D1.1

FORWARD LOOKING SMART MANUFACTURING USE CASES, REQUIREMENTS AND KPIS

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Forward looking smart manufacturing use cases, requirements and KPIs

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Short abstract:	Many future-looking use cases are introduced with 5G. In 5G-SMART, seven of these foreseen use cases are put into practice in trial 5G systems. An additional six use cases are also explored. D1.1 includes key requirements, KPIs and challenges identified for these selected 13 use cases.
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Disclaimer

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Executive summary

This report gives an overview of forward-looking use cases explored in the 5G-SMART project. These use cases have been selected to cover a broad range of application areas for 5G in smart factories of the future. Specifically, the use cases allow us to trial and validate 5G capabilities in various scenarios related to factory automation, process automation, human-machine interfaces (HMIs) and production IT, as well as to logistics and warehousing. In the trials of the 5G-SMART project, 5G compliant with 3GPP release 15 will be used as a baseline due to the availability of 5G components during the execution of the project. A total of 13 use cases are investigated out of which seven use cases are considered for experimental evaluations and validations at the 5G-SMART trial sites. The trial sites are an Ericsson smart factory in Kista, the Fraunhofer IPT shop floor in Aachen, and the Bosch semiconductor factory in Reutlingen.

The specification of the use cases in this document includes a description, current state of the art, benefits of the use case, as well as requirements put on the 5G communication system and the associated challenges. Strong focus will be given on detailing the trial use cases but, in addition to this, further use cases are described in this document with the intention to show the variety of possible 5G-empowered smart manufacturing use cases. These go beyond what is possible with current 5G Release 15 technology and the aim is to complement, or add to, the use cases described in e.g. 3GPP [TS22.104] and 5GPPP [5GACIA2] and motivate further development of the 5G standards.

Contents

1 Introduction

The European manufacturing sector is of paramount significance for the European economy. In 2009 almost every 10th enterprise was classified to be in the manufacturing domain and represented more than 30% of the European work force, with manufactured products being the majority of European exports [EU2020]. A fourth industrial revolution has started with the objective of making the vision of highly efficient, connected and flexible smart manufacturing a tangible reality. For instance, to further improve efficiency in production, and be able to deliver more customized products, today's production lines need to be highly integrated so that information is more easily shared between different systems. In addition, the production line needs to be highly flexible to incorporate dynamic configuration changes without compromising safety. In general, by increasing the quality of the process the final products get cheaper and better. Real-time process monitoring plays a key role here.

There are two trends driving the development of smart manufacturing. These are 1) more flexible production, to meet the need of increased customization, and 2) more autonomous operations and monitoring to increase productivity and improve quality. The digital transformation of industry fueled by Industry 4.0 and the development of 5G cellular technology, is in many ways a response to these trends.

A key part of the digital transformation is the information technology/operational technology (IT/OT) convergence that is changing both the communication infrastructure as well as the automation systems in the factories. Intelligence is being moved from devices and dedicated controllers into the edge and cloud for increased flexibility and cost-efficiency. A fast, reliable and secure 5G network enables more flexible deployment, service re-configuration and new mobility solutions including mobile robots, augmented workers and wireless sensors for monitoring in challenging production environments.

1.1 5G Use cases in Smart Manufacturing

As 5G continues to be developed, more and more applications and use cases (UCs) in smart manufacturing can be realized. A likely scenario is that 5G will first be introduced in use cases where wired solutions cannot be used. This is the case, for example, in applications where mobile robots or Automated Guided Vehicles (AGVs) are utilized. These use cases simply cannot be realized using wired industrial networks and existing wireless technology (e.g. Wi-Fi) shows limitations in performance and scalability. Other use cases where wired connections are unwanted include the case where additional sensors are introduced in the machinery. In these cases, the aim is to eliminate the wear and tear of the cable but also improve flexibility.

Another important aspect to consider is the integration of 5G and industrial LANs. This includes both legacy networks that needs to be supported as well as new industrial wired solutions like Time-Sensitive Networking (TSN) [TSN][Bruckner19]. In many cases huge investments have been made on existing industrial networks and in the future these installations would benefit from ongoing activities on 5G/TSN integration [5GS20-D51][5GTSN19].

The vision for 5G is that the technology will enable the digital transformation from a hierarchically connected factory to a fully connected smart factory that goes beyond and encompasses a large connected eco systems as shown in Figure 1.

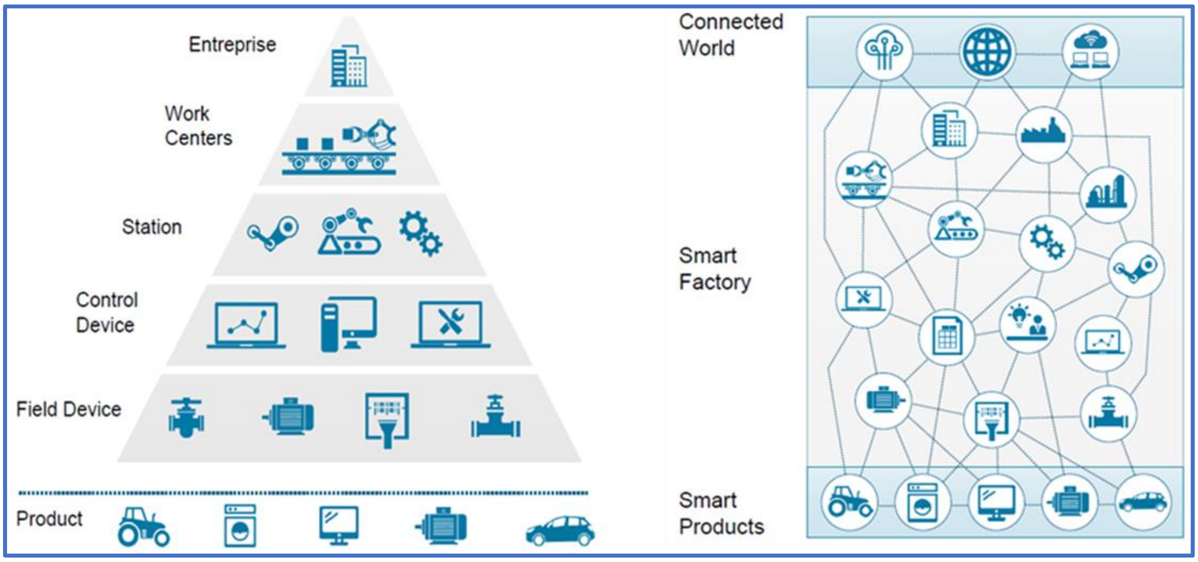

Figure 1: 5G and the digital transformation (source: Plattform Industrie 4.0)

By utilizing the global footprint of 5G, it will be possible to connect businesses in an unprecedented way. Different supply chains and manufacturing sites can be connected to support on demand production. Remote service and collaboration can be carried out to enhance skills of workers on site. Smart products can utilize the cellular network to support the plug-and-produce vision of Industry 4.0.

1.2 Objective of the Document

5G-SMART aims to trial and validate 5G technological and architectural features for various use cases in the smart manufacturing domain. The objective of this document is to summarize the investigations and findings made within 5G-SMART on the use cases to be trialed in 5G-SMART and other forward-looking use cases in smart manufacturing.

Taking previous work by e.g. 3GPP, 5G-ACIA, NGMN, etc. into account, 5G-SMART's efforts include specifying the project's use cases with respect to well-established 5G KPIs and metrics, which will be followed by the evaluation of 5G performance against the KPIs in the 5G-SMART trial testbeds. This report describes demands for the smart factory use cases considered within 5G-SMART, which are empowered by ultra-reliable low latency communications (URLLC), enhanced mobile broadband (eMBB) and massive machine-type communications (mMTC) services, building upon the 3GPP Release-15 work.

1.3 Relation to other Documents

1.3.1 Documents within 5G-SMART

This deliverable has a strong relationship to all other 5G-SMART deliverables, both published and upcoming, for which in many ways it serves as input and the baseline. A summary of the relation between this deliverable and other already published deliverables and reports is given in Table 1.

Deliverable	Description and relation to D1.1
D2.1 Design of 5G-Based Testbed for Industrial Robotics	D2.1 describes the testbed for the robotics trials in Kista, which has been designed by taking into account the requirements of the use cases determined in D1.1.
D3.2 Report on System Design Options for Monitoring of Workpieces and Machines	D3.2 describes the testbed and design options for the trials in Aachen, building on the related use cases described in D1.1.
D5.1 Report on New Technology Features to be Supported by 5G Standardization and its Implementation Impact	D5.1 describes technology features needed to be supported in future 5G standardization. The selection of 5G features to focus on has been made based on the use cases described in D1.1.
Report on common language and terminology	The work by 5G-SMART on finding a common terminology and language between OT and ICT players, provided in the appendix of D1.1., is considered to be interesting for a wide audience and will, therefore, also be published as a separate report.

Table 1: Summary of the relation of D1.1. and other deliverables in 5G-SMART

1.3.2 Documents outside 5G-SMART

Smart manufacturing is a domain with intelligent and adaptive production systems, which impose versatile demands on computational resources and communication infrastructure in terms of, e.g., safety, quality of service (QoS), flexibility, and security. A number of different fora are discussing smart manufacturing use cases, including for instance 3GPP, 5G-ACIA, and NGMN. In 3GPP, use cases and their demands for smart manufacturing have for instance been specified in the scope of the Release 15 [TR22.804]. From 5G-ACIA, for example, the work on 5G traffic models [5GACIA1] has served as input. The recently released white paper by 5G-ACIA on use cases and key industrial requirements [5GACIA2] will be valuable input for the rest of the project, where the intention is to investigate identified industrial requirements but potentially also add newly identified requirements to the list. For the NGMN report [NGMN2019] on 5G end-to-end (E2E) technology to support URLLC requirements of the verticals, 5G-SMART partners have provided a significant input.

1.4 Trial Sites

The implementation and validation of the use cases to be trialed will be carried out at three trial sites located across Europe, namely in Kista (Sweden), Aachen (Germany) and Reutlingen (Germany), as depicted in Figure 2. The three trial facilities bring different perspectives: the Kista site will focus on industrial robotics use cases, the Aachen site will focus on integrating 5G into the networked adaptive production, and the Reutlingen site will provide the validation of 5G in a real operational factory environment, as well as a characterization of channel propagation characteristics.

The trials will provide a platform to validate 5G capabilities for current and future manufacturing applications. Specifically, the trials will consist of 5G New Radio (NR) systems, along with standalone on-premise networks and edge cloud in the factory to support various manufacturing applications.

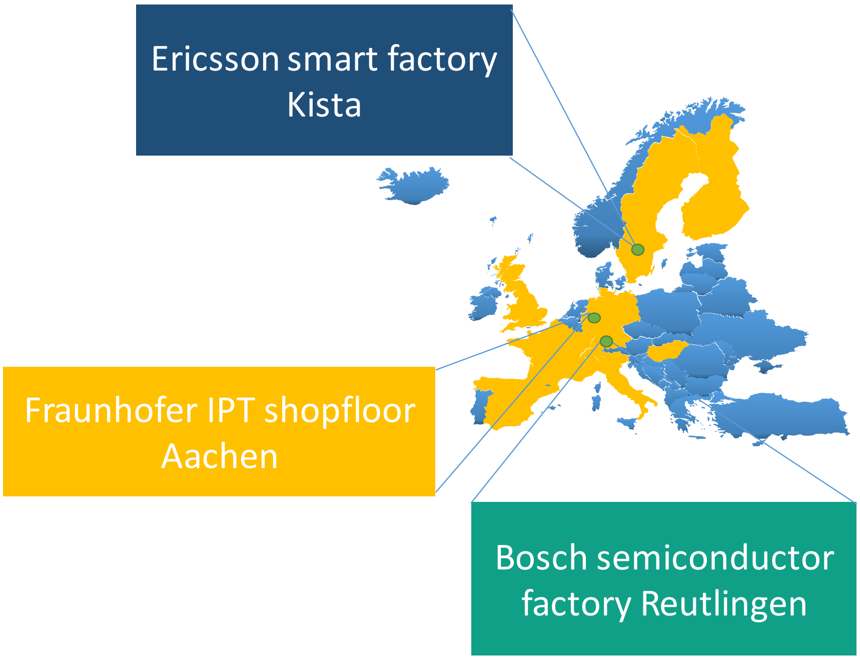

Figure 2: Location of the three 5G-SMART trial sites

1.5 Structure of the Document

This document is divided into seven sections. After this introductory section, Section 2-4 describe all 5G-SMART trial use cases, providing insights into their requirements and KPIs. All trial use cases are summarized in Section 5. In Section 6, additional forward-looking use cases are explored. Finally, summary and conclusions are given in Section 7.

The appendix provides a list of abbreviations used in this document as well as a collection of relevant terminology and definitions.

2 Kista Trial

5G-SMART Kista trials will demonstrate Use case 1 (UC1), Use case 2 (UC2) and Use case 3 (UC3) on industrial robotics and validate 5G service URLLC. For this factory site, Ericsson has implemented the 5G testbed as a 5G Non-Standalone Architecture (NSA, or Option 3 as defined by 3GPP Release 15) network. The network deployment at the site consists of both 4G LTE and 5G NR radio access technologies with the corresponding base stations (eNB/gNB), and a virtualized core network, a so-called Evolved Packet Core (EPC), also supporting 5G NR. An Edge cloud platform supports user-/operator-specific service functions, including robotics control.

The 5G network will interconnect hardware equipment and software applications which are needed to realize real-world industrial robotics applications. Two single-arm stationary robots will be installed and connected to the trial testbed via a 5G-access router (or User Equipment, UE). A mobile robot platform will be deployed at the Kista factory premises and equipped with a separate UE. An augmented reality (AR) headset for information visualization will also be deployed in a similar fashion. Both stationary and mobile robots will be pre-configured to allow hosting different auxiliary devices, such as laser sensors. A system of video cameras will be mounted on ceiling and/or walls of the factory to assist, e.g., motion planning for the mobile robot platform as well as object recognition/localization.

The Edge cloud will also be leveraged to validate new functionality to commission and control robot operations over 5G. All that includes running software-based functions, such as mobile robot localization, robot motion planning and object localization, in execution platforms on top of the 5G testbed infrastructure. For more details on the 5G communication network solution, please refer to deliverable D2.1 [5GS20-D21].

In Table 2, the three use cases to be demonstrated at the Kista trial site are listed and have been classified according to 3GPP TR22.804 [TR22.804]. In the following subsections the use cases will be described in more detail.

