REPORT ON IMPLEMENTATION OF OPTIONS FOR THE TRACKING AND INLINE QUALITY ASSURANCE SYSTEM

Deliverable D2.4

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Executive Summary

This document provides a comprehensive implementation plan for the three use cases defined in Deliverable 2.1 [1]. The use cases "Environmental Condition Monitoring" and "Track and Tracing of Workpieces" will be implemented using the Wireless Sensor Platform (WSP) described in Section 2. It covers the architecture of the WSP, detailing both hardware and software components, including various sensors and the 5G devices that can be integrated. Additionally, it addresses the cloud architecture for data processing and the advanced networking features used for the use case. The implementation options for the "Inline Quality Assurance System for Machining" use case are described in Section 3. The section outlines the overall architecture, the Operation Technology (OT) devices and the measurement setup used to measure the relevant Key Performance Indicators (KPI). It emphasizes on the different features for the communication layers, including traffic shaping and reliability mechanisms such as Frame Replication and Elimination for Reliability (FRER).

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List of Acronyms and Abbreviations

AAS	Asset Administration Shell
AI	Artificial Intelligence
BLE	Bluetooth Low Energy
BLISK	Blade Integrated Disk
BMS	Battery management system
CAM	Computer Aided Manufacturing
CC-Link IE	Control & Communication Link Industrial Ethernet
DetNet	Deterministic networking
DT	Digital Twin
FRER	Frame Replication and Elimination for Reliability
GPIO	General purpose input output
IEEE	Institute of Electrical and Electronics Engineers
I2C	Inter Integrated Circuit
I2S	Inter-IC Sound
KPI	Key Performance Indicator
LGA	Land Grid Array
M.2	Next generation form factor (NGFF) M.2
MAC	Media-Access-Control
MQTT	Message Queuing Telemetry Transport
NTP	Network Time Protocol
OT	Operation Technology
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
PTP	Precision Time Protocol
SPI	Serial Peripheral Interface
TSN	Time-Sensitive Networking
UART	Universal Asynchronous Receiver Transmitter
URLLC	Ultra Reliable and Low Latency Communications

USB	Universal Serial Bus
WSP	Wireless Sensor Platform

1 Introduction

In the context of Industry 4.0, Industrial manufacturing is undergoing a significant transformation through digitalization. By connecting physical production with its digital counterpart the digital twin, companies can achieve greater flexibility and efficiency through enhanced automated system monitoring, control, and planning. The integration of various components involved in the manufacturing process such as machines, devices, the factory cloud, and human operators—makes information more accessible from anywhere. This complete visibility across processes and assets transforms the factory into a cyber-physical production system. Smart manufacturing is enabled by adopting new technologies like cloud computing, digital twins, and integrating artificial intelligence (AI) to manage and optimize manufacturing processes.

1.1 Objectives of the document

This document explores the potential use of 5G/6G technology in manufacturing, focusing on various use cases and design options. The document continues the discussion from the previous document, which mentions the requirements for the three use cases: “Environmental Condition Monitoring”, “Track and Tracing of Workpieces”, and “Inline Quality Assurance for Machining”. This document focuses on the technical implementation of the use cases [1]. This includes the technical architecture of the solution for the use cases, the hardware development and the software design for the sensor platform and the cloud system needed to realize the use case. In addition to the representation, a brief discussion on the beyond 5G features such as Asset Administration Shell (AAS), Reduced Capability (RedCap), Time-Sensitive Networking (TSN) that are integrated and the added benefits for the use case.

1.2 Relation to other activities

The content provided in the 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).

2 Implementation of the wireless sensor platform

A wireless sensor platform has been developed for the use cases "Environmental Condition Monitoring" and "Track and Tracing of Workpieces". The environmental condition monitoring involves gathering machine parameters such as power consumption, coolant feed rate, humidity, temperature, vibration, etc. These are then analyzed to realize a digital twin of the machine. The Track and Tracing of Workpieces use case involves:

- Monitoring a workpiece throughout the manufacturing process,
- Tracking it along the way,
- Tracing its condition during each process.

To create the digital twin and enable the track and tracing, a wireless sensor platform is to be implemented. The sensor platform integrates several sensors used to monitor various parameters relevant to the workpiece and the machine and transmit the acquired data wirelessly over the 5G network. The following section will discuss the overall solution architecture.

2.1 Architecture

The solution architecture for the use cases is presented in the picture.

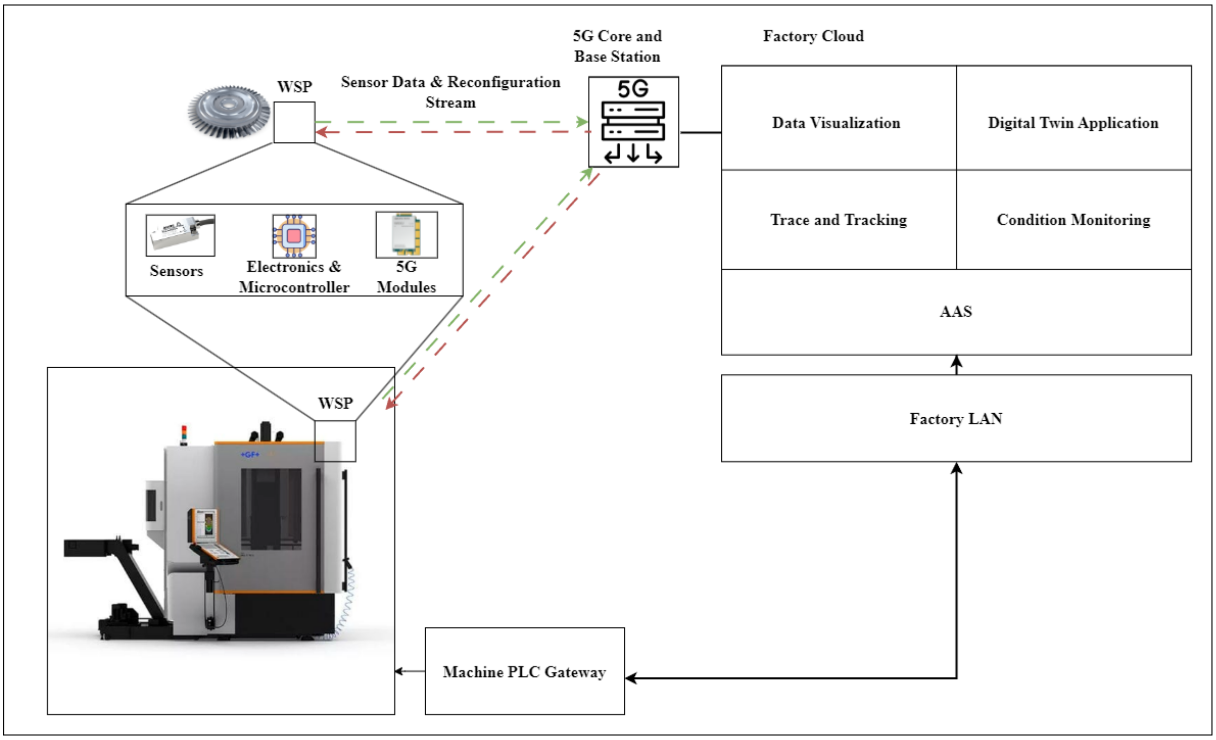

Figure 1 : Architecture of the energy and tracking use cases.

To monitor the various parameters for the explored use cases in TARGET-X, the sensor platforms integrate multiple sensors to acquire various sensing parameters ranging from temperature, pressure, acceleration, orientation, power measurements, etc. The wireless sensor platform also has additional interfaces to integrate external sensors for extended measurements. The acquired data from the sensor system are sent to the cloud application for monitoring and control. To provide flexibility and useability, wireless 5G technology is integrated in the sensor system to send the data.

The data from the sensors are processed in Factory cloud. For the each use-case, software modules are developed and integrated to enable the data processing and analysis. The **Condition Monitoring** module contains the necessary data analytics for the processing of sensor data stream and extracting features. In **Track and tracing** module, algorithms to calculate the approximate location and tracing of the hardware based on sensor data is implemented. The analyzed data are then sent to **Data visualization** module to interpret and visualize it in a dashboard. The digital twin module is responsible to create the **Digital Twin** of the machine and the application to provide deeper insights. The **Asset Administration Shell(AAS)** hosted on the cloud contains all the necessary data models that is required for interoperability of the applications and data interpretation.

Since both use cases require embedded sensor hardware, decision is made to make a single hardware Printed Circuit Board (PCB) that can work in conjunction with the use cases by changing the core processing module without changing the whole hardware and the 5G device. This reduces the effort on hardware designing and improves the reusability of the hardware for various application.

The data from the sensor platforms are received by the application hosted in the factory cloud with communication over the 5G network.

2.2 Hardware architecture of the sensor platform

The hardware architecture of the sensor platform is presented in Figure 2. The sensor platform is designed with high flexibility and a variety of interfaces to be interoperable with different external sensors, further integrated onboard sensors are integrated.

