5G CONNI

Private 5G Networks for Connected Industries

Deliverable D1.1

Report on Use Cases & Requirements

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Abstract

This document collects the results of the analysis of 5G CONNI use cases and their requirements on a private 5G network as part of WP1, which form the fundamental basis for further work in WP2-5, especially for the implementation of demonstration setups at the planned, interconnected private 5G network trial setup between Europe and Taiwan.

Six use cases have been identified, which are relevant in the 5G CONNI context of private 5G networks for connected industries. The use cases are: (1) DECT phones replacement in office and manufacturing sites, (2) shop floor asset tracking using on-board and on-premise sensing devices, (3) cloud-based controllers for CNC, (4) process diagnostics by CNC and sensing data collection (UC-1), (5) using augmented/virtual reality for process diagnosis (UC-2), and (6) robot platforms with edge intelligence and control (UC-3). The latter three use cases have been selected for a possible implementation at the interconnected trial setup between Europe and Taiwan. Here, UC-1 targets at continuous data visualization and tool condition monitoring to reduce unscheduled downtime caused by tool breakage. UC-2 helps process engineers set up workpieces or monitor abnormal conditions during machining by detecting and visualizing vibration, collision, acoustic emission, temperature, or energy consumption, and thereby reducing the costs for trial-and-error. Finally, UC-3 combines video analytics and robot motion control in the cloud enabling collaborative robots, higher production efficiency and pooling of centralized control. The three use cases have been thoroughly analyzed with respect to traffic type characteristics, scenarios and use case classes, their functional and non-functional requirements, the benefits they bring to manufacturing, and challenges that might occur during their implementation and validation.

One essential part of the use case analysis is the identification of functional requirements. A functional requirement describes a feature or function, the 5G System must have or must be able to perform. Thirteen such functional requirements have been identified, of which four are shared by all the three use cases: (1) Provisioning and (2) monitoring of end-to-end QoS, (3) secure remote access, and (4) edge computing support. The other functional requirements are more specific to the individual use cases: Support for (5) mobility management, (6) energy efficiency, (7) network capability exposure, (8) priority, QoS and policy control, (9) time synchronization, (10) localization services, (11) context-aware networks, (12) 5G-LAN type services and (13) proximity services. In addition to functional requirements, a system is characterized by non-functional, QoS-related, measurable attributes. Because the 5G CONNI use cases are related to different scenarios, use case categories and traffic characteristics, the non-functional requirements are rather diverse. They range from high data rate requirements, to stringent positioning and timeliness demands.

In addition to the use case-specific requirements, additional use case-unspecific functional requirements on a private 5G network have been derived as a first result of the analysis of the requirements and concerns regarding suitable operator models. 61 such requirements have been identified, which are derived from 19 goals, where each of the goals falls into one of eight categories, namely: (1) Subscriber and identity management, (2) cyber-security, (3) monitoring and alerting, (4) slice and network management, (5) service availability, (6) access control, (7) voice services, and (8) charging.

The use case analysis and identification of additional functional requirements on a private 5G network will help derive a system architecture along with technological developments in WP2-4. Further analysis and conceptualization of the use cases for the trial setups will be conducted in WP5 on the basis of the results in this document. Also, the use case-unspecific functional requirements will be further refined and extended in WP1-2.

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List of Acronyms

3GPP	3rd Generation Partnership Project
5G	5th Generation Mobile Communications
5G CONNI	5G for Connected Industries
API	Application Program Interface
AR	Augmented Reality
ISA/IEC	International Society of Automation / International Electrotechnical Commission
ACL	Access Control List
AI	Artificial Intelligence
AGV	Automated Guided Vehicle
BT	Bluetooth
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CMM	Coordinate Measuring Machine
CN	Core Network
CNC	Computer Numerical Control
CPE	Customer Premise Equipment
CSA	Communication Service Availability
CSR	Communication Service Reliability
DAQ	Data Acquisition
DECT	Digital European Cordless Telephone
DHCP	Dynamic Host Configuration Protocol
DDoS	Distributed Denial of Service
eMBB	Enhanced Mobile Broadband
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved Universal Terrestrial Radio Access Networks
ERP	Enterprise Resource Planning
E2E	End-to-End
FW	Firewall
gNB	gNodeB
gPTP	Generic Precision Time Protocol
HMD	Head-Mounted Display
HMI	Human Machine Interface
HSM	Hardware Security Module
HSS	Home Subscriber Server
ICT	Information and Communications Technology
IEEE	Institute of Electrical and Electronics Engineers
IMS	IP Multimedia Subsystem
IMSI	International Mobile Subscriber Identity
IMT	International Mobile Telecommunications
IoT	Internet of Things
IP	Internet Protocol
IPC	Industrial Personal Computer

IT	Information Technology
KPI	Key Performance Indicator
LAN	Local Area Network
LAN-VN	LAN Virtual Network
LiDar	Light Detection and Ranging
MAC	Medium Access Control
MCx	Mission Critical Services
MEC	Multi-Access Edge Computing
MES	Manufacturing Execution System
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communications
mmWave	Millimeter Wave Communications
MNO	Mobile Network Operation
MSGin5G	Message Service Within the 5G System
MTBF	Mean Time Between Failures
MVNO	Mobile Virtual Network Operator
NFV	Network Function Virtualization
NPN	Non-Public Network
NR	New Radio
NS	Network Slicing
NSI	Network Slice Instance
O&M	Operation and Management
OAM	Operation, Administration and Maintenance
OPC UA	Open Platform Communications Unified Architecture
OTT	Over-The-Top
PBX	Private Branch Exchange
PC	Personal Computer
PDA	Personal Digital Assistant
PDU	Packet Data Unit
PER	Packet Error Rate
PLC	Programmable Logic Controller
PLMN	Public Land Mobile Network
ProSe	Proximity Services
PTT	Push-To-Talk
QoS	Quality of Service
RAN	Radio Access Network
RASI	Responsibility, Accountability, Support and Information
RAT	Radio Access Technology
RF	Radio Frequency
SDN	Software-Defined Networking
SIM	Subscriber Identity Module
TCP	Transmission Control Protocol
TSN	Time-Sensitive Networking
UDM	Unified Data Management
UE	User Equipment

UPF	User Plane Function
URLLC	Ultra-Reliably Low-Latency Communications
V2X	Vehicle-to-Anything
vLAN	Virtual Local Area Network
VM	Virtual Machine
VoIP	Voice over IP
VPN	Virtual Private Network
VR	Virtual Reality
WAN	Wide Area Network
webRTC	Web Real-Time Communication

Table of Contents

1 Introduction

1.1 Objective of this Document

The 5G CONNI project aims at providing an integrated end-to-end 5G test and demonstration network for industrial applications. This network will be developed to serve a number of industrial use cases, which leverage 5G network and edge computing capabilities, and which will be implemented at two interconnected industrial trial sites in manufacturing facilities in both, Europe and Taiwan.

The deliverable at hand is a result of Work Package 1, “Use Cases and Requirements”. It reviews and summarizes the current status of industrial 3GPP use cases, and outlines the identification and the in-depth analysis of potential innovative industrial 5G use cases relevant for 5G CONNI including their associated requirements for 5G in an industrial setting. The purpose of this use case analysis is building the basis for the definition of new private 5G network architectures and operator models, and measurements and tools for application specific network planning, tuning and monitoring. Additionally, the identified requirements will serve as a benchmark against the performance of innovative new technologies and enabling components in the context of eMBB and URLLC radio communications, mobile edge computing, core network design and joint optimization of these components, which the 5G CONNI consortium plans to develop in other Work Packages.

The analysis is carried out in more detail for three use cases, which are selected for practical realization as part of a technology demonstrator in Work Package 5. All use cases are elaborately described concerning their purpose, their benefits for industrial use and their identified requirements, which do not only include classical non-functional quality-of-service but also functional requirements on the 5G network.

While this first analysis reveals requirements that are tailored to the 5G CONNI use cases, installing, managing and operating a private 5G network in a live production environment generate another set of functional requirements that are mostly related to end device and performance management, cyber security, network monitoring, usability and the like. The deliverable at hand also lists and describes these use case-unspecific functional requirements in more detail.

1.2 Structure of this Document

This deliverable is structured as follows. Section 2 provides some preliminary information that is relevant for the definition and descriptions of the use cases considered in 5G CONNI. The information includes descriptions of some important terms and technologies, definitions of related functional and non-functional requirements that are mostly use case-specific followed by a brief review of use case groups considered by 3GPP. Section 2 then briefly introduces use cases, the description of which go beyond the ones in standardization, and discusses some important factors that need to be considered when selected use cases are implemented at the two 5G CONNI trial sites. These selected use cases are elaborately described in Section 3, specifying the functional and non-functional requirements for each use case and outlining important aspects for their implementation and validation at the trial sites. While Section 4 summarizes the use case-specific requirements, Section 5 collects and discusses functional requirements on private 5G networks in the context of private networks in industries that go beyond the use cases.

2 Preliminary Considerations

This section serves the purpose of providing information, which is the basis for the detailed discussion of the selected 5G CONNI use cases in Section 3. In particular, while Section 2.1 introduces relevant terms and briefly summarizes important technologies around private 5G networks, Sections 2.2 and 2.3 contain the definitions of functional and non-functional requirements, which are largely based on [1, 2, 3]. The requirements of 3GPP industrial use cases are summarized in Section 2.4 and use cases that are relevant to the 5G CONNI project are introduced in Section 2.5. Finally, Section 2.6 discusses some important aspects of the two trial sites in Europe and Taiwan, where selected use cases will be implemented.

2.1 Terminology

The following sub-sections make the reader more familiar with some important terminology and technology, which are relevant for the subsequent use case analysis and descriptions.

2.1.1 Edge Computing

Edge computing, see Figure 1, is the key technology of 5G to meet the requirements of high bandwidth and low latency applications, and to enhance security in that enterprises prevent their own data going through the Internet or a third-party managed wide area network. **Edge Cloud** is suitable for covering larger areas and can serve for more than one enterprise or factory. Edge cloud applications require stable data transfer to background services. To enable edge cloud, the 5G user plane function (UPF) provides a local breakout to the local Data Network close to the user equipment (UE) [4]. On the other hand, **Multi-access Edge Computing (MEC)** is deployed locally in smaller areas closer to the site, where the service is needed. For the local breakout, MEC solutions include UPF and bump-in-the-wire technology in ETSI [5], which allow low latency and high bandwidth applications, e.g. in a smart factory.

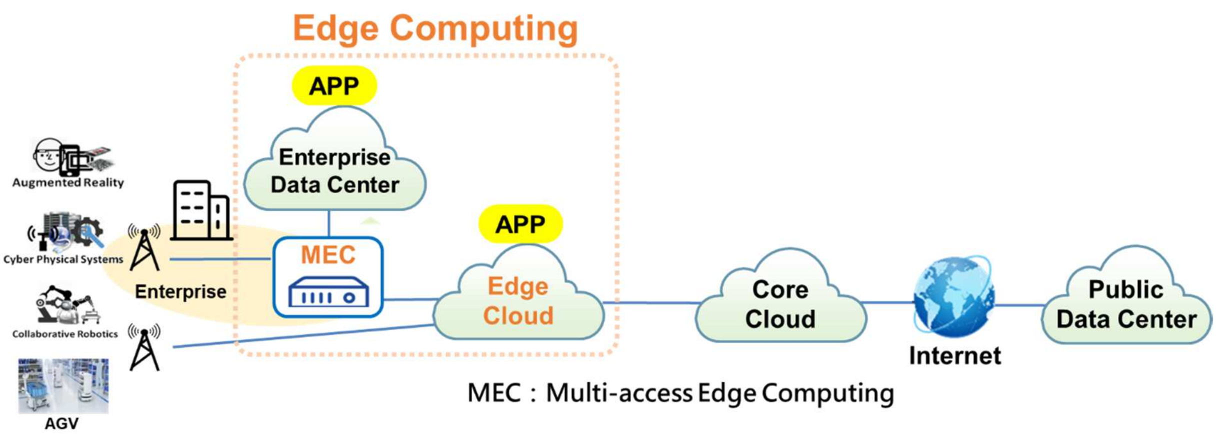

Figure 1: Edge Computing

2.1.2 Network Slices

Network slices allow operators to provide customized logical networks [2], including different functional requirements, such as priority, security, policy control, and mobility, and different performance requirements, such as latency, mobility, reliability, and data rate. Each network slice is a complete end-to-end network, including radio access network functions and core network functions. IMT-2020 usage scenarios are divided into enhanced mobile broadband services (eMBB), massive multi-machine type communication (mMTC), ultra-high reliability and ultra-low-latency communication (URLLC) as shown in Figure 2. Network slicing technology provides different network requirements, e.g. latency, bandwidth and mobility in smart factories, enabling the creation of logical networks for individual use cases and/or UEs/UE groups, such as a “staff” slice and a “Machinery” slice.

The combination of Network Function Virtualization (NFV) and Software-Defined Network (SDN) technologies accelerate the implementation of network slices. Virtualization technology can distinguish resources to different targets. SDN brings a central control node: the controller, which configures the data flow for a large number of network equipment and thereby enables dynamic, programmatically efficient networks.

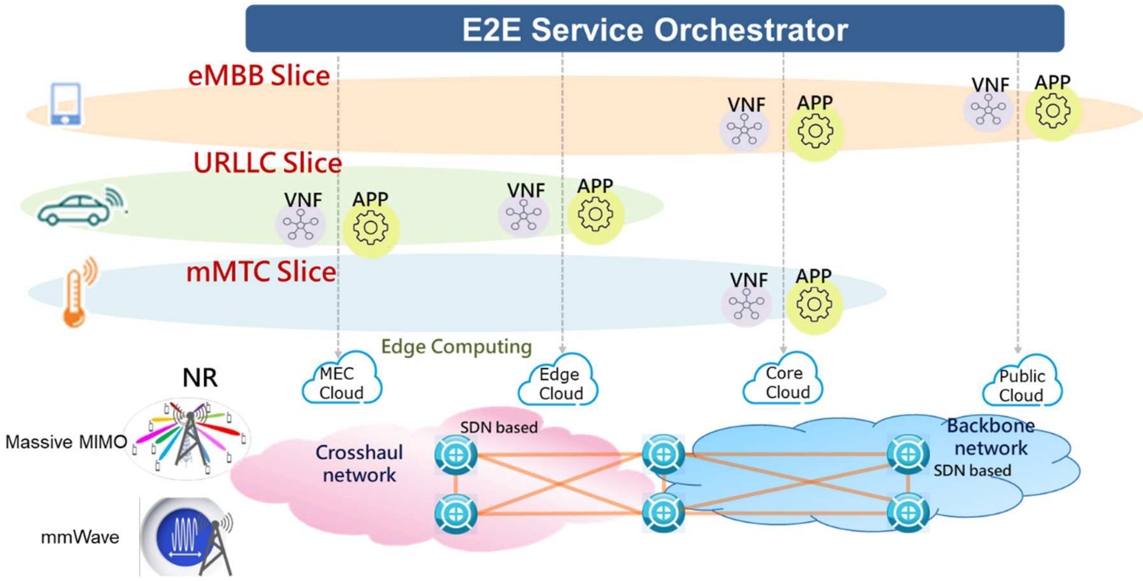

Figure 2: Network Slices

2.1.3 Life-cycle Management of Network Slices

The **lifecycle of network slices (NS)** information is described in [6] and is comprised of the four following phases: Preparation phase, Instantiation/Configuration and Activation phase, Run-time phase and Decommissioning phase, as shown in Figure 3. In the preparation stage, users will define the instantiated components, functions, resource configuration and all related workflows in the NS template. Then the user needs to prepare the network environment resources required by the NS template, and finally put the NS template into the NS system. In the next phase, Instantiation/Configuration and Activation phase, the NS system will link the network environment resources with the requirements in the network slice template and activate the related workflow. After completing the above actions, the NS enters the Run-time phase. At this stage, the NS can provide network communication services to users and provide related maintenance functions to the operators, and the operators can adjust the relevant configuration settings of the NS at this stage. When this NS does not need to be used, the operator can switch the NS from the run-time phase into the decommissioning phase. At this stage, the NS system will release all network environment resources, which are related to the NS template, and then remove the NS. Through the above four phases, users can completely manage the life cycle of an NS and develop their own NS according to their needs.

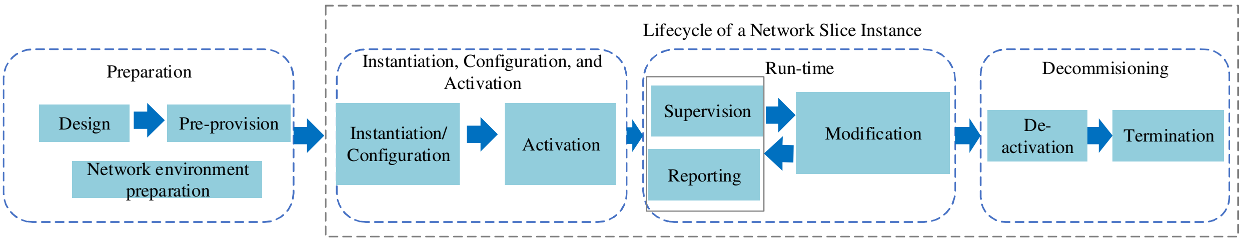

Figure 3: Lifecycle Phases of an NS and NSI [6]

2.1.4 Factory IT

Factory Information Technology (IT) principally focuses on the industrial automation and information system in the field of Operation Technology (OT) and is, therefore, a significant topic of the automation pyramid [7]. Security requirements of OT typically differ from the ones of IT security and some are more stringent because production equipment must continue its operation within the factory except during well-planned maintenance time windows, unlike IT equipment, which can go through ad-hoc maintenance procedures. OT security is becoming even more critical as many devices have the ability to connect to the Internet. Therefore, a collection of OT security-related principles needs to be employed, which are, for example, part of the ISA/IEC 62443 [8]. The ISA/IEC 62443 particularly introduces the principle of "zones" and "conduits" and, through this concept, emphasizes physical segregation in industrial factories to meet high security standards. In ISA/IEC 62443, a zone is an abstract concept, which integrates several devices or functions into one zone, and each zone has its own security level. The security level is used to indicate the specific zone security requirements. A conduit is an abstract communication channel, which provides secure means for communication, which allows different zones to communicate with each other.

