.3 Factory cloud level Architecture

The Figure 8 illustrates the architecture of the factory cloud software stack. Data from 5G wireless sensor platforms is transmitted to the factory cloud system through the 5G core network. Simultaneously, machine process information is acquired via the factory LAN network. These diverse data sets are subsequently utilized for comprehensive data analytics within the factory cloud.

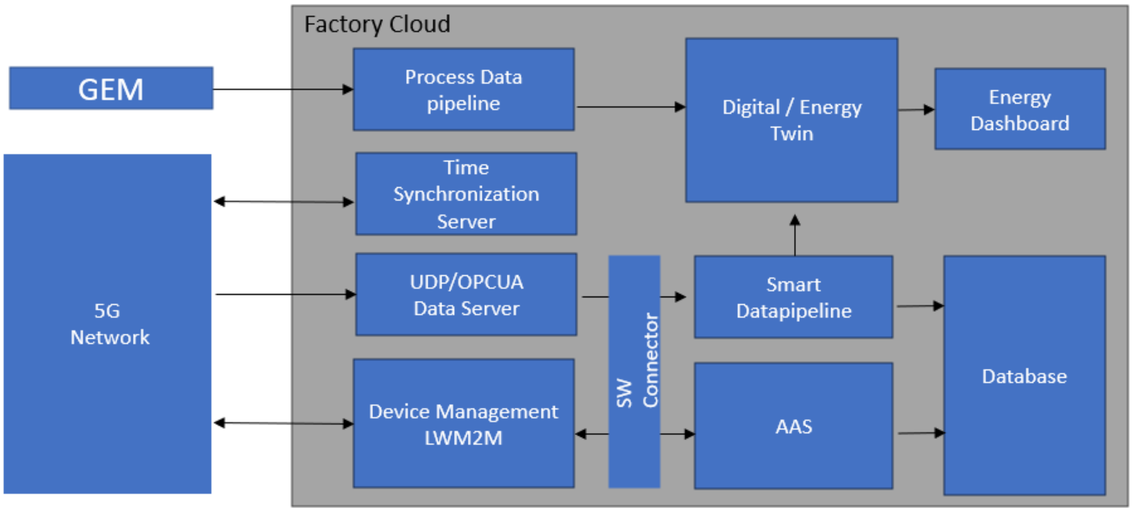

Figure 8 : Factory cloud architecture of the Wireless smart sensor platform.

The factory cloud architecture is used to fulfil the following tasks of:

Condition Monitoring: In the context of monitoring machine and process conditions, 5G wireless smart sensor data is collected and analysed for valuable insights in the Digital / Energy Twin software module. This information, combined with machine process data, enables a detailed analysis of machine conditions. The processed data finds applications in predictive maintenance, quality control, and similar areas.

Trace and Tracking: For tasks involving workpiece trace and tracking, integrated wireless smart sensor data is harnessed. Information from sensors like Inertial Measurement Units (IMUs) is fused with 5G network data to estimate the workpiece's location at any given time. Additionally, data from LPWAN networks and other sources is integrated for enhanced accuracy. Environmental data and condition information, such as vibration data, contribute to precise trace and tracking in a digital environment.

Data Storage: The analysed data resulting from the above processes is stored for future use, serving purposes such as datasets for predictive maintenance and modelling machine and workpiece conditions. All incoming data is stored in a database with a timestamp, and the structure of the stored data is defined by the Asset Administration Shell (AAS).

Data Visualization: Another facet of the cloud's functionality is to offer real-time visualization of the system's gathered information. This includes a dashboard of connected sensors, interactive visualization of incoming data streams, and the retrieval of stored data from the database.

Digital/Energy Twin: The concluding step in overall condition monitoring and trace and tracking is the creation of a digital twin for both the machine process and the entire lifecycle of the workpiece. The digital twin of the system (the machine and the workpiece) is created using the information from all the sensor data and the machine information. The digital twin can be pertaining to the process induced characteristic (vibration, temperature) or energy consumed for process (energy twin). This is achieved with the assistance of the AAS and data collected from sensor systems and machine data. Through modelling and data fusion, a digital twin of the product and machine can be realized.

5 Design options for the Inline Quality Assurance for Machining use case

The architecture for the use case given consists of two main levels: the field-level and the factory cloud-level. At the field-level, sensors, devices, and a field gateway collect data from the industrial environment using protocols like CC-Link IE TSN. On the factory cloud-level, cloud infrastructure handles data storage, processing, the DT and analytics. Real-time analytics and historical data analysis are employed to derive insights. Visualization tools present the processed data through dashboards, reports, and alerts. Both levels are described in the following section.