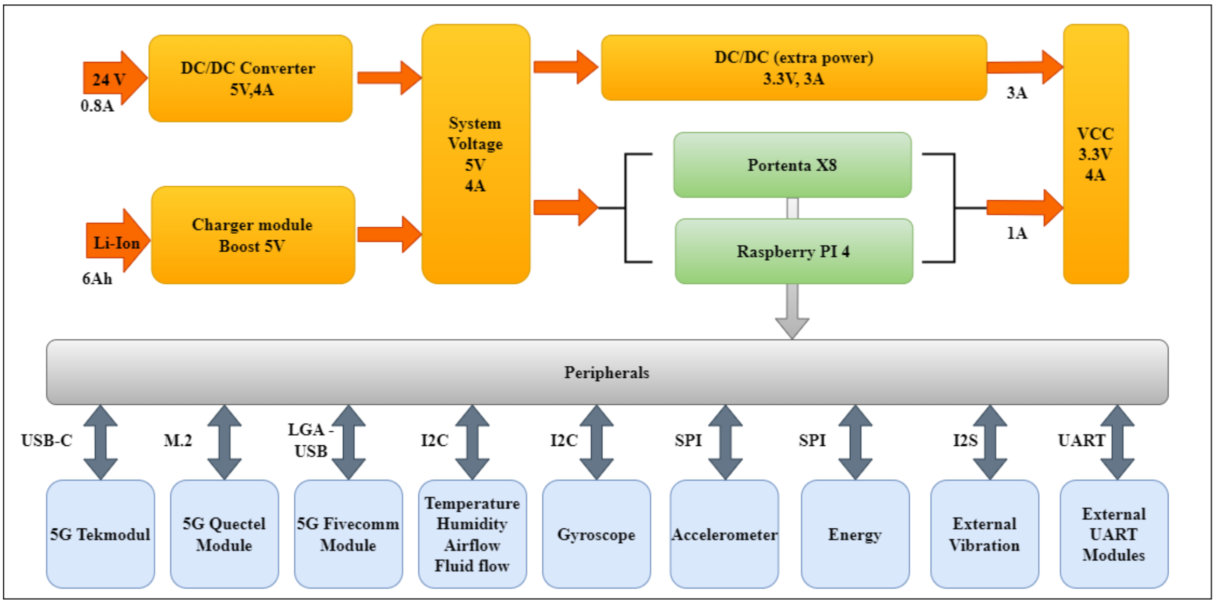

Figure 2: Hardware architecture of the sensor platform.

The use case environmental and condition monitoring requires monitoring various parameters such as vibration, air flow rate, coolant feed rate, energy, etc. This requires the sensor platform to possess high processing power, while also ensuring easy prototyping and seamless machine integration. The sensor platform system is integrated into the workpiece for the track and tracing use case, which goes through various manufacturing stages. This requires the sensor platform to be highly energy efficient while providing processing functionality such as data acquisition, analytics, and fusion and transmission over the 5G network. In addition, the sensor platform must be highly compact with a small footprint that can be integrated into the workpiece.

The hardware is designed to meet diverse requirements and minimize development efforts. It features a modular processing hardware module that can be easily swapped based on specific needs. For condition monitoring, the Raspberry PI is the chosen processing hardware, offering the required processing power, ease of prototyping, 5G integration, and affordability. For track and tracing,a smaller form factor is preferred and so the Portenta X8 is used instead of Raspberry PI.. Hence, the sensor platform has a high-density connector for the Portenta X8 and has a Raspberry PI GPIO header, which can be interfaced directly as a cape on Raspberry PI.

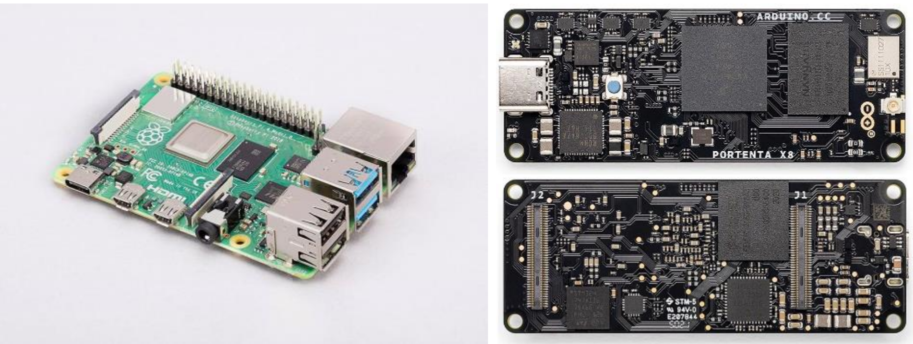

Figure 3 : Raspberry Pi 4(left)[19] & Portenta X8 (Right)[20].

The 5G device used also depends on the use case under study, for condition monitoring a 5G modem developed by Fivecomm for the project is being used. It is designed to fit into a stacking formation, providing all the necessary functionalities together with the Raspberry Pi 4 and the sensor platform. In the track and tracing use case, commercial 5G M.2 modules are used. The Type C interface of the Portenta X8 and the mPCIe/M.2 interface can be used for connectivity. This integration significantly reduces the form factor, making it easy to integrate into workpieces.

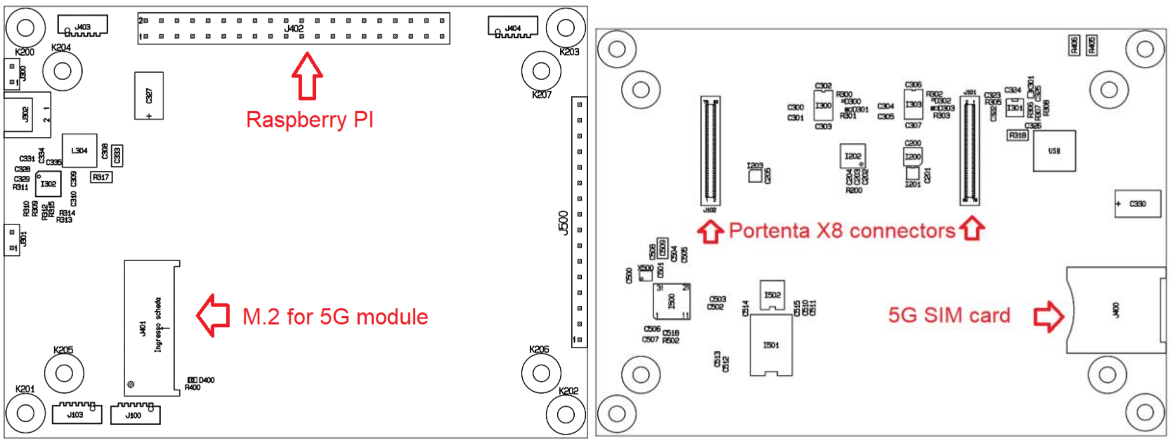

Figure 4 Hardware components for the sensor use cases.

The hardware also includes various sensor modules integrated directly into the board. These are:

2.2.1 Temperature sensor

The Texas Instruments TMP116 is a tiny 2.0mm x 2.0mm integrated circuit, which comes pre-calibrated from factory in order to provide ±0.2°C accuracy with minimal current consumption. It is integrated in the circuit board, therefore it measures the temperature inside the MSP, and it is connected on a system wide I2C. The same device could be in principle externally connected and integrated into a detachable sensor directly on the workpiece, without any architecture or software change.

2.2.2 Humidity sensor

The Texas Instruments HDC2022 is a tiny 3.0mm x 3.0mm relative humidity sensor with IP67 water and dust proof certification. It is mounted on the electronics board and connected to the I2C system bus as an example of integration, so that the same device can be realized in a detachable sensor to be applied on the workpiece and used without any software change.

2.2.3 Accelerometer

The ST Microelectronics LIS2DH12 is an ultra-compact 2.0mm x 2.0mm sensor with 3-axis and low power. It has a bandwidth of 5.3 kHz suitable for most macroscopic mechanical vibrations, with an SPI interface for connecting to the processor for fast acquisition.

As an alternative, or in addition, the electronics board includes the Inter-IC Sound (I2S) high speed bus for an external connection to a detachable accelerometer.

From the stream of acceleration samples, the processor can detect the characteristic frequency, as well as calculate the amplitude of vibration. Such information is of primary importance to keep under control both the quality of the machining process, and the condition of the tools and machine.

2.2.4 Gyroscope

The ST Microelectronics A3G4250 is a MEMS technology gyroscope, that is capable of providing the orientation of the board – and therefore of the workpiece to which the MSP is attached – in the 3D space.

This is particularly useful for Trace and tracking, supplementing the localization of the workpiece, so that the object is closely followed along each step of the production line, including robotic movements.

2.2.5 Energy and power measurement sensor

The Analog Devices ADE9000 is a special purpose analog front-end conditioning and sampling system, specifically devoted to concurrent AC voltage and current monitoring. The device includes filtering and processing in order to analyze the active and reactive components of both the electric quantities, in order to calculate instantaneous power consumption, as well as

The mentioned sensors provide the necessary means to sense the key parameters such as vibration, orientation, and environmental condition of the component they are being placed. Additionally, these sensors are low-power, suitable for wireless battery-powered devices.

For environmental and condition monitoring, sensors like the integrated electronics piezo electric (IEPE) vibration sensor, air flow rate, and coolant sensor are integrated inside the machine. In addition, the power current transformer is connected to the machine power line to measure energy.

This requires the sensor to have an external interface. To achieve this, modular connection modules with UART and I2C interfaces with power supply are provided for easy integration.

The power sensor requires additional module to isolate the high voltage line from the core controller power lines and is interfaced as an add-on module.

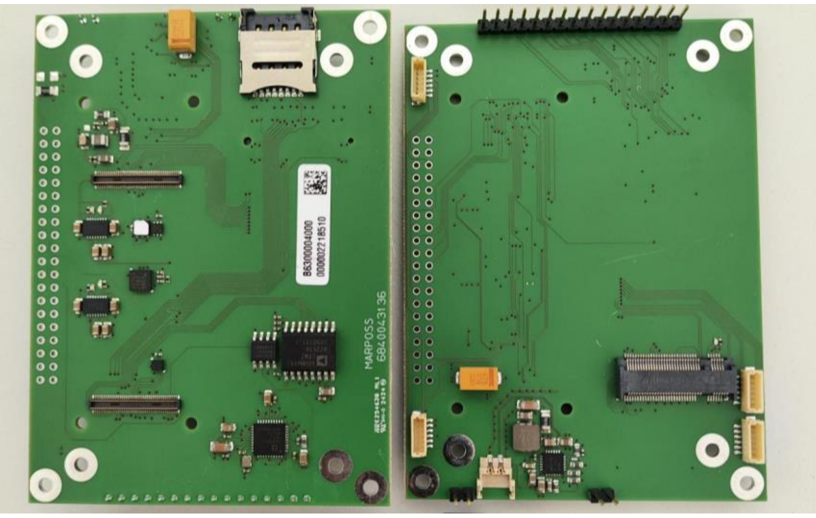

Figure 5: Snapshot of the sensor hardware PCB of dimension 950mm X 700mm.