Use cases at the Kista trial site		Factory automation	Process automation	HMIs and Production IT	Logistics and warehousing	Monitoring and maintenance
UC1	5G-Connected Robot and Remotely Supported Collaboration	X			X	
UC2	Machine Vision Assisted Real-time Human-Robot Interaction over 5G	X		X	X	
UC3	5G-Aided Visualization of the Factory Floor	X		X		X

Table 2: The Kista trial use cases' classification

2.1 Use case 1: 5G-Connected Robot and Remotely Supported Collaboration and Use case 2: Machine Vision Assisted Real-time Human-Robot Interaction over 5G

Use case 1 focuses on a factory-floor collaboration between stationary robots and a mobile robot, which are connected to the 5G network, while use case 2 complements use case 1 by considering an interaction between the mobile robot and a human (e.g. a human worker).

2.1.1 State of the Art

Factory automation is concerned with enhancing the level of industrial production to a massive scale, while also optimizing for cost efficiency and production flexibility. To meet these objectives, factory processes and workflows must be optimized, which in many cases calls for the use of both stationary and mobile robots.

Implementation of collaborative and other robotic tasks for factory automation relies today on wired-based communication between mechanical parts of a robot and its controller software, which manages the robot motion. In case of stationary robots, their controller software often runs in an external hardware that is connected over wire to the robot body, while allowing translational or rotational motion of one or more robotic arms. For a mobile robot, this controller software is usually deployed "on-board" the robot platform and controls the motion path of the platform base by influencing, for example, speed of its wheels. Again, the controller software runs in a specialized hardware on the mobile robot platform and is usually wired to the rest of the platform. Both stationary and mobile robots can still be connected over wireless links to a network infrastructure, but this connectivity option is regularly not used for controlling the robot motion and is, instead, used for assigning specific work tasks or monitoring the robot status. With respect to interactions of mobile robots and human workers, they rely today on video cameras and optical sensors on-board each mobile robot.

Stationary robots are generally characterized by a large footprint in factories, which also their external hardware with the controller software contributes to. Besides the cost of the external controller unit, its size and cable connection to the robot limits the flexibility on the factory floor. A similar conclusion with respect to the cost and their footprint also pertains to mobile robots, for which mobility is one of the crucial operational demands.

2.1.2 Benefits of the Use cases

Several benefits of using 5G are foreseen with respect to these use cases. Deploying robotics-related functions in an Edge cloud would allow specialized robot controller hardware to be simplified, thus resulting in a decreased overall robot cost. Taking advantage of a joint equipment, like video cameras, to be shared among multiple mobile robots and then removing that equipment type from the robot units would further decrease their production and maintenance cost. Another direct impact of offloading robotics functions to an Edge cloud is the ability to miniaturize hardware, which needs to stay on-board robot units, thus reducing the total robot footprint. This has a significant influence on the factory floor structure with several tens or hundreds of robot units. In addition, providing powerful wireless communication allows to decrease the total length of cabling that is required to interconnect robots with the networking infrastructure, while also facilitating any needed restructuring in the future. Deployment of mobile robots on the factory floor enables a reduction of the number of personnel that is directly involved in, e.g., assembling processes, making them available for other factory tasks. Other benefits of exploiting stationary and mobile robots that are interconnected over a 5G wireless-based network infrastructure include improved flexibility of production organization on a factory floor as well as support for accelerated changes in the production processes.

2.1.3 Use case Descriptions

UC1 involves two single-arm stationary robots and one mobile robot, which are all connected to the 5G trials network over wireless links (Figure 3). The mobile robot will be tasked to approach a stationary robot that holds an object, take over this object from the stationary robot, move in space to the other stationary robot, and then let that robot take over the object. At the same time, as the UC2 objective, a human worker will be moving around on the factory floor, potentially creating an obstacle in the robots path (Figure 3). The task of the mobile robot will be to avoid any physical contact with the human worker and go around her/him on its route towards the destined stationary robot. The *general task planning* function, which is responsible for issuing global commands such as “deliver item A from worker X to worker Y” (where “workers” are the stationary robots), will be deployed in Edge cloud. The Edge cloud platform for running this and other functions in software is co-sited with the 5G system inside factory premises. Two core functions in these use cases, *motion planning for the stationary robots* and *motion planning for the mobile robot*, will also be deployed in the Edge cloud and be responsible to control the object transfer operation. A system of at least three video cameras will be employed, and it is planned that it oversees the factory floor 5G testing area with the robots, resides outside of the robot units and is mounted on, e.g., the walls, and that it is connected to the trials 5G network via wired connections. This camera system will provide video image feed for machine vision processing and estimation of an object’s position and orientation in the physical environment, which is based on marker tags which are worn by the tracked objects (e.g. the mobile robot and the transferred object). The latter information will be used by the *motion planning* functions, but also by a function of tracking the human worker. Other functions will be deployed in the Edge cloud as well, such as *simultaneous localization and mapping* (SLAM) for producing a virtual map of the mobile robot’s physical environment and *mobile robot localization* for tracking the position and orientation of the mobile robot, to assist the *motion planning for the mobile robot*. Several robotics-related functions will, however, be retained on-board the robot units, such as safety management (for the cases of lost network connectivity) and *status reporting*.

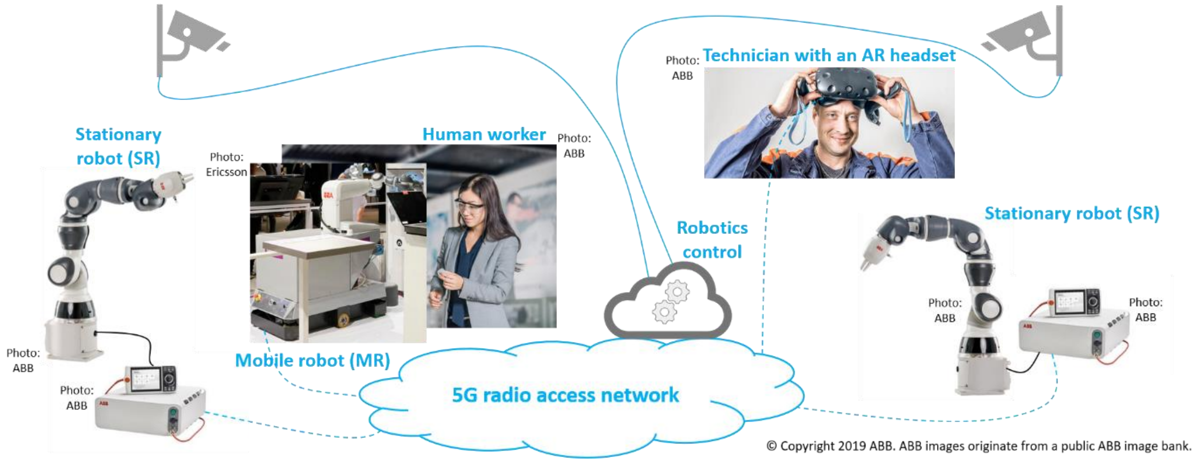

Figure 3: A setup illustration for use case 1-3

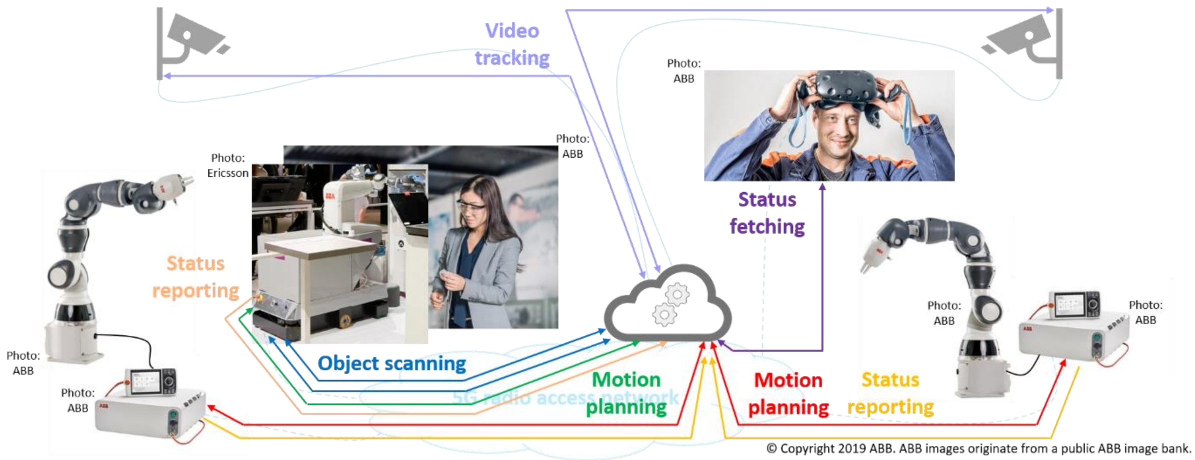

Figure 4: An overview of communication streams in use cases 1-3

2.1.3.1 Communication streams

In these use cases we have the following communication streams (Figure 4):

1) Communication between the mobile robot and edge-based control functions
   a. Communication to the mobile robot from the edge:
      i. Control and management data (motion planning)
   b. Communication from the mobile robot to the edge:
      i. Sensor data (object scanning)

ii. Monitoring data (status reporting)
iii. Control and management data (motion feedback)

2) Communication between a stationary robot and edge-based control functions
   a. Communication to a stationary robot from the edge:
      i. Control and management data (motion planning)
   b. Communication from a stationary robot to the edge:
      i. Monitoring data (status reporting)
      ii. Control and management data (motion feedback)
3) Communication between video camera system and a supervisory machine vision function
   a. Communication from the camera system to the supervisory machine vision
      i. Sensor data (video tracking)

2.1.4 Requirements and Challenges

2.1.4.1 Operational Requirements

Operational requirements for use cases 1 and 2 include:

Network configuration management for monitoring and, to some extent, managing the system that is provisioned for the 5G trials. This is essential to allow, e.g., specifying application service properties such as QoS demands, collecting network-related performance metrics and deploying software in the Edge cloud by authorized applications.

Fault management to supervise the network and display and tracks alarms efficiently, allowing users to manage network problems quickly and effectively.

Mobility management support for end devices, such as the mobile robot platform, with the mobility demands that fit to the limited-size space of a factory.

Security management for communication services to guarantee their confidentiality and data integrity, while providing privacy of both robotics-related end devices and applications.

2.1.4.2 Functional Requirements

The 5G system for the use case 1 and 2 trials needs to support the following basic features, based on requirements from 3GPP TS 22.261.

(1) *End-to-end (E2E) QoS support* for communication services with QoS demands in terms of latency, reliability and/or average data rate, covering all required segments of the 5G system (e.g. the access and core networks). Control applications for motion planning of both stationary and mobile robots

impose very strict performance requirements on the application level, thus calling for all involved parts of the underlying 5G system to perform optimally.

(2) *Energy efficiency support* for user equipment with a limited battery capacity. Such is the case for the mobile robot platform, which comprises different hardware components in need of energy and for which it is essential that energy is consumed optimally. This calls for the 5G system to minimize energy consumption with respect to communication.

2.1.4.3 Performance

Performance-related requirements are summarized in Table 3 and Table 4, where they are presented against the identified communication stream and correspond to the application layer demands (i.e., the Communication service interface (CSI)-to-CSI perspective in Figure 10). Where necessary, other representations of the associated metrics are defined. A range of targeted values is provided for some of the metrics, meaning that any value from the range is valid for the given use cases. Again, this is to facilitate a flexibility in design of the 5G trials network as well as to identify performance trade-offs at the overall 5G system level during the evaluation and validation phase.

Average data rates are specified in both downlink (variable r_{DL}) and uplink (variable r_{UL}) directions in Table 3. *Motion planning for stationary robot* and *for mobile robot* exhibit data rates of up to 1 Mbit/s and 0.5 Mbit/s, respectively. These values can be changed by modifying the transfer interval value; for instance, with the same packet size, an increase of the transfer interval value would lead to a decrease of the data rate. *Object scanning* relates to each laser scanner on-board the mobile robot that collects “readings” of physical objects and, in such a way, recognizes potential obstacles in the mobile robot’s environment. Similarly, to *motion planning*, the latter communication stream introduces data rates of up to 2 Mbit/s.

Table 3 expresses the latency requirements through the end-to-end perspective. For the two *motion planning* communication streams, the latency assumes the round-trip time, i.e., from a robot unit to the associated control application in the Edge cloud and back. In the latter case, the two-way latency needs to be strictly lower than the transfer interval value (i.e., the latency threshold), since the robot controller software generally assumes that a previously sent motion reference message is acknowledged before the next motion reference message can be transmitted. Please note that the latter two-way latency definition inherently also includes all the processing delay in a robot unit and the Edge cloud as well. The latency requirements for *object scanning* will be explored in the validation and evaluation phase.

Communication stream	Communication service availability, target value	End-to-end latency, maximum	Average data rate	Remarks
Motion planning for stationary robot	≥ 99.99%	< transfer interval	DL < 1Mbit/s UL < 1Mbit/s	transfer interval of [5-40] ms
Motion planning for mobile robot	≥ 99.99%	< transfer interval	DL < 0.5Mbit/s UL < 0.5Mbit/s	transfer interval of [10-50] ms
Object scanning	To be explored	To be explored	DL < 2Mbit/s UL < 2Mbit/s	

Table 3: Performance Requirements from UC1 and UC2

Communication stream	Message size [Byte]	Transfer interval, target value [ms]	End device speed	# End devices	Service area	Communication attributes	Remarks
Motion planning for stationary robot	In the order of 500	5-40	< 1m/s	2-3	$50m^2$	Periodic, deterministic, symmetrical	
Motion planning for mobile robot	In the order of 500	10-50	< 1m/s	2-3	$50m^2$	Periodic, deterministic, symmetrical	Network-based localization support not used
Object scanning	In the order of 500					Periodic	

Table 4: Complementary Requirements from UC1 and UC2

Communication service availability (Table 3) relates to delivering a packet within its pre-set time interval, which is determined by the associated latency requirement. If the packet is traveling between its source and destination longer than the given latency threshold, it is useless and deemed lost.

With respect to service area, the 5G testbed network should provide connectivity with the specified QoS requirements over a typical factory size (but for the 5G trials, $50m^2$ would be sufficient). Speed pertains to the mobile robot and support for its ground speed of up to 1 m/s is desired from the 5G system. Localization/positioning error also refers to the mobile robot, but its metric value of up to 2 cm will be realized with the application-level techniques, i.e., no specific network-based localization support is required.