2.1.5 Time-Sensitive Networking

Time-sensitive networking (TSN) is defined as the time-sensitive mechanism of Ethernet data transmission standards by the task group of IEEE 802.1 working group. The purpose of TSN is adding certainty and reliability features, such as features for clock synchronization, scheduling and path selection, to Ethernet making TSN essential for the data transmission of industrial applications. While the standardization of TSN is still ongoing, TSN is seen as promising technology opportunity to establish a unified foundation for industrial communications, mostly because of the contention of various current industrial communication standards, as seen in Figure 4.

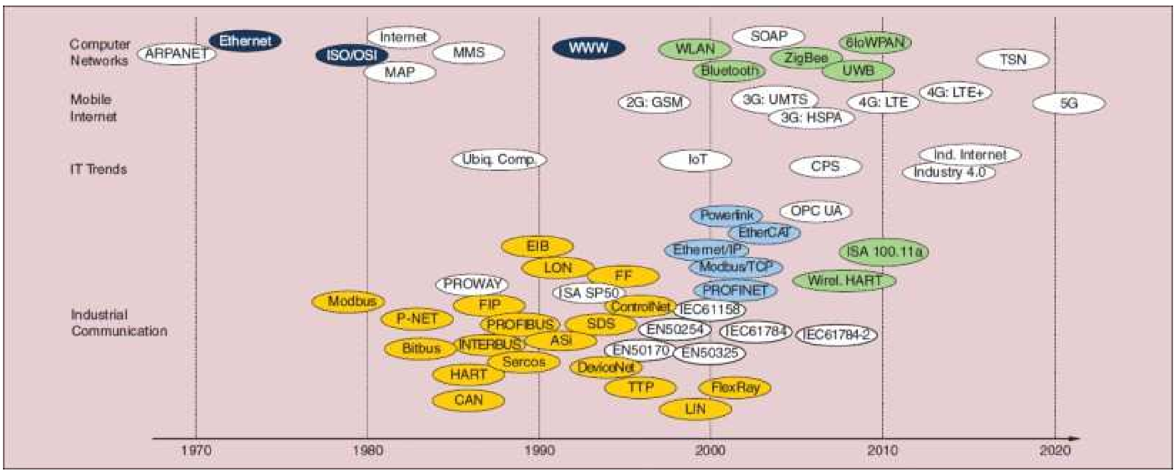

Figure 4: The Evolution of Industrial Communications [9]

2.1.6 User Plane vs. Control Plane vs. Operation & Management Traffic

Control plane, user plane and operation & management (O&M) traffic are three integral components of a telecommunications architecture, as shown in Figure 5. **Control plane traffic** contains control operations, such as security control for user authentication, authorization and message encryption, session and QoS management using transport bearers, and mobility management. In 5G, control plane traffic occurs between the UE and the Access and Mobility Function (AMF) via the N1 interface, between the radio access network (RAN) and the AMF via the N2 interface, and between the UPF(s) and the Session Management Function (SMF) via the N4 interface (black lines in Figure 5). Additionally, signaling messages are exchanged between the AMF and SMF and a number of other control services, namely for User authentication, data exposure, policy, charging and network slicing. For these services, 5G devises two architectural options: a traditional protocol-based one, and Service Based Architecture, inspired by modern software and web/cloud engineering technologies. **User plane traffic** (blue lines in Figure 5), also called data plane traffic, contains data packets generated by the subscribers, which are exchanged between the RAN and a UPF via the N3 interface, or, optionally, between the RAN and an Intermediate User Plane Function (I-UPF) via the N3 interface and between the I-UPF and the UPF Session Anchor via the N9 interface. While the UPF (Session Anchor) can forward user plane traffic towards (a public) data center, the I-UPF allows for a local breakout for ensuring that production data does not leave factory premises and for offloading computational tasks of industrial applications to a local edge cloud. **Operation & management (O&M) traffic** of a networking device include the communication of the systems that provide services for management, monitoring, provisioning and configuration.

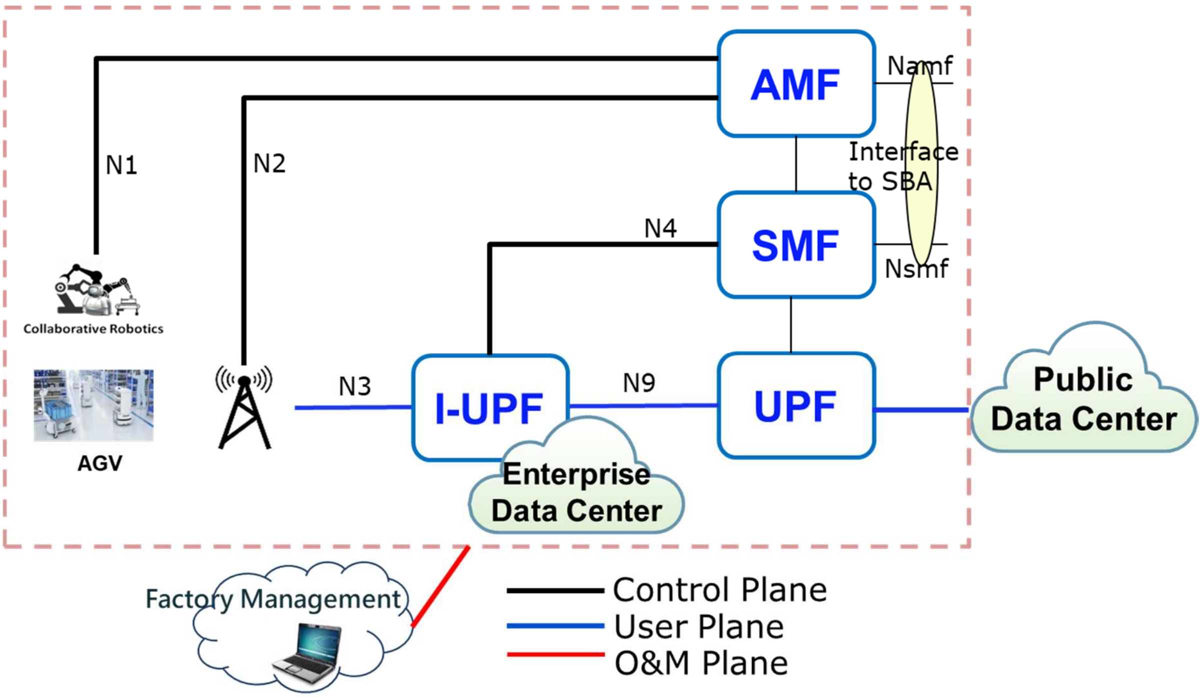

Figure 5: User Plane vs. Control Plane vs. O&M Traffic

2.1.7 Machine Tools

A machine tool is a machine for handling or modifying shape, surface quality of metal or other rigid materials, usually by cutting, boring, grinding, shearing, or other forms of deformation. Machine tools mentioned in this document are considered to be milling or turning machines, which use rotating milling tools or stationary cutting edge to remove material from workpiece.

Modern machine tools are controlled by computerized numerical control systems, which calculate motion commands and drive the tool to move along trajectories defined in NC codes.

2.1.8 Machining Process

Machining is a process which removes material from workpieces by rotating or stationary tools. The processes are also known as subtractive manufacturing, in distinction from processes of controlled material addition or 3D printing.

2.1.9 Manufacturing Execution Systems

Manufacturing execution systems (MES) are software systems used to operate manufacturing systems or shop floors by tracking orders, manufacturing processes, material flows and quality control systems using shop floor data collection mechanisms. MES consist of modules, such as a database, supplier management, material management, production, equipment management and quality management.

2.1.10 Enterprise Resource Planning

Enterprise resource planning (ERP) integrates internal resource and workflows to manage resource allocation and reduce response time to customer requirement. Current ERP systems may also extend to resource integration of customer and supplier to further optimize resource allocation within a wider range.

2.2 Definition of Functional Requirements

One essential part of the use case analysis is the identification of functional requirements. A functional requirement describes a feature or function, the 5G System must have or must be able to perform. Table 1 collects all functional requirements that are relevant for the 5G CONNI use cases along with their descriptions.

Table 1: Collection of Relevant Use Case-Specific Functional Requirements

ID	Requirement	Description	Source
FR-1	*Mobility management support*	5G will support UEs with a range of mobility management needs, including UEs that are • stationary during their entire usable life (e.g. sensors embedded in infrastructure), • stationary during active periods, but nomadic between activations (e.g. fixed access), • mobile within a constrained and well-defined space (e.g. in a factory), and • fully mobile. Moreover, some applications require the network to ensure seamless mobility of a UE so that mobility is hidden from the application layer to avoid interruptions in service delivery while other applications have application specific means to ensure service continuity. But these other applications may still require the network to minimize interruption time to ensure that their application-specific means to ensure service continuity work effectively. For a use case with mobile end devices, seamless mobility can be a strict requirement. This is usually the case, when an end device requires a continuous, perhaps also URLLC, connection.	[2] clauses 6.2.2, 6.2.3

FR-2	*Energy efficiency support*	Small form factor UEs typically have a small battery and this not only puts constrains on general power optimization but also on how the energy is consumed. With smaller batteries it is more important to understand and follow the limitations for both the maximum peak and continuous current drain. This is especially required for mMTC use cases.	[2], clause 6.15.2
FR-3	*End-to-end QoS support*	The network must offer means to provide the required QoS (e.g. reliability, latency, and bandwidth) for a service and the ability to prioritize resources when necessary to meet the service requirements. Existing QoS and policy frameworks handle latency and improve reliability by traffic engineering. In order to support 5G service requirements, it is necessary for the 5G network to offer QoS and policy control for reliable communication with latency required for a service and enable the resource adaptations as necessary. Such use cases often fall into the URLLC category.	[2], clause 6.7.2
FR-4	*Network capability exposure support*	This network service provides information about network functions, network capacity, achievable KPIs, etc. It allows third parties to manage network slices (in the sense of life-cycle management) through appropriate APIs and to monitor performance measures in an encrypted manner. This service is especially relevant for use cases that are adaptive to network capabilities, such as provisioned data rate or latency.	[2], clause 6.10.2
FR-5	*Priority, QoS and policy control support*	Depending on the use case combination and the mix of traffic types, this service enables, e.g. prioritization of URLLC traffic over eMBB traffic. Especially for mission-critical use cases, this is required to manage priorities and QoS guarantees easily (in particular with slice management) and to have mechanisms to enforce the priorities.	[2], clause 6.7.2
FR-6	*Time synchronization support*	This is a service that provides time synchronization capabilities, e.g. for the integration of TSN and 5G. This is often required by URLLC use cases.	[2]
FR-7	*Localization service support*	5G positioning services aims to support verticals and applications with positioning accuracies better than 10 meters, thus more accurate than earlier location services. Use cases with mobile end devices or for the purpose of asset tracking may require localization support from the 5G network. Localization support can be realized by absolute of relative positioning techniques.	[2], clause 6.27.2
FR-8	*Context-aware network support*	The network should have APIs, such that it can be managed and automatically configured based on context information, i.e. information from the actual industrial application. Source of such information can be the Manufacturing Execution System or the end devices themselves.	[2], clause 6.11.2
FR-9	*Real-time end-to-end QoS*	This service provides appropriate APIs to monitor the network status, health, condition and QoS parameters for active applications. For URLLC use cases with stringent QoS requirements, real-time monitoring of the	[2], clause 6.23.2

	monitoring support	network QoS allows for pro-active alerting and management of the system as well as the application for continuous support of the use case.	
FR-10	*5G LAN-type service support / Layer-2 LAN switching capability support / Ethernet transport services support*	This service is required mainly by URLLC use cases that use Ethernet transport services with routing of non-IP packets with required QoS. This service supports routing and prioritization of Ethernet frames based on, e.g. vLAN tags or IDs. The service includes support for time-aware scheduling (IEE 802.1Qbv).	[2] clause 6.24.2 and 6.26.2
FR-11	*Proximity services support*	This service supports the direct communication between mobile end devices in close proximity, either with support or without support (using different spectrum) of the RAN. Proximity services can also support 5G LAN-type communication directly between close end devices. Also multicast is possible.	[10], clause 5.10
FR-12	*Secure remote access support*	Some use cases may require remote access to end devices (e.g. field devices) for monitoring or maintenance purposes. This may be realized by secured/tunneled access using a dedicated vLAN/VPN – also from public 5G network (e.g. through secured 5G LAN-type service).	5G CONNI
FR-13	*Edge computing support*	Applications, for which computational tasks are offloaded to the cloud and which have stringent requirements on latency, required edge computing support with a well-integrated 5G-edge cloud architecture.	5G CONNI

2.3 Definition of Non-Functional Requirements

In addition to functional requirements, a system is characterized by non-functional, quality-of-service-related, measurable attributes. Failing to meet non-functional requirements imposed on the 5G System by an industrial application can lead to malfunctioning of the application.

2.3.1 Use Case Categorization

IMT-2020 use case scenarios are grouped into enhanced mobile broadband services (**eMBB**), massive machine type communication (**mMTC**), and ultra-reliable low-latency communication (**URLLC**) [11]. eMBB is the profile that requires high data rates for use cases such as high-resolution video streaming and virtual reality. Techniques to achieve data rates of up to 10 or 20 Gbps are massive MIMO, network slicing and using large bandwidths, including the ones in the mmWave spectrum. While URLLC use cases have strict requirements on timeliness (e.g. end-to-end latency of 1 ms, jitter of several µs) and reliability (e.g. availability of 99.999 %), a very large number of end devices communicate in a comparatively small area in mMTC use cases (very large connection density).

In addition to the broad classes above, use cases can also be categorized according to traffic types. Because in most cases, URLLC and mMTC traffic originates from machines or sensors and their underlying processes, data traffic will increasingly be characterized by determinism and periodicity. In this regard, [1] classifies 5G use cases according to **deterministic periodic communication**, **deterministic aperiodic communication** and **non-deterministic**

communication. While deterministic periodic communication is characterized by stringent requirements on timeliness of the transmissions, which occur every transfer interval, deterministic aperiodic communication has no present sending time. Deterministic aperiodic communication mostly applies for event-driven transfers. Non-deterministic communication includes all non-real time traffic.

5G URLLC will, for the first time, enable distributing control applications, while sensor and actuator data will be exchanged using cellular technology. Such control applications exhibit different activity patterns depending on their purpose and environmental conditions. Such activity patterns are defined in [1] as **open-loop control**, **closed-loop control**, **sequence control**, and **batch control**. In open-loop control applications, commands are provided to an actuator but no feedback from the actuator/sensor is used to compute the commands. The lack of feedback is tolerable if the influences of the environment on the process are negligible. Closed-loop control application are characterized by non-negligible influences of the environment on the process, such that the controller requires feedback information from the sensors to properly compute the commands (physical target values). In sequence control systems, multiple actions are taken in a fixed sequence or based on the current state of the system. Sequence control can be open-loop or closed-loop control. Batch control describes the production of finite quantities of material (batches) with a pre-defined order of processing actions.

2.3.2 Definition of Requirements Related to Reliability

Industrial 5G applications are often characterized by high reliability needs because it is necessary that production has to be maintained while interruptions and production downtimes are avoided.

In this regard, the **communication service availability (CSA)** is defined as the "percentage value of the amount of time the end-to-end communication service is delivered according to an agreed QoS, divided by the amount of time the system is expected to deliver the end-to-end service." The communication system is considered unavailable to the industrial application when an expected packet is impaired or untimely after the application's survival time has elapsed. A packet is untimely if its transfer time is larger than the maximum end-to-end latency [1, 2]. In addition, the **communication service reliability (CSR)** is defined as the "ability of the communication service to perform as required for a given time interval" and it is often indicated by the mean time between failures (MTBF) [1, 3]. At the lower communication layers, the **packet error rate (PER)** defines an upper bound for a rate of non-congestion related packet losses (PDUs, e.g. IP packets), where a packet loss is also indicated by untimely delivery [4, 10]. In the context of network layer packet transmissions, **reliability** is defined as the "percentage value of the amount of sent network layer packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of sent network layer packets" [2].

2.3.3 Definition of Requirements Related to Timeliness and Traffic Characteristics

Besides reliability-related KPIs, industrial applications impose stringent timeliness requirements on the communication system and exhibit certain traffic characteristics, especially applications with distributed sensing and control.

KPIs related to timeliness are the following. The **end-to-end (E2E) latency** is defined as the time that takes to transfer successfully a given piece of information from a source to a destination, measured at the communication service interface (CSIF) (excl. the higher communication layers) [1, 2, 3]. This latency is allowed to fluctuate only within a specific range quantified by the **jitter**, which is the maximum deviation of a time parameter, here the end-to-end latency or update time, relative to its target value [3]. In contrast to the E2E latency, the

transmission time includes higher communication layers, i.e., it is defined as the time that takes to transfer successfully a given piece of information from a source to a destination, measured at interfaces between the application and the communication system [3]. For video applications, which are part of an industrial control process, the **video latency** is the time instant between a video frame is recorded at a sender and the time instant it is consumed by a control process decision algorithm at the receiver (including encoding and transfer of video information, decoding, video analytics in the cloud and the decision by an algorithm). For AR/VR use cases, which enable visual interactions with the digital twin, the **motion-to-photon latency** is critical, which refers to the latency between the physical movement of a user's head and updated picture in the AR/VR headset [2].