For powering, the sensor platform has several methods. When connected to Raspberry Pi, the board is powered by the 5V lines on the RPI GPIO connector. Additionally, a 24V to 5V step down module is integrated, enabling the system to be powered by the DIN rail of the machine system. When used for track and tracing, the board is powered by a Li-Ion battery through a BMS system that regulates the voltage to 5V and provides necessary current to power the sensors, 5G and the microcontroller. The module also enables to charge the battery when connected to a 5V or 24V supply, avoiding the necessity to remove the battery for charging.

In terms of connectivity, the module has ~~an~~ M.2 interface to connect the 5G NGFF wireless communication module. Additionally, the microcontrollers USB interface can be used to connect the 5G modules. For the trace and tracking use case, to complement the positioning feature of the 5G, additional wireless technology such as BLE, UWB module are integrated. These technologies can be used together with 5G to enhance the precision and accuracy of the sensor platform for tracking and tracing. The first version of the integrated sensor platform can be seen in Figure 6.

Figure 6: Sensor Platform integrated in a housing.

2.2.6 5G modules

Two different 5G modules are used in TARGET-X. The first 5G module is a LGA-type module provided by Fivecomm, which is mounted on top of the Raspberry Pi or a Portenta X8 device and connected through a USB interface. The second alternative is to use commercially available M.2 5G modules, connected by using the Portenta X8 mPCIe interface. The use of one option or the other depends on the use case under study.

Environmental Condition monitoring

For the environmental condition monitoring use case which include measurement of energy metrics condition monitoring of machine, the new 5G module developed by Fivecomm is used. The module is based on the latest Release-16 device from Quectel, the RG520N series. The 5G module comes in the form factor of a Raspberry Pi, making it easy to stack, along with the sensor platform. Some of the most relevant characteristics of the 5G module developed by Fivecomm are presented in the following table.

Table I Characteristics of the RG520N 5G module.

Supply voltage [1]	3.3-4.4V
Technologies supported	5G-SA, 5G-NSA, LTE, WCDMA
Frequency bands Supported	5G: n1/3/5/7/8/20/28/38/40/41/75/76/77/78 LTE: b1/3/5/7/8/20/28/32/38/40/41/42/43
data rates (measured interfacing with RPI4) [2]	5G-SA: 410 Mbps (DL) / 110 Mbps (UL) 5G-NSA: 925 Mbps (DL) / 90 Mbps (UL) LTE: 55 Mbps (DL) / 35 Mbps (UL)

available interfaces [3]	USB2.0/3.0/3.1, PCIe 3.0/4.0, RGMII

Notes: 1. The board internally converts the 5V or 9-12V input to 3.8V for the module

2. Measured in different networks under more realistic conditions than what is advertised by the manufacturer

3. In the implementation developed for the project only the USB interface is used

The designed module and its integration within the PCB is shown in Figure 7, with its more relevant components labeled.

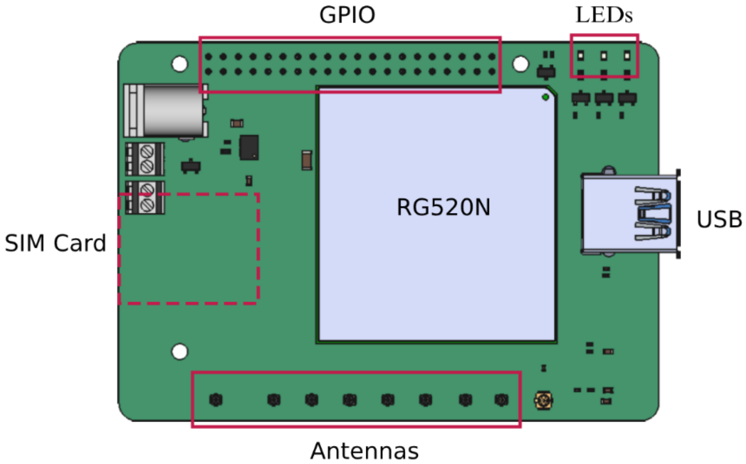

Figure 7: 5G board and more relevant components design.

The modem operates in the following way: First, the power-up process needs to be controlled through two GPIO pins. To accommodate to the other components of the solution, Fivecomm modified its initial design, previously used in other solutions and verticals such as robotics in TARGET-X, and modified it accordingly. In the condition monitoring use case, the modules employs GPIO from Raspberry PI to perform the power-up process, which needs to follow the behavior described in the following figure.

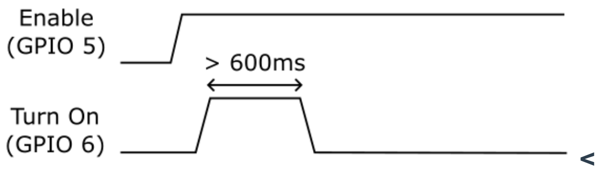

Figure 8: Turning on procedure for the Fivecomm 5G modem.

Similarly, for turning off the module, the same two pins are used, while the time for the power off procedure should be respected before removing power, as shown in Figure 8. Note that, alternatively, the modem can be turned off using the AT command.

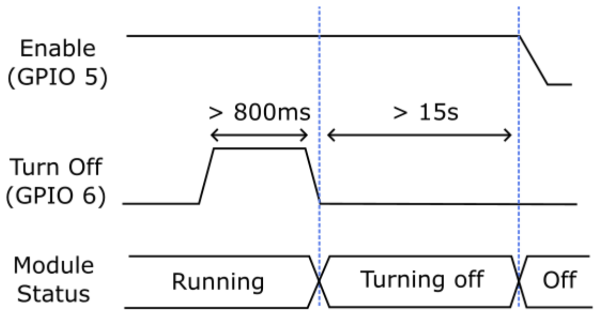

Figure 9: Turning off procedure for the Fivecomm 5G modem.

For configuration, the module employs AT commands, which are sent to the modem via the USB2.0 traces using a serial communication tool such as minicom or socat, with a baudrate of 115200 bps. To finish the connectivity procedure, the *NetworkManager* tool, included in most Linux distributions can be used.

Track and tracing use case

For track and tracing, a 5G module as shown in Figure 10 is interfaced directly via the M.2 interface, keeping the small form factor. This provides the flexibility of connecting various legacy 5G modules, such as RM520N, as well as the new Rel 17 devices, such as the RM255C Redcap module. One advantage of using the Redcap module is lower energy consumption making it more suitable for battery operation.

Figure 10 : Quectel RM255C M.2 module with Qualcomm modem chipset. [21]

2.3 Software architecture of the sensor platform

In contrast to hardware developments in previous projects such as 5G-SMART, where the data acquisition and processing hardware was based on a microcontroller solution, the data processing hardware developed in TARGET-X will run on a Linux operating system. In this way, the development required to connect to 5G and network protocols such as Message Queuing Telemetry Transport (MQTT) can be minimized. However, it must be ensured that data acquisition does not overload the operating system, e.g. because of too frequent interrupts, and constant sampling rate must be guaranteed at the same time. For this reason, the ADE9000 was chosen for the energy measurement and the PCM1863 for the vibration measurement. Both ICs handle data acquisition and processing independently and buffer the data until the operating system is ready to read the results.

2.3.1 Signal processing

The ADE9000 is a highly integrated energy metering IC designed for three-phase energy metering and power quality analysis. It communicates via SPI so that it can be connected to both the Portenta X8 and the Raspberry Pi. Currently there is no driver for the ADE9000 in the Linux kernel for convenient data access. For this reason, the best way to read data from this IC is to access the SPI interface directly in a user space application. This application was written in ANSI-C, which not only handles the data acquisition from the ADE9000, but also forwards the data via MQTT.

To access the SPI interface from an application under Linux, there is the character device which behaves like a file. All write or read operations to this special file are sent to the ADE9000 instead. In this way, this metering IC must be configured first and is then ready for data acquisition. A plot of a first test measurement is shown in Figure 11, done at a Chiron FZ08 machining center during idle and cutting time.

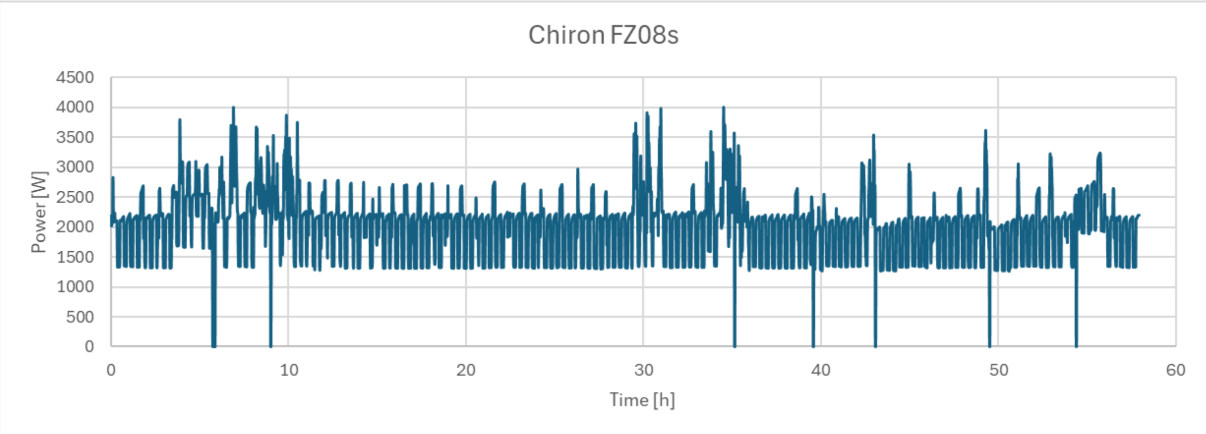

Figure 11 ADE9000 test measurement.