2.1.4.4 Technical Challenges

Technical challenges in UC1 and UC2 include running multiple “competing” low-latency, deterministic communication streams on the same 5G infrastructure. Edge cloud resources must also be optimized to support the E2E requirements put forth. Another challenge is to find a good tradeoff and configure the robot application to optimize network resources in the best way.

2.1.5 Summary

Use cases 1 and 2 explore the factory floor collaboration between stationary and mobile robots, while considering the presence of human workers. General task planning and motion planning functions are deployed in the Edge cloud and robot control commands are delivered over the 5G network. A vision system connected to the 5G network oversees the factory floor area and provides information about the physical location of the robots.

2.2 Use case 3: 5G-Aided Visualization of the Factory Floor

This use case covers the large aspect of factory automation which relies on mobile robots to transport assets across a factory floor and provision them to stationary robots in the assembling process. With so many different units and items on the factory floor, from stationary and mobile robots to materials and goods, it is challenging to monitor the status of assembling and other production processes. This is where augmented and virtual reality (VR) can offer novel means of information representation and visualization and are, thus, expected to have a valuable role in factory floor tasks (e.g., acquiring a step-by-step training on-site).

Use case 3 focuses on an AR-based visualization of information from the factory floor, which stems from stationary and mobile robots. Like robot units, an AR headset is also connected to the 5G network for the trials. A distinctive feature of this use case is that collection and pre-processing of information for the visualization is offloaded to an Edge cloud. Analogously to use case 1 and 2, the Edge cloud for use case 3 assumes a separate computing resource that is located inside factory premises at the close proximity of the end-devices and that hosts a platform for running software applications. Different information on the status of both stationary and mobile robots is collected and visualized in the AR headset. Tracking changes of the headset's field-of-view is done by the same video system as used in use case 1 and 2. This use case falls into the application areas of factory automation, HMIs and production IT, and monitoring and maintenance.

2.2.1 State of the Art

Visualization of the factory floor information relies today on standard end-user devices, such as HMIs and industrial PCs. This calls for special approaches to organizing and presenting the information on devices with a limited screen size. AR headsets with a see-through display offer a desirable option for the information visualization, since they can keep hands of human workers free for other assignments. Such headsets are equipped with a specialized hardware that allows them to process information locally, e.g. video from the mounted cameras. However, this hardware significantly contributes to the overall purchasing cost of an AR headset. Furthermore, many commercially available AR headsets connect to a network infrastructure over a cable, which limits the bearers' mobility and influences overall user experience. This is especially hindering for human workers handling different materials and equipment.

A forward-looking solution to make AR headsets more affordable for a wide-scale usage is to offload information storage and processing to an Edge cloud platform. It is expected that the cloud-based processing would allow hardware in AR headsets to be simplified, resulting in this equipment becoming more lightweight and, thus, offering better ergonomics. It would also positively affect energy consumption of such a headset. The offloading of the information processing to the Edge cloud would as well facilitate easier incorporation of other information, for example health and productivity status of robot units. In order to, at the same time, guarantee flexibility of use and mobility for the factory worker wearing the AR glasses, the AR headsets on the factory floor need to be wireless. The requirements on the communication between AR headset and Edge cloud is explained in the following. Such communication demands are driven by user expectations, where a movement of an AR headset (due to, e.g., a person changing her/his view direction) must be followed by timely rendering and display of the information that augment the physical environment. If the latter is not met, a person that wears an AR headset may feel the lag. A timely display of the augmented information can only be supported by a timely delivery of information from the Edge cloud to the AR headset. The main challenge of use case 3 is to build an overall system architecture that enables collection of different factory floor information in a centralized repository in the Edge cloud, AR-related pre-processing of that information in the Edge cloud, and timely delivery of the information that needs to be visualized to the AR headset.

2.2.2 Benefits of the Use case

Several benefits of using 5G are foreseen with respect to this use case. Deploying AR-related pre-processing in the Edge cloud would allow hardware on the AR headset to be simplified, thus possibly resulting in its decreased procurement cost. Another direct impact of the latter change is the ability to miniaturize hardware that is on board the AR headset, which makes it more lightweight and, thus, offering better ergonomics. It would also positively affect energy consumption of the headset by reducing the need of local processing although some additional energy is consumed by increased communication. In addition, providing powerful wireless communication removes the need for cables to interconnect AR headsets with the network infrastructure, improving human mobility and overall user experience.

Other benefits of this use case include easier incorporation of different information, when AR-related pre-processing is offloaded to the Edge cloud, and faster overview of assignments status on the factory floor.

2.2.3 Use case Description

Use case 3 involves at least two stationary robots and one mobile robot from use case 1 and 2, along with an AR headset with see-through display and integrated video cameras, which are all connected to the 5G testbed network over wireless links (Figure 3). Stationary robots will be tasked to report their status information in terms of, e.g., time in production and estimated lifetime of robot joints, while, for example, battery charge level and planned motion path will be reported for the mobile robot. Assuming the deployment of robotics-related functions as in use case 1 and 2, core functions of this use case will also be in the Edge cloud, namely collection of the reported status information, and pre-processing of visualization information for the AR headset.

2.2.3.1 Communication Streams

Communication services in this use case include delivery of the status reporting information from both stationary and mobile robots, and information for AR-based visualization in the headset. The corresponding communication streams are (Figure 4):

1) Communication between the AR headset and the Edge cloud
    a. Information feed to the AR headset from the Edge cloud (status fetching)
2) Communication between the robots and the Edge cloud
    a. Status information from the mobile robot to the Edge cloud (status reporting)
    b. Status information from a stationary robot to the Edge cloud (status reporting)

2.2.4 Requirements and Challenges

2.2.4.1 Operational Requirements

Operational requirements for use case 3 include:

Network configuration management for monitoring and, to some extent, managing the system that is provisioned for the 5G trials. This is essential to allow, e.g., specifying application service properties such as QoS demands, collecting network-related performance metrics and deploying software in the Edge cloud by authorized applications.

Fault management to supervise the network and display and tracks alarms efficiently, allowing users to manage network problems quickly and effectively.

Mobility management support for end devices, such as the mobile robot platform, with the mobility demands that fit to the limited-size space of a factory.

Security management for communication services to guarantee their confidentiality and data integrity, while providing privacy of both robotics-related end devices and applications.

2.2.4.2 Functional Requirements

The 5G system needs to support the following basic features, based on requirements from 3GPP TS 22.261.

(1) *End-to-end (E2E) QoS support* for communication services with QoS demands in terms of latency, reliability and/or average throughput, covering all required segments of the 5G system (e.g. access and core networks). Control applications for motion planning of both stationary and mobile robots impose very strict performance requirements on the application level, thus calling for all involved parts of the underlying 5G system to perform optimally.

(2) *Energy efficiency support* for user equipment with a limited battery capacity. Such is the case for the mobile robot platform and AR headset, which comprises different hardware components in need of energy and for which it is essential that energy is consumed optimally. This calls for the 5G system to minimize energy consumption with respect to communication.

2.2.4.3 Performance Requirements

Performance-related requirements of this use case are presented against the identified communication streams and correspond to the application layer demands (i.e., the CSI perspective in Figure 10). Where necessary, other representations of the associated metrics are defined. A range of targeted values is provided for some of the metrics, meaning that any value from the range is valid for use case 3. This is to facilitate a flexibility in design of the 5G testbed network as well as to identify performance trade-offs at the overall 5G system level during the evaluation and validation phase. Values for the given requirements are summarized in Table 5.

Average data rates are specified in both downlink and uplink directions Table 5Status reporting for stationary robot and status reporting for mobile robot exhibit data rates of up to 1 Mbit/s. Status fetching, on the other hand, exhibits data rates of less than 5 Mbit/s and 1 Mbit/s in the DL and UL directions, respectively.

The latency requirements are expressed through the end-to-end, two-way (or round-trip) perspective, e.g. from the AR headset to the associated application in the Edge cloud and back. For the AR-based application the round-trip time delay is highly relevant, i.e., the delay of requesting an information to be visualized, transmitting the request to the Edge cloud, processing the request in the Edge cloud, preparing the AR-related information in the Edge cloud, transmitting that information back to the AR headset, and rendering the augmented view in the AR headset. To avoid a person feeling any lags, this whole two-way time delay of status fetching needs to be less than [100-200] ms, differing from person to person. Whether the information display is perceived due to possible lags or not, furthermore depends on the type of content that is superimposed. Therefore, different lag values will be evaluated during the testing phase. Since they are non-deterministic type of communication streams, latency demands are not specified for status reporting for stationary robot and status reporting for mobile robot. However, the same table structure from use case 1 and 2 is used here for the sake of consistency.

Communication stream	**Communication service availability, target value**	**End-to-end latency, maximum**	**Average data rate**	**Remarks**
Status reporting for stationary robot	Not relevant	Not relevant	DL < 1Mbit/s UL < 1Mbit/s	
Status reporting for mobile robot	Not relevant	Not relevant	DL < 1Mbit/s UL < 1Mbit/s	
Status fetching	≥ 99.0%	< lag	DL < 5Mbit/s UL < 1Mbit/s	Lag should not exceed [100-200] ms

Table 5: Performance Requirements from UC3

Communication stream	**Message size [Byte]**	**Transfer interval, target value [ms]**	**End device speed**	**# End devices**	**Service area**	**Communication attributes**
Status reporting for stationary robot	Implementation-specific	Not relevant		2	$50m^2$	Aperiodic, non-deterministic, asymmetrical
Status reporting for mobile robot	Implementation-specific	Not relevant	< 1m/s	1	$50m^2$	Aperiodic, non-deterministic, asymmetrical
Status fetching	Implementation-specific	Not relevant	< 1m/s	1	$50m^2$	Aperiodic, deterministic, asymmetrical

Table 6: Complementary Requirements from UC3

Communication service availability (Table 5) relates to delivering a packet within its pre-set time interval, which is determined by the associated latency requirement. If the packet is traveling between its source and destination longer than the given latency threshold, it is useless and deemed lost. This metric applies for status fetching to the AR headset.

Other performance-related requirements relate to whole UC3 (Table 6). With respect to service area, the 5G testbed network should provide connectivity with the specified QoS requirements over a typical factory size (but for the 5G trials, $50m^2$ would be sufficient). Speed pertains to a human technician that wears the AR headset and support for up to 2 m/s is desired from the 5G system.

2.2.4.4 Technical Challenges

Technical challenges in use case 3 include the need for both AR-based application, 5G system and Edge cloud resources to support the E2E performance requirements.

3 Aachen Trial

At the Aachen trial site, 5G-SMART will realize use cases 4 and 5 in order to address and validate 5G services at the Fraunhofer IPT shopfloor. The site facility has been equipped with a new standard-compliant indoor 5G NR system from Ericsson and will be further upgraded with new features over the course of the project. The 5G system operates in mid-band at 3.7-3.8 GHz. The spectrum usage has been granted by the national regulator of Germany Bundesnetzagentur (BNetzA) according to the current licensing procedures. To support use cases for edge computing, a factory cloud has been deployed at the shop-floor with local breakout functionality. The factory cloud has been developed by a collaborator of Fraunhofer IPT, German Edge Cloud, with the vision to fulfill industrial application requirements, and will enable seamless integration of industrial applications (in this trial, processing of data coming from the multi-sensor platform for different monitoring applications). For wireless acoustic emission monitoring application, a few UEs will be integrated with the measurement equipment, which will support high bandwidths (more than 8 Mbit/s per sensor) for large data streams. The application executed on the cloud will handle data streams with data pipeline processing capabilities, which will allow for a flexible deployment of algorithms in a plug-and-play fashion. For the multi-sensor measurement platform, 5G modules will be integrated with the measurement device. Both use cases will be realized on the shop-floor of the Fraunhofer IPT and validated in different manufacturing use cases.

In Table 7, the use cases demonstrated at the Aachen trial site have been classified according to 3GPP TR22.804 [TR22.804].

Use cases at the Aachen trial site		Factory automation	Process automation	HMIs and Production IT	Logistics and warehousing	Monitoring and maintenance
UC4	5G for Wireless Acoustic Workpiece Monitoring		X			X
UC5	5G Versatile Multi-Sensor Platform for Digital Twin	X	X	X		X

Table 7: Use case classification at the Aachen trial site

3.1 Use case 4: 5G for Wireless Acoustic Workpiece Monitoring

Use case 4 focuses on time-critical process optimization. A *Genior Modular (GEM)* monitoring system from Marposs and an edge device at the Fraunhofer IPT in Aachen will be connected to an indoor 5G system receiving and processing data from the wireless sensor system and providing feedback information to the numerical control (NC) of the machine tool.

A wireless real time detection of tool wear- and breakage-related effects during cutting process will be realized via an acoustic emission (AE) sensor. AE sensors can be widely used for monitoring of cutting processes such as:

- monitoring of tool wear,
- detection of tool breakage,
- detection of collision of the machine's spindle, and
- detection of inhomogeneities of the workpiece material.

Use case 4 will focus on tool wear and breakage.

3.1.1 State of the Art

Besides wired connections, common wireless technologies in manufacturing are currently Bluetooth, Wi-Fi and ZigBee, where Bluetooth is mainly used for machine-integrated sensors like touch probes or force sensors, and Wi-Fi for connectivity for workers and machines in particular. ZigBee is mentioned by sensor associations like the AMA Association for Sensors and Measurement in Germany [AMA], but it is not widely spread on shop floors. Furthermore, wireless transmission with proprietary protocols is relatively more visible compared to standardized solutions. While all the above-mentioned technologies cannot fulfill high requirements of timeliness, reliability, data rates, scalability and availability, 5G is seen as a key enabler in manufacturing applications.

Due to the fact that certain applications require wireless sensors (e.g. 5-axis milling) and demand for tight timing conditions, new solutions for the future production are needed. Existing wireless communication standards lack performance in terms of latency and data throughput. Bluetooth, on one hand, delivers a rather low latency in the single millisecond range, yet it suffers from communication range and data-rate and therefore is limited to point-to-point connections, typically inside machines. Because of that, it generates increased efforts to integrate Bluetooth sensors into the production IT. Wi-Fi communication, on the other hand, shows an acute limitation in terms of jitter free communication.. This is critical for immediate reactions, e.g. stopping machining upon tool breakage detection or collisions of the machine spindle. Acoustic emission sensors typically have sampling rates in the MHz-range and can generate data output rates of up to 100 Mbit/s depending on the application. In conclusion, low latency of the signal transmission is required as well as a very high data throughput.