The traffic characteristics of industrial control applications are usually characterized by the time intervals between two consecutively sent (or received) sensing and control messages, and the size of the respective message. In particular, the **transfer interval** is the time difference between two consecutive application data transfers from an application to the 3GPP system [1] and, for periodic communication, the **update time** is defined as the time between two consecutive messages delivered from the communication system to the application [1, 3]. On the application layer, the **sampling rate** is the number of samples per second, e.g. taken by a sensor and measured in Hz or kHz, while the **message size** is defined as the (maximum) size of the user data packet delivered from the application [1]. For industrial applications, the **survival time** is of high importance. It is a time parameter originally used in automation systems and it describes the time that an application may continue without an anticipated message before the communication system is considered unavailable. Therefore, the survival time indicates the time for the communication service to recover from a failure or, given the transfer interval, the maximum number of allowed consecutive packet losses [1, 10, 3]. Finally, the **response time** is the time period that elapses between a request and a response.

Traffic characteristics that are not only specific to control applications but for any other application as well are the following. The **service area** is the geographic region, in which a 3GPP communication service is required to be accessible [1, 2]. Each application or communication endpoint has certain capacity demands. Here, the **service bit rate** for deterministic communication is the minimum data rate the communication system guarantees at any time. For non-deterministic traffic, the service bit rate is defined as the provided information rate averaged during a time window [1]. Furthermore, the **connection density**, which is the number of UEs being part of a service in a given service area, and the **area traffic capacity**, which is the total traffic throughput served per geographic area [2], are required information for dimensioning of the 5G network on the shop floor. Finally, the **UE speed** is considered to be the maximum speed a UE moves across the shop floor.

2.3.4 Definition of Requirements Related to Positioning

Positioning services using 5G are likely to become important on the shop floor, because with this, a plethora of different heterogeneous positioning and localization technologies can be avoided, thereby reducing complexity and costs. In this regard, a number of requirements related to positioning are of relevance. While the **position accuracy** describes the relative or absolute closeness of a measured UE position to its true value [10], the **positioning service availability** is the "percentage value of the amount of time the positioning service is delivering the required position-related data within the performance requirements, divided by the amount of time the system is expected to deliver the positioning service according to the specification in the targeted service area" [2]. Moreover, the **positioning service latency** is the time between triggering the determination of the position information and the information being available at the system interface [2].

2.3.5 Definition of Requirements Related to Energy Efficiency

The **battery lifetime** refers to the operational time of battery powered end devices.

2.4 Review of 3GPP Industrial Use Cases

The following Table 2 summarizes the requirements of use case groups or categories that have been collected in 3GPP and are mainly contained in [1, 2, 10].

Table 2: Collection of Industrial Use Cases Considered by 3GPP

Use Case Class	Functional and Non-Functional Requirements
Motion control: A motion control system is responsible for controlling moving and/or rotating parts of machines in a well-defined manner, for example in printing machines, machine tools or packaging machines [1, 2, 10].	The 5G system shall be able to support high performance enhancements for time-sensitive networking, and support cryptographic security to safeguard or protect data transmitted over the network.
	CSA: 99.999% to 99.999999%; CSR: < 10 years Message size: 20 to 50 bytes; E2E latency, transfer interval and survival time: 500µs to 2 ms; UE speed: ≤ 72 km/h; Service area: 50 m x 10 m x 10 m.
Control-to-control: For large machines, controls are used to cluster machine functions, and need to be synchronized and exchange real-time data. For individual machines, often need to communicate for controlling and coordinating the handover [1, 10].	CSA: 99.9999% to 99.999999%; CSR: < 10 years; Message size: < 1k bytes; E2E latency, transfer interval and survival time: 10 ms to 50 ms; Service area: up to 1000 m x 30 m x 10 m.
Mobile control panels with safety: Safety control panels have mostly a wire-bound connection to the equipment they control and with an ultra-reliable low-latency wireless link [1, 10].	The 5G system shall support an indoor vertical positioning service for mobile control panels with vertical positioning accuracy better than 3 meters.
	CSA: 99.9999% to 99.999999%; CSR: 1 month to 1 year; Service bitrate: > 5 Mbit/s; Message size: 40 to 250 bytes; E2E latency and transfer interval: < 30ms; Survival time: < 12 ms; UE speed: ≤ 7.2 km/h; Service area: 50 m x 10 m x 4m.
Mobile robots: Mobile robot systems can be divided in operation in indoor, outdoor and both indoor and outdoor areas. These environmental conditions have an impact on the requirements of the communication system [1, 10].	The 5G system shall be able to support changing between network-controlled ProSe communications.
	CSA: 99.9999%; CSR: 1 week to 10 years; Message size: 40 and 250 bytes; E2E latency, transfer interval and survival time: 1 ms to 500 ms; UE speed: ≤ 50 km/h; Number of UEs: ≤ 100; Service area: ≤ 1 km^2.
Remote access and maintenance: In factories, there are needs to perform occasionally updated for remote access and maintenance to devices and entities, and maintenance information also needs to be	CSR: 1 month; Message size: 20 to 50 bytes; Service bitrate: ≥ 1 Mbit/s; UE speed: ≤ 72 km/h; Number of UEs: ≤ 100; Service area: 50 m x 10 m x 10 m.

collected and distributed periodically [1] .	
Augmented reality: For the applications like i) monitoring of processes and production flows, ii) step-by-step instructions for specific tasks and iii) ad hoc support from a remote expert [1, 2, 10].	The 5G system shall support an indoor vertical positioning service for augmented reality with vertical positioning accuracy better than 3 meters.
	CAS: 99.9%; CSR: < 1 month; E2E latency: < 10 ms; UE speed: < 8 km/h; Service area: 20 m x 20 m x 4 m.
Closed-loop process control: For use cases for process automation, several sensors are installed in a plant and each sensor performs continuous measurements. The measurement data are transported to a controller, which takes decisions to set actuators. [1, 2]	The 5G System shall support i) limitation to short-range communications, ii) direct device connection between the controller and actuators, iii) allocation of licensed spectrum for closed-loop control operations, iv) reservation of dedicated air-interface resources for each link, v) combination of multiple diversity techniques within stringent E2E latency constraints and vi) utilizing OTA time synchronization to satisfy jitter constraints.
	CSA: 99.9999% to 99.999999%; CSR: ≥ 1 year; E2E latency and transfer interval: ≥ 10ms; Message size: 20 bytes; Survival Time: 0s; Number of UEs: 10 to 20; Service area: ≤ 100 m x 100 m x 50 m.
Process monitoring: For process and asset monitoring in the area of process automation, a large number of industrial wireless sensors are installed in the plant to give insight into process and environmental conditions, asset health and inventory of material [1, 2].	The data are transported to displays for observation and/or to databases for registration and data analysis. The operation for this use case can be in a wide service area, and interaction with the public network may be required.
	CSA target value: 99.99%; CSR: ≥ 1 week; E2E latency: < 100 ms; Transfer interval: ≤ 1 s; Bit rate: 200k to 2M bits/s; Battery lifetime: ≥5 years; Message size: 20 to 250 bytes; UE density: ≥ 1 UE / m²; Range: <500 m; Service area: ≤ 10 km x 10 km x 50 m.
Plant asset management: Timely recognition of any degradation and continuous self-diagnosis of components are used to support and plan maintenance [1, 10].	The operation for this use case can be in a wide service area, and interaction with the public network may be required. The 5G system shall be able to provide service to an out-of-coverage UE via indirect communication while meeting the performance requirements specified for the process automation use cases.
	CSA target value: 99.99%; E2E latency and Transfer interval only several seconds; Message size: 20 to 255 bytes; Number of UEs: ≤ 100 000; Service area: ≤ 10 km x 10 km x 50 m.

2.5 Collection of Additional Use Cases

In the following sections, six use cases are described, which are relevant for the conceptualization and analysis of the 5G CONNI system. Three of them are selected for demonstrator implementations at the trial sites, the latter being described in Section 2.6.

2.5.1 DECT Phones Replacement in Office and Manufacturing Sites

Phone calls in office and manufacturing sites are carried through the company's PBX system, which terminals may be DECT phones to allow employees to move around the company premises. Typically, DECT phones are not as feature-rich as modern smartphones, so companies are looking for solutions to evolve the legacy PBX+DECT systems in order to leverage all the computing and communication capabilities offered by smartphones. Nevertheless, an integrated corporate ICT system including the i) 5G network ii) smart devices and iii) custom corporate applications can open up a new set of opportunities for innovation in the enterprise world.

In today's companies, human communications occur through different heterogeneous wireless and wired technologies. In manufacturing sites, production plants, warehouses and similar, it is still common to find the workers using traditional push-to-talk radio devices, which enable medium-long range infrastructure-less communications, including group and broadcast calls. On the other hand, office staff uses modern PBX systems, e.g., with VoIP and webRTC integration, and other software communication platforms through multiple types of connected terminals, such as desktop phones, PCs, smartphones and audio/video conference devices. Whereas PTT devices are relatively cheap and provide large wireless coverage, their limited bandwidth limits their use to voice calls only. On the contrary, modern PBX systems and VoIP software benefit from broadband connectivity and offer enhanced features, such as instant messaging, file sharing, video conferencing, screen sharing, but have little wireless freedom, mostly bound to DECT phones and the WiFi network.

A 3GPP mobile system based on either LTE or 5G provides a single ICT platform to realize the use cases above, through the use of standard technologies for the network, terminals and applications. A Voice over LTE/5G integrated with Mission Critical Services enables an enterprise to provide QoS-guaranteed voice calls, group calls, PTT, instant messaging, data transfer and many other services to powerful handheld devices, such as smartphones and tablets. Being an all-IP technology, the system can be integrated to the PBX system and/or other OTT application in a smooth way. With respect to 4G, 5G offers better manageability of the network services through network slicing and aims at providing better integration with the application domain, in addition to existing IMS and Mission-Critical services for Push-to-talk, Video and Data transmission (usually abbreviated as MCx), through an extended set of APIs.

The integration of MCx services with a 5G system and IMS enables workers in a factory to use smartphones for instant calls and group calls, as well as for video calls, using the push-to-talk mode, i.e., no dial-in. This is important to coordinate activities of technicians on the shop floor, to share images and recordings in real time with other teams or to send emergency alerts in the same way as first responders and public safety agents do. Nevertheless, the same device can be used as regular phone to make calls both with colleagues in the office and external people, or as a PDA to retrieve/upload data from the local cloud (e.g., to send a barcode scan of an item in the warehouse to an inventory to fetch the item's data sheet). Different from previous mobile communications systems, 5G not only enables PTT application to have guaranteed bit rate, but also to manage the service as a whole through the network slicing concept.

The new 5G concept of unified data management (UDM) facilitates the exposure of network and subscribers data to applications. As an example, the SIM credentials of a subscriber may serve to authorize the employee who carries the device to access the company's facilities. For instance, the company can let an employee in by first detecting her position using the localization capabilities of the 5G network, and then authorizing his access after examining her network credentials. This method can effectively replace badges as a method to enforce access control.

2.5.2 Shop Floor Asset Tracking Using On-Board and On-Premise Sensing Devices

Conventional asset tracking on the shop floor relies on check-ins and check-outs of materials between production stations so that the production management system can identify the location of specific parts, workpiece, assembly, fixture (devices used to clamp workpiece at specified orientation), and tools on the shop floor. The time delay between check-ins and check-outs may cause problems in the production management system as one is not able to track the location and the path of the material between check-ins and check-outs. Although the latest AGV systems are equipped with sensors, such as ultrasonic sensor and LiDar, so that the AGVs can autonomously navigate and track themselves with very high spatial and time resolution, it only tracks materials handled by AGVs and can only navigate through a pre-defined map with fixed shop floor layout.

Using the eMBB and mMTC characteristics of a 5G network, cameras, LiDar, ultrasonic, infrared, and other sensors can be installed and wirelessly connected around the factory so that not only the AGV dispatching system but also other material flow systems, such as storage systems and conveyor systems, can utilize the ubiquitous sensor data to track, plan and optimize material flow.

Challenges of a holistic shop floor asset tracking are the following. First, the planning for sensor locations, which can cover different material flow lines, such as tools, workpiece, fixture and AGVs, needs to be carried carefully in order to have a 100 % coverage of asset tracking across the shop floor. Second, other positioning sensors at important check points of material flow, such as laser, ultrasonic and infrared sensors, need to be deployed. Third, the required locations of gNBs need to be evaluated in order to cover the entire material flow area, while the functional requirements shall be linked with the speed of the material flow. Furthermore, 5G network parameters need to be planned to incorporate data from various sensors with various sampling rates while maintaining synchronization. Finally, the design of the data interface and scheduling algorithms of the production management system must be adapted to respond to the dramatically increased information.

2.5.3 Cloud-Based Controller for CNC

To meet the requirements of small batch production or massive customization, configuration of machine tools or production stations need to be flexible. The architecture of the conventional CNC systems for machine tools are fixed, that is, once the configuration and number of axis is decided, the software architecture and control block diagram is fixed. However, in order to meet the massive customization scenario, the number of moving axis and combination of hybrid manufacturing processes (e.g. additive and machining processes) must be able to be modified with very low cost to quickly respond to many small batch or one piece contracts. Although the industrial control over 5G network or cyber-physical control has been described in [1] and communications for automation in vertical domains, such as factory of the future has been described in [3], design, implementation and deployment of a cyber-physical controller is still needed to define actual specification for various scenarios, such as flexible machining machine, which consists of many spindles and moving axis to perform sequential operations of a specific part, or a specialized production station, which consist of additive 3D printing machine and subtractive milling or turning machines.

As shown in Figure 6 from [1], a cyber-physical system consists of actuators, processes, and sensors, which are equipped at physical machines. A distributed motion controller implements the derivation of the motion commands generated by the interpolator module in the edge cloud, which are sent to the control loop to generate pulse commands to actuator.

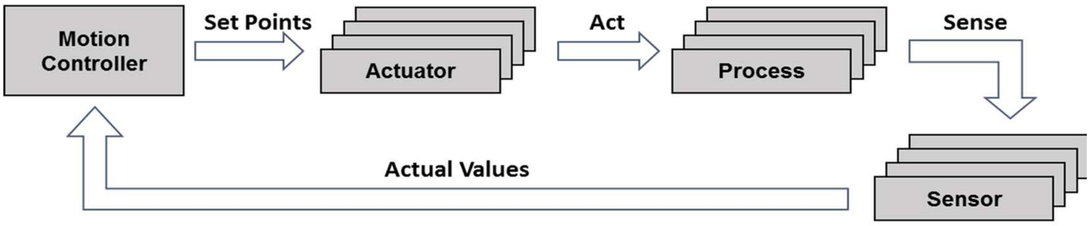

Figure 6: Schematic Representation of a Motion Control System [1]

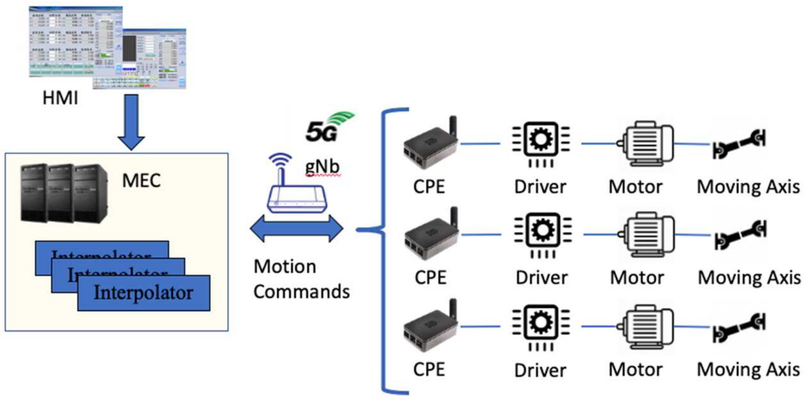

Figure 7: Illustrated Architecture of the Distributed Motion Control System for CNC.

Communication KPIs, such as service availability, reliability, packet error rate, end-to-end latency are crucial to cyber-physical controllers. Since block diagrams of the cyber-physical controller are distributed across the physical device and virtualized cloud computing platform, the challenge will be to plan for the distribution of the control blocks to ensure all the KPIs are fulfilled for specific use case.

Machine builders shall benefit from the cloud-based CNC technology as they can deliver more options of machine configurations (combinations of linear or rotary axis) to customers without increasing the cost of designing and implementing the control system. Manufacturing shop floors can link arbitrary machines, robots, material handling systems into a temporary intelligent “island of automation” to quickly suit the needs of specific production task.

2.5.4 Process Diagnostics by CNC and Sensing Data Collection

Machining process can be diagnosed by analyzing sensing data from accelerometer, current sensor, microphones and acoustic emission sensors. Features from multiple sensors are usually used to detect events such as tool wear, spindle wear or vibrations caused by misalignment of workpiece.

Current method for process monitoring requires a dedicated high-performance computer for data collection and analysis on each machine. This makes it difficult to deploy process diagnostic system in the whole shop floor due to the high cost and lack of flexibility in the factory of the future, where material routing and machine layout are flexible.

The maturity of cloud computing technology and the emerging 5G technology brings new opportunity for large scale process diagnostic and condition monitoring for multiple machines across process chain.