The vibration is measured using a Marposs VA-3D accelerometer connected to the HiFiBerry DAC+ ADC. This expansion board for the Raspberry Pi adds a sound input to this single board computer and is based on the stereo ADC PCM1863 from Texas Instruments. The PCM1863 can capture a two-channel input signal with a sampling rate of 192 kHz at 24 bits. A four-channel variant of this IC is also available, which would enable the usage of a three-axis accelerometer. Since the IEPE interface of the sensor requires a constant voltage interface, an additional interface board is needed to connect the piezo accelerometer to the line-in of the HiFiBerry expansion board. This interface board was implemented as shown in Figure 12. To integrate the vibration measurement into the WP2 solution, both PCBs must be put on top of the 5G-Modem from Fivecomm.

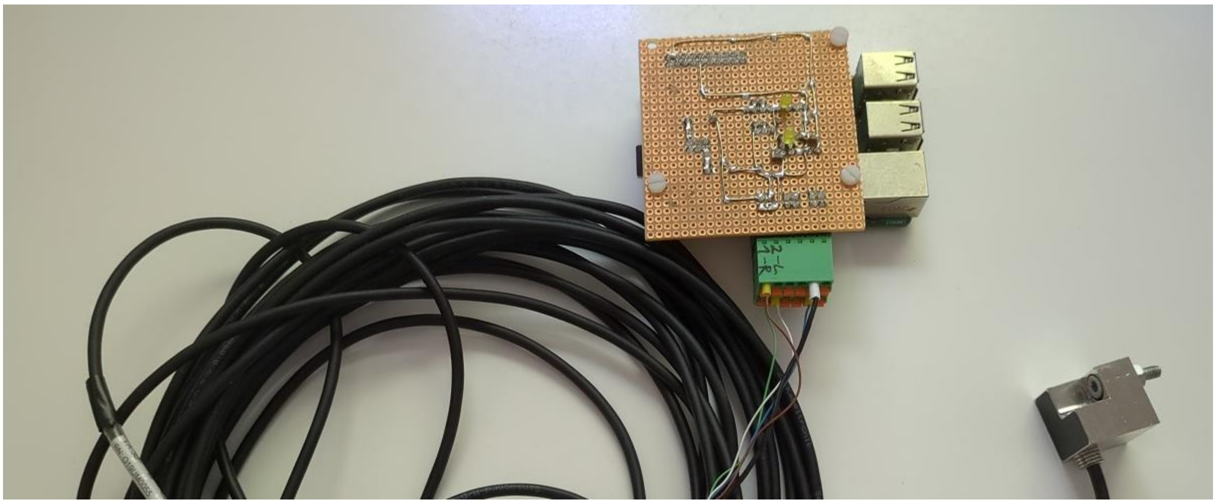

Figure 12: PCM1863 test setup.

The Ti PCM1863 ADC communicates via I2S (integrated Inter-IC Sound) for audio data and I2C for control. To be able to use this device under Linux, the device tree must be adapted accordingly so that the corresponding drivers are loaded at startup. The configuration of the signal gain can then be done with the alsamixer tool. A few steps are then required to be able to use the libalsa (Advanced Linux Sound Architecture) API for data acquisition. First, the ALSA interface must be set up, then the PCM device must be configured for acquisition (input) and finally the data can be read in a loop. A plot of a first test measurement is shown in Figure 13.

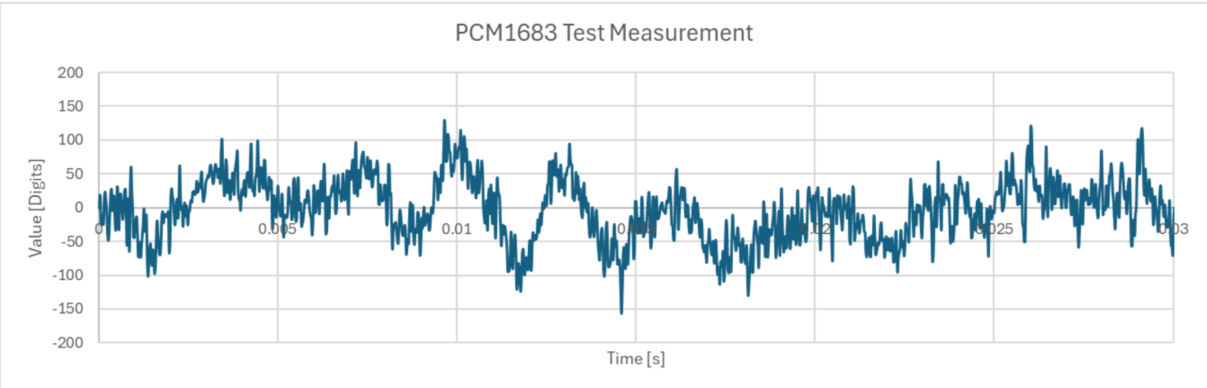

Figure 13: Test measurement with PCM1683 and VA-3D.

2.3.2 Data structure and stream of the wireless interface

As already mentioned in the previous section, the signal data of the WSP will be forwarded via MQTT to a broker in the IPT 5G-network. By using the MQTT-protocol for data exchange, different server applications in the edge cloud can access the data at once for further analysis. Possible applications are the Asset Administration Shell (AAS) or C-Thru from MMS. A data analysis of the WSP data can be seen in Figure 14.

Since the 5G-modem is connected via USB, the modem-drivers will be loaded automatically once the drivers are installed and the device is connected. In addition, there is a GPIO to deactivate the modem to save battery power. This GPIO could also be set in the ANSI-C application.

The easiest way to establish a 5G-connection under Linux is to install the tools network-manager and modem-manager, which allow the configuration of the cellular network in a GUI. Once the 5G-connection is up and running, it behaves like a standard Ethernet connection.

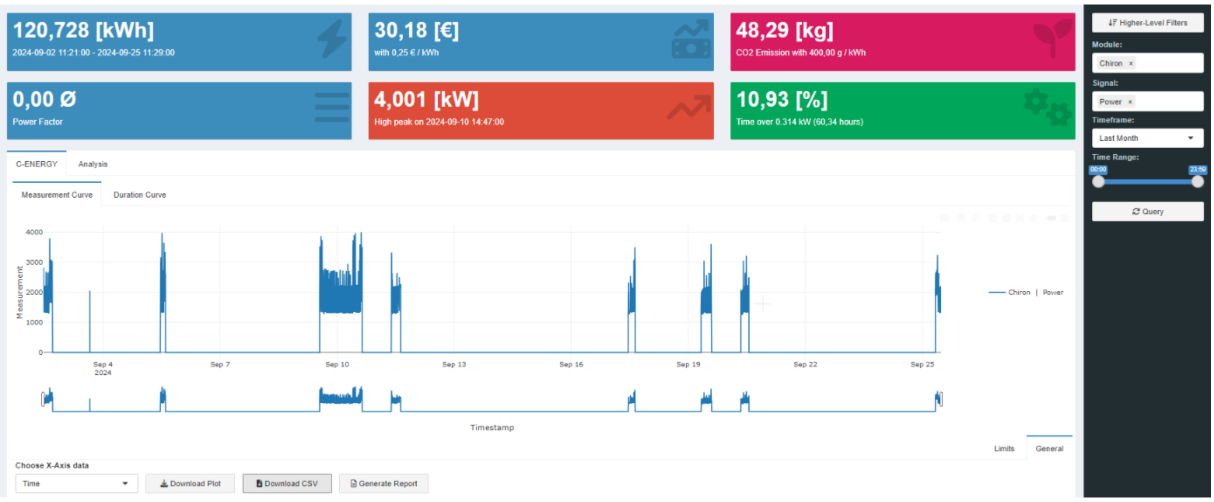

Figure 14: WSP data in MMS C-Thru.

2.4 Cloud Integration

2.4.1 Cloud Architecture and the implementation of its components

To analyze, store and use the data provided by the wireless sensor system, a cloud architecture will be implemented, as shown in Figure 15. The application, hosted in the Fraunhofer Edge cloud, is designed with a modular structure, dividing it into distinct software modules, each serving a unique use case functionality.

The **Gateway,** a robust physical connection, interconnects the 5G network to the factory cloud networks, where the packets are routed. Its role in ensuring seamless connectivity and data transfer instills a sense of security in the system's operations.

The protocol data servers are a versatile component of the application. They translate data from various protocols and feed it into the application layers, where it can be processed, analyzed, and stored. This layer provides an abstraction, enabling the integration of heterogeneous devices and ensuring interoperability.

Multiple SW modules then access the data from the servers.

The **device management** modules keep track of the wireless sensor platform, track its statistics and battery status, and store the sensors' configuration. It also provides API to interact with the Asset Administration Shell to create wireless sensor platform assets.

The **Data Analysis Module** contains the software that analyses the data from the multiple sensors, analyzes and provides features and usable information that can be used to create an application such as digital Twin, energy analysis, anomaly detection, etc., additionally for a use case such as track and tracing, it provides the necessary algorithm needed to triangulate the position and trace the sensor platform based on the BLE, UWB and the 5G information.

To synchronize the wireless sensor platforms and the cloud application, a time server is needed to be used as a reference for synchronizing the modules before the start of the application. This is achieved by using the Network Time Protocol (NTP) server module.

The data from the sensors, processed and analyzed data are then stored in the **Database**. The Database can be accessed via API by applications such as AAS and the Digital Twin for further analysis.

The **Asset Administration Shell (AAS)** provides the necessary device and network infrastructure modeling information. This information can then be used to fine-tune the application, such as reconfiguring the sensor platform, moving the device to a new 5G cell, etc.