3.1.2 Benefits of the Use case

3.1.2.1 Quantifiable Benefits

Cost reduction: All cutting tools are affected to wear off during manufacturing. This is an effect, which comes naturally and cannot be avoided. In order to guarantee the quality of the part, tools are exchanged when reaching a certain wear limit. Generally, companies assess the tool wear condition during production in order to adapt the machining processes and plan for the best tool lifetime, i.e., not to exchange a tool too early, while avoiding the risk of a tool breakage at the same time. It has been shown that AE sensors are essential to understand and predict tool wear conditions and can lead to an increase of the tool lifetime of approximately 18%. Tools can easily have costs of multiple 100s of EUR. In a conventional milling process this can lead to a cost reduction of approx. 2.000 EUR p.a. per machine.

Optimization of production process due to better understanding and real-time data storage. A better understanding will offer shorter ramp-up times for manufacturing processes. This will affect the overall equipment effectiveness (OEE).

3.1.2.2 Other Benefits

New and better applicability: wireless AE sensors can be used for new applications, which are impossible to achieve with wired sensors, e.g. deep hole drills.

3.1.3 Use case Description

A factory shop floor at the Fraunhofer IPT in Aachen is equipped with an indoor 5G system and an edge device and monitoring system targeting 5G-enabled real-time monitoring of workpieces and machining processes. An AE system enables the detection of tool wear and tool breakage during machining and will be integrated into a 5-axis milling machine for monitoring the milling process of a jet engine component. Because of the 5-axis movement of the part and the AE sensor attached to the part and the high-pressure cooling lubricant during machining, a wireless connection of the sensor is essential. Besides that, even if a wired connection would be an option, for sensor retrofits, machines typically have to be dismantled in order to feed in cables for power and data connection, which results in huge efforts and costs. This can generally be seen as an additional motivation for wireless connections in process monitoring for machine tools.

Figure 5 shows the concept for the architecture use case for the wireless AE system. As a machine-near approach with a high grade of communication efficiency it will transmit data from the sensor to the analysis and monitoring hardware, via the 5G network with low latency. The monitoring hardware (the GEM monitoring unit in Figure 5) is connected to the machine with a reliable and safe automation bus system. The machine is being monitored and controlled based on a smart AE sensor mounted on the machine table near the machined part. The electronic circuitry includes components for amplification, filtering and sampling with high rates. The raw data or the pre-processed data will be passed through the signal processing unit to the 5G transceiver. This pre-processing allows a high grade of flexibility to adapt to the uplink bandwidth requirements and calculation of Fast Fourier Transform (FFT), peak values and so on. Therefore, the pre-processing may be carried out by an embedded system, e.g. microcontroller, FPGA or DSP. Thus, events like the first contact from the cutting edge of the tool with the work piece material can be evaluated very fast.

Data streams for use case 4 can be divided in the Measurement Data Stream (shown by A in Figure 5), which relies on a wireless 5G connection between AE sensor and the 5G base station and 5G core and then transits into a wired connection to the GEM and the attached edge device. In the edge device additional data processing is executed. Depending on the application of the AE sensor, via a M2M Communication (shown by C in Figure 5) different kind of control data will be transmitted with a wired connection to a process control unit of the machine tool. This unit can be the NC control running on the Programmable logic controller (PLC) or the PLC itself. Furthermore, Configuration Data (shown by B in Figure 5) are being generated from software running on the edge device, then transmitted via wired connection to the 5G core and radio network, where it transits into a wireless 5G connection to the AE sensor, which can change its configuration based on data received in (B). The wireless connectivity requirements by (A), (B) and (C) are very different, so that their functional and non-functional requirements are described separately.

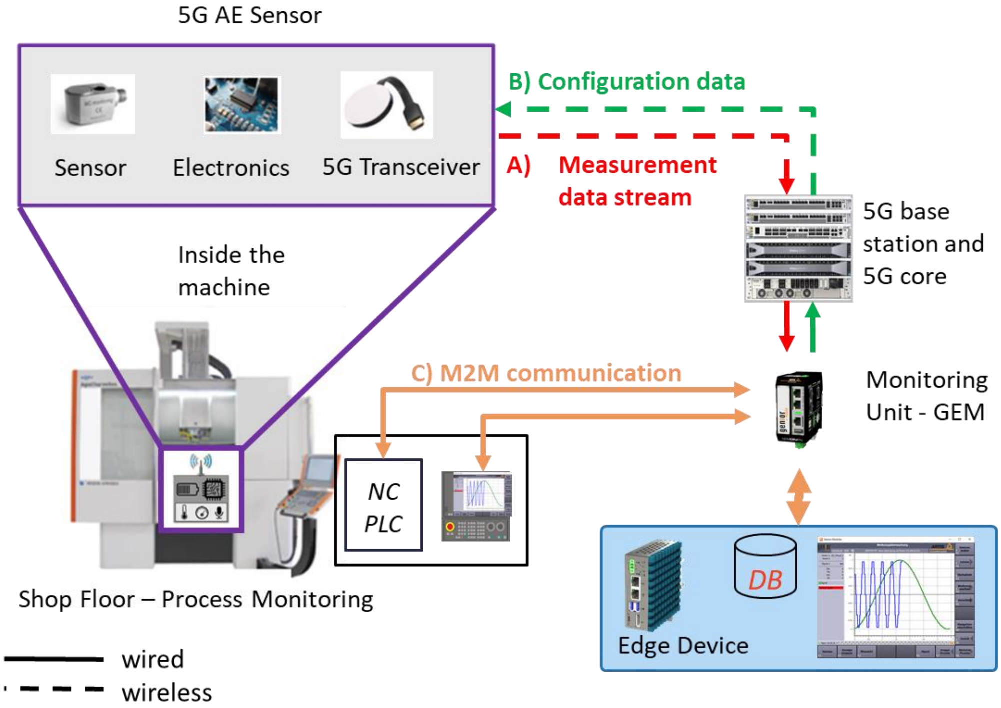

Figure 5: 5G-based wireless acoustic emission sensor system for in-process monitoring during manufacturing

3.1.3.1 Communication Streams

Three different communication streams have been identified

1) Measurement data between sensor and base station (AE spectra on the uplink of the AE sensor system)
2) Configuration data from base station to sensor (deploying updated configuration parameters to the sensor system)
3) M2M communication between the GEM monitoring system, the edge device and the machine. Machine, GEM and edge device have a wired connection, i.e., Ethernet cable or optical fiber.

3.1.4 Requirements and Challenges

3.1.4.1 Operational Requirements

Operational requirements for use case 4 include:

Network configuration management for monitoring and managing the system that is provisioned for the 5G trials. This is essential to allow, e.g., specifying communication service properties such as QoS demands, collecting network-related performance metrics and deploying software in the Edge cloud by authorized applications.

Fault management to supervise the network and display and tracks alarms efficiently, allowing users to manage network problems quickly and effectively.

Security management for communication services to guarantee their confidentiality and data integrity, while providing privacy of both equipment and applications.

3.1.4.2 Functional Requirements

The 5G system for the UC4 trial needs to support the following basic features, based on requirements from 3GPP [TS 22.261].

(1) *Time synchronization* between the sensor and the machine it is operated in, in order to align the sensor data to certain positions on the workpiece.

(2) *Deterministic latency* for having the possibility to react on critical events detected such as tool breakage or collision.

(3) *Constant uplink throughput* for transmitting streams for continuous monitoring with large data rates.

(4) *Low energy consumption* of the transmission. This may result in longer battery lifetime of the battery-driven AE sensor system.

3.1.4.3 Performance Requirements

Performance requirements of the communication streams (A) and (B) are listed in Table 8 and Table 9. For traffic stream (A), the average data rate of 8 Mbit/s will be required in the first step, potentially bandwidth delivered by the sensor system will increase, if more powerful electronics and higher ADC (Analog-Digital-Converter) with higher dynamic resolution (up to 16 Bit) are being used in the AES. Furthermore, higher sampling rates than 1 MHz might be used in the future, which will also require more powerful computing resources such as FPGAs or ASICs. Then, the average data rate can increase, too. Also, the low latency support is needed in order to react immediately on critical events such as tool breakage or collision. In addition, time synchronization is required, in particular if an end-device operates in coordination with others. In that case, a synchronization error between machine computerized numerical control (CNC) and sensor is required in order to map AE spectra to positions of the tool on the workpiece surface as a digital twin, while the mapped points must be within the tolerance of the part. In order to calculate the synchronization error (i.e. max. variation of delay between the clocks of the sensor system and machine control), the tolerance of the part has to be divided by the feed rate of the tool. For example: in order to achieve a position error of 10 µm for a federate of 100 mm/s, the synchronization error need to be below 100 µs.

For the traffic stream (B), a transfer interval of larger than 1000 ms is necessary for transmission of configuration parameters to the sensor systems such as start/stop, frequency limits for automated peak fitting.

Communication stream	Communication service availability, target value	End-to-end latency, maximum	Service bit rate	Remarks
Measurement data	≥ 99.999%	<10 ms	>8 Mbit/s	
Configuration data	≥ 99.999%	Not relevant	Low	

Table 8: Performance Requirements UC4

Communication stream	Message size [Byte]	Transfer interval, target value [ms]	UE speed	# UEs	Service area	Communication attributes	Remarks
Measurement data	1-1024	1	<0.5 m/s	1	15m^2	Periodic, Non-deterministic, Asymmetrical	Time synch <0.1 ms
Configuration data	>1204	<1.000	N/A	1	15m^2	Aperiodic, Non-deterministic, Asymmetrical	

Table 9: Complementary Requirements UC4

Further requirements of UC4 are provided in Table 9. In terms of service area, there is the 15 m maximum distance between the sensor and next 5G radio antenna. Altogether there will be 8 radio antennas positioned equally spaced in a shop-floor size of approx. 30 × 90 m². During transmission, the sensor can be moved by the machine in a volume of 1 m³. Communication density corresponds to one sensor per machine, which has an average footprint of 15 m². In terms of mobility requirements, we have to note that the given value relates to the movement of the sensor inside the machine, and therefore it is not relevant for the 5G system design.

3.1.4.4 Technical Challenges

Technical challenges in UC4 is low latency requirements competing with data rates, which may grow during the runtime of the project up to multiple Mbit/s, running multiple AE sensor systems simultaneously on the same 5G infrastructure and consequently finding a good tradeoff to optimize network resources in the best way. Another challenge may be the energy consumption required to transmit high data rates leading to low battery lifetimes.

3.1.4.5 Summary

UC4 explores the low-latency feature of 5G for highly sophisticated time-critical process monitoring. Benefit of the use case is a large economic impact of the underlying applications such as tool breakage detection or tool wear monitoring, which will support companies to extend their tool lifetime, increase the quality of processes and products and safe time and costs. Some of the effects detected with the

AE sensor system may require an instant reaction in order to not scrap the part of damage the machine tool.

3.2 Use case 5: 5G Versatile Multi-Sensor Platform for Digital Twin

Use case 5 is categorized in the application area of factory and process automation. Within this use case, a versatile multi-sensor platform (MSP) will be developed and evaluated. It will integrate different sensors such as accelerometer, force, microphone, temperature and humidity sensor into one compact device.

3.2.1 State of the Art

In today's production, one can find different kinds of sensors, which are usually separated stand-alone systems not being aggregated in a platform format. Yet, industrial processes can be monitored with periodic sensor data transmissions for multiple parameters via different transmission technologies. However, data throughput is limited to certain amounts and only a limited number of sensors can be used wirelessly, resulting in a limited applicability and mobility. Furthermore, most of the currently available wireless communication standards do not meet latency and throughput requirements.

Additionally, for very challenging manufacturing tasks, there is a need to measure multiple parameters per part simultaneously, e.g. acceleration, temperature and strain, which can give information about the vibration behavior as well as deformation due internal stress or because of temperature changes.

3.2.2 Benefits of the Use case

Several benefits of using 5G are foreseen with respect to this use case. Optimization of production processes due to the monitoring possibility of a lot of process information in real-time will enable a higher quality of the workpieces. For the case of vibration monitoring of the milling processes of jet engine components, it has been estimated that the economic benefit of using 5G in manufacturing in terms of reducing the rework rate from 25% to 15%, resulting in a reduced machining time and a global cost saving of around 360 million EUR p.a. and a CO2-equivalent reduction of 16 million tons [ERI18].

Other benefits of use case 5 include an improved automation possibility of production processes due to versatile information given with the MSP. Due to a standardized MSP, for which sensor requirements can be configured externally, process and condition monitoring can be made a lot easier.

Furthermore, the MSP delivers valuable information for the digital twin of the workpiece and the machine tool. The digital twin represents the real state of the production process. By comparing it to the target-state, a fault detection and process diagnostics can be done. Combining the result of the detection with logistic and process data, each intermediate step of the production process can be evaluated. This needs a detailed representation of the process-states in the cloud. The control loop and the workers on the production floor can use this information for steering the process and minimizing the production waste by improving efficiency and safety. The monitoring of the condition of the machine tool can lead to reduced maintenance and downtime costs.

3.2.3 Use case Description

This use case describes the scenario, for which a number of machines and work pieces can be monitored simultaneously. More than 10 multi-sensor platforms will be developed and integrated into multiple machines and attached to multiple workpieces in the trial facility of Fraunhofer IPT in Aachen.

Using the future localization feature of 5G, workpieces can also be traced on the shop floor along different stages of the value chain. Furthermore, the MSP can also be used to acquire infrastructure data, as shown in Figure 6.Figure 6: Application domains for multi-sensor-platforms for process and condition monitoring of machine tools, workpieces and infrastructure.