5.1 Field Level Architecture

In a first step, a field level communication pipeline supporting TSC and 5G needs to be implemented. In this use case, the pipeline will be set up and tested with commercially available industrial devices instead of prototypes to ensure the reliability and performance of the product under real-world conditions. Since DetNet devices are not yet available, a 5G-TSN pipeline will be setup. After investigating the available options, a test system with the following components is to be set up:

- iQ-R system with one RCPU and one CC-Link IE TSN master (RJ71GN11-T2)
- iQ-R system with one RCPU and two CC-Link IE TSN local stations (RJ71GN11-T2)
- One CC-Link IE TSN remote station (NZ2GN2B-60AD4)

The length of the transmission data between the CC-Link IE Master station and the assigned stations is defined as follows:

Table 6: Different length of transmission data to be tested for the PLC to field use case.

Module	Receive		Transmit	
	Binary devices	Word devices	Binary devices	Word devices
Local station (RJ71GN11-T2)	32	384	32	384
Local station (RJ71GN11-T2)	32	32	32	32
Remote station (NZ2GN2B-60AD4)	32	32	32	32

Devices in Mitsubishi PLCs are assigned data types. Word devices are 16-bit values, while binary devices are boolean values. In the table (1st row), this means that for receiving, there are 32 boolean values and 384 16-bit values. For transmitting, there are also 32 boolean values and 384 16-bit values. The selected transmission data lengths result in a minimum transmission time of 26.00µs for the cyclic data and a minimum TSN cycle time of 142.00µs at 1Gbps.

To ensure that no CC-Link IE TSN packet arrives too late within a CC-Link TE TSN cycle with an expected latency of the 5G system of up to 2ms, the TSN cycle and the TSN time slots are set as shown in the followingFigure 9.

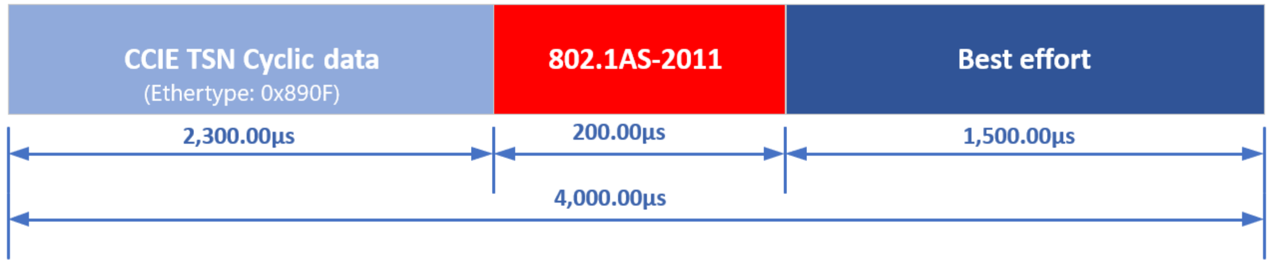

Figure 9: TSN cycle time for the PLC to field use case.

CC-Link IE TSN is based on TSN technology, which is located in Layer 2 of the OSI reference model and consists of CC-Link IE TSN proprietary protocols and Ethernet standard protocols in Layers 3 through 7.

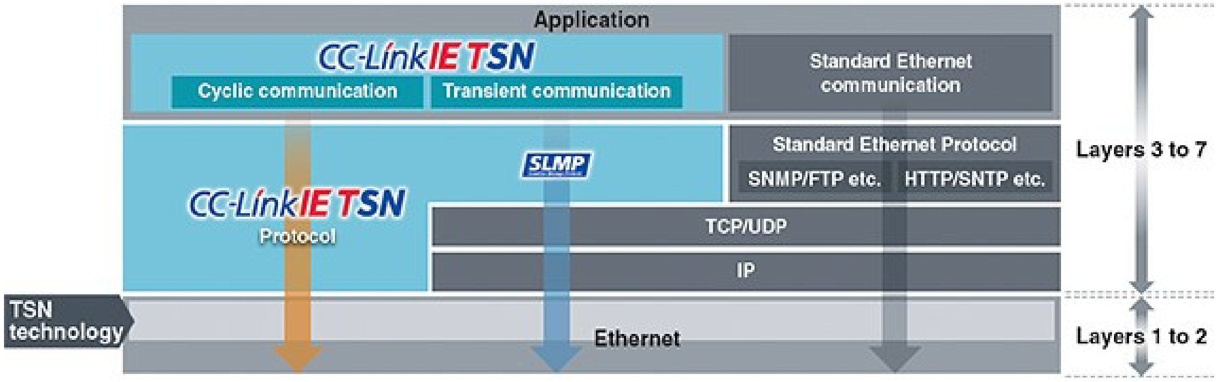

Figure 10: Comparison of the OSI reference model with the CC-Link IE TSN protocol [9].