All the analysed data from the other SW modules can be used to create a Digital Twin. The Digital Twin module accesses the information from the AAS, the sensors, and the Database to create a digital replica of the manufacturing process, with the replica providing real-time information on the condition of the machine, the workpiece, and the environment.

In addition, a human interaction dashboard has also been developed to easily onboard the sensor platforms and manage them by configuration and OTA, as well as provide live data visualization for monitoring.

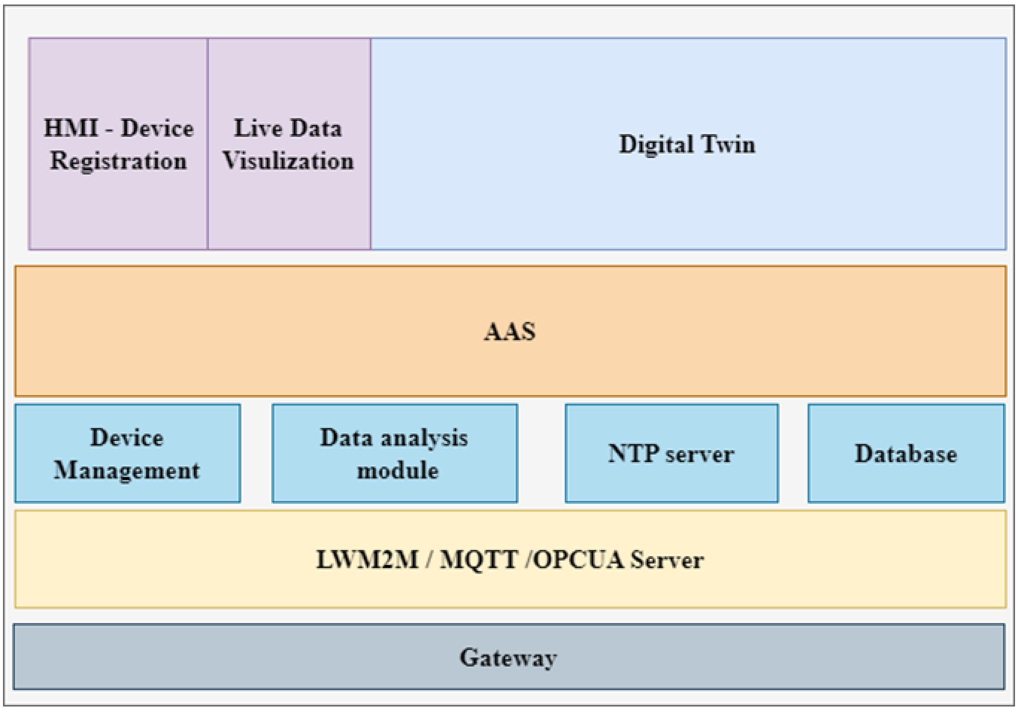

Figure 15: Cloud architecture for the wireless sensor platform.

Trace and Tracking

For the use case of Track and Trace, the sensor platform must be positioned and tracked throughout the manufacturing process. This requires wireless technology capable of localizing and tracking the sensor platform. Traditionally, GPS/GNSS is used for localization with the help of satellites and GNSS modules. However, since the application operates indoors, satellite visibility may be significantly reduced, making GPS/GNSS impractical.

For this project, 5G technology is planned to assist in localizing the sensor modules. To assist the 5G based localization, a secondary localization based on Bluetooth Low Energy or Ultra wide Band is developed in parallel. This can support the 5G network to have improved accuracy and precision in positioning.

Achieving localization using BLE or UWB involves installing corresponding beacons throughout the manufacturing shop floor. These beacons transmit or broadcast their identifier. The sensor platform with BLE nearby identifies the broadcaster, the beacon, and uses this to determine its position. With more beacons, it's easy to track the sensor platform with additional identifiers and signal strength that can be used to triangulate the position. The signal triangulation can happen either on the sensor platform or in the cloud.

The following picture shows the possible integration of beacons on the shop floor at the Fraunhofer IPT.

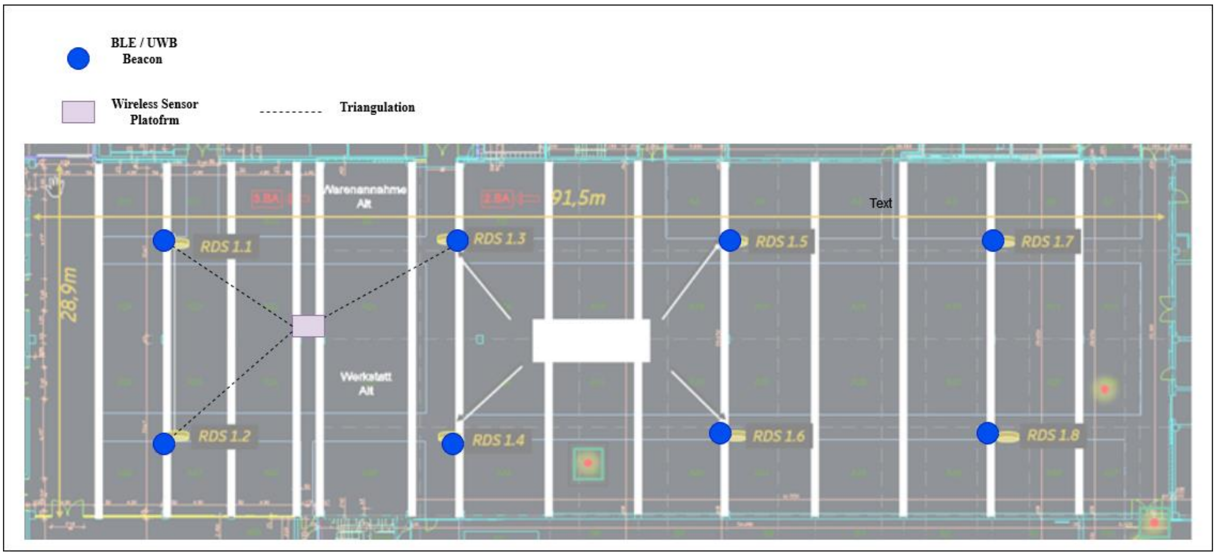

Figure 16: Plan of the IPT shopfloor with possible position for further beacons.

2.5 Interface towards beyond 5G features

2.5.1 Network and device AAS

The digitalization of the enterprises highly relies on the efficient and interoperable communication among the assets participating in a manufacturing task. Especially in the use cases of condition monitoring and tracing, it is critical to integrate different subsystems to have a holistic realization where network becomes an integral part of the industrial ecosystem. As these use cases require solutions and products from different vendors to interact with minimum human intervention as possible, creating digital representations of the assets and establishing a common understanding in the virtual domain with pervasive communication becomes a promising approach.

In this regard, AAS is a promising framework that enables the integration of any industrial asset into digitalized world. AAS, by creating the digital representations of products, field devices, controllers and many other industrial assets, can create a virtual world where the participants at different layers can communicate with each other.

Besides the industrial assets, such as mobile robots and wireless sensor platform (WSP), the flexibility of AAS principles enables one to create the digital representation of 5G system as well. In particular, 5G-ACIA proposes the vision of 5G Network (NW) AAS and 5G UE AAS as the potential way of integrating 5G system into IT/OT domain [2].

TARGET-X aims to realize this vision by creating the 5G NW AAS and 5G UE AAS, which are capable of representing the 5G system from different aspects. While 5G NW AAS, which is considered as the digital twin of industrial 5G network by 5G-ACIA, stores the up-to-date data provided by the network via exposures, similar concept applies to the 5G UEs and their AAS representations. By achieving this synchronized data flow between the physical and virtual counterparts, TARGET-X intends to enhance the degree of automation in network management and device orchestration. Correspondingly, the standardized communication interfaces and data models play an important role in achieving interoperable information exchange between any AAS participating in the business.

Even though there exist different ways of using AAS for different objectives, TARGET-X proposes to position AAS as an integration point between industrial domain and 5G system. In particular, AAS can be assigned with the role of exchanging requirements and configurations in condition monitoring and tracing use cases.

With the introduction of novel use cases at the factory floor with more stringent requirements, 5G network needs to provide higher performance and value-added services in addition to always-on connectivity. Faster data rate, reliable communication and low latency interaction are the intrinsic capabilities of the private 5G network deployments. However, due to dynamicity of the surrounding and variety of the requirements, the interaction between the systems should not become a bottleneck. In other words, we need interoperability and higher degrees of automation, which can be provided by AAS in these use cases.

As discussed, we propose to create an AAS representation of the WSP and the PLC (Programmable Logic Controller). Since the exchange of contextual information, real-time communication of a requirement and reconfigurations need to happen among different subsystems, inter-AAS operations are envisioned to bring added value to the condition monitoring and tracing use cases. The communication and interaction between the AAS instances as well as AAS and physical assets will enhance the automation degree.

The first way of utilizing AAS is the interoperable data exchange [3]. In this use case, AAS of the industrial assets (e.g., WSP) can define the expectations from the network, such as data rate. In case of dynamicity in the environment, expectations might change as well. Therefore, these requirements should be communicated with the network without manual human intervention. 5G NW AAS can collect requirements from different assets via their AAS representations. In this direction, different approaches can be used for inter-AAS communication (e.g., NW AAS and device AAS), such as standardized REST API and MQTT. With the integration of intelligent models, 5G NW AAS can reconfigure the network to support these use cases and meet the expectations.

The opposite way of interaction is possible as well. In other words, in addition to the data flow from industrial domain towards the network (e.g., expectations from the network), there is a potential data flow from network to the industrial domain as well (e.g., measurements). The typical operations and contents of 5G NW AAS are designed to fetch performance measurements from the network. Whenever a degradation is detected or failure is observed, 5G NW AAS can inform other devices in the environment. For example, when the network is heavily loaded, 5G NW AAS can inform AAS of WSP, so that sensor data generation frequency can be decreased to mitigate the problem in the network.