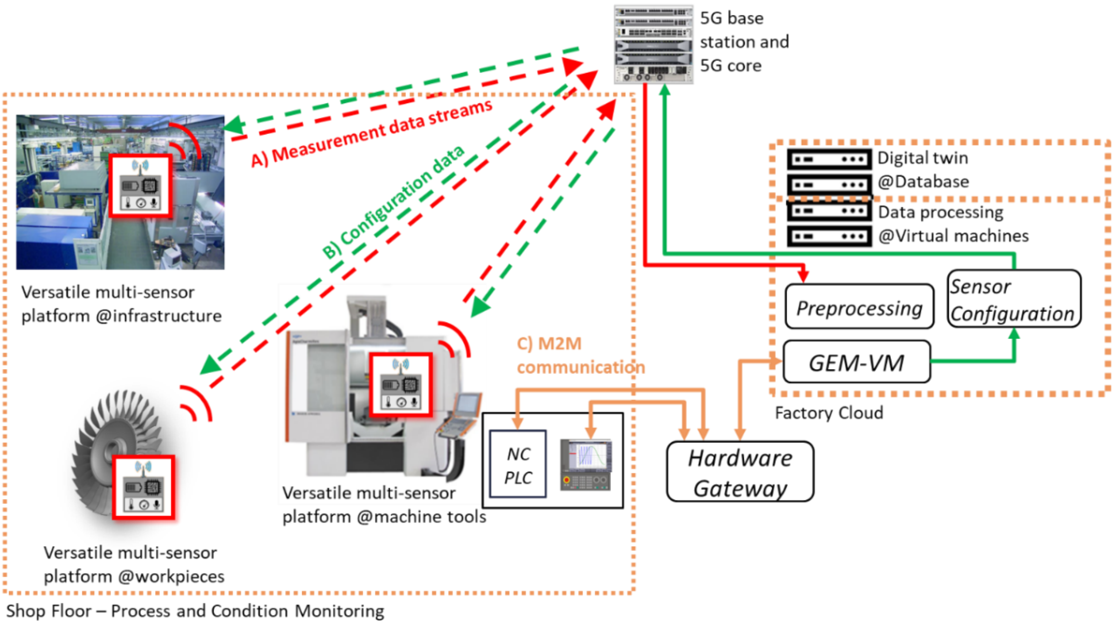

Figure 6: Application domains for multi-sensor-platforms for process and condition monitoring of machine tools, workpieces and infrastructure.

In the first case, the condition of machine tools such as temperature and vibration behavior or noise emission can be measured. The main application of the MSP will be the monitoring of workpieces by the acquisition of process data such as acceleration (vibration, shock), temperature or inclination on the same platform. Furthermore, the MSP has a 5G UE, which can serve as a localization tag in order to trace the position of the workpiece. This position information can be used to trigger additional processes, e.g. start of a CNC program upon detection that a workpiece is inserted into a machine. A third application area is that the MSP can be used within the infrastructure is, e.g., temperature monitoring. Having multiple MSPs distributed in the infrastructure will then allow the creation of heatmaps. Within the Fraunhofer IPT Aachen trial as many of the different above-mentioned applications as possible will be addressed. The technical capabilities, which will be achieved during the runtime of the project, will influence the applicability in different scenarios, so validation tests will change over time as the performance will be constantly optimized. The use cases for infrastructure monitoring would require multiple MSPs transmitting data with rather low performance requirements such as low measurement frequencies or higher latencies, so this case can be associated with mMTC. 5G-SMART will not exploit this application domain, as the project does not allow to realize a high number of devices, while 5G transmission for infrastructure data is not very ambitious.

The data transmitted by the different MSPs will be analyzed in an edge cloud computing approach, where also digital twins of workpieces and machine tool, respectively, will be realized in databases.

The edge cloud in our case is located in the IPT premises close to the shopfloor, so that you can also call it Factory Cloud.

3.2.3.1 Communication Streams

Use case 5 has three major communication streams as shown in Figure 6 Figure 6: Application domains for multi-sensor-platforms for process and condition monitoring of machine tools, workpieces and infrastructure.(A) measurement data stream, containing various measurement parameters and different transfer rates and volumes depending on the application field of the MSP, (B) configuration data on the downlink for deploying updated configuration parameters to the MSP, and (C) M2M communication between the edge cloud system and the machine. Machine and edge cloud have a wired connection, i.e., Ethernet cable or optical fiber. The edge cloud is directly connected with the local 5G network. The corresponding communication streams are summarized below:

1) Measurement data between sensor and 5G network
2) Configuration data from 5G network to sensor
3) M2M communication between the edge cloud system and the machine (wired connection)

3.2.4 Requirements and Challenges

3.2.4.1 Operational Requirements

Operational requirements for use case 5 include:

Network configuration management for monitoring and managing the system that is provisioned for the 5G trials. This is essential to allow, e.g., specifying communication service properties such as QoS demands, collecting network-related performance metrics and deploying software in the Edge cloud by authorized applications.

Fault management to supervise the network and display and track alarms efficiently, allowing users to manage network problems quickly and effectively.

Security management for communication services to guarantee their confidentiality and data integrity, while providing privacy of both equipment and applications.

3.2.4.2 Functional Requirements

The 5G system for the use case 5 trial needs to support the following basic features, based on requirements from 3GPP TS 22.261.

(1) *Time synchronization* between the MSP and the machine it is operated in, in order to align the sensor data to certain positions on the workpiece or in case of machine condition monitoring in order to assign sensor data to certain manufacturing steps.

(2) *Deterministic latency* for having the possibility to react on critical events detected, such as resonant vibration of the workpiece.

(3) *Constant uplink throughput* for transmitting streams for continuous monitoring with medium data rates from different MSPs simultaneously.

(4) *Network slicing capability* to address different groups of sensor platforms, which may have different security or performance requirements.

(5) *Network capability exposure* to align the connectivity according to the actual sensor configuration, which can result in different measurement frequencies depending on the application.

(6) *Localization services* for tracing workpieces or workpieces on pallets on the shop floor and inside machines. Localization ideally operates independently from the UE type.

(7) *Low energy consumption* of the transmission device. This may result in longer battery lifetime of the battery-driven MSP

3.2.4.3 Performance Requirements

Performance requirements of the streams (A) and (B) are listed in Table 10 and Table 11, respectively. For communication stream (A), the user experienced data rate for a single MSP depends on the actual sensor configuration, i.e. which and how many sensors are integrated and actively recording measurement data, which measurement rate is set for the different sensors etc. Bandwidth may potentially scale up by simultaneously using multiple MSPs as soon as compact 5G modem platforms become available, which can be integrated on the printed circuit board (PCB) level. At least 10 MSPs are planned to be operated at the same time. Also, the low latency support is needed in order to react immediately on critical events, such as tool resonant vibration states of workpieces or chatter marks. Jitter will be non-critical (up to 1 ms), as this only leads to artifacts in the amplitude distribution of sensor data, which is more important than its temporal distribution (i.e., jitter). In addition, time synchronization is required, in particular if an end-device operates in coordination with others. In that case, a synchronization accuracy of less than 100 µs between machine CNC and sensor is required, in order to map sensor data to exact positions of the tool on the workpiece surface as a digital twin. For the communication stream (B), a transfer interval larger than 1000 ms can be assumed for transmission of configuration parameters to the sensor systems such as start/stop, measurement frequencies, enabling/disabling certain sensors as well as transmitting data from the onboard sensors.

For the different requirements, only the most extreme ones have been taken into account. For measurement data, traffic is categorized as non-deterministic, since missing or jittered sensor data is not critical (because e.g. amplitude vs. frequency matters).

Communication stream	Communication service availability, target value	End-to-end latency, maximum	Service bit rate	Remarks
Measurement data	≥ 99.999%	<10 ms	depending on sensor configuration	
Configuration data	≥ 99.9%	Not relevant	Low	

Table 10: Performance requirements of use case 5

Communication stream	Message size [Byte]	Transfer interval, target value [ms]	UE speed	# UEs	Service area	Communication attributes	Remarks
Measurement data	1024	15	<0.5 m/s	>10	15m^2	Periodic, Non-deterministic, Asymmetrical	Time synch <0.1 ms
Configuration data	1	>1.000	N/A	>10	15m^2	Aperiodic, Non-deterministic, Asymmetrical	

Table 11: Complementary requirements of use case 5

In terms of Service area, there is the maximum 15 m distance between sensor and the nearest 5G radio antenna of which multiple are positioned equally spaced in a shop-floor size of 30 x 90 m². During transmission, the sensor can be moved by the machine chamber in a volume of 1 m³ of used for workpiece and process monitoring. Communication density corresponds to one sensor per machine, which has an average footprint of 15 m². When used for monitoring of the infrastructure, multiple MSPs are distributed in the whole shopfloor area. In terms of mobility requirements, the velocity of < 0.5 m/s relates to the movement of the sensor inside the machine, and the velocity of < 1.5 m/s relates to the workpiece/pallet traced during transport on the shop floor (inside one cell). And during transmission of configuration data, it is unlikely to have a simultaneous movement of the MSP ongoing. Accordingly, the velocity is not relevant for the 5G system design.

For a better understanding of the requirements towards 5G connectivity, it is important to have a look at the measurement quantities of the different sensors, which can be integrated into the MSP. The following general assumptions can be made for the MSP:

- Resolution of measurement data should be ≥ 16 bit
- Different communication service reliability levels:

  - High: 99.999%
  - Medium: 99.99%
  - Low: 99.9%
- Internal sensors integrated inside the housing of the MSP to monitor the condition:
  - Temperature: ~1Hz measurement frequency, 100 ms latency, low-level transmission reliability (e.g. detection of printed circuit board, or PCB, overheating)
  - Humidity: ~ 1Hz measurement frequency, 100 ms latency, low-level transmission reliability (water ingress and box intrusion detection, e.g. by cooling lubricant)
- Generic sensor interfaces:
  - Digital Inputs: configuration cycle time ~1 s, setting time ≤1 s (connection of external sensors (e.g. liquid sensor), encoder signals (e.g. from machine axes)
  - Digital Outputs: gate signal, PLC-standard type e.g. 24 V, 40 mA (set voltage to start/trigger external sensor or synchronize events, configuration of smart sensors)

The parameters can be furthermore subdivided into requirements specific for the two use case scenarios ‘workpiece and process monitoring’ and ‘machine condition monitoring’ (see Table 12 and Table 13). The end points for the specified latency are defined here as the sensor as the first end-point and the machine as the second one.

Measurand	**Frequency**	**Latency**	**Reliability**	**Applications**
Requirements on external quantities				
Acceleration	≤ 50 kHz	< 10 ms	high	Process monitoring of the workpiece
Sound	≤ 50 kHz	< 10 ms	medium	Scratching/Screaming
Temperature	≤ 100 Hz	< 100 ms	medium	Thermal behavior
3-DOF Force	≤ 30 kHz	< 10 ms	high	Mechanical load of clamping or machine
Torque	≤ 30 kHz	< 10 ms	high	Cutting force
Strain	≤ 2 kHz	< 10 ms	high	Cutting force
Requirements on positioning				
Position	≤ 10 Hz	< 100 ms	low	Relative orientation, workpiece tracing, intralogistics

Table 12: Parameter sets for use case scenario ‘workpiece and process monitoring’

Measurand	Frequency	Latency	Reliability	Applications
Requirements on external quantities				
Sound	≤ 50 kHz	< 10 ms	Medium	Scratching/Screaming
Temperature	≤ 100 Hz	< 100 ms	Medium	Thermal behavior
Strain	≤ 2 kHz	< 10 ms	High	Cutting force

Table 13: Parameter sets for use case scenario ‘machine condition monitoring’

It is planned to integrate up to three sensor modules into the MSP. Depending on the selection there will be different data transmission characteristics.

3.2.4.4 Technical Challenges

The technical challenges to solve for use case 5 is related to designing and implementing an architecture of the MSP, which one the hand fulfills the need for versatility and flexibility for ease of use in multiple applications in production. Therefore, it is planned to enable easy sensor exchange without redesign of the electronics (plug-and-play). The MSP will therefore also need an embedded software which allows for a configurability of the platform. Another challenge is synchronization of the MSP with the machine it is operated in, especially when the MSP is used for process monitoring and when measurement data will be aligned with the machine´s tool path and the part geometry. From the transmission and processing aspect, it needs to be found out, what is the optimum configuration, which on the one hand allows for energy efficiency and low battery consumption while allowing a short overall time budget for data acquisition, 5G transmission, edge cloud computation of feedback information, receiving of results at the machine.

3.2.4.5 Summary

Use case 5 explores the low-latency feature of 5G for versatile monitoring solutions, both for process monitoring in machining as well as for condition monitoring for machines and devices. Benefit of the use case is an advance in process diagnostics and control as well a condition monitoring as a basis e.g. for predictive maintenance. Furthermore, the use case will make use of an early edge cloud integration with the 5G network and the shopfloor IT. This integration can serve as a blueprint for companies who are interested in capabilities for data-driven production use cases with time critical data processing requirements.

4 Reutlingen Trial

At the trial site with Bosch in Reutlingen, 5G-SMART will realize use cases 6 and 7 and validate 5G URLLC and eMBB services. The trial will realize the deployment of a 5G system in an operational factory, conduct the first-ever electromagnetic compatibility (EMC) testing of 5G, and carry out channel measurements at 3.7 GHz and 26 GHz in a manufacturing facility. The trial will have 5G indoor base stations with standalone deployment operating at 5G mid-band spectrum (3.7-3.8 GHz). The trial site also includes industrial equipment (AGVs and TSN/I-LAN applications) to support the realization and demonstration of the use cases. To enable 5G-based AGV to AGV communication and AGV fleet control, distributed cloud solutions will be developed and deployed along with 5G core network functions.

In Table 13, the use cases demonstrated at the Reutlingen trial site have been classified according to 3GPP [TR22.804].

Use cases Reutlingen trial site		Factory automation	Process automation	HMIs and Production IT	Logistics and warehousing	Monitoring and maintenance
UC6	Cloud-based Mobile Robotics	X			X	
UC7	TSN/Industrial LAN over 5G	X				

Table 14: Reutlingen use case classification

4.1 Use case 6: Cloud-based Mobile Robotics

Transporting production material, raw or manufactured, within a factory is an integral part of the production in many factories. The transport typically takes place between the storage and production sites, or between manufacturing machines in different stages of the production. The Bosch semiconductor factory in Reutlingen is a large factory with high degrees of automation and 24/7 in-operation. Here, an efficient transport of material is of great importance, simply because issues or interruptions in the transport can significantly impact the overall productivity, and hence the overall turnover. Indicators for the transport efficiencies include accuracy, availability, safety, speed, capacity, as well as resource- and cost-efficiency.