In this use case various sensors will be attached on machine tool and aggregated into an edge computing device. CPE will be installed on selected CNC station and the collected data will be buffered by an edge computing device and afterwards transferred to the edge data center via CPEs and gNBs. A data analysis system will be implemented and deployed in an edge data center and conduct data visualization and tool condition monitoring to reduce unscheduled downtime caused by tool breakage.

This use case is selected to be implemented as a demonstrator and explained in more detail in Section 3.1.

2.5.5 Using Augmented/Virtual Reality for Process Diagnosis

Conventional machining process planning relies on time-consuming trial-and-error activities to determine force-related parameters, such as feed rate, spindle speed, depth of cut and width of cut. In order to reduce the cost for trial-and-error, additional diagnosis models are used to detect vibration, collision, acoustic emission, temperature, or energy consumption.

Virtual reality or augmented reality provide a new way of interaction between humans, machines and digital models by superimposing graphical objects, such as 3D models, charts, vector fields and text messages on top of a video image. This gives process engineers a great opportunity to combine expertise from various domain knowledge and reveal full productivity of machines.

Current high-end virtual or augmented reality requires cable-connected end user devices in order to transfer high-resolution video and 3D graphics at high frame rates, which limits the mobility on the shop floor. This use case tries to utilize the high data rate along with low latency properties of 5G communication and establish a wireless virtual reality or augmented reality system to help process engineers set up workpieces or monitor abnormal conditions during machining.

This use case is selected to be implemented as a demonstrator and explained in more detail in Section 3.2.

2.5.6 Robot Platform with Edge Intelligence and Control

Robot platforms in manufacturing are used for a plethora of different tasks, from collecting, sorting and inspecting workpieces to more complex tasks such as collaboratively carrying and manipulating objects. Offloading of robot intelligence to the cloud is a promising approach to increase the flexibility of the production system, to lower the cost of robotics equipment and to improve the scalability through softwarization and pooling of computing resources.

Therefore, this use case considers a mobile robot platform, e.g. a robot arm with a gripper hand, whose motion control functions are offloaded to a nearby edge cloud. 5G is considered to interconnect the robot arm with the backend, because exchanging motion control messages and feedback in the form of the current state of the machine necessitates fulfilling strict timeliness and reliability requirements. In addition, an additional sensor, e.g. a camera mounted onto the robot arm, is considered for the purpose of workpiece inspection, whose data stream is also sent over a 5G link to the edge cloud. Then, robot arm path planning and motion control adjustments can be directly made based on the output of the video analytics function by exchanging values between the offloaded control and intelligence functions in the edge cloud.

This use case is selected to be implemented as a demonstrator and explained in more detail in Section 3.3.

2.6 Description of Trial Sites

Three of the use cases outlined in the previous section are selected for implementation at two trial sites as part of Work Package 5. This section describes the trial site focusing on some specifics relevant for the demonstration implementations and studies.

2.6.1 BOSCH Factory

It is planned that the use case “Robot platforms with edge intelligence and control” will be implemented as a demonstrator in one of BOSCH’s factories. The benefits of setting up the demonstrator with an integrated private 5G network in a real plant environment are to investigate some distinct specifics of factories in addition to investigations on the actual use case. In the 5G CONNI project, the following specifics will be considered in more detail:

(1) **Enterprise IT Security**: The interconnection and the operation of a private 5G network in a factory with a 5G network functions located off-premise produces a number of IT security concerns. In fact, for some 5G deployment and operation models, in which production-critical communication infrastructure is operated by externals potentially using third-party WAN infrastructure, dedicated IT security mechanisms are required to ensure data integrity, confidentiality and availability.

(2) **Factory IT Security**: Using a private 5G network for the communication of various production assets including robots raises similar security questions for the IT infrastructure on the shop floor. In particular, the concept of security zones and conduits, as introduced in ISA/IEC 62443 [8], will be the basis to evaluate how the robot platform and the 5G infrastructure on the shop floor can be securely integrated.

(3) **Radio Wave Propagation**: The shop floor is assumed a challenging environment, in which it may be difficult to set up a multi-cellular 5G network, because many strong reflections on large metallic objects may result in a spatially, highly fragmented cell partition with strong interference. Moving metallic objects, such as automated guided vehicles or robots, can additionally cause unfavorable radio propagation dynamics. Since the planned demonstrator requires URLLC communications, the RAN setup will be of high importance and different RAN deployment scenarios will be studied. Planned channel measurements in the BOSCH factory will be carried out to pre-evaluate the different options.

(4) **Safety:** The demonstrator will be installed in a real production environment, in which factory personnel is present. This requires studying the implications on additional safety measures that need to be taken in addition to the case, in which a robot is connected through wire.

2.6.2 ITRI Site

ITRI is the largest research institute in Taiwan for industrial application research. The Intelligent Machinery Technology Center (IMTC) is one of the research centers of ITRI and focuses on machine tool technology including machine tool design, machining process optimization and intelligent software for machine tool operation as well as shop floor management. These technologies have been implemented and transferred to industrial partners; however, for most small and medium companies in Taiwan, it is still not easy to figure out what are the necessary building blocks of an intelligent manufacturing shop floor. Moreover, building such an intelligent shop floor calls for large-scale investment, therefore a pilot production site is needed to integrate and demonstrate full scenarios of an intelligent shop floor.

The pilot production site is a government-supported project with the objectives to demonstrate mixed production use cases using all Taiwanese machine tools and evaluate emerging new technologies such as 5G, AI and cyber-security to see how these new technologies can be integrated with previous research achievements such as machining optimization, process diagnostics and compensation.

Since 5G is one of the emerging new technologies for consumer and industrial sectors, ITRI had initiated several projects on 5G infrastructure, AI and cloud, and will use the pilot production site as the testing and verification environment. Network devices, industrial use cases as well as new 5G-enabled equipment will be installed and tested on the shop floor. This makes it a perfect linkage between the 5G CONNI project and Taiwanese machine makers, network device makers as well as software developers. Two use cases are selected to be implemented in this site:

(1) Process Diagnostics by CNC and Sensing Data Collection: Deploy a process diagnostics system for tool condition and vibration monitoring at the edge cloud and collect massive amount of process data from CNC and sensors.
(2) Using Augmented/Virtual Reality for Process Diagnosis: Associating vibration data with color-coded tool path plots and show them on a tablet or head-mount display to help machine operators adjust process parameters during the prototyping stage of a new production task.

Data collection from CNC and sensing systems are achieved by the IoT software system called VMX. The VMX system acts as the backbone of the information flow of the shop floor, which collects data from machine tools, robots, automated guided vehicle (AGV) and coordinate measuring machines (CMM, a special kind of machine tool that is used to measure geometric errors of workpiece by using high precision touch probe).

There are two specific challenges that arise from integrating 5G network in the pilot production site:

(1) Integrating 5G network system without disturbing the existing networking system, on which the whole production system is running, and
(2) Planning and designing a way to demonstrate the achievements of the implemented use cases without interfering the on-going production tasks.

ITRI shall continue to update the hardware and software in the pilot production site and link with universities, research institutes, and industry by using IoT and cloud computing technology to conduct more research and development projects for intelligent manufacturing.

3 Detailed Description of Use Cases

As part of the 5G CONNI project, three use cases are selected as demonstrators that will be implemented at the trial sites described in Section 2.6. The subsequent three sub-sections provide an in-depth analysis of the aforementioned use cases, including an elaborate discussion about their benefits and their functional and non-functional requirements on the 5G System, followed by the description of some important aspects related to their implementation and validation.

3.1 UC-1: Process Diagnostics by CNC and Sensing Data Collection

The subsequent paragraphs detail the use case "Process Diagnostics by CNC and Sensing Data Collection" introduced in Section 2.5.4 .

3.1.1 Use Case Description

There have been many research and development activities on using sensors to collect data from machining processes as well as machine components in order to analyze product quality or machine conditions. Almost all modern CNC controllers support software and hardware interfaces to access internal data. Most applications utilize sensor data and CNC data together to implement functions, such as tool condition monitoring, chatter detection, and spindle health check. For example, accelerometer or spindle loading data is required and associated with CNC data and work orders to predict tool wear conditions and to issue an alarm message to the machine operator or shop floor manager prior to tool breakage. For a typical high speed, high precision machining task, attaching sensors at the spindle and at the workpiece with sampling rates between 10 and 400 kHz is needed in order to collect all necessary physical quantities, such as vibration, current, and voice to analyze the machining process.

Current methods for process monitoring require a dedicated high-performance computer for data collection and preprocessing of data, such as filtering and feature extraction. The analysis process is conducted afterwards on either the same computer or another dedicated workstation. This makes it difficult to deploy process diagnostic systems across the entire shop floor due to the high costs and the necessary degree of flexibility in the factory of the future, where material routing and machine layout are flexible. In the above-mentioned high speed, high precision machining situation, where various sensors are installed on the spindle and the workpiece, the total required data rate can exceed 200 Mbps per machine and the 5G system is considered to fulfill the high data rate requirement of sensing data collection.

As shown in Figure 8, the use case consists of a machine tool, an on-line monitor system, and an analysis system. Sensors, such as accelerometers, current sensors, and microphones, are attached on spindle of the machine tool and workpiece. Accelerometers are used to detect vibrations caused by spindle rotation, material removal caused by cutting edges, or the vibration modes of the tool, holder, bearings and spindle shaft. Current sensors are usually used in conjunction with accelerometers to analyze machining processes with low cutting forces, such as finishing or grinding. Microphones are used to detect chatter, which is a regenerative vibration during machining. The on-line monitoring system is an industrial PC, which executes monitoring software for data collection from sensors and CNC, and for visualization. The collected data will be transferred to the analysis system, which is deployed in the edge data center to conduct data quality and integrity checks and process diagnosis.

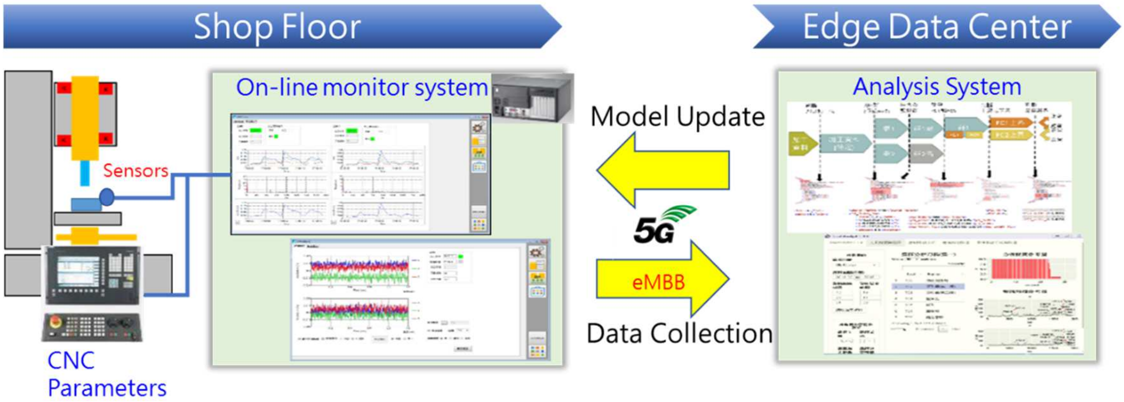

Figure 8: Components of the "Process Diagnostics by CNC and Sensing Data Collection" Use Case

By using 5G and cloud computing technology, such as virtualization and containerization mechanisms in the edge data center, the connections between the on-line monitor system and the analysis system are replaced by the 5G network by utilizing the eMBB capabilities. Various process diagnostics tasks can be offloaded from the edge computing device to reduce the hardware cost and increase the flexibility by combining algorithms in the virtualized computational environment. The sensing and CNC data are collected and buffered in the on-line monitoring system and then uploaded to the analysis system. Uploading data can benefit from the enhanced mobile broadband properties of the 5G network. Models for process diagnosis and condition monitoring are implemented in the analysis system, which monitors the machining process in real-time. With the accumulated data, the model parameters or threshold values can be updated according to the pre-defined events such as tool wear, tool change or workpiece change. The updated model parameters and threshold values must be transferred back to the on-line monitor system to fit the actual machining parameter.

All connections between sensing device, on-line monitoring system and analysis system are based on TCP/IP. For the data transmission between on-line monitoring system and analysis system, secured OP CUA client/server is implemented.

3.1.2 Use Case Benefits

With the rapid changing consumer demands in the global market, manufacturing industries are facing challenges on small batch, massive customization, and short time-to-market. This calls for flexible shop floor layout in order to meet various production requirements. Therefore, cable-connected shop floors are less suitable for the production scenario in the future. In this regard, the benefits of using 5G for data collection and process diagnosis are the following. For factories that usually carry out small production batches, high quality and high precision workpiece process stability is crucial and can be achieved by process diagnosis systems. Analysis systems, such as process diagnosis, machine health, and quality control can be deployed in the edge data center in terms of virtualized and containerized services and can be dynamically allocated for specific machines or production tasks. Since the data collection and feedback loop communication is realized by the 5G network, data collection systems can be deployed in a flexible way reducing time and cost for redesigning machine and cable layouts. Moreover, data can be collected at higher sampling rates and transferred to the analysis system and signal features at higher frequency range can be used to train machine learning or deep learning models. By doing so, it is possible to establish process models with higher accuracy. Being able to deploy the analysis system or other computational burden in the edge data center may reduce the total cost to setup process diagnosis systems for a whole shop floor, as one wants to avoid high-end industrial PCs per machine and allocate computing resource more efficiently in the edge data center using virtualization and containerization technology. Data from multiple sensors and CNC can be transferred to the edge data center and aggregated with data from the production management system, such as the enterprise resource planning (ERP) and manufacturing execution system (MES) to reveal more insights. For example, sensing data may reveal that a spindle health condition is degrading and that the spindle requires a scheduled maintenance; therefore, the scheduling system is triggered to re-schedule production orders.

3.1.3 Technical Challenges and Requirements

The use case "Process diagnostics by CNC and sensing data collection" involves two traffic types, **data collection traffic for uploading the sensors and CNC data** and **traffic for the update and modification of model parameters**. The data collection belongs to the eMBB traffic class, which requires high data rate and is classified as non-deterministic with an asymmetrical traffic between the uplink and downlink directions (generating larger data volumes for the transfer in the uplink). On the other hand, the model update traffic follows aperiodic traffic type.

The use case "Process diagnostics by CNC and sensing data collection" imposes a number of **functional requirements** on the 5G System, in particular,

(1) ***End-to-end QoS Support (FR-3)****:* This use case has stringent requirements in terms of data rate, the fulfillment of which is essential for correct process diagnosis. All the sensing data and CNC parameters need to be received correctly and in the correct order at the analysis system. To this end, the 5G system shall be able to support the required QoS in an end-to-end fashion.
(2) ***Real-time end-to-end QoS Monitoring Support (FR-9)****:* The network may not always be able to guarantee the required QoS of the use case due to unpredictable impairments of the wireless channel. In such cases, it is critical that the analysis system is notified in a timely manner. For example, the analysis shall discard the data collected during the affected period of time, otherwise it has a negative impact on the accuracy of the diagnosis because the output of the analysis system will be based on incomplete information. In this regard, the 5G system needs to provide sufficient monitoring QoS information as input for the application to adapt the operational mode.
(3) ***Secure Remote Access Support (FR-12)****:* This enables factory personnel to have remote access to end devices including CNCs, robots, conveyors and IPCs for monitoring or maintenance purposes. This may be realized by secured/tunneled access using a dedicated vLAN or VPN if not on-site.
(4) ***Edge Computing Support (FR-13)****:* Instead of using dedicated hardware and software for each machine cell, various process diagnostics tasks are offloaded to an edge cloud, which reduces the hardware cost and increase the flexibility to combine algorithms in the virtualized computational environment.

The following paragraphs discuss the **non-functional requirements** of this use case.

The total required **service bit rate** for data collection per machine is approximately 208 Mbps, which stems from the sensing data originating from accelerometers, current sensors, microphones and acoustic emission sensors. The sampling rates and data rates for each type of sensor, which are typical choices for machining process diagnosis, are shown in Table 3.

Table 3: Sensor Configurations of the "Process Diagnostics by CNC and Sensing Data Collection" Use Case

Sensors	Sampling rate	Data rate[1]
6 accelerometers (3 on spindle, 3 on the workpiece)	100 kHz	115.2 Mbps
4 current sensors (1 on spindle, 3 on linear axis)	100 kHz	76.8 Mbps

[1] Values are estimated based on a combination of theoretical evaluation and measurements.

2 microphones	44.1 kHz	16.93 Mbps

The numbers above already give a good insight in the amount of data that needs to be transmitted. However, a large overhead can observed during the data collection tests, such that higher data rate requirements can be expected, unless alternative payload designs for sensing data or communication by other IoT protocols is be considered in future implementations Usually, stations for such machining processes are distributed across the entire shop floor. Hence, the **service area** equals the shop floor area, which is typically about a few 1000 square meters large (or 2644 square meters in this specific case). In this area, the **connection density**, or number of UEs, is usually a few tens (or 11 stations in this specific case), such that the required uplink **area traffic capacity** amounts to roughly 86.5 Mbps per 100 square meters. The machines are considered to be stationary, so the **UE speed** is zero.

3.1.4 Use Case Implementation at Trial Site

In order to implement the “Process diagnostics by CNC and Sensing Data Collection” use case, steps are planned as follows.