In order to create the AAS of WSP and related machines in the use cases, we use Eclipse BaSyx which is an open-source framework to create and work with AAS. BaSyx already provides capabilities to integrate active functions into AAS in addition to the flexible creation of submodels and submodel elements. Even though there exist many options, we use MQTT-based interaction between the AAS of network and WSP for exchanging knowledge. The knowledge to be exchanged is, but not limited to, are summarized in TABLE II.

TABLE II: Data streams between different AAS.

DATA TYPE	SOURCE	DESTINATION
SENSOR DATA	WSP	WSP AAS
SENSOR RECONFIGURATION	WSP AAS	WSP
SENSOR RECONFIGURATION PROPOSALS	5G NW AAS	WSP AAS
REQUIREMENTS	WSP AAS	5G NW AAS
NETWORK MANAGEMENT	5G NW AAS	5G
NETWORK MEASUREMENTS	5G	5G NW AAS
5G UE RECONFIGURATION PROPOSALS	5G NW AAS	5G UE AAS
5G UE RECONFIGURATION	5G UE AAS	5G UE

As specified in TARGET-X deliverable D1.1, end-to-end QoS support for conditional monitoring use case defines upper/lower threshold for average data rate, latency and availability. There also exist additional communication attributes, which can be communicated with the network for enhanced support. These requirements can be defined by MSP and communicated with the network via AAS. If latency requirement (e.g., < 20 ms) cannot be satisfied due to a reason, 5G NW AAS can either reconfigure the network (e.g., increase priority, handover to another cell) or device (e.g., decrease frequency).

Trace and tracking of workpieces define a similar set of requirements. Therefore, AAS can apply similar principles to support this use case in addition to the environmental condition monitoring. While network can benefit from the data provided by MSP and machines for optimized network management, MSP and machines can also make use of insights provided by 5G NW AAS to optimize their operations without any degradation in performance.

For efficient, scalable and real-time operations, TARGET-X proposes to deploy AAS instance at the factory edge. Hence, we can minimize the latency for not just inter-AAS communication but also consumption of related services (e.g., tracing).

2.5.2 RedCap

The use of 5G Rel-17 Reduced Capability (5G RedCap), is also explored in the WP2 manufacturing use case, as the sensor platform that drives the application runs on a battery. The reduced capabilities involve trading off the features of the 5G, such as reduced bandwidth and slightly higher latency, but significantly reduce the power consumption of the modules, making it attractive for the Industrial IoT wireless sensor platforms.

As a preliminary step, a RedCap RM255C module (M.2) was compared with the 5G Rel-16 RM520N series. The RedCap measurements were performed with a series of data transmission of varies packet sizes. The results show that the 3GPP Rel-16 RM520N series 5G module consumes on average 1 -1.1W, with a spike on power of up to 1.3W when the signal strength is too low. On the other hand, the RedCap module consumes around 0.43W, which represents almost half of power consumption. This reduction in power comes with tradeoff in terms of latency and throughput, which will be evaluated in future work.

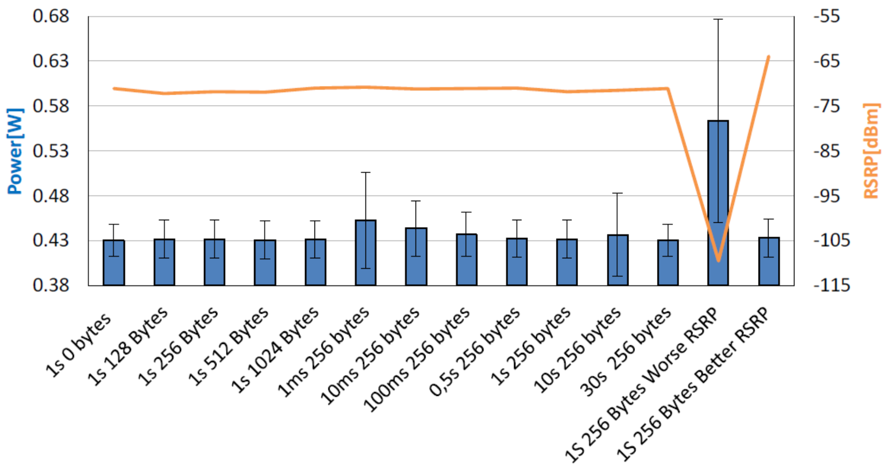

Figure 17: Average power measurements with Quectel RedCap RM255C in a 5G SA network.

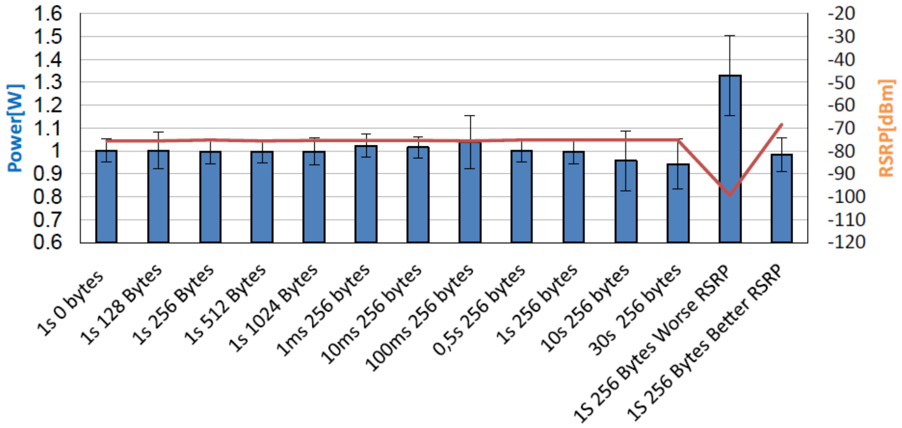

Figure 18: Average power measurements with Quectel RM520-GL in a 5G SA network.

With such promising results, Fivecomm, as UE hardware developer, additionally decided to design and produce new RedCap modems integrating Quectel RG255C modules (LGA type), a different alternative to the RM255C series that permits to integrate them into a PCB and provide all needed interfaces as required by use case owners and particular verticals.

The following figure shows, on the left side, the M.2 module used for the measurements showed above and, on the right side, the LGA module integrated by Fivecomm into their new board.

Figure 19: RM255C (left) and RG255C (right) RedCap module series employed in TARGET-X.

Note that the module has a size of 32 × 29 × 2.4 mm, which is clearly reduced compared to the original size of 41 × 44 × 2.75 mm from the RG520N 5G Rel-16 modules previously implemented. Currently, the module has been already integrated into a first design of the PCB prototype and is under test as this report is being written. Similar results as the ones shown in Figure 17 and Figure 18 are expected. The final prototype as well as its validation and comparison results are expected to be reported in the final report D2.5.

3 Implementation of the inline quality assurance system for machining

Industrial processes such as milling or turning involve a high degree of complexity in process control, which can only be monitored by more intelligent and adaptive systems. In particular, the integration of sensor technology into the process chain for inline quality assurance enables closer monitoring of process parameters and more efficient production with fewer rejects [4]. However, the integration of these sensors is made more difficult by two factors: firstly, the specific environmental conditions in a production hall due to, for example, high dynamics, lots of metal enclosures, high temperatures or the use of cooling lubricants. On the other hand, the very high demands of the industry on the communication infrastructure. In particular, real-time communication with high reliability poses a challenge when setting up a wide sensor network [5, 6].

In order to use sensor networks for inline quality assurance under these environmental conditions and in compliance with the high requirements, TARGET-X is investigating how existing, commercially available, robust OT systems can be wirelessly integrated into production using Beyond 5G technologies. Various approaches such as Time-Sensitive Networking (TSN) or Deterministic Networking (DetNet) are being investigated here.

3.1 Overall architecture

In Figure 20 the overall architecture of an inline quality assurance system is given. A sensor is integrated to a workpiece or in a machine, the sensor data is sent as an analog signal towards a Data Acquisition (DAQ) device, transforming the data into a digital format and sending it via a wireless system towards a Programmable Logic Controller (PLC) for further data analysis. After analyzing the data, it can subsequently adapt the process. Different wired solutions for such systems exist, but due to the high requirements towards real-time [7], there are no wireless solutions available.

The implementation and validation of the architecture in WP2 will focus on the wireless connectivity, aiming for real-time transmission between the remote station and the Master. For this, different data streams need to be investigated and implemented, such as: Broadcasting messages, Time Synchronization over the air, real-time data and non-real-time data. The setup of the architecture will be done in three phases, first the field devices for the sensor to control pipeline, then the measurement setup for the validation of the wireless solution, and then the communication layer focusing on deterministic and high reliable wireless transmission.

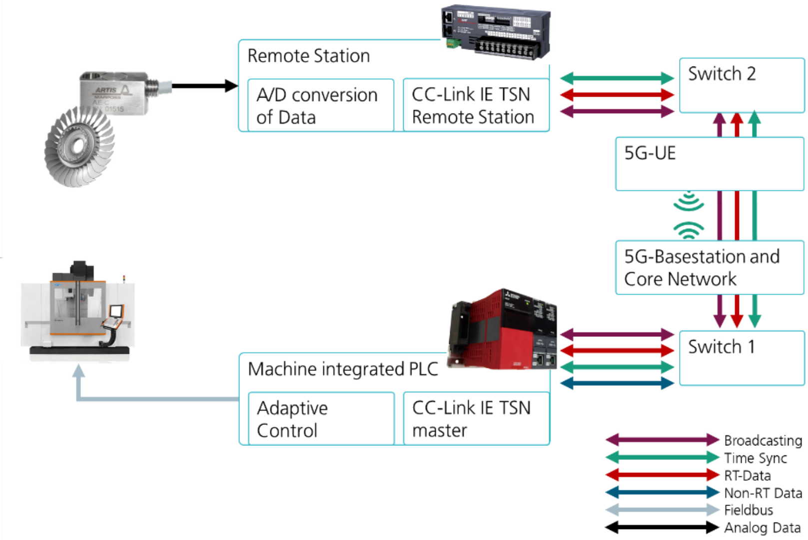

Figure 20: Overall architecture of an inline quality assurance system.