4.1.1 State of the Art

Today, the material transport in the semiconductor factory is partially or fully automated through utilizing driverless mobile robots, e.g. Automated Guided Vehicles (AGVs). The state-of-the-art AGVs operate based on a local, on-board intelligence (i.e., inside each individual AGV), where the whole processing is realized. This includes input/output (I/O) processing related to the AGV sensors and actuators/motors, the corresponding control logic, and other application layer control algorithms for navigation and execution of tasks. The navigation plans and tasks are usually programmed into the intelligence onboard the AGVs using either specific wired interfaces, or through Wi-Fi. In particular, dispatching AGVs for different tasks is usually performed via external systems, e.g. a centralized fleet management. The decisions made by the fleet management system are then loaded to the local AGV controllers over Wi-Fi. With the intelligence of each individual AGV being realized locally, operation and management lack flexibility, in particular in scenarios related to the smart factories of the future with a sizable fleet of AGVs, where a high degree of modularity, programmability and flexibility is expected from all building blocks of manufacturing sites. For instance, consider a manufacturing environment with a large fleet of AGVs, which requires a dynamic adaptation and customization of AGV's operations, due to changes in requirements or changes in operation policy. In that case, executing required software updates and configurations for AGVs individually can be challenging, resource-intensive and time-consuming. In extreme cases, the software updates might further require hardware upgrades (e.g., upgrading processing units or memories), which can add to the required efforts and costs. Additionally, the communication between external systems (e.g. fleet management) and individual AGVs over Wi-Fi might become inefficient and, in some cases, infeasible, e.g. operation of AGVs in large indoor/outdoor areas of the Bosch semiconductor factory has proven infeasible due to the limited reliability of Wi-Fi in the factory and hand-over delays.

4.1.2 Benefits of using 5G

With the use of 5G, dynamicity and flexibility are brought into the operation of AGVs in the production environments. As opposed to Wi-Fi, 5G enables time-critical communication with e.g. bounded latencies and enables to shift the local intelligence from the individual AGVs and realizing it in a remote computing environment of an critical cloud at the edge of the network infrastructure. Additionally, a collocation of software from several AGVs in the same processing environment is made possible, as well as enriching the control with data that otherwise would be inconvenient or infeasible on individual devices (e.g., shared maps, operational/usage data sets). The benefits of taking this approach are manifold and go beyond facilitating software management for an individual or a selected group of AGVs. For instance, it enables a more energy- and cost-efficient AGV fleet management, or a tightly synchronized collaboration among several AGVs interacting with the environment to execute a challenging task. Simultaneous localization and mapping (SLAM) capabilities of an AGV can enhance the route selection for other AGVs in real-time, i.e., one AGV detects an obstacle, the other one reacts by finding another path to the destination. Due to a possible improved software management, down times are expected to be reduced. Furthermore, a reduced total cost of ownership (TCO) is expected, resulting from the above benefits and from the reduction in the maintenance complexity.

Apart from the immediate effects on the factory floor, decoupling the control intelligence from the AGV physical platform has positive effects on the future development in the related research areas, as it enables the physical platform and control intelligence to evolve separately from each other and with lesser degrees of interdependencies. This could accelerate the innovations in the field of automated transport in smart factories of the future.

Furthermore, interactions and collaborations among individual AGVs and control logic (also from other industrial devices) based on other sensory inputs are facilitated, which in turn enables new use cases, e.g. performing challenging tasks that require a tightly synchronized collaboration among several AGVs.

4.1.3 Use case description

This use case focuses on the feasibility, flexibility, and performance of wirelessly controlled AGVs in a real manufacturing shop floor equipped with 5G technology. Besides the need for low-latency and reliable radio connectivity provided by 5G as an enabling technology, one novelty of this use case is the possibility to decouple the closed-loop control of the robot from the robot's embedded system and place it into a cloud execution environment while sustaining the KPIs, like sufficiently low execution end-to-end latency and adequate fault-tolerance given by the communication service reliability. The use case can be categorized under factory automation as well as logistic and warehousing.

In the use case two physical AGVs will be operated: A commercially available AGV and a research AGV, both of them being 5G-enhanced. The reason for using two different types of AGVs is that each of the platforms are more suited for validating specific aspects of the use case, i.e., suitability for operation in a real production environment as well as moving AGV intelligence to the factory cloud. Moreover, this will allow us to validate the common use of a map through two different platforms. The research AGV is designed and build up from scratch allowing full control over its architecture and functionalities. It is equipped with cameras and different types of sensors to allow for localization and safety. Major control functionalities of the research AGV will be realized in the cloud. Apart from the two physical AGVs, with the help of several virtual AGVs, fleet management will be investigated in this use case. Note that the AGVs used are of the category autonomous mobile robot (AMR) which do not depend on any guidance of the AGVs in form of e.g. physical tags or stripes in the factory. A high-level illustration of the use case is depicted in Figure 7.

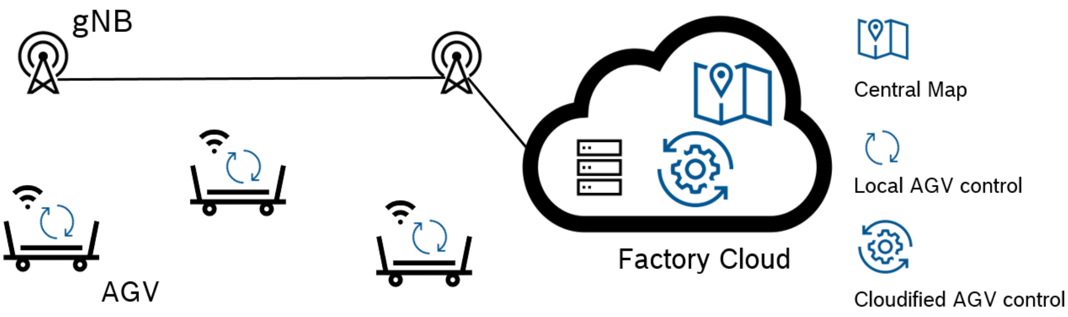

Figure 7: High-level illustration of use case 6

4.1.3.1 Communication Streams

The realization of the AGV control involves the development of several software modules that communicate with each other. The collaborative control further requires components to be implemented such as a global map in the edge cloud where the jointly collected knowledge is manifested. The global map is exploited, for example, in the trajectory planning and control of each AGV to avoid paths that are reported to be unavailable by the other instance. Here, the main functional components are shown in Figure 8 and also listed and further explained.

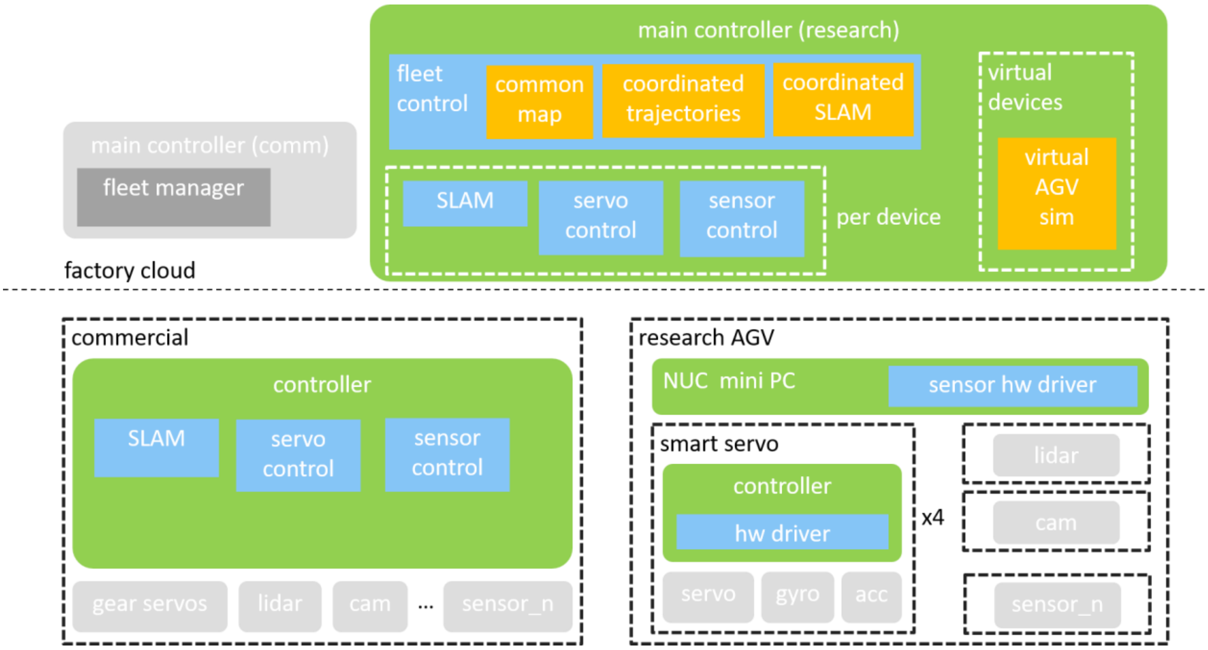

Figure 8: System architecture of use case 6

Fleet control is the main business logic that external users, e.g., factory plant operators interact with. It receives commands like “move a free AGV to position X within the lab”.

Trajectory control is the movement of the AGV along a pre-planned path. The path is a result of a trajectory planning that uses all available information in order to provide the most efficient path. This information might include the actual working paths and blocks in the workspace and the actual as well as future positions of other AGVs. Trajectory control monitors the AGV positions in real time and issues commands for the next movements.

SLAM stands for Simultaneous Localization and Mapping. With this component the device measures the surrounding environment and creates a map, while simultaneously it also tries to localize itself on the self-created map. When the device moves, SLAM tries to identify the new location based on the existing map and extends the map with new measurements. The source of the map is usually a point cloud, detected by Laser imaging, detection and ranging (LiDAR) or 3D camera sensors. Usually the resulting map is the floor plan of the area, where the device can freely move. The **Global map** is where the AGVs commonly store their actual views of their surroundings. The global map covers all the workspace area where the AGVs have ever been. The global map is always updated with the newest information coming from the AGVs, so it always changes with time. Moreover, future states with the locations of the fleet can be estimated as well, when the trajectories are also known.

IPC is Inter Process Communication, the way how the different components talk to each other. This communication should be managed in order to be efficient, reliable, fast, scalable and should handle different service priorities.

Safety control stops the device in an emergency, i.e., when there is a risk of collision with humans, other AGVs, equipment, or walls. Safety control is a separated, high reliability system on the device impacting on very low level in order to prevent any software or hardware errors to block the safety functions. Besides the automatic functions, safety is available for manual triggering as well.

Cloud safety is a shadow pair of *Safety* in that it does not actually stop the device during emergencies but signals such an intent. Its output will be compared with that of S*afety*, and its purpose is to demonstrate whether safety functions could be moved to the factory cloud or not.

Figure 8 illustrates the architecture of the system, including the factory cloud part and the two AGV types (research and commercial). We show the software components of the commercial and the research AGVs. The controller of the commercial AGV is closed, except data coming out on standard interfaces, there is no access to the internals. For this reason, the main components, the SLAM algorithm, the servo and sensor controls are assumed to be inaccessible from the outside. Still, not all, but many AGV manufacturers provide some interface, on which one can drive their device with high level commands not using their official software. This way a carefully selected commercial AGV can be driven from the factory cloud through its own controller.

The research AGV is built up with similar components to the commercial AGV, however all the software components are open for development. The actuator has a servo motor, encoders, gyroscope and accelerometer sensors and their own controller. The drivers of the sensors are running inside the actuator. The factory cloud can access the actuator and all its sensors through a communication link which may be going through a mini PC residing on the research AGV. The mini PC may be used if needed as a driver for all the sensors that are not placed inside the actuators, but still belongs to the research AGV, as well as, it may be applied as a gateway between the actuators and the 5G network. These sensors are the lidar or the depth camera, for example.

On the top of the software architecture there is the factory cloud and the services running in it. There is a main controller for the research and the commercial AGVs. Depending on the interface to the commercial AGV, these main controllers may share common modules facilitating a better cooperation among commercial and research AGVs. Otherwise, the commercial AGVs are running their own software stack and the cooperation is realized on a very high level only. In case there is a suitable interface available for the commercial AGV, the collaboration is planned to be realized as sharing a global (common) map built in the factory cloud, for instance, to optimize path selection and route execution.

The main controller of the research AGV contains per device SLAM algorithm, servo control and sensory data collection point. The sensors track the movement and the surroundings of the research AGV, while the servo control drives it. Based on the collected sensor data the SLAM algorithm creates a map and localizes the AGV device. All this information is pushed up to the fleet control of the research AGVs that handles all the research AGVs running in the same workspace. The fleet control component gathers the individual maps created by the AGVs and merges them into a global map using the coordinated SLAM module. This map is pushed back to the per device SLAM component, this way the AGVs have a more comprehensive, and more fresh view of the actual workspace even in those regions where they have never been. The coordinated SLAM module maintains the global map and helps the localization of the AGVs. AGVs also report their positions and the coordinated trajectories component takes this information into account when it plans the trajectories of the AGVs. Knowing the global map, the actual and the planned future positions of the AGVs are the key to create the trajectory for a new AGV job or reorganize the actual routes for a more efficient solution or in the case of changes, e.g., temporary path blocks in the global map.

Additionally, the main controller can handle virtual devices as well. Virtual AGVs are essential to those trials where a large number of AGVs are handled as a fleet, because the number of real AGVs participating in the field trial is rather limited. Instead, the same main controller is designed to drive virtual AGVs that are built from exactly the same software components as the research AGV and run in a simulated environment sharing the details of the real workspace. The sensor outputs are simulated, but still reflects the conditions as they would sense the real environment. Similarly, the simulated AGV moves based on the control messages as a real AGV. The simulation results can be visualized as well, helping to understand the most interesting situations.

4.1.4 Requirements and Challenges

In this section the overall requirements of the use case are described. These are structured into performance KPIs, functional requirements and operational requirements. In general, a major challenge to address for these use cases is to find the right balance between (1) the strict requirements on the AGV platform from the real production environment; (2) the technical features and certifications of the commercially available AGV platforms that can be used for the use case realization; (3) the 5G radio coverage to be deployed during the project at the Reutlingen factory; and (4) how efficiently the realization can demonstrate the benefits of 5G as well as (edge-)cloud-control.

4.1.4.1 Performance KPIs

The traffic between AGV platform and the remote intelligence unit depend to a high extend on the scope of the cloudification, i.e., what control and application functions are decoupled from the AGV and implemented in the edge cloud.

Characteristics of the two traffic stream between AGV and the control intelligence are given in Table 15: and Table 16: . For the control intelligence of the AGV in the cloud, the majority of the traffic is uplink from AGV to the remote-control unit, in particular in case the AGV is equipped with cameras for navigation. In addition, the closed-loop control of the AGV from the cloud requires cyclic exchange of navigation data with the AGV within a guaranteed delivery time.