While implementing control communications that ensure real-time performance, the same network can be used to integrate communications from other networks and information communications with IT systems, increasing system configuration freedom.

5.2 Factory cloud Level Architecture

After the setup of the field-level communication pipeline, the PLC to remote communication will be extended with different factory cloud applications, as shown in Figure 11.

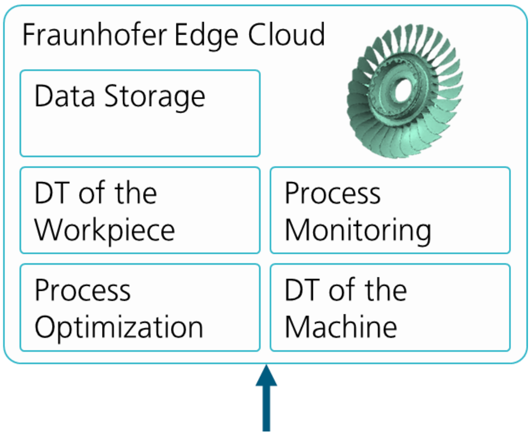

Figure 11: Factory cloud application level.

Data storage: Data storage is essential in industrial applications to securely and reliably store the vast amount of data generated by various processes and systems. This is achieved through a range of tools such as relational databases (e.g., MySQL, Microsoft SQL Server, Oracle), time-series databases (e.g., InfluxDB, TimescaleDB), distributed file systems (e.g., HDFS, GlusterFS), object storage (e.g., Amazon S3, Google Cloud Storage) and edge storage solutions (e.g., Redis Edge, Apache Kafka). The data storage is the foundation for artificial intelligence, predictive maintenance, optimization, data-driven decision-making and tracking over the life cycle of the product and the machine.

Process monitoring: A process monitoring software will be implemented, running in the factory cloud leveraging data from the data storage to perform analysis of the industrial applications, enabling proactive monitoring and optimization of processes. By utilizing factory cloud computing capabilities, the software can scale seamlessly to handle large volumes of data and provide actionable insights to improve efficiency and productivity. This factory cloud-based approach allows for remote access, collaboration, and integration with other systems, enhancing the overall effectiveness of industrial applications monitoring.

Process optimization: Subsequent to the process monitoring software, a process optimization algorithm, which can be AI-based, leverage the data collected by the monitoring software to identify patterns, anomalies, and inefficiencies in industrial processes. These algorithms employ machine learning techniques to continuously analyze the data and make recommendations for process improvements, leading to increased productivity and cost savings. By utilizing AI, the optimization algorithms can adapt and learn from the data, enabling them to refine their recommendations over time for even better process optimization results.

Digital Twin: In a last step a digital twin of the workpiece and the machine will be implemented, connected to the AAS of the device and the 5G-network. The digital twins play a crucial role in interconnecting the industrial shopfloor, enabling seamless communication and data exchange. By creating virtual replicas of physical assets, such as workpieces and machines, the digital twin allows a seamless integration of the data storage, the process monitoring and the process optimization. With the integration of 5G network and Asset Administration Shell (AAS) technology, the digital twin can be interconnected, enabling high-speed and reliable communication between various components on the shopfloor, facilitating efficient data sharing and decision-making in industrial environments.

6 Conclusions

In conclusion, this deliverable presents different use cases of the cloud native production testbed in TARGET-X using 5G/6G technologies in manufacturing, with an emphasis on wireless production and condition monitoring. Besides the use case description, clear communication requirements are given, to identify further 5G/6G features necessary for improving the efficiency of such use cases. With these requirements and features in mind, the document proposes design alternatives for the implementation of the use cases, including the overall structure, hardware configuration, and software setup. These design options enable first trials and validations of early 5G/6G features, leaving the flexibility for future developments.

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