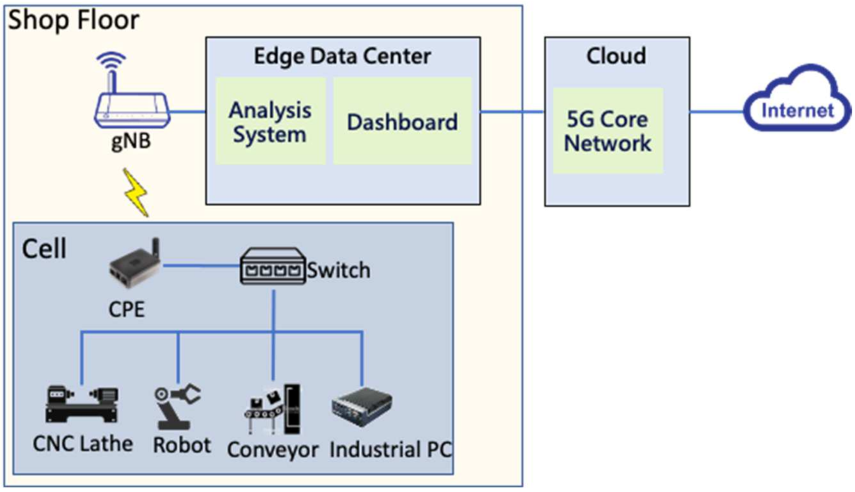

Figure 9: Architecture of the Use Case for the Target Cell

Figure 10: The Target CNC Cell at the Site

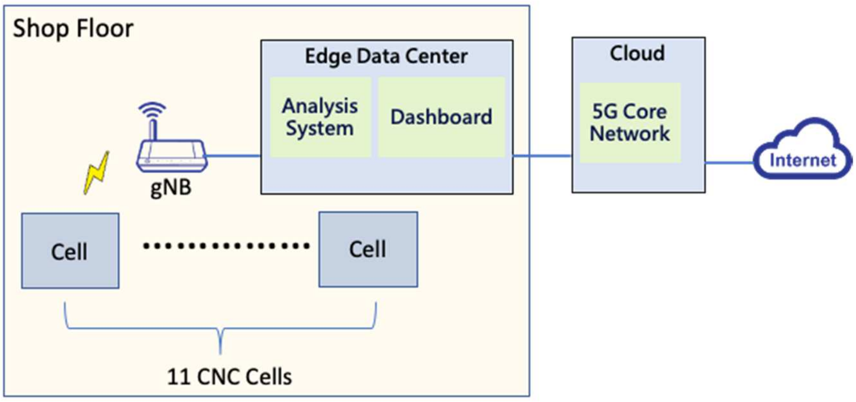

Figure 11: High-Level Architecture of the Use Case to be Implemented

At first, the data collection and process diagnosis will be investigated at one target cell shown in Figure 9 and in Figure 10, which consists of a CNC lathe, a robot, and a conveyor. All of this equipment will be connected to an industrial PC running the on-line monitor system for data collection. The collected data will be uploaded to the analysis system in an edge data center using a 5G CPE and a gNB. A more detailed analysis of the requirements for this use case will be conducted. To this end, a network emulator will introduce different impairments (bandwidth limitations, latency, and packet loss) to evaluate the effects on the applications. Then, the aforementioned steps are repeated for an extended setup of 11 CNC cells distributed across the entire shop floor as shown in Figure 11.

A site survey and channel measurement for cell planning will be conducted (main activities in WP3). An appropriate propagation model for coverage prediction will be selected and coefficients will be calibrated based on actual field measurements. Then, the target capacity will be determined based on the traffic profile and an appropriate number of gNBs will be derived as well as the optimal placements.

As part of WP2, the end-to-end 5G network architecture will be investigated and determined, including the RAN, core network, edge data center and transport network. This also includes resource planning for the edge data center (e.g. number of virtual machines, containers, CPU, memory, disk space), based on the software modules required for this use case. Furthermore, sensor locations on the machine and a more in-depth sensing system specification including sampling rate and feature extraction will be investigated, which also depends on the data rate that the 5G system is able to achieve. Finally, methods to evaluate data quality and integrity and to visualize and demonstrate the use case will be developed.

In addition, the following security and safety requirements are considered in three categories:

(1) **Information Technology (IT):** Confidentiality is the first priority as the IT system is the gateway to the Internet. Hence, conventional methods, such as firewalls, authentication control and system patches are used.

(2) **Communication Technology (CT):** Traffic control between CPEs, gNBs and other network devices are monitored and checked against pre-trained traffic patterns. Availability is the first priority, as the CT system is the internal backbone for all information flow that runs the shop floor.

(3) **Operation Technology:** Pass control to shop floor equipment, device management and certification are needed to ensure computers, USB dongles, PLC, DAQ devices are authorized and certified without any hazardous or infected binary codes in the storage or firmware. Communications and message transactions must also be authenticated and encrypted to ensure all traffic is safe.

Technical challenges related to the implementation of this use case include transforming a running shop floor from cable-connected to 5G-connected without affecting the ongoing production schedule, channel sounding and evaluating the layout of all the CPEs and gNBs on a shop floor full of metallic structures, machine tools, and high voltage (380V) cables, and defining the scenario on how many sensors and physical quantities are required for specific process diagnostic tasks.

3.1.5 Use Case Validation and Demonstration

A small batch production with 100 pieces will be processed on the target cell. Data collection, process analysis will be conducted for these 100 pieces to validate and demonstrate the use case. The validation will be carried out with three steps. (1) Testing of all attached sensors (e.g. accelerometers, current meters, microphones) and data acquisition devices to ensure sensing data can be collected without disturbance or electrical noises. (2) Checking whether the sensing data are properly aggregated and synchronized across the 5G network by analyzing data integrity in the MEC. (3) Conducting the data collection, process diagnostics across the 5G network with different process analysis models and comparing the result against the work flow across an existing wired network. Dashboard applications will be implemented to show flow rate, process diagnostics, and network conditions for demonstration.

3.2 UC-2: Using Augmented/Virtual Reality for Process Diagnosis

The subsequent paragraphs detail the use case “Using Augmented/Virtual Reality for Process Diagnosis” introduced in Section 2.5.5.

3.2.1 Use Case Description

Conventional machining processes rely on computer-aided manufacturing (CAM) software to generate tool paths along a workpiece geometry. However, most CAM software packages generate tool paths based on geometrical data without considering force and vibration. This makes it difficult to select machining parameters, such as feed rate and spindle speed, which have significant effects on force and vibration. Difficulties in selecting parameters may cause the process planning to be costly and time-consuming due to the trial-and-error for machining test.

Manufacturing processes usually contain a large amount of CNC and sensing data, which cannot be directly seen from the real manufacturing environment. Diagnosis systems are available to provide additional information for process engineers. However, reading and interpreting output from various digital models means that the process engineer must have multi-discipline expertise and must be able to make decisions by combining results from several diagnostic software systems used on the shop floor, which is difficult in practical manufacturing scenarios.

Augmented and virtual reality (AR, VR) makes it possible to superimpose graphical objects, such as 3D models, charts, vector fields and text messages on the real workspace through tablet computers or head-mounted displays. Research on AR in manufacturing falls mainly into three topics: AR-assisted assembly and maintenance, AR-enabled process monitoring, and AR-based machining simulation. However, most researchers use Ethernet, WiFi or video cables (e.g., HDMI and display port) to connect the physical machine, the AR/VR device and the backend graphical processing unit, which limits either the mobility or the amount of visual information transmitted between the user and the digital twins.

In this use case, features from sensing data will be associated with machine coordinate values. Tool paths will be plotted and color-coded according to features, such as the vibration level. The color-coded tool paths will be superimposed on the machine 3D model so that the process engineer can observe machining conditions in a more intuitive way and shorten the trial-and-error process planning time. High resolution and high frame rate video streams are rendered remotely in the edge cloud and are transferred to the lightweight end user device, such as tablet computer or head-mounted display connected through the 5G network, to achieve high mobility on the shop floor.

Components involved are shown in Figure 12 and described as follows:

(1) **Image Input:** The AR/VR user device could be a tablet computer or head-mounted display, which is responsible for capturing image for object recognition, spatial tracking and interaction with the user by overlaid images.

(2) **Object Recognition:** An object recognition system is used to recognize the machine type, machine name, components, such as spindles, rotary tables, workpieces, fixtures, and tools in the image. The recognized results are then linked with the digital twins to query corresponding 3D models, sensing data, and condition values, and synthesized as virtual objects in the AR/VR scenes.

(3) **Spatial Tracking:** A spatial tracking system detects the spatial relationships between recognized objects so that the virtual objects can be put in the right place and with the correct orientation in the scene.

(4) **Information Overlay:** A system to superimpose the virtual objects on images of the physical world captured by the user device.

(5) **Interaction Interface with Digital Twins:** This is the key component to achieve user experience for process monitoring by AR/VR. This component is implemented by using APIs from commercial packages or third-party to access data in various digital twins. For example, cutter locations can be accessed from a process model and paths of the cutting tool around physical workpiece are shown; finite-element models can be accessed and thermal error distributions around machine structures can be shown; tolerance and assembly instructions can be accessed from the product model to help machine operators or process engineers plan for the process; and control parameters can be accessed from the controller model to help machine operators tune or calibrate the machine according to production scenarios.

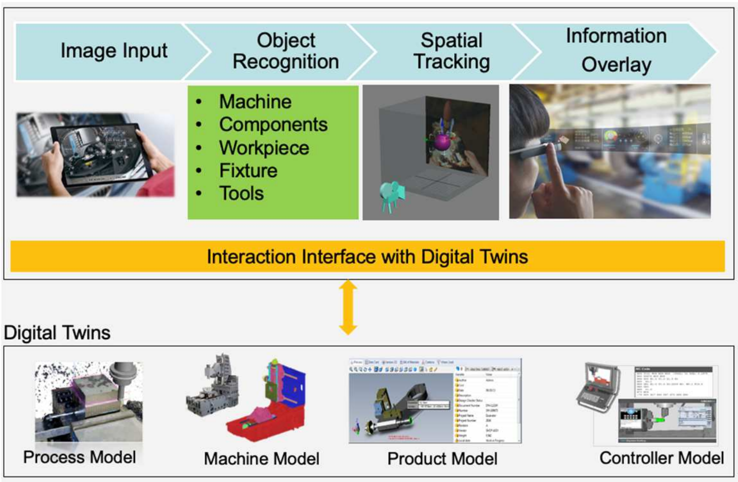

Figure 12: Components of the "AR/VR for Process Diagnosis" Use Case

In this use case, the AR/VR user device is a thin client that transmits image data and user interaction commands to other software components, such as object recognition, spatial tracking, information overlay, and digital twins, which are deployed in the edge cloud. Communication between user devices and other software components is realized by the 5G System. Since the 5G-enabled AR/VR device is not available in the market for the moment, a tablet computer with 5G CPE dongle will be used in this use case to demonstrate the scenario.

All connections between the AR/VR device, digital twins, object recognition and spatial tracking modules are based on TCP/IP.

The architecture of the use case is illustrated in Figure 13. The 5G network will be deployed on the shop floor to connect equipment, such as a CNC, robot, conveyor and AGV. Each manufacturing cell and user device will be connected with a CPE to link with the gNB and the edge cloud. In Figure 13, items within blue boxes will be implemented and deployed in terms of cloud computing service or end user application.

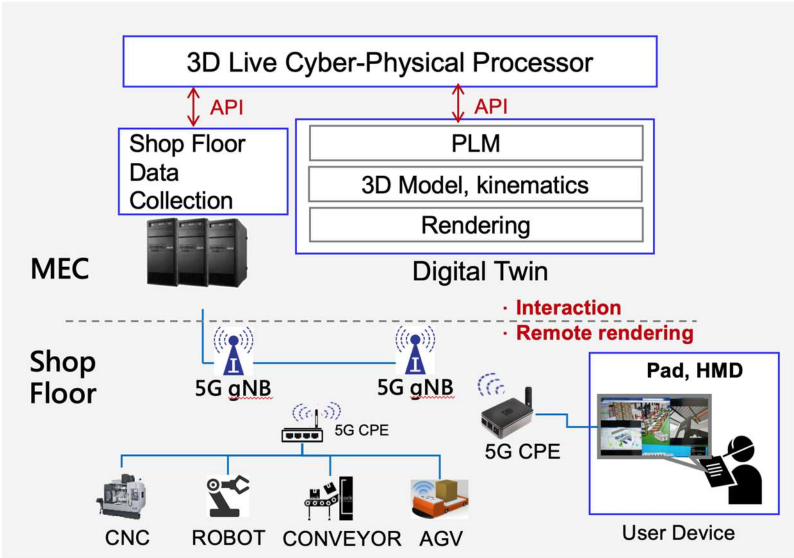

Figure 13: Illustration of the Architecture of the "AR/VR for Process Diagnosis" Use Case

All communications between CPEs, gNBs and MEC are based on TCP/IP. Shop floor data collection is achieved by a secured OPC UA client server pair.

3.2.2 Use Case Benefits

The AR/VR user interface provides end users with an opportunity to interact with various digital twins at the same time without jumping around multiple displays and multiple diagnosis software systems, reducing the total time and cost for prototyping or pilot production. The lightweight head-mounted display allows users to stay focused on the machining process with both hands free to do physical tasks. Superimposed 3D objects, color-coded fields, charts, text from multiple digital twins provide key information for process engineers to optimize the machining process. For example, if the color of a tool or spindle can be modified according to temperature or vibration, machine operators can immediately detect abnormal conditions and modify process parameters or press the feed hold button to prevent damage on the machine. If the tool paths are plotted with different colors according to vibration values, then the process engineer can modify the feed rate or spindle speed to achieve smoother machining process and hence better surface quality of the workpiece.

3.2.3 Technical Challenges and Requirements

The use case "Using Augmented/Virtual Reality for Process Diagnosis" entails data transmissions with high data rate and low latency requirements, while the video traffic is classified as **non-deterministic** with a **symmetrical** share between the uplink and the downlink. The use case can be classified into the **augmented reality** class as summarized in Section 2.4.

The use case "Using Augmented/Virtual Reality for Process Diagnosis" imposes a number of **functional requirements** on the 5G System, in particular,

(1) ***Mobility Management Support (FR-1)****:* In order for factory personnel wearing HMDs to move freely around the shop floor, the 5G system shall support seamless mobility in such a way that a handover from one base station to another one does not have any observable impact on the user experience.
(2) ***Energy efficiency support (FR-2):*** Since factory personnel might have to wear the mobile end devices for a longer period of time, energy efficiency is also an important requirement. These devices have to be lightweight and highly energy-efficient and in the meantime they should not become very warm.
(3) ***End-to-end QoS Support (FR-3)****:* This use case has stringent requirements in terms of data rate and latency, the fulfillment of which is essential for an excellent visual interaction with the digital twin and avoid getting sick after some time. The augmentations of manufacturing data have to smoothly follow any movements of the user. To this end, the 5G system shall be able to support the required QoS in an end-to-end fashion.
(4) ***Priority, QoS and Policy Control Support (FR-6)****:* The 5G network must be able to provide the required QoS (e.g. reliability, latency, and bandwidth) for a service and the ability to prioritize resources when necessary to meet the service requirements. Since there're two use cases with different QoS requirements will be implemented at the shop floor, the use case "Using Augmented/Virtual Reality for Process Diagnosis" with stringent requirements in terms of latency and bit rate should have priority over the other described in section 3.1.
(5) ***Localization service support (FR-7):*** In order to render the manufacturing data (augmentations) on the proper positions of each video frame, localization service is an essential part of the AR/VR use case.
(6) ***Real-time end-to-end QoS Monitoring Support (FR-9)****:* The 5G system needs to provide sufficient monitoring QoS information as input for the application to adapt the operational mode. For the AR/VR use case, the digital twin server should be able to support the adaptive codec of the video streaming based on the QoS achievable by the 5G system.
(7) ***Secure Remote Access Support (FR-12)****:* This enables factory personnel to have remote access to end devices including CNCs, robots, conveyors, IPCs, HMDs and tablets for monitoring or maintenance purposes. This may be realized by secured/tunneled access using a dedicated vLAN or VPN if not on-site
(8) ***Edge Computing Support (FR-13)****:* In order to reduce the AR/VR equipped UEs' functionality and power consumption and the end to end latency, the 5G system shall support offloading complex video processing tasks to an edge cloud.

The following paragraphs discuss the **non-functional requirements** of this use case.

According to [3], potential requirements on video transmission for augmented reality are as follows

1. bi-directional transmission of video streams with a frame rate ≥ 60 Hz
2. HD (1280 x 720) or Full HD (1920 x 1080) resolution

By looking at the latest AR/VR products in the market it is observed that most commercial product are moving toward 2K video streaming. Moreover, in order to completely avoid motion sickness in AR/VR user experience, up to 90Hz frame rate is required. As shown in Table 4, a physical cable is necessary to achieve 2K video streaming with up to 90Hz frame rate. Using the eMBB capabilities that 5G promises, we can achieve such a bit rate without having a physical cable between the user device and digital twin server. This has the additional benefit that remote rendering through the 5G network makes it possible to build more lightweight end user devices that consume less power. To this end, the 5G system shall support the bi-directional transmission of video streams with 4K, 8K resolution and up to a frame rate of 120 fps, which requires the **service bit rate** up to 1 Gbps.