Communication stream	**Communication service availability, target value**	**Communication service reliability, mean time between failures**	**End-to-end latency, maximum**	**Service bit rate**	**Remarks**
Between AGV & Control Intelligence	≥ 99.999%		< transfer interval	DL < 10Mbit/s UL 1-100Mbit/s	

Table 15: Characteristic parameters of the AGV use case

Communication stream	Message size [Byte]	Transfer interval, target value [ms]	End device speed	# End devices	Service area	Communication attributes
Between AGV & Control Intelligence	In the order of 500	10-100	0-2.8m/s	2-4	100m^2	Periodic, deterministic asymmetrical

Table 16: Influence quantities of the AGV use case

4.1.4.2 Functional requirements and challenges

The following requirements are imposed on the underlying 5G communication network, which wirelessly connects an AGV with its control logic in the edge cloud:

(1) IP connectivity: communications between AGVs and their remote-control logic require a reliable and low-latency IP connectivity service between the two.

(2) Seamless mobility: AGVs move in a specified factory environment, and this environment might be covered by several 5G cells. Therefore, a proper operation of the AGVs requires a seamless service continuity across the whole mobility area.

(3) End-to-end QoS: the stringent performance requirements on the communication service between the AGV and its controller in the edge cloud necessitates an end-to-end QoS support including 5G radio access network (RAN), core network, the edge cloud, as well as in-factory transport network.

(4) Energy efficiency support: AGVs operates on batteries, with a limited battery capacity on-board. Therefore, it is important that the 5G system does not cause any excessive energy consumption with respect to communication.

(5) Security protection: production facilities implement strict security regulations—according to IEC62443—to ensure the confidentiality and integrity of production information. A commonly adopted security measure is to segment the production IT infrastructure into several security zones. To be compliant with the security regulations, the 5G communication system should provide required functions for secure integration into the existing IT infrastructure.

(6) Environmental requirements: Requirements imposed by the Bosch semiconductor factory are for instance clean room certification: semiconductor production requires strict protection against the presence of particles in the environment. Accordingly, the 5G communication system should also comply with the clean room certification requirements (clean room certification ISO 3). Moreover, Electrostatic discharge (ESD) conformity was identified as a potential requirement.

4.1.4.3 Operational requirements and challenges

As mentioned earlier, AGVs play important roles in the productivity of the semiconductor factory, and accordingly it is crucial that the 5G-based AGV fleet fulfils the following operational requirements:

Usage Simplicity: the cloud-based mobile robotics should not make the onboarding of AGVs, operation and maintenance of the overall system (for material transport) more complex than the today's system. In particular, it is important to master the complexity associated with large number of wireless links in areas with a large concentration of AGVs.

Service guarantees and 24/7 operation support: the availability and reliability of the cloud-based AGV control should be at least at the same level as in conventional AGVs with a 24/7 operation support to avoid interruption in the production.

Integration into existing IT infrastructure: the cloud-based mobile robotics system should be integrated into the production IT infrastructure taking into account all requirements and restrictions. For instance, the restrictions of the security isolations (security zones) should be considered when an AGV crosses different cellular cells.

4.2 Use case 7: TSN/Industrial LAN over 5G

Networking among field-devices, machines and their corresponding controllers in an industrial manufacturing environment is an essential prerequisite of factory automation. The networking enables various components of a production line to exchange various messages, e.g. motion control commands and status updates, which are critical for automatic execution of manufacturing tasks. The criticality of the networking applications, together with boundary conditions like functional safety in manufacturing environments, usually put strict QoS requirements on the underlying networking infrastructure, e.g. in the form of very short communication latencies (sub-ms), low delay variations (jitter), the guaranteed delivery of messages and availability (99.9999%). These requirements, which also vary from one industrial domain to another and from one application to another, have resulted in the introduction of many networking architecture models and protocols, which are collectively referred to as industrial LAN (I-LAN) technologies.

4.2.1 State of the Art

Due to the stringent requirements of the industrial applications, today all operational I-LANs are realized based on fixed (wired) communication networks. Limited flexibility for setting up new production lines or for restructuring an existing production line, as well as complex and costly maintenance, are major drawbacks of the wired I-LAN realizations. In particular, this can be an issue in view of the recent trends for making the industrial environments as flexible as possible, e.g. smart factories of the future in the context of Industry 4.0. Two examples of such trends include virtualization and cloudification of machine and device controllers, as well as the introduction of TSN as a converged industrial LAN/Ethernet technology. The expectation is that over time the TSN technology, as specified by IEEE 802.1 working group in several standard specifications, will replace legacy industrial Ethernet technologies, and thereby simplifying the machine-to-machine connectivity in the industrial environment.

To achieve the full flexibility, one can go a step further and realize the TSN/I-LAN networking based on a wireless technology, see D5.1 for more information [5GS20-D51]. This has not been feasible so far, simply because no existing wireless technology could support the tough requirements—e.g., in terms of latency and reliability—of many industrial machine-to-machine applications.

4.2.2 Benefits of using 5G

By replacing some of the fixed interconnections between TSN/I-LAN nodes with 5G, the number of cables to be drawn and maintained will be reduced. Moreover, due to a reduction of connectors wear and tear, in particular for the mobile machines/controllers, the maintenance costs can be reduced.

Apart from the maintenance costs, replacing the cables for communications between controllers and machines with 5G communications results in a great flexibility for implementation and adaptation of the industrial manufacturing infrastructure. Consequently, this can improve the productivity of manufacturing through reducing the time for setting up or customizing a production cell/line and improving the maintenance, among other things.

4.2.3 Use case description

This use case focuses on investigating and validating the applicability of 5G for transporting the critical machine-to-machine traffic of TSN/industrial LAN applications. The use case is categorized under factory automation.

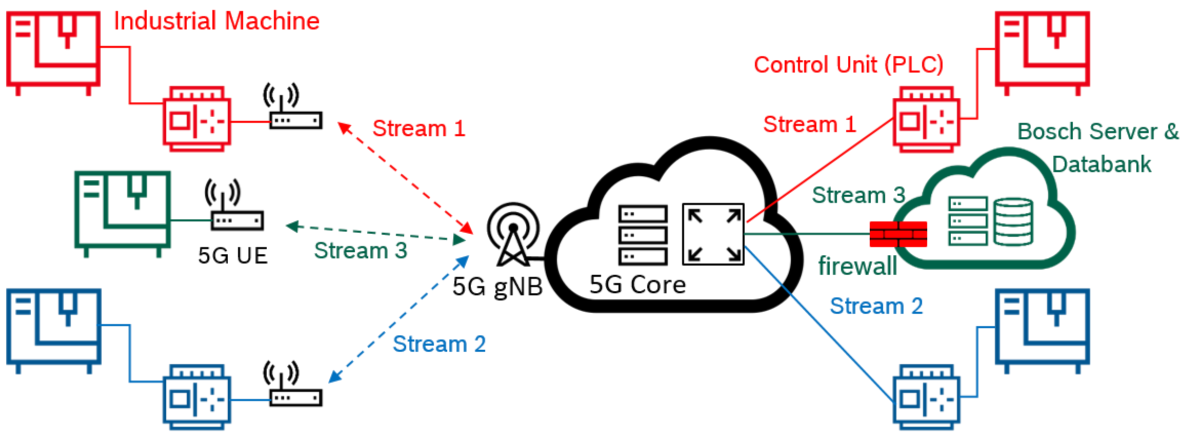

Figure 9: End-to-end system architecture of the TSN/Industrial LAN use case

The use case will look into controller-to-controller (C2C) applications, which could be for instance large machines like industrial printers or packaging systems, where different subsystems are managed through individual control units, i.e. programmable logic controller (PLC), and a timely exchange of information among these controllers are required for the desired operation of the system as a whole. Another example is the case, where different production units contribute to manufacturing a product and controllers at each of these units need to inform each other about status of the production.

In order to validate the feasibility of transporting traffic from critical machine-to-machine applications over 5G communications networks, in this use case, we focus on the C2C applications based on programmable logic controller (PLC) with periodic deterministic traffic. The C2C applications (e.g., PLC controllers) communicate to each other through their TSN ports (or a switch), where the communication between the ports traverses over the 5G network.

4.2.3.1 Communication Streams

Figure 9 illustrates the end-to-end system architecture of the use case. The system is composed of two subsystems, namely industrial automation as well as the 5G network. The 5G subsystem provides connectivity services for communications among components in the industrial automation subsystem. Specifically, three pairs of industrial automation components (color-coded with red, blue and green in Figure 9) will be set up, where two components in each pair communicate with each other. This results in three separate traffic streams, Stream 1, 2 and 3. The first two streams are experimental TSN traffic based on C2C applications. The C2C communications will be deterministic, periodic and symmetric traffic between controllers with stringent performance requirements. Stream 3 represents communications between an operational industrial machine in the factory and the backend servers.

4.2.4 Requirements and Challenges

In this section the overall requirements of the use case are described. These are structured into performance KPIs, functional requirements and operational requirements.

4.2.4.1 Performance KPIs

Note that the characteristics of C2C traffic depend largely on the features of the corresponding applications. For example, while some isochronous applications require a guaranteed latency in the range of 100 µs, some applications can tolerate a few tens of ms. The traffic characteristics of the C2C applications under consideration for this trial are given in Table 17: and Table 18: .

In addition, the performance requirements of the corresponding applications are summarized in the tableTable 18: . The number of 5G modems connected to a PLC or to a machine in the service area can potentially be large, e.g. in the extreme case, where at a few locations there is a large concentration of controllers.

Communication stream	Communication service availability, target value	End-to-end latency, maximum	Service bit rate
C2C traffic	99.9% – 99.999%	< transfer interval	DL > 1 Mbit/s UL > 1 Mbit/s

Table 17: Characteristic parameters TSN/wireless LAN use case

Communication stream	Message size [Byte]	Transfer interval, target value [ms]	Survival time	UE speed	# Ues	Service area	Communication attributes
C2C traffic	In the order of 500	4-10	< 2 x Transfer_ Interval	No	< 10 UEs per m^2	100m x 100m	Periodic, deterministic, symmetrical

Table 18: Influence quantity TSN/wireless LAN use case

4.2.4.2 Functional requirements and challenges

The underlying 5G communication network, which wirelessly connects two TSN switches (or two TSN end-points), should fulfill the following requirements:

(1) Layer-2 LAN switching capabilities for TSN/I-LAN frames.

(2) Time synchronization (common clock) with the overlay TSN/I-LAN network (for applications requiring isochronous timing, or for IEEE 802.1Qbv). In this use case, the applications do not require isochronous timing.

(3) Seamless mobility: machines might move inside the factory environment, and this environment might be covered by several 5G cells. Therefore, a seamless service continuity across the whole mobility area is required. Note that the seamless mobility is not required for applications with isochronous timing (where applications need to exchange data synchronously at a defined periodic rate [IITTSN18]). In this use case, we will not consider mobile controllers.

(4) End-to-end QoS: to replace the cable between TSN/I-LAN nodes with 5G communication, the underlying 5G system should provide a guaranteed end-to-end QoS all the way from one TSN node to the other.

(5) Network status and capability exposure: to transport TSN/I-LAN traffic over 5G, the underlying 5G system should expose network status and enable configurations of QoS parameters through APIs.

(6) Network slicing: network slicing may be considered to support transporting multiple TSN streams with different QoS requirements over the same communication platform.

(7) Security protection: production facilities implement strict security regulations—according to IEC62443—to ensure the confidentiality and integrity of production information. A commonly adopted security measure is to segment the production IT infrastructure into several security zones. To be compliant with the security regulations, the 5G communication system should provide required functions for secure integration into the existing IT infrastructure.

4.2.4.3 Operational requirements and challenges

Realizing the communications between machines in the factory floors using wireless technology in general brings about several operational challenges as elaborated below:

Usage Simplicity: replacing the cables with 5G links should not make operation and maintenance of the overall system (inter-machine communications) more complex than the today’s system. In particular, it is important to master the complexity associated with large number of wireless links in areas with a large concentration of wirelessly connected machines.

Service guarantees and 24/7 operation support: the availability and reliability of the inter-machine communications should be at least at the same level as in conventional wired networks with a 24/7 operation support to avoid interruption in the production.

Integration into existing IT infrastructure: the wirelessly connected machines should be integrated into the production IT infrastructure taking into account all requirements and restrictions. For instance, the restrictions of the security isolations (security zones) should be considered when a machine crosses different cellular cells.

5 Summary of Trial Use cases

In total seven use cases have been chosen for the three trial sites in 5G-SMART. They all represent different industry applications where 5G technology will have significant impact. This includes use cases from mobile robotics and augmented workers to smart sensors and AGV operation. In addition, the trials will explore different features of 5G including low latency communication, mobility support, end edge cloud data processing. The planned implementation and evaluation of the trial use cases will therefore provide valuable insights of the early available 5G products. While 5G feature sets both on the device and the infrastructure side with regards to newer releases will become available commercially, the 5G SMART trials would provide an early look into the use case realizations and valuable insights on the technology integration.

6 Additional Forward-Looking Use cases for Smart Factories

The previous sections have described the trial use cases in the 5G-SMART project. In this section, additional future-looking use cases are explored. Different use cases for 5G in industry are given in e.g. 3GPP [TS22.104], and 5G-ACIA [5GACIA2][5GACIA3][5GACIA4]. The aim of 5G-SMART has been to complement those or add new ones.

The use cases described in the following were proposals from both OT and Information and Communications Technology (ICT) companies in the project. The proposals have been reviewed and refined. Several proposals were also merged to create larger use cases. In the end, many of the forward-looking use cases that received most interest are the ones that go beyond a single factory setting or challenge the traditional supplier relationship. Many times, these use cases can be seen as extensions to the the ones being trialed.

In Table 19, the additional forward-looking use cases are listed and have been classified according to 3GPP [TR22.804].