3.2 Field devices

3.2.1 Remote station and sensor

A CC-Link IE TSN remote station from Mitsubishi Electric is used for the sensor connection of the demo setup. This can be an A/D conversion module or a digital I/O module. CC-Link IE TSN Class B with 1Gbps is used for deterministic communication.

Figure 21: CC-Link IE TSN remote stations [8].

3.2.2 Machine integrated PLC

An iQ-R series from Mitsubishi Electric is used for the PLC integrated into the demo machine. Adaptive control is performed via a PLC program on an RnCPU which receives the sensor data via a CC-Link IE TSN master module.

Figure 22: iQ-R series PLC with CC-Link IE TSN [8].

3.2.3 Software architecture

Figure 23 shows a simplified software architecture with the essential modules required for sensor data transmission with CC-Link IE TSN over a deterministic 5G network.

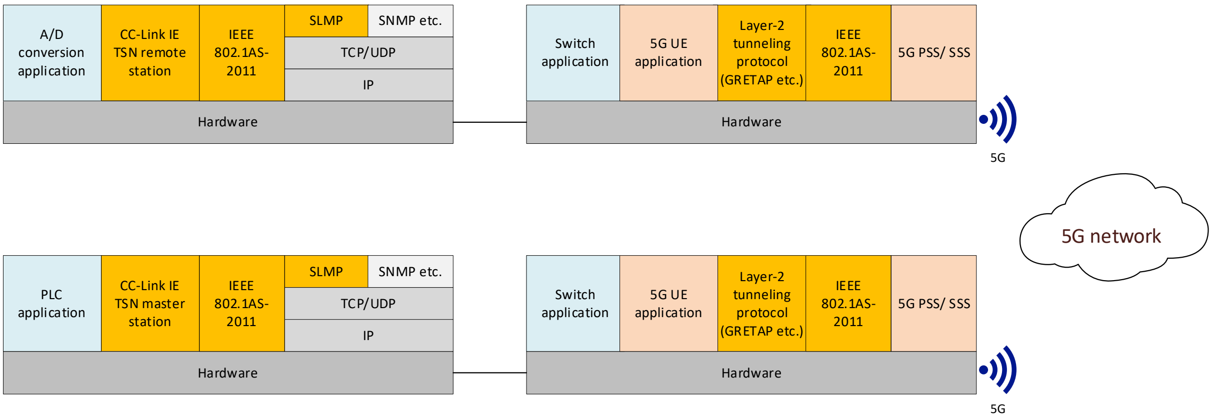

Figure 23: Software architecture for CC-Link IE TSN data transmission.

3.3 Measurement setup

Real-time communication is needed in the industry to ensure timely decision-making, enhance operational efficiency, and maintain safety in critical applications. It allows systems to respond immediately to changes or events, which is vital in environments such as manufacturing, healthcare, and transportation. Important KPIs to validate real-time capabilities include:

- One way (End-to-end) **Latency**: the time that it takes to transfer application data of a given size from a source (field device) to a destination (PLC).
- **Jitter**: the variation of a time parameter, typically the end-to-end latency.
- **Packet Loss Rate**: percentage of packets lost during transmission.
- **Time synchronization error**: the value of the time difference between a synch master (that is used as the timing reference) and any device operating on time-sensitive applications.

To validate the implemented real-time communication infrastructure, a measurement setup, capable of measuring these KPIs has been implemented as shown in Figure 24. The setup consists of two measurement streams that are combined in a data logger for later evaluation. As shown on the left in Figure 24, two passive Ethernet Taps have been integrated in the communication pipeline, mirroring the packets towards a traffic capturing device. This device captures the data with high resolution and a precise hardware timestamp. The data is then forwarded to the log PC to calculate the latency between the two taps, the jitter and the package loss of the communication pipeline. The second measurement stream is shown on the right of Figure 24, using two high precision clocks connected and synchronized to the network. Using a Pulse Per Second (PPS) output, a PPS-Analyzer is connected to the clocks measurement the time synchronization error with high accuracy. The combination of these methodologies allows for a comprehensive assessment of both timing accuracy, latency, jitter and package loss.

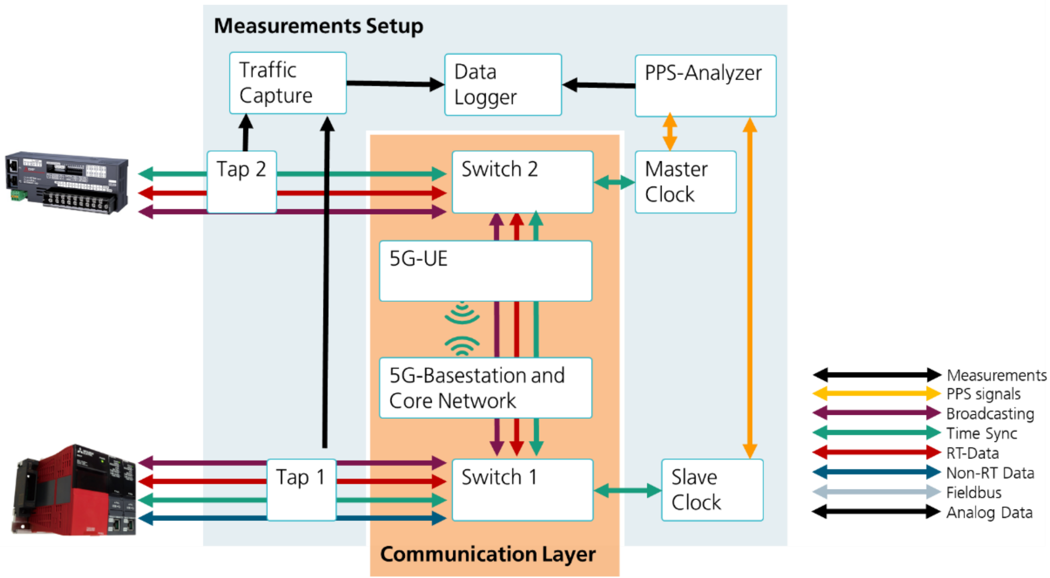

Figure 24: Measurement setup for the real-time communication validation.

3.4 Communication layer

To evaluate the performance of wireless communication for industrial real-time traffic, different setups for the communication layer marked in orange in Figure 24 will be used.

3.4.1 Traffic shaping using TSN

In this section, we outline the setup used to evaluate the performance and functionality of the IEEE 802.1Qbv and 802.1AS standards. These protocols play a crucial role in TSN by enabling precise time synchronization and traffic scheduling. The setup shown in includes the following components:

5G mid-band system operating in 3.7-3.8 GHz: The 5G mid-band system operating in the 3.7-3.8 GHz frequency range represents a significant advancement in wireless communication technology. This spectrum provides a balanced combination of coverage and capacity, making it ideal for industrial deployments.

URLLC test system: The Ultra Reliable Low Latency Communication (URLLC) system is designed to meet the stringent requirements of applications where reliability and low latency are critical. It is a pre-commercial, standard compliant test system for 5G communication. Operating at 28 GHz with 200 MHz of bandwidth, the URLLC test system provides different various 3GPP Rel. 15/16/17 features, such as Ethernet PDU sessions, time synchronization, traffic classification and prioritization [9].

TSN switches: For these trials, TSN switches from Moxa are used, engineered to provide deterministic and reliable data transmission in industrial Ethernet applications. These switches support IEEE 802.1 standards, enabling precise time synchronization and traffic scheduling to ensure low-latency communication. With robust features such as redundancy, high availability, and enhanced security, Moxa's TSN switches are ideal for critical applications in sectors like manufacturing, transportation, and smart grids, facilitating seamless integration of time-sensitive data streams.

Layer 3 tunnel: A Layer 3 tunnel implemented on a microcontroller serves as a vital solution for transmitting Layer 2 traffic over the 5G mid-band system that supports only Layer 3 protocols. By encapsulating Layer 2 frames within Layer 3 packets, this approach enables seamless communication between devices that rely on Ethernet protocols while leveraging the high-speed, low-latency capabilities of 5G networks. The microcontroller manages the encapsulation and decapsulation processes, ensuring that data is correctly formatted for transmission and received without loss of integrity. Using this tunneling mechanism, the layer 2 traffic of the CC-Link IE TSN pipeline can be transmitted via the mid-band 5G system.

Using these components, the two setups shown in Figure 25 Figure 25have been implemented:

Test setup 1: Precommercial implementation using the URLLC test system.

For a first validation, an implementation using the URLLC testbed will be done. The integration of the commercial OT-hardware requires a clear set of features and standards including time synchronization using gPTP, Layer 2 communication and 802.1 Qbv. The URLLC supports L2 traffic and time synchronization but not with gPTP. Therefore, a translation of different synchronization profiles, such as PTP needed to be implemented, mainly using the TSN switches. These switches are equipped to interpret and convert PTP messages from one profile to another, facilitating compatibility between diverse network components. By effectively managing this translation, the TSN switches ensure that all devices maintain accurate time synchronization. In Figure 25 on the left side the setup of the TSN-5G bridge is shown.

Test setup 2: Combined implementation of URLLC test and 5G mid-band system.

Using the results and knowledge gained from the first setup, a second setup using a commercially available 5G mid-band system will be implemented. To create the Layer 2 compatibility, a Layer 3 tunnel has been implemented to encapsulate the 5G mid-band system and enable the sending of the RT-Data and the Broadcasting messages. Since the commercial 5G mid-band system does not support time synchronization yet, the synchronization messages are filtered in the TSN-switches and forwarded via the URLLC test system for an over-the-air time synchronization.