Table 4: Specifications on Data Transmission and Imaging for Latest (late 2019) AR/VR Products

Product	Connection Type	Resolution	Frame Rate
Microsoft Hololens 2	Wireless (WiFi, BT)	2048X1080	60 Hz
HTC Vive Cosmos Elite/Pro	Cable (DisplayPort)	2880X1700	90 Hz
Oculus Quest	Wireless (WiFi, BT)	2880X1600	72 Hz
Oculus Rift-S	Cable (DisplayPort)	2560X1440	80 Hz
Sony PlayStation VR	Cable (HDMI)	1920X1080	90-120 Hz

Usually the manufacturing cells are distributed around the entire shop floor and the factory workers with HMDs or tablets are allowed to inspect any cell they want. Hence the **service area** equals the shop floor area, which is typically about a few 1000 square meters large (or 2644 square meters in this specific case). In this area, the **connection density**, or number of AR/VR devices, is around 6 devices in this specific case, such that the required **area traffic capacity** amounts to roughly 227 Mbps per 100 square meters. When the workers are moving from one cell to another, the seamless mobility support is required, so the **UE speed** is about 3 m/s. Indoor positioning service is necessary for this use case with horizontal **positioning accuracy** better than 1 m and **positioning service latency** less than 15 ms.

When user is interacting with various digital twins with AR/VR devices, calculating the superimposed AR/VR images could be time-consuming, especially when the digital twins are not deployed in the same edge data center. In addition to the video, image streaming modules, the process of querying, integrating information from various digital twins as well as the deployment model shall be carefully designed. In order to avoid cyber-sickness, the **motion-to-photon latency**, or the latency between capturing a new image and displaying the augmented image based on the newly captured image, shall be smaller than 50 ms. To this end, the one-way **end-to-end latency** of the 5G system shall be 10 ms or less.

From the analysis of the non-functional requirements of the use case “Using Augmented/Virtual Reality for Process Diagnosis” above, it becomes apparent that it entails two distinct traffic types that make use of two different 5G service classes. The AR/VR video frame transmissions are mainly characterized by high data rates in both, the uplink and the downlink, and are therefore associated with the **eMBB** service class. Because the user interacts with the digital twins additional stringent latency requirements are imposed on the data transmission, leading to the fact that this use case also makes use of the **URLLC** service class.

3.2.4 Use Case Implementation at Trial Site

For the further concrete plan of implementation of a related demonstrator in WP5, a more in-depth analysis of the requirements and specifications will be conducted. It includes the selection of the end user device, i.e. an AR/VR HMD or tablet computer, the definition of the interaction scenario between the end user and the digital twins, the preparation of 3D models for the target machines, machining cells and robots, and the association of shop floor sensing data with the 3D model. It is planned to use on machine tool and one robot, and the VR HMI software needs to be designed and implemented together with the software agent allocated in the MEC that runs together with the digital twins of the machine tool and robot. The digital twins software could be commercial CAD/CAM packages with external APIs.

Figure 14 shows the planned physical setup of the use case. The 3D live cyber-physical processor is a software agent located in the MEC. The agent will act as a bridge between user and digital twin, which in this use case will be implemented by Dassault CATIA and Enovia package. Data collection from shop floor will be implemented in terms of an OPC UA client as the shop floor equipment is connected with industrial PCs with OPC UA server for data items from CNC and DAQ. In this setup, the user device will be a tablet PC or HMD with a camera module. Using the camera module on the tablet PC and markings or QR codes on machines, the relative position and orientation between the end user and the equipment can be identified and transformed into corresponding viewport(a polygon viewing region in computer graphics) and navigation commands to the 3D model. Sensing data can be associated with corresponding 3D components to show process status information. For example, vibration levels can be shown on the 3D model of the spindle as color-coded contour. Machining tool paths can also be drawn in different colors according to different vibration levels, the percentage of spindle loading as well as other current values.

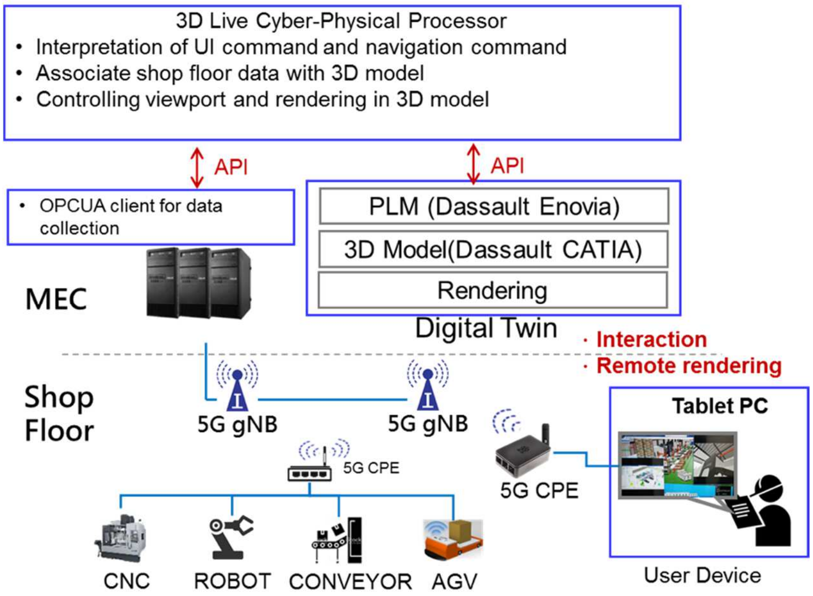

Figure 14: Physical Setup of the "AR/VR for Process Diagnosis" Use Case

Because manufacturing applications and processes require particular safety and security measures, the following considerations are important for the AR/VR use case as well. Orphaned wearable devices could be tampered and, in some situations, headwear devices will have excessive and direct exposure to the Internet without protection. In addition, the application software for the AR/VR use case should be carefully designed to avoid security breaches including API exploitation, exploiting known vulnerabilities, app manipulation, and password guessing. Also, smoothness of the data plane is very important. Thus, the security measures need to counteract potential route injection, traffic sniffing, data model injections, and buffer overflow. On factory premises, the network security measures primarily consider perimeter security, network zoning and traffic separation. In particular, not only the video stream but also user input and interaction commands between the user device and the digital twin server should be encrypted. Regarding the core network on the cloud platform, security issues like cloud orchestration vulnerabilities and virtualization attach interface must be coped with. For example, insecure APIs allow the deployment of malicious VMs, and hypervisor and VM vulnerabilities distribute attacks to virtual infrastructure.

Other technical challenges are related to the design of the VR/AR software. In order to offload the video analytics and graphical tasks from the UE to minimize complexity and power consumption, computer graphics expertise is required to design and implement the remote rendering and streaming architecture.

3.2.5 Use Case Validation and Demonstration

The demonstrator will be implemented in the ITRI pilot production site to accomplish a machining process parameter optimization, which is a common task in job shop or small batch production. In job shop or small batch production, the cost for process planning and testing is significant in overall cost, therefore process engineers need to find the best machining parameter, such as feed rate and spindle speed as soon as possible to reduce the cost for trial-and-error. Machine coordinate values and corresponding vibration raw data will be collected by the OPC UA client for data collection in Figure 13. The tool path along a workpiece will then be plotted using the collected coordinate values and will be color-coded according to the vibration level. This information will be superimposed with the 3D model of the machine tool. Users of the end device will see a 3D model of the machine tools moving in real time with the real machine and the color-coded tool paths will also be plotted in real time on the workpiece.

Machine users will use the plotted tool paths and other 3D objects, such as charts or text messages, to optimize the machining parameters. Performance between users using the conventional trial-and error method and users with AR/VR devices will be compared to validate the results. Performance can be measured in terms of total process planning time, cycle time for the workpiece before and after optimization, as well as the surface quality before and after optimization.

3.3 UC-3: Robot Platform with Edge Intelligence and Control

The subsequent paragraphs detail the use case “Robot Platform with Edge Intelligence and Control” introduced in Section 2.5.6.

3.3.1 Use Case Description

In today’s manufacturing processes, stationary robot platforms perform a variety of different tasks mostly at designated locations inside a plant. Such tasks include assembly, inspection, packaging, and other processes. Motion control of stationary robots is carried out using a controller that is connected through wire with the robot’s mechanical parts of, for instance, the robot arm. The controller is usually specialized hardware and software, which sends control signals in the form of physical target values, e.g. joint torque, speed or location of mechanical parts, to the motors. Sensors measure the actual values and feed them back to the controller, which then calculates new target values based on the actual ones and the underlying control function that was initially programmed. The time it takes to compute target values by the control function, to send them to the actuators, to carry out the movement on the basis of the target values, to measure the actual values and to send them back is usually referred to as the cycle time. Normally the cycle time is not allowed to take more than a few milliseconds in order to allow a fast motion of the movable parts of the robot with the required accuracy. More compact, semi-mobile robot platforms, having, for instance, only one, less heavy robot arm with a gripper, are used to carry out tasks on less heavy workpieces. Especially for processing of smaller batches of products, such robot platforms can already be used with a flexibility up to a certain extent. Nevertheless, the necessity of a steadily increased plant productivity, of an enhanced flexibility on the shop floor and higher cost efficiency calls for further automation in factories, while the degrees of product diversity and customization is growing further. Still, also semi-mobile robots have their control system on-board, which makes them rather heavy, costly, with a larger footprint at the factory floor.

5G technology brings, among others, two essential building blocks that promises a considerable increase of agility, flexibility and efficiency to manufacturing in general, and to mobile robot platforms in particular: First, ultra-reliable low-latency communications (URLLC), with end-to-end latency in the order of the cycle time for motion control, and, second, 5G’s integration with edge computing. Hence, the goal of this use case is to remove the controller, i.e. the programmable logic controller (PLC) or the industrial PC (IPC), from the robot platform and to migrate the control function in the form of a software package to the edge cloud. A 5G link is considered to interconnect the robot arm with the backend to fulfill the timeliness and reliability requirements imposed by the exchange of motion control messages (e.g. target values of joint positions or velocities) and feedback messages in the form of the current state of the machine (e.g. joint angles and torques). In addition, camera systems can be mounted onto the robot arms for workpiece inspection, while the logic and intelligence for video analytics is also a virtualized software package running in the edge cloud.

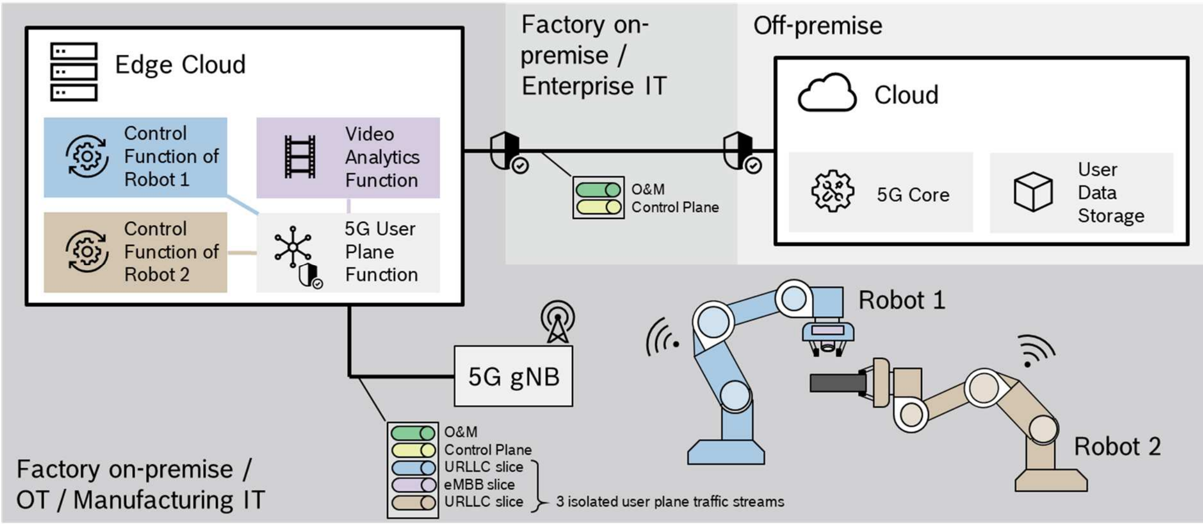

Figure 15: Illustration of the Architecture of the "Robot Platforms with Edge Intelligence and Control" Use Case.

Figure 15 illustrates the high-level description of the use case using an example with two collaborating robots (light blue and ochre), of which one has a camera system (pink) installed for the purpose of workpiece inspection. In order to make the robot arms more versatile, lightweight and mobile, both control functions and the video analytics intelligence are software instances (e.g. in the form of virtual machines or containers) running in the edge cloud, thereby avoiding costly controllers integrated with the robot arms.

In addition to the robot control and the video analytics functions, the 5G user plane function (UPF) runs on the edge cloud and is responsible for an appropriate user plane data routing, secure traffic isolation, e.g., through network slicing, and ensuring QoS to the data streams. Logically, the edge cloud and parts of the 5G network are parts of the manufacturing IT and, therefore, require a dedicated IT security setup as explained in the use case implementation paragraph.

One possible action for robots with edge control and intelligence is that "robot 1" (blue) inspects a workpiece for quality control using its industrial camera system. Upon smart detection of quality issues in the edge cloud, the relative camera position can be altered or "robot 2" (ochre) can hand over the workpiece to "robot 1" (blue), which receives it for further processing. All interactions are facilitated through jointly coordinating the movements of both robots using the control function instances in the edge cloud and by possibly exchanging information among them.

3.3.2 Use Case Benefits

5G is considered the first wireless technology that allows having a closed-loop control over a wireless link because of 5G's promises of ultra-low latency and high reliability. Moving intelligence to a nearby edge cloud and closing the control loop wirelessly over 5G can bring a plethora of different benefits to the user of the robot and the factory in general. Some of them are as follows.

First, offloaded control functions enable robots to move more freely across the shop floor. This is accomplished by removing the internal controller and by removing cabling between an external controller and the mechanical parts of the robot, and especially if powering of the robot can be realized through batteries or also wirelessly over induction, for example. This can lead to increased utilization of robots in a plant in general because by being mobile such robots can be easily and quickly moved to locations where needed, for example to support humans at another work place. Furthermore, through centralized control at the edge cloud, multiple robots can collaborate in a more flexible manner because sensory, control and task data can directly be exchanged through appropriate interfaces between the control function software instances. Tasks that are more complex can be assigned to a larger number of mobile, collaborative machines on the shop floor and by removing the IPC or PLC from the entire platform makes them less heavy, less expensive and more versatile, while they altogether have a smaller footprint on the shop floor. Moreover, higher production efficiency can also be achieved by centrally managing, troubleshooting, monitoring and programming the robots through the edge cloud and, perhaps, even remotely. Then, quick changes of production lines and tasks for small batch production and high customization are enabled by such flexible robot systems with centralized control, management and configuration. All of the aforementioned benefits ultimately unlock a great potential for reductions in capital and operational expenditures for robots platforms and more complex, multi-agent production systems.

3.3.3 Technical Challenges and Requirements

The use case “Robot platforms with edge intelligence and control” entails two traffic types, namely motion control traffic for mechanical operation of the robot and video traffic for intelligent video analytics in the edge cloud. While the **robot motion control traffic** follows a ***closed-loop control*** activity pattern, the video traffic does not follow such a pattern. Although the image analysis information supports and influences the decision about robot arm movements, it is not directly coupled with the control loop application between the controller and the actuators/sensors. Because of this, the **video traffic** is classified as **non-deterministic** with an **asymmetrical** traffic share between the uplink and the downlink directions (generating larger data volumes for the transfer in the uplink). In contrast to the video traffic, the **robot motion control traffic** is **deterministic**, **periodic** and **symmetrical**. Depending on the actual implementation, the use case can be classified into the **control-to-control**, **motion control** and **mobile robot** classes as summarized in Section 2.4.

The use case “Robot platforms with edge intelligence and control” imposes a number of **functional requirements** on the 5G System, in particular,

(1) ***End-to-end QoS Support (FR-3)****:* Both, the video traffic and the motion control traffic streams exhibit stringent QoS requirements (e.g. latency, survival time and service bitrate), which are necessary for the operation of the entire robot system. In this regard, QoS must be guaranteed in an end-to-end fashion, i.e. from the motion control and video analytics applications running on the edge cloud, to the 5G gNodeB, to the 5G end device module, to the robot.
(2) ***Network Capability Exposure Support (FR-4)****:* Stringent latency and reliability must be guaranteed to ensure the proper and safe operation of the robot. Therefore, the factory personnel must, at any time, be able to retrieve information about the current network utilization, available capacity and status of the UEs, as well as to make capacity enhancements or configurations for the network slices associated with the robot platform.
(3) ***Priority, QoS and Policy Control Support (FR-5)****:* The fact that the robot platform requires two traffic streams with diverse QoS requirements necessitates prioritization of

the motion control traffic stream and means to enforce the priorities, QoS guarantees and policies.

(4) ***Time Synchronization Support (FR-6)****:* In discrete automation, and for isochronous operation of robots in particular, jitter constraints are very tight in the order of one µs, which requires synchronicity of clocks of the different, collaborating robot systems.

(5) ***Context-Aware Network Support (FR-8)****:* Context information of the robot applications (control and video), which include traffic characteristics (e.g. transfer interval and message size) and QoS requirements (e.g. end-to-end latency), are essential information to the 5G System for a proper setup of network slices and other network and RAN configurations.

(6) ***Real-time end-to-end QoS Monitoring Support (FR-9)****:* End-to-end QoS must be monitored in real-time in order to identify potential capacity bottlenecks, which could eventually jeopardize the proper operation of the robot platform. If QoS is monitored in real-time, countermeasures can be taken to prevent a (further) degradation of QoS that could lead to a full stop of the manufacturing processes carried out by the robot platform or that could even cause unwanted movements of the robot arm harmful to factory personnel.

(7) ***Edge Computing Support (FR-13)****:* In order to be able to shift motion control functions and intelligence to the edge cloud, the edge computing system must be integrated into the overall 5G system in a manner, such that the applications' latency and reliability requirements are met.

In addition to the functional requirements above, the following requirements can be of importance depending on the specifics of the robot system:

(a) ***Mobility Management Support (FR-1)****:* For mobile robot platforms, which autonomously move across the shop floor, seamless mobility must be ensured. Ensuring a seamless handover between two cells is particularly challenging if the closed-loop control function is providing necessary commands during the handover.

(b) ***5G LAN-type Service Support (FR-10)****:* Robot platforms, whose controllers require (industrial) Ethernet communication, particularly require 5G LAN-type services, potentially with time-aware scheduling functionalities and prioritization of Ethernet frames.

(c) ***Proximity Services Support (FR-11)****:* Collaborating robots are typically in close vicinity to each other making direct device-to-device communication, i.e. Proximity Services (ProSe), possible. ProSe could not only reduce the end-to-end latency between two robots, it could also be more robust against harmful inter-cell interference if the spectrum for ProSe is managed by the 5G RAN.

(d) ***Secure Remote Access Support (FR-12)****:* Factory personnel typically require direct access to field devices, machines or robots for management purposes.

The functional requirements (a) to (d) are considered here to be optional and will not be investigated further for the implementation of the demonstrator in WP5.

The following paragraphs discuss the **non-functional requirements** of this use case.

The robot arm and the camera is assumed to be not in a functional mode when the robot platform is moving, such that seamless mobility is not necessarily required during operation. Therefore, the ***service area*** is an indoor shop floor with a typical size of 100 m x 100 m x 15 m. The ***number of UEs*** (number of robot platforms) on the shop floor considerably varies depending on the type of production and the workpieces that are processed. It can range between one and a few tens per shop floor. The ***UE speed*** during operation is assumed less than 2 m/s.

Motion control traffic for robots is typically characterized by transfers of control signals in fixed time intervals, i.e. every ***transfer interval*** T_{TI}, which is here considered to be maximally 20 ms, but it could also be as short as 5 ms. The 5G System must be designed and configured in a way, such that, within the transfer interval, the robot motion controller sends the target values to the actuators, the robot carries out (parts of) the movement and the sensors send actual values back to the controller for updating the target values of the next iteration. Therefore, the ***transmission time*** T_{TM} must fulfill

$$T_{\mathrm{TM}} < \frac{1}{2}(T_{\mathrm{TI}} - T_{\mathrm{Pr}} - T_{\mathrm{RM}}),$$

where T_{Pr} and T_{RM} are the time for processing at the edge cloud (computation of new target values) and the time for robot movements, respectively. Hence, the transmission time must be below 10 ms. Reserving about 6 ms for robot movements (5 ms or 25 % of the transfer interval) and control processing (1 ms), for example, leaves a 7 ms transmission time. Since the transmission time is the sum of the end-to-end latency and the time for processing at the higher communication layers, the ***end-to-end latency*** must be shorter than the transmission time, i.e. below 7 ms in this case. For a transfer interval of 5 ms, the transmission time can be assumed to be below 1.4 ms and the end-to-end latency around 1 ms. In the case that an expected target value from the controller is untimely or lost, the actuators of the robot arm perform actions based on linearly or non-linearly extrapolated target values until a certain point, when the robot puts itself into safety mode. This time interval between the last successfully received target value and the start of the safety mode is the **survival time**. The larger the survival time, the larger is the error between the real and the extrapolated target values and hence the actual values, e.g. the actual position of the robot hand. In general, there is a trade-off between the motion speed, the accuracy of the state of the robot and the maximally allowed survival time. Considering a reasonably high accuracy at a high motion speed, the survival time is assumed here to be 20 ms. If the transfer interval is 20 ms, one packet loss already causes a failure, whereas a transfer interval of 5 ms allows for at most three consecutive untimely or lost target values at a survival time of 20 ms. Every transfer interval, the motion controller sends target values to the actuators in the downlink and the robot arm sends the measured actual values back to the controller in the uplink. The amount of information transmitted every transfer interval substantially depends on the type of robot. In particular, the ***message size*** scales with the degrees of freedom of the motion. For a robot arm with seven degrees of freedom, a message size of 200 byte is assumed. The ***service bit rate***, as the minimum data rate the system guarantees at any time to for the deterministic closed-loop control, is the message size divided by the end-to-end latency resulting in approximately 228 kbps and 1.6 Mbps.

Compared to the motion control traffic, the non-deterministic video traffic exhibits a much higher service bit rate. Depending on the used codec, image resolution and image sampling rate, the **service bit rate** can vary between a few 10s of Mbps and some 100s of Mbps for compressed video and can also amount to several Gbps for uncompressed content. Industrial cameras often have a relatively high sampling rate, typically 135 fps. For example, the average video bit rate of a Full HD, 135 fps video stream encoded using MJPEG is about 330 Mbps.

As the “Robot platforms with edge intelligence and control” use case utilizes its industrial camera system and the video analytics software to detect quality issues of a workpiece, the dynamic path and motion planning of the robot arm depends on the video processing and analysis latency. In order to guarantee sufficiently fast and smooth robot arm movements, the video processing and analysis latency should be rather short. This observation leads to the requirement that the entire **video latency**, which is composed of time for encoding and transfer of video information, decoding, video analytics in the cloud and the decision by an algorithm to plan further arm movements, is in the order of $N \cdot T_{\mathrm{TI}}$ with N being a small integer.

From the analysis of the non-functional requirements of the use case “Robot platforms with edge intelligence and control” above, it becomes apparent that it entails two distinct traffic types that make use of two different 5G service classes. The traffic for the video analytics application is mostly characterized by a high data rate in the uplink, and is therefore associated with the **eMBB** service class. The exchange of motion control messages for the robot arm in both, the uplink and downlink, requires strict latency and reliability measures, and thus belongs to the **URLLC** service class.

Further requirements that are independent of the 5G System are a low-delay control function in the edge cloud and appropriate low-delay video technology, which includes low-delay image processing and object recognition and suitable codecs that achieve a sufficiently large compression while ensuring the fulfillment of the latency constraints.

3.3.4 Use Case Implementation at Trial Site

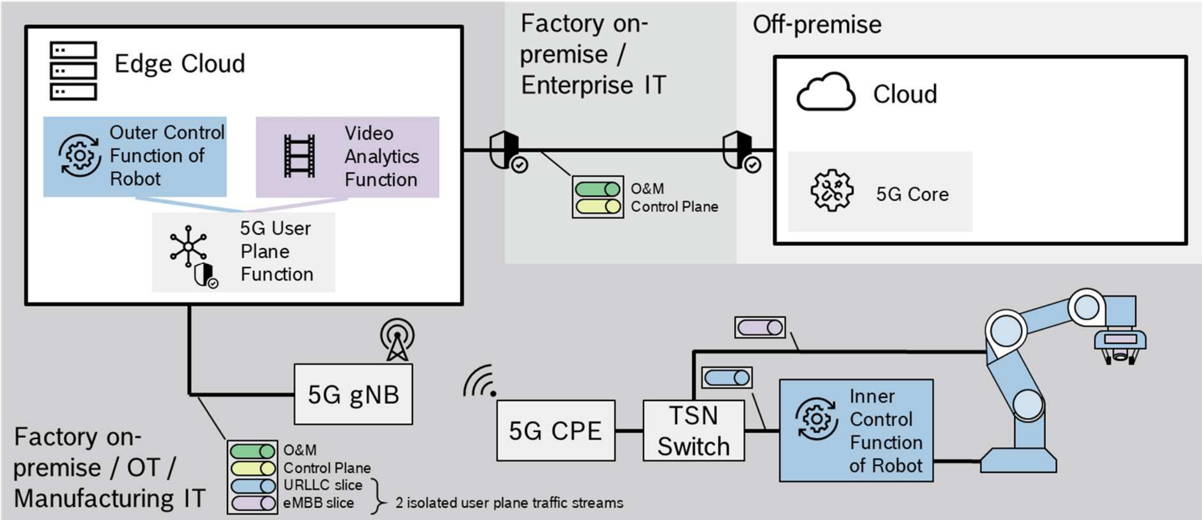

Figure 16: Demonstrator Setup of the "Robot Platforms with Edge Intelligence and Control" Use Case

For the further concrete plan of implementation of a related demonstrator in WP5, a more in-depth analysis of the requirements and specifications will be conducted. It includes the definition and initial setup of the demonstrator, the development of a human safety concept and the definition of a specific system procedure for demonstration purposes.

The demonstrator setup considerations include, for example, the choice of the virtualization technology, latency and computation power requirements of the edge cloud and the selection of appropriate hardware/software, including the selection of appropriate camera system and video analytics software. Another design consideration to enhance flexibility is the split of the control function into an outer and an inner control loop, where the latter should have a minimal footprint (e.g. as an interpolator), see Figure 16. Once the overall architecture is specified in more detail (WP2), a more in-depth specification of the functional split of the inner and the outer control loop will be possible, which also strongly depends on the latency and reliability achievable by the 5G system that is planned to be installed at the site. Also a more detailed investigation (along with analyses in WP2) on the specific security requirements, both in the research lab and later at the shop floor, will be conducted and solutions to achieve these requirements are planned to be developed.

3.3.5 Use Case Validation and Demonstration

A possible demonstration procedure could be the following: There can be several workpieces on a table in front of the robot for quality inspection. The robot dynamically inspects a workpiece, where dynamically means that the robot arm movements are planned according to the results of the image processing function (i.e. presence of a quality issue). Upon the detection of a quality issue, the malicious workpiece is being removed from the set and put to another location.

The validation of the use case using the demonstrator will be carried out from two perspectives. First, the proper functioning of the demonstration procedure will be tested. For example, various robot control configurations (e.g. variable transfer interval for the out control loop) will be tested in terms of robustness (i.e. achieving the non-functional requirements such as the end-to-end latency or packet error rate) while the video stream can have different bitrates (i.e. variable bit rate traffic). Second, tests related to security and ease-of-use will be conducted, which can include penetration tests for proper isolation of the different traffic streams (control and video) and traffic types (user plane, control plane and O&M traffic), and experiments concerning easy onboarding and deboarding of the robot in the 5G system. Other tests related to functional requirements listed in Sections 3.3.3 and 5 can also be part of the validation phase.

4 Summary of the Use Case Requirements

The following provides a summary of the requirements of the use cases elaborately described in the previous section. As seen in Table 5, the 5G CONNI use cases cover two different use case scenarios, i.e. eMBB and URLLC, where different traffic streams per use case have different requirements, especially for UC-3, which combines video traffic and motion control traffic into one system. Also, the 3GPP use case categories are well represented by the 5G CONNI use cases, while they have diverse traffic characteristics. It is important to note that both use cases, UC-1 and UC-2, are planned to be installed in the same environment and to be served by the same 5G System, such that the requirements of the combined use cases are imposed on the 5G System. In addition, strict QoS provisioning, e.g. in the form of network slicing, is necessary to make both use cases work at the same time.

Table 5: Overview of Use Case Classification and Traffic Characteristics

Use Case	Use Case Scenario(s)	Use Case Categories (Section 2.4)	Traffic Characteristics
UC-1	eMBB	Remote access and maintenance, process monitoring	Non-deterministic, asymmetrical
UC-2	eMBB, URLLC	Augmented reality	Non-deterministic, symmetrical
UC-3	eMBB, URLLC	Mobile robots, motion control, control-to-control	**Video:** Non-deterministic, asymmetrical; **Motion control:** Deterministic, periodic, symmetrical

Table 6 collects all functional requirements identified during the 5G CONNI and the mapping to the chosen use cases. It is important to note that, on the one hand, the use cases have four functional requirements in common, which can be assumed to be relevant to many industrial applications: Provisioning and monitoring of end-to-end QoS, secure remote access and edge computing support. On the other hand, the other functional requirements are more specific to the individual use cases.

Table 6: Overview of Functional Requirements of the Selected Use Cases

FR-ID	Functional requirement	UC-1	UC-2	UC-3
FR-1	Mobility management		x	(x)
FR-2	Energy efficiency		x	
FR-3	End-to-end QoS	x	x	x
FR-4	Network capability exposure			x
FR-5	Priority, QoS and policy control			x
FR-6	Time synchronization		x	x
FR-7	Localization service		x	
FR-8	Context-aware network			x
FR-9	Real-time end-to-end QoS monitoring	x	x	x
FR-10	5G LAN-type service support / Layer-2 LAN switching capability support / Ethernet transport services			(x)
FR-11	Proximity services			(x)

FR-12	Secure remote access	x	x	(x)
FR-13	Edge computing	x	x	x

Because the 5G CONNI use cases are related to different scenarios, use case categories and traffic characteristics, the non-functional requirements are rather diverse. They range from high data rate requirements to stringent positioning and timeliness demands, see Table 7.

Table 7: Overview of Non-Functional Requirements of the Selected Use Cases

KPI	UC-1	UC-2	UC-3
Service bitrate	208 Mbps per machine	Up to 1 Gbps per device	228 kbps – 1.6 Mbps for control traffic 100s Mbps for video traffic
Communication area	Some 1000 m² (2644 m² for demo setup)	Some 1000 m² (2644 m² for demo setup)	100 m x 100 m x 15 m
Connection density	10s per shop floor (11 for demo setup)	Up to 10 per shop floor (6 for the demo setup)	1 to few tens per shop floor
Area traffic capacity	86.5 Mbps per 100 m²	227 Mbps per 100 m²	100s Mbps per 100 m²
UE speed	stationary	< 3 km/h	< 2 km/h
Positioning accuracy	n/a	< 1 m (horizontal)	n/a
Positioning latency	n/a	< 15 ms	n/a
Motion-to-photon latency	n/a	< 50 ms	n/a
End-to-end latency	n/a	< 10 ms	1 ms – 7 ms
Transfer interval	n/a	n/a	5 ms – 20 ms
Transmission time	n/a	n/a	1.4 ms – 7 ms
Survival time	n/a	n/a	20 ms
Message size	n/a	n/a	200 bytes
Video latency	n/a	n/a	< N times transfer interval

5 Functional Requirements on Private 5G Networks Beyond Use Cases

The 5G CONNI system is planned to be designed, such that the use case-specific functional requirements as summarized in Section 4 are fulfilled. In the specific context of private 5G networks for industries, additional functional requirements that go beyond the use cases are of very high relevance. A few of them have already been identified mostly in [2] but many of them have not yet found (sufficient) expression in standardization documents. In order to address this, a thorough analysis of use case-unspecific functional requirements has been conducted from multiple perspectives: The factory owner, the factory personnel and the private 5G network operator. The latter can be a classical M(V)NO or the local factory IT, for instance. This analysis produced a number of requirements that are specific to private networks in industry and that can be grouped into eight categories, namely: Subscriber and identity management; Cyber-security; Monitoring and alerting; Slice and network management; Service availability; Access control; Voice services; and Charging. Later, this collection of functional requirements will specifically serve the purpose of designing and evaluating the different architecture and deployment options in Work Package 2. The requirements collected and analyzed are described more elaborately in the subsequent sections.

5.1 Subscriber and Identity Management

Subscriber and identity management systems are essential building blocks of any IT system and of cellular systems in particular. Current public cellular networks are designed in a manner, such that their subscriber and identity management systems (e.g. Home Subscriber System (HSS) in 4G LTE network) scale to 100.000s or millions of subscribers. In contrast to public cellular networks, private 5G networks for industries are required to provide a lean subscriber and identity management, which is flexible, accessible, robust and secure enough for industrial use. The Unified Data Management (UDM) function of the 5G core provides most of the subscriber and identity management functionalities in 5G networks. Fulfilling the requirements of this category aims at two main goals: Secure and robust subscriber profile management (SI-1 to SI-6) and the integration of "third party" subscriber identity management systems used in factories (SI-7 to SI-11). Table 8 collects the requirements of this category.

Table 8: Subscriber and Identity Management Requirements

Category 1: Subscriber and Identity Management				
Goal	**ID**	**Requirement**	**Description**	**Source**
Secure and robust subscriber profile management	***SI-1***	*Secure provisioning of subscriber profiles*	The 5G CONNI system shall enable the provisioning of subscriber profiles in a secure way, so that a single non-privileged OAM user is not able to import and export the data in clear text.	5G CONNI
	SI-2	*Subscriber profile backups*	The 5G CONNI system shall enable creating secure backups of the subscribers' profiles.	5G CONNI
	SI-3	*Subscriber profile backup recovery*	The 5G CONNI system shall enable fast recovery of subscriber profile backups.	5G CONNI
	SI-4	*Subscriber profile migration*	The 5G CONNI system shall enable authorized users to migrate backups of the subscribers' profiles from one system to another.	5G CONNI

	SI-5	*Subscriber database logging*	The 5G CONNI system shall log all the operations performed by users on the subscribers' databases.	5G CONNI
	SI-6	*Subscriber identity protection*	The 5G CONNI system shall protect a subscriber's identity from active and passive attacks.	[2], clause 8.5
Integration of third-party subscriber identity management	***SI-7***	*Third-party subscriber identity management system support*	The 5G CONNI system shall support network access using identities, credentials, and authentication methods provided and managed by a third party.	[2], clause 8.5, 5G CONNI
	SI-8	*Third-party subscriber identity management integration*	The 5G CONNI system shall support the integration of third party (corporate, factory) identity-, credentials- and authentication systems through providing appropriate APIs.	5G CONNI
	SI-9	*Automated subscriber management*	The 5G CONNI system shall support the automated discovery of field devices, and easy IP address management and assignment.	5G CONNI
	SI-10	*Flexible IP assignment*	The 5G CONNI system shall support flexible IP assignment for devices, i.e. DHCP and/or statically assigned IPs, for the standardized management of manufacturing assets in a factory.	5G CONNI
	SI-11	*IPv6 support*	The 5G CONNI system shall support IPv6.	5G CONNI

5.2 Cyber Security

Availability of the system and data, data confidentiality and data integrity are essential requirements in any IT system, including the manufacturing IT. Data availability and confidentiality are requirements of utmost importance because the underlying IT system is the basis for critical production and manufacturing processes and production data is one of the most important assets of a factory. Corresponding requirements that are to be imposed on the 5G system are, among others, to minimize the risk of attacks, i.e. not only through external attackers but also through internal attackers (e.g. spread of viruses through data storage devices), and the support of zoning and conduits for the compartmentalization of the logical or even physical communication infrastructure. Compartmentalization (or segmentation) is an established concept in factories, in which compartments (security zones or segments) enable private and isolated communication among certain groups of end devices (e.g. field devices of one production line) in order to prevent the spread of threats, such as viruses. The concept of zones and conduits is introduced in ISA/IEC 62443. Considering these conditions, fulfilling the requirements of this category aims at six main goals: Detection and mitigation of external attacks (CS-1 to CS-8), ensuring data privacy (CS-9 to CS-11), support for zoning and conduits, i.e. ISA/IEC 62443, (CS-12 to CS-17), audit and verification of 5G-native security features (CS-18 to CA-20), network-driven encryption (CS-21 to CS-22) and hardened systems (CS-23). Table 9 collects the requirements of this category.