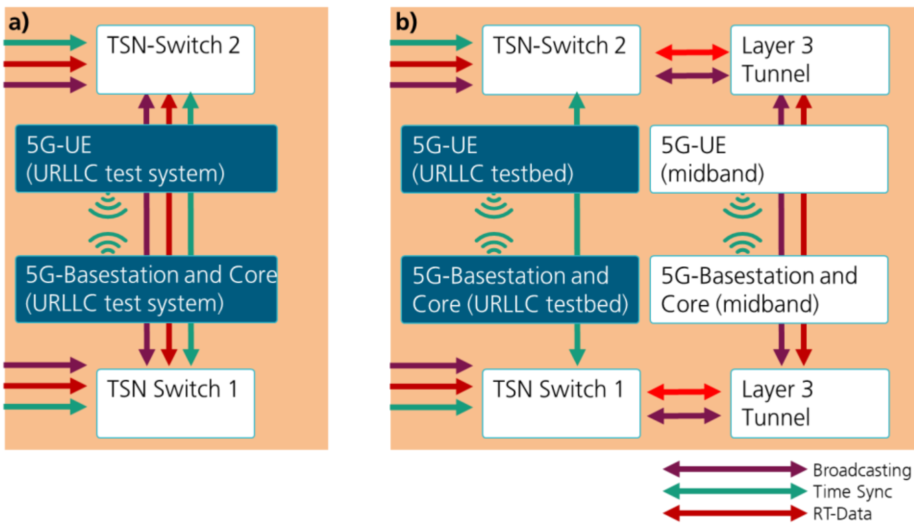

Figure 25: Setup for Traffic shaping using TSN. a) Test setup 1: Precommercial implementation using the URLLC test system. b) Test setup 2: Combined implementation of URLLC test and 5G mid-band system.

3.4.2 Traffic shaping using DetNet

Test setup 3: Combined implementation of URLLC test and 5G mid-band system for DetNet traffic.

To test the combination of TSN, DetNet and 5G, a similar setup then Setup 2 will be used. Instead of the Layer 3 tunnels implemented, DetNet provides a Layer 3 compatibility and can directly be used as Layer 3 tunnel. Due to the compatibility of TSN and DetNet mechanisms, a fast integration of DetNet as Layer 3 bridge over the 5G system can be achieved [10]. The setup is shown in Figure 26.

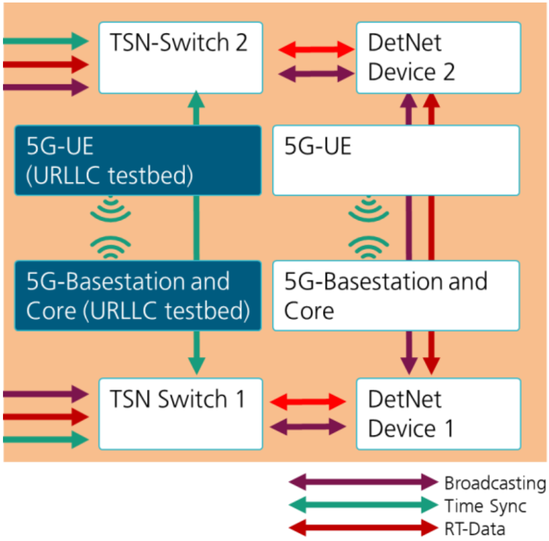

Figure 26: Test setup 3: Combined implementation of URLLC test and 5G mid-band system for DetNet traffic.

3.4.3 Reliability using FRER

In this section, we describe the setup to implement and validate high reliability communication via 5G using IEEE 802.1CB, or "Frame Replication and Elimination for Reliability," in industrial context. FRER enhances network reliability by replicating critical data frames and transmitting them through multiple paths. This redundancy ensures that if one path fails, the data can still be received via another route, thereby minimizing downtime increasing reliability—a crucial factor for continuous industrial operations. Besides the 5G systems, TSN switches and Layer 3 tunnel described in Section 3.4.1 the following component has been added to the trials:

5G mmW system deployment at 26 GHz: The 5G mmWave non-public network operates at 26 GHz (5G n258 band) with a system bandwidth of 800 MHz, designed specifically to meet the needs of industrial applications. This technology is particularly well-suited for scenarios requiring high data rates and minimal mobility, such as in industrial automation, smart factories, or dense urban environments.

Using these components, the two setups shown in have Figure 27 been implemented:

Test setup 4: Redundant communication via 5G SA mid-band and 5G NSA mid-band systems.

The messages sent from the OT-Hardware is replicated in TSN Switch 2. Then it is sent redundantly through two different 5G-UEs via 5G to the TSN Switch 1 for the elimination of the second message. In Setup 4 two different 5G mid-band systems with different cores are used, one NSA and one SA. With this setup a redundancy in 5G-core and 5G-UE can be achieved, validating how hardware redundancy enhances the reliability of 5G communication. The setup is shown in Figure 27 a).

Test setup 5: Redundant communication via 5G NSA mid-band system.

Again, the messages sent from the OT-Hardware is replicated in TSN Switch 2. Then it is sent redundantly through two different 5G-UEs via 5G to the TSN Switch 1 for the elimination of the second message. In Setup 5 one 5G NSA mid-band system is used. With this setup only a redundancy in 5G-UE can be achieved, validating how FRER can benefit a setup with only one 5G core. The setup is shown in Figure 27 b).

Test setup 6: Redundant communication via 5G SA mid-band and 5G NSA mmWave systems.

The messages sent from the OT-Hardware is replicated in TSN Switch 2. Then it is sent redundantly through two different 5G-UEs via 5G to the TSN Switch 1 for the elimination of the second message. In Setup 6 two different 5G systems with different cores and different spectrums are used. One NSA system in the mmWave spectrum and one SA in the mid-band spectrum. With this setup a redundancy in 5G-core, 5G-UE and spectrum can be achieved, validating how hardware and spectrum redundancy enhances the reliability of 5G communication. The setup is shown in Figure 27 c).

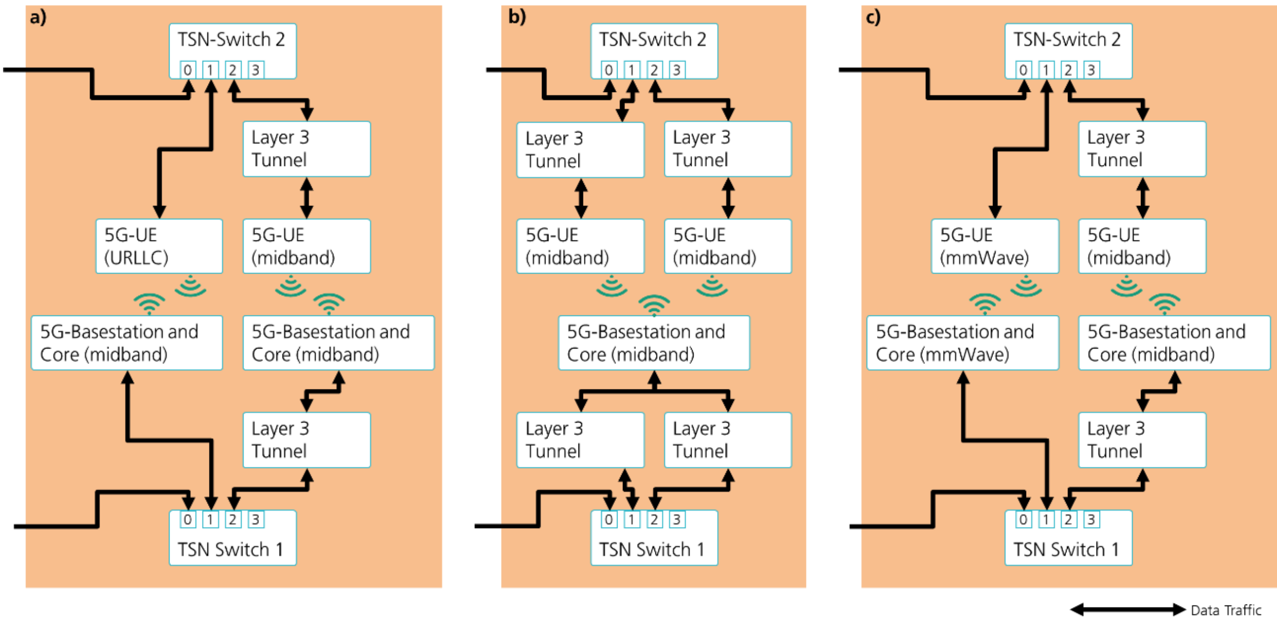

Figure 27: Setup for high reliable communication using FRER. a) Redundant communication using 5G SA mid-band and 5G NSA mid-band systems. b) Redundant communication using two UEs in the 5G NSA mid-band system. c) Redundant communication using 5G SA mid-band and 5G NSA mmWave system.

4 Conclusions

This deliverable document presents a comprehensive framework for the implementation of the Wireless Sensor Platform (WSP) and the Inline Quality Assurance System for Machining. The detailed exploration of the sensor platform's architecture demonstrates a robust integration of hardware components, including various sensors to capture critical environmental and operational data. The inclusion of different 5G modules and features shows the versatility of the implementation and the use cases. The cloud integration strategy outlined in the document further enhances the platform's capabilities, providing a scalable architecture for data storage and processing. This ensures that the data collected is not only accessible but also actionable, enabling informed decision-making and fostering innovation.

The Inline Quality Assurance System's architecture emphasizes the importance of real-time and high reliability communication within machining processes. By incorporating advanced communication layers and reliability mechanisms, this system assures high data integrity and operational efficiency. The focus on field devices, including remote stations and integrated PLCs, ensures seamless integration with existing manufacturing systems, thereby minimizing disruption during implementation.

Future work will focus on the practical deployment of these systems, addressing potential challenges and paving the way for continuous improvements in sensor technology and quality assurance methodologies. By adopting these innovative solutions, organizations can not only enhance their operational efficiencies but also drive sustainable growth in a rapidly evolving technological landscape.

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