Table 9: Cyber Security Requirements

Category 2: Cyber Security				
Goal	**ID**	**Requirement**	**Description**	**Source**
Detection and mitigation of external attacks	***CS-1***	*Secure O&M traffic*	The 5G CONNI system shall transport securely control plane and O&M traffic between a factory IT entry point and an external network service provider (encryption/encapsulation of O&M traffic, avoidance of DDoS).	5G CONNI
	CS-2	*Jamming*	The 5G CONNI system shall detect and mitigate jamming attempts.	5G CONNI
	CS-3	*Rogue clients*	The 5G CONNI system shall detect and mitigate rogue client access attempts to the 5G network and factory IT infrastructure (integration of ACL, FW rules).	5G CONNI
	CS-4	*Compromised network operator*	The 5G CONNI system shall detect and mitigate unauthorized access attempts through a compromised external network service provider.	5G CONNI
	CS-5	*SUPI/SUCI catcher attacks*	The 5G CONNI system shall detect and mitigate SUPI/SUCI catcher attacks.	5G CONNI
	CS-6	*Spoofing*	The 5G CONNI system shall provide security measures against spoofing and unauthorized manipulation of system configurations.	5G CONNI
	CS-7	*Location information protection*	The 5G CONNI system shall be able to protect user location information from active/passive attacks.	[2], clause 8.7
	CS-8	*Tampering and spoofing protection of user location production*	The 5G CONNI system shall support mechanisms to protect the production of the user location information and user positioning-related data against tampering and spoofing (and detect tampering and spoofing attacks).	[2], clause 8.7
Data privacy	***CS-9***	*Local end device authentication*	The 5G CONNI system shall provide mechanisms for local, on-premise device authentication.	5G CONNI
	CS-10	*Local user plane*	The 5G CONNI system shall ensure that user plane data stays on-premise for data privacy reasons.	5G CONNI
	CS-11	*Lean, off-premise control plane*	The 5G CONNI system shall ensure that production-related information (e.g. activity of end devices) cannot be inferred from control plane information transferred between the factory and an off-premise 5G Core.	5G CONNI

Support of ISA/IEC 62443 and LAN-type communications incl. virtual networks	***CS-12***	*Support of zones and conduits via API*	The 5G CONNI system shall natively support the configuration and maintenance / operation of zones and conduits as introduced in ISA/IEC 62443 via a documented and exposed API to be able to receive and manage externally driven conduits.	5G CONNI
	CS-13	*LAN-VNs*	The 5G CONNI system shall support 5G LAN-virtual networks (5G LAN-VN) with appropriate integrity protection and confidentiality mechanisms, incl. such methods for URLLC.	[2], clause 6.26.2.2, 5G CONNI
	CS-14	*Management of 5G LAN-VNs*	The 5G CONNI system shall enable factory personnel to easily establish and manage 5G LAN-VNs.	[2], clause 6.26.2.3, 5G CONNI
	CS-15	*Traffic filtering and prioritization*	The 5G CONNI system shall support traffic filtering and prioritization based on MAC or vLAN tags.	[2], clause 6.24.2
	CS-16	*Secure remote access*	The 5G CONNI system shall enable secure remote access to field or other devices on the shop floor by extending private communication in 5G LAN-VNs beyond the shop floor.	[2], clause 6.26.2, 5G CONNI
	CS-17	*Authentication of non-3GPP devices*	The 5G CONNI system shall provide a mechanism to authorize and "authenticate legacy non-3GPP devices for 5G LAN-VN access."	[2], clause 8.3, 5G CONNI
Audit and verification of 5G security	***CS-18***	*Log and audit 5G security mechanisms*	The 5G CONNI system shall provide a mechanism to enable an automation application to log and audit the 5G security mechanisms.	[3], clause 6.4.3
	CS-19	*Verification of 5G security 1*	The 5G CONNI system shall provide a mechanism, with which a vertical automation application verifies that the required 5G security mechanisms are actually active.	[3], clause 6.4.2
	CS-20	*Verification of 5G security 2*	The 5G CONNI system shall provide an interface, with which factory personnel verifies that the required 5G security mechanisms are actually active.	[3], clause 6.4.2
Network-driven encryption	***CS-21***	*Network-driven encryption of traffic*	The 5G CONNI system shall offer a network-driven encryption of the user plane and control plane traffic in an end-to-end fashion if such traffic is routed off-premise (comparable to WAN encryption by providers).	5G CONNI
	CS-22	*Key management*	The 5G CONNI system shall natively support the usage of externally	5G CONNI

		with network-driven traffic encryption	provided key management and key storage systems (HSM) to give the user of the network full control over the used encryption keys for network-driven traffic encryption.	
Hardened systems	***CS-23***	*System hardening*	The 5G CONNI system shall be provided on hardened systems where unnecessary ports and protocols can be switched off.	5G CONNI

5.3 Monitoring, Logging and Alerting

Because ensuring the operation of industrial processes is essential for the sustainability of a factory, private 5G networks require extended capabilities for monitoring, logging and alerting. On the one hand, factory personnel needs to be informed as fast as possible about (imminent) networking issues that could affect production. On the other hand, any configuration and performance alterations need be monitored and logged in order to provide the highest degree of security and robustness, and a sufficient basis for the clarification of liability questions. Fulfilling the requirements of this category aims at three main goals: Alerting to inform IT and factory personnel (MA-1 to MA-5), monitoring for performance, liability and security purposes (MA-6 to MA-9), and support for a unified monitoring platform. Table 10 collects the requirements of this category.

Table 10: Monitoring, Logging and Alerting Requirements

Category 3: Monitoring, Logging and Alerting				
Goal	**ID**	**Requirement**	**Description**	**Source**
Alerting and logging	***MA-1***	*Alarms (3GPP)*	The 5G CONNI system shall generate alarms upon occurring of user-defined events related to the 3GPP domain (e.g., network attach/detach, malfunction of core-RAN interfaces, etc.).	5G CONNI
	MA-2	*Alarms (networking)*	The 5G CONNI system shall generate alarms upon occurring of user-defined events related to the networking domain (e.g., link failure).	5G CONNI
	MA-3	*Alarms (virtualization)*	The 5G CONNI system shall generate alarms upon occurring of user-defined events related to the virtualization environment (e.g., exceeding resource consumption).	5G CONNI
	MA-4	*Pro-active alarms*	The 5G CONNI system shall generate alarm pro-actively prior to expected or imminent user-defined events.	5G CONNI
	MA-5	*Logging of alarms*	The 5G CONNI system shall be able to forward alarms via encrypted protocols to an external log server.	5G CONNI
Monitoring and logging	***MA-6***	*Network capability exposure support**	The 5G CONNI system shall provide APIs to obtain information about networking capabilities, guaranteed performance and supported services	[2], clause 6.10.2,

			in an encrypted manner to factory personnel to help, among others, decide about onboarding of additional mission critical applications, etc.	5G CONNI
	MA-7	*Monitoring and logging for liability*	The 5G CONNI system shall provide means to monitor and log all configuration activities of the network service provider and the user (e.g. factory personnel, local IT). This shall ensure an appropriate information base in the case of liability issues between the user and the network service provider. The monitoring and logging system shall be adaptive to different operation models (in the sense of separation of responsibilities, RASI, between the user, the local factory IT and the network service provider).	5G CONNI
	MA-8	*Real-time E2E QoS monitoring support**	The 5G CONNI system shall provide functionalities for the factory owner, the user or the network service provider to monitor end-to-end quality-of-service in real-time to identify communication bottlenecks that potentially jeopardize services i.e. manufacturing processes. Monitoring information is, e.g. QoS parameters and events, statistical information of service parameters and error types, information to identify type and location of communication errors.	[2], clause 6.23.2, [3], clause 8.2.3, 5G CONNI
	MA-9	*Flow based IP traffic monitoring*	The 5G CONNI system shall support IPv4/IPv6 flow-based monitoring to provide traffic analysis, DDoS detection and accounting.	5G CONNI
Monitoring platform	***MA-10***	*Unified monitoring platform*	The 5G CONNI system shall enable a platform to collect relevant information from each network element through appropriate APIs or northbound interfaces.	5G CONNI

5.4 Slice and Network Management

The fourth category contains requirements that are related to the configuration of the 5G CONNI system in response to the use case-specific non-functional QoS requirements. In particular, the factory personnel should be able to configure the network by easily creating and managing end-to-end network slices for various applications and without dealing with too many technicalities. Fulfilling the requirements of this category aims at two main goals: Creation and management of network slices, priorities and policies (SN-1 to SN-3) and the support for multiple service sites with central network management / central 5G Core (SN-4). Table 11 collects the requirements of this category.

Table 11: Slice and Network Management Requirements

Category 4: Slice and Network Management				
Goal	**ID**	**Requirement**	**Description**	**Source**
Creation and management of network slices, priorities and policies	***SN-1***	*Slice creation support*	The 5G CONNI system shall enable a network administrator to create slices for each service, for instance, an "Office" slice, used for intranet services and office staff calls; a "Production" slice, used by workers in the production sites; a "Machinery" slice, used to connect the machinery.	[2], clause 6.1.2.2, 5G CONNI
	SN-2	*Shop floor slice lifecycle management support*	The 5G CONNI system shall enable the factory personnel to manage network slices easily, fast and securely for individual end devices, groups of end devices, services and traffic types on the shop floor. Slice management includes creation, activation, configuration, and deactivation of network slices. The network slicing architecture contains access slices (both radio access and fixed access), core network (CN) slices and the selection function that connects these slices into a complete network slice comprised of both the access network and the CN. It supports the following main features: 1. Isolation between network slices 2. E2E network slicing 3. Operator can tailor to their specific needs	[2], clause 6.1.2.2, 5G CONNI
	SN-3	*Priority, QoS and policy control**	The 5G CONNI system shall enable the factory personnel to assign and enforce priorities and QoS to end devices, device groups, services, etc. in an easy manner.	[2], clause 6.7, 5G CONNI
Multi-site support	***SN-4***	*Multi-site support*	The 5G CONNI system shall support multi-site operation and management (O&M) with a central 5G Core located in a regional or global data center for the centralized O&M can reduce complexity and effort.	5G CONNI

5.5 Service Availability

Outage of components that are involved in manufacturing processes can cause downtimes leading to great monetary losses for a factory. Because private 5G networks will be seen as key infrastructure components in the factory of the future, the same system availability requirements apply for them as for manufacturing assets. Fulfilling the requirements of this category aims at three main goals: Securing the availability of system data (SA-1 and SA-2), avoiding unplanned system downtimes (SA-3 to SA-5) and avoiding strong interference from adjacent networks that could be harmful to the proper operation of the private 5G network. Table 12 collects the requirements of this category.

Table 12: Service Availability Requirements

Category 5: Service Availability				
Goal	**ID**	**Requirement**	**Description**	**Source**
Securing system data	***SA-1***	*Backup support 1*	The 5G CONNI system shall be able to backup and restore system data and configuration files.	5G CONNI
	SA-2	*Backup support 2*	The 5G CONNI system should be able to restore backup data generated by a previous system release version.	5G CONNI
Avoiding downtimes	***SA-3***	*Availability of a private 5G network*	The 5G CONNI system shall maintain critical functions running when there is no connection to public networks such as the Internet.	5G CONNI
	SA-4	*Outage protection*	The 5G CONNI system shall be robust to outage of RAN and Core components and of the underlying infrastructure by utilizing appropriate failover and redundancy concepts.	5G CONNI
	SA-5	*Scheduled maintenance*	The 5G CONNI system shall allow scheduled maintenance and updates in pre-defined time windows (hardware and software).	5G CONNI
Avoiding harmful interference	***SA-6***	*Interference management*	The 5G CONNI system shall carry out interference management with adjacent (private) networks.	5G CONNI

5.6 Access Control

Network selection and attachment processes of user equipment can consume considerable resources that could otherwise be used by other applications. Moreover, such unnecessary connection attempts by end devices that are not part of the network can even have adversarial effects for ongoing mission-critical communications serving critical production processes. Therefore, such effects need to be avoided and appropriate requirements are taken from [2] and listed in Table 13.

Table 13: Access Control Requirements

	Category 6: Access Control			
Goal	**ID**	**Requirement**	**Description**	**Source**
Robustness and confidentiality through access control	***AC-1***	*Unified access control support*	The 5G CONNI system shall support unified access control, through which UE access is allowed or blocked based on Access Identities that indicate the type of service a UE is requesting, e.g. Mission Critical Service.	[2], clause 6.22.2

	AC-2	*UE-NPN association 1* (NPN support)	The 5G CONNI system shall support a mechanism to prevent a UE with a subscription to a non-public network from automatically selecting and attaching to a PLMN or non-public network it is not authorized to select.	[2], clause 6.25.2
	AC-3	*UE-NPN association 2* (NPN support)	The 5G CONNI system shall "support a mechanism to prevent a UE with a subscription to a PLMN from automatically selecting and attaching to a non-public network it is not authorized to select."	[2], clause 6.25.2

5.7 Voice Services

Telephony is an essential service that is required inside plants for factory personnel. Nevertheless, many factories require the installation of dedicated (cellular) indoor networks in order to overcome large penetration losses caused by thick concrete walls. Rolling out two distinct networks for voice services and for manufacturing use cases not only increases complexity but also is most likely uneconomic. Therefore, the 5G CONNI system shall fulfill voice service requirements as listed in Table 14.

Table 14: Voice Services Requirements

Category 7: Voice Services				
Goal	**ID**	**Requirement**	**Description**	**Source**
Voice service support	***VS-1***	*Voice call support*	The 5G CONNI system shall support different services for both human and machine communication. Whereas machine type communication are data only, human communications include both data and voice services. For the latter, the system shall support: Voice and video calls to local numbers within the private network, group/broadcast calls to local numbers within the private network, and, optionally, voice/video calls to numbers of other PLMNs.	5G CONNI
	VS-2	*Emergency call support*	The 5G CONNI system shall support IMS emergency services, as support for emergency calls from inside a factory is important or even legally required, while at the same time, for entirely private/isolated NPNs, no other information leakage is to be ensured.	[2], clause 6.25.2

5.8 Charging

Private 5G networks provide the opportunity for new business and operation models in a changing ecosystem and with a flexible, service-oriented networking architecture. In this regard, two additional requirements related to charging become relevant, which are both identified in [2] and listed in Table 15.

Table 15: Charging Requirements

Category 8: Charging				
Goal	**ID**	**Requirement**	**Description**	**Source**
Charging in NPN	***CG-1***	*Charging based on services used*	The 5G CONNI system shall enable the network service provider to charge based on services, slices, access types and capacity used as well as performance requested (and delivered).	[2], clause 9.1
	CG-2	*Charging for 5G LAN-type communications*	The 5G CONNI system shall enable the network service provider to charge for 5G LAN-type communication services, even if the communication is private.	[2], clause 9.2

* This can be a use case-specific functional requirement as well, if the application itself requires information about the network capabilities (provisioned resources) to adapt the operational mode of the industrial application.

6 References

[1] 3GPP, TS 22.104 V17.2.0, "Service Requirements for cyber-physical control applications in vertical domains; Stage 1 (Release 17)," 2019-12.

[2] 3GPP, TS 22.261 V17.2.0, "Service requirements for the 5G system; Stage 1 (Release 17)," 2020-03.

[3] 3GPP, TR 22.804 V16.2.0, "Study on Communication for Automation in Vertical Domains (Release 16)," 2018-12.

[4] 3GPP, TS 23.501 V16.4.0, "System architecture for the 5G System (5GS); Stage 2 (Release 16)," 2020-03.

[5] ETSI White Paper, "MEC Deployments in 4G and Evolution Towards 5G," February 2018.

[6] 3GPP, TR 28.801 V15.1.0, "Study on management and orchestration of network slicing for next generation network (Release 15)," 2018-01.

[7] International Society of Automation, "ANSI/ISA-95 Enterprise-Control System Integration".

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[9] M. Wollschlaeger, T. Sauter and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," *IEEE Industrial Electronics Magazine,* vol. 11, no. 1, pp. 17-27, March 2017.

[10] 3GPP, TR 22.832 V17.1.0, "Study on enhancements for cyber-physical domains; Stage 1 (Release 17)," 2019-12.

[11] ITU, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," September 2015.