Additional forward-looking use cases		Factory automation	Process automation	HMIs and Production IT	Logistics and warehousing	Monitoring and maintenance
UC8	5G-Enabled Remote Expert	X	X	X	X	X
UC9	5G Empowered Cross-domain and Inter-company Collaboration	X	X	X	X	X
UC10	AGV and UAV Realtime Trajectory Adaption with AI for Smart Factories	X	X		X	
UC11	5G Enabled Metrology and Process Control across Machine and Factory Boundaries	X	X			X
UC12	5G Enabled Seamless Device Plug and Play	X	X	X		X
UC13	AI-assisted Production Quality Management	X	X			X

Table 19: Classification of additional use cases

6.1 Use Case 8: 5G Enabled Remote Expert

6.1.1 State of the Art

Remote service solutions for critical plant assets have been on the market for several years. While remote guidance typically is designed to function seamlessly through a mobile device, with hands-overlay, pointer, and additional guiding tools, we are now starting to see industry solutions using AR technology for remote collaboration. With the introduction of 5G, these solutions should become even more capable in terms of data rate, mobility support and indoor tracking.

6.1.2 Benefits of using 5G

Bounded low latency and high throughput 5G communication will enable enhanced remote collaboration. This will improve e.g. AR- and VR-based solutions on the market to also include e.g. haptic feedback and tactile features. Another advantage with cellular communication is the inherent support for mobility including fast cell handover.

6.1.3 Use case Description

In this use case a technician or remote expert, not located on premises, provides help in critical tasks. These tasks could be e.g. maintenance, configuration or repair operation on connected robots / machines, for example, to remotely allow fast post-failure recovery. A combination of AR and VR technologies enables a field service technician to share his or her view of a situation using the headset’s in-built cameras and receive guidance directly from an expert through on-screen annotations, chat, and document sharing. In addition, haptic feedback sensors can be used to enhance the remote collaboration, for example by providing the sense of force needed to turn a valve. This improves asset and production availability for customers as maintenance actions can be completed faster without the need of having experts travelling to the production site. The relevance for this has been become apparent in recent containment measures following the Covid-19 pandemic.

In one example the expert can guide remote field service personnel through a sequence to replace a part, for instance. The remote expert can see what the local user. see via the AR or VR device and guides them through the service action. The same methods can be used in e.g. deployments, commissioning or training.

In a different scenario, the remote experts use a mobile robot deployed at the factory to perform service tasks. Here the remote expert would need access to the factory resources in real-time and at a reasonable level of granularity: production units, application management, KPIs, digital twin and other useful operational data.

6.1.4 Requirements and Challenges

A major challenge in this use case is to provide end-to-end QoS including low-latency communication across large geographical distances possibly over both public and private 5G networks. One challenge is to prevent the “sea sickness” effect caused by delay in the video stream. In the case of remote control of a mobile robot there will be strict requirements on 5G including latency, availability, reliability and redundancy. This to ensure safe operation of the robot from a remote location.

Tracking the position of a field service technician will also put requirements on the 5G system. This will support the remote expert in guiding the people on premise and improve the remote collaboration.

Another challenge is data security. Video feeds from inside of the production plant will be highly sensitive and this information cannot be disclosed. The same holds true also for different fault conditions in the plant. End-to-end security across different networks and computing platforms is therefore a hard requirement including different access rights depending on user.

6.2 Use Case 9: 5G Empowered Cross-domain and Inter-company Collaboration

6.2.1 State of the art

Today, parts are typically delivered to the factory and then transported to the line stations using intra-logistics via manual labor or AGVs. A small stock of parts as buffer combined with semi-automated lineside delivery is a common approach in many factories. Larger companies have third-party suppliers located in-house that do kitting and intra-logistics.

6.2.2 Benefits of using 5G

5G has a unique global footprint that could connect businesses in a way not possible before. It would allow manufacturing sites, transports and factories to share a common communication infrastructure with suppliers. This shared infrastructure enables companies to optimize logistics processes and production flows for the manufacturing eco system.

6.2.3 Use case Description

This use case considers cross-domain collaboration between manufacturing companies throughout the supply chain [Pennekamp19], towards the Internet of Production (IoP). Such inter-company cooperation aims to reduce product development costs, increase gains in profit margins and improve quality and safety. The data generated by the production machinery and robots on a shop floor is no more isolated and available to the machinery owner only. On the contrary, it is shared in an automated and secured manner among authorized stakeholders, able to provide raw data on similar machinery or on complementary domain for improved production, maintenance and monitoring. For example, this would allow a manufacturer to fine-tune its production lines based on the data received directly from providers and related to the workpieces used on these production lines.

One example of such collaboration is where you have suppliers delivering parts to a factory directly to the assembly line (i.e., lineside delivery). The goal of lineside delivery on assembly lines is improving efficiency and productivity by delivering the right parts to the right place at the right time. So, the supplier would be responsible both for the transport to the factory and the intralogistics using e.g. AGVs. In the Reutlingen trial we consider the use of AGVs for intralogistics. The lineside delivery use case described here would expand on that and integrate supplier logistics with intralogistics in the factory.

6.2.4 Requirements and Challenges

A major challenge in this case is the sharing of information between the manufacturing site and the suppliers. This implies incorporating foreign data into local processes and context-aware data record, exchange and combination with other sources, towards an enhanced digital twin. Obviously, this does not primarily impose requirements on the 5G solutions, however, there are areas where also the 5G systems will be affected.

Tracking of goods needs to support a holistic solution covering both off-site and on-site tracking including indoor. Outdoor tracking is likely done with GPS or a 5G network (or a combination), with the latter technology also used for indoor positioning. This implies that driverless trucks or AGVs need to roam from public to private network in a seamless way.

Security is, like in many of the industrial use cases, of the highest importance and security support for communication services to guarantee their confidentiality and data integrity need to be implemented. Secured information sharing between interested parties in real time, at a reasonable level of granularity, is required.

6.3 Use Case 10: AGV and Real-time Trajectory Adaption with AI for Smart Factories

6.3.1 State of the art

AGV systems are primarily used to transport items in manufacturing facilities, warehouses, and distribution centers. The downside of most deployed AGV solutions in industry used today is the lack of flexibility. Most use an in- or on-floor guidance system (e.g. magnetic strips). Others use onboard sensors for obstacle avoidance, but still follow a fixed path. The result is an inability to deviate and redirect due changes in production or obstructions in its path. Some deployed solutions require the AGVs to be “confined” to a dedicated area where human workers will not interfere.

In use case 6, cloud-based mobile robotics using 5G is explored. The use case considers fleet management of AGVs where several critical functions are deployed in the cloud including trajectory control and SLAM.

6.3.2 Benefits of using 5G

The benefits of using 5G identified for use case 6 also applies for this use case including bounded latency and high availability, please see 4.1.2 for more details. The native support for cloud and edge technology in 5G is also a clear advantage when considering AI processing. In the case where more advanced sensors, e.g. high definition cameras, are used as input to the AI unit the high throughput of 5G will also be a benefit.

6.3.3 Use case Description

In this use case we consider a scenario where AI is used to optimize fleet management of AGVs to better adopt to the dynamic environment of a factory. One example is where AI is used to teach the mobile robots how to avoid human workers based on behavior and movement of the workers. Other examples of where AI can be used to increase productivity, are when the robots can avoid jamming or to solve the issue of a collision due to a failure of an AGV or in reacting to the detection of the presence of objects that obstruct a predefined trajectory. When the factory devices are connected to the 5G network, the AGVs exchange speeds, positions, trajectories and maneuvers and other useful data to the cloud. This information is used as input by the AI system that allows redefining the trajectories for solving the traffic jam and immediately informing/ monitoring the incident with the maintenance personnel.

6.3.4 Requirements and Challenges

The AGV real-time trajectory refinement will impose tough requirements on both network availabilty as well as reliable communication. The current position of the AGV needs to be communicated with short time intervals in order to support accurate sub-meter positioning. All AGVs also need to be time synchronized.

Efficient hand over and 5G coverage is needed to support seamless mobility of the AGVs across the factory floor. In general, factories impose a challenging radio environment and careful planning and deployment need to be made to guarantee smooth operation of the AGVs.

6.4 Use Case 11: 5G Enabled Metrology and Maintenance across Machine and Factory Boundaries

6.4.1 State of the art

Sensor systems for industrial processes are already today commonly used to supervise and control manufacturing processes. They are mainly connected using Ethernet or fieldbus protocols over wires. Wireless solutions do exist (e.g., Wireless IO link and WirelessHART) but they are limited in their potential and can only address a fraction of use cases. Furthermore, different parts of the process are not connected and typically there are “islands” of connected systems in a factory.

6.4.2 Benefits of using 5G

5G is designed to support large wireless sensor networks (often referred to mMTC) including native cloud connection. The coverage of 5G, including public networks, is also a benefit in the case where the communication is not limited to a single factory site.

6.4.3 Use case Description

In this use case we envision two scenarios. First, we consider the case when a large part, if not most, of the measurement equipment is equipped with a 5G connection, both for workpiece measurement and for machine monitoring. Especially in the case of workpiece measurement, the sensor is usually very flexible by itself in terms of application to different parts. However, it is often placed and fixed into a specific production station due to the typical point-to-point and paired connection to an industrial PC as well as due to the need to track and manage its usage, setting and calibration. In combination with the latency, reliability and throughput performances of 5G that will be exploited in real-time industrial applications, the 5G mMTC services will break the physical boundaries of a machine, or of a measurement station, or even of the factory itself, by removing the restrictions of a local installation of the control or monitoring system. With measurement processing, equipment planning, and maintenance operations moved to the cloud, the resulting flexibility will allow equipment to be moved and applied to the most convenient operation independent on geographical location. This is then an extended scenario, where the manufacturing process is distributed across multiple sites.

6.4.4 Requirements and Challenges

On site, the 5G network must be able to support a potentially high number of devices located in proximity of each other. Furthermore, the 5G network is required to manage different QoS depending on application and sensor type. For some type of sensors (e.g. vibration sensors, video) large data transmissions to the edge can be foreseen and bandwidths up to 1 Gbit/s will be required.

One challenge is power consumption on battery-powered sensors. Low power UEs is a must since replacing batteries in a massive sensor deployment quickly becomes very time consuming and costly.

When distributing functionality between different sites, the wide area 5G network needs to provide the same performance as the on-site network. Requirements on security and data integrity will increase for a multi-site solution to safe-guard business sensitive information.

6.5 Use Case 12: 5G Enabled Seamless Device Plug and Play

6.5.1 State of the art

Device plug and play is at the heart of Industry 4.0, but the need for easier device integration has existed in industrial automation for many years. The complexity of industrial systems that includes legacy solutions installed 10-20 years ago provides a challenging task for any device integrator. Choosing equipment from a single supplier will often result in easier integration, but plant operators are then faced with the concern of vendor lock-in. In practice, the need for compatibility with legacy systems and very complex installations make the plug and play vision in Industry 4.0 still only a vision for most manufacturing sites.

6.5.2 Benefits of using 5G

One benefit in this use case is the reduced installation time for new or updated equipment. This is mainly achieved by the instant-on connectivity that 5G provides. A device could be installed in a plant, connect to the 5G network and automatically configure itself before being granted access to the plant network. This will reduce the manual work during commissioning and, thus, improve uptime and reduce cost. Maintenance is also simplified since replacing a part becomes less cumbersome. Wi-Fi is main competing wireless technology in terms of capacity and easy deployment. However, comparing 5G with Wi-Fi it lacks proper support for mobility and there is no proper QoS guarantee mainly when increasing the devices connected to Wi-Fi networks. In Wi-Fi networks the latency and jitter increase with the number of users while in 5G the latency remains almost constant when increasing the number of users.

6.5.3 Use case Description

In this use case we consider a scenario where a new machinery is added to the floor plant to replace old or malfunctioning device in the production chain. After the new machine is powered up and connected to the 5G network, the IT personnel using the floor plant console management can immediately visualize the new device and automatically add it to the specific zone with the required security and resource allocation. The new machine immediately becomes part of the production monitoring system, fault management, asset tracking and lifetime management. A machine learning (ML) module will be assigned to the new machine to continuously measure the status of the machine, location (in case of moving device) and overall performance analysis to identify any deviation in its functioning or that might lead to a faulty system which will affect the production. The ML will warn the IT support team about any anomality in the machine itself, the location of the machine or lack of system resources for the machine to successfully carry on with its functions. This provides a plug and play system for replacing machines and reduces the maintenance cost with AI-enhanced asset lifetime management and system resources monitoring with predictive failure analysis.

6.5.4 Requirements and Challenges

The plug and play functionality require automatic configuration of new devices to efficiently connect to the floor plant system. This includes allocating network resources to automatically connect new devices and assign the required resources. In order to work with non 5G devices (legacy or others) there is a need for 5G-LAN integration.

One challenge is security to ensure that devices can join the network and are assigned to the appropriate network resources. The plug and play vision must not be contradictive to the need of having full control over plant assets.

6.6 Use Case 13: AI-assisted production quality management

6.6.1 State of the art

Data analytics have been used in industry for decades to optimize production performance. In that sense AI and machine learning are new "tools" that are now available due to the ability to handle and process large amount of data sets. The same reasoning holds true also for cellular networks where traffic patterns have been analyzed to optimize performance.

6.6.2 Benefits of using 5G

There are two main aspects to this use case. The main benefit for this use case is improved quality and productivity by running analytics on the process data. Being able to collect, process and analyze large data sets in an automated way can support plant operators in decisions on how to efficiently run the factory process. Many of these machine tools and work pieces are moving objects that require wireless connectivity. This can be enabled by a reliable and scalable 5G network. 5G provides higher reliability and possibility to collect large amount of data from multiple devices compared to e.g. Wi-Fi where capacity and latency increases linearly with the number of connected devices. In addition, by applying AI and analytics also on network components (e.g. 5G routers, switches, etc.) the network can also become more autonomous and automatically respond to changes in the factory. This will also provide improved quality and productivity but also improved resilience.

6.6.3 Use case Description

This case is focused on the monitoring of different tasks in the assembly process to identify possible causes for quality issues or production defects. In this use case all the production or assembly lines will include video cameras in addition to other sensors to collect all ambient, contextual data and movements of the different machines tools and work pieces involved in the production. The sensors are connected over a reliable and scalable 5G network.

All the data will be collected in different AI-enabled modules to analyze and process the data to identify the optimal conditions that result in the best quality products. The AI-based system continuously monitors all the processes on different sites to learn and find the optimal settings that constantly improves the quality. Moreover, the system can take action (e.g. notify operator) based on analysis of possible deviations e.g. machine reaching end of life period or starting to malfunction. It is then possible to isolate the product that might have possible defect and run through different quality checking process. This system can be applied to both assembly machines as well as assembly personnel that can learn and improve their working methodology. The system will manage not only the resources in the production but also networking, radio, processing and other components that have to be dynamically re-organized to handle the processing of production data and changes in the quality checking process for final products

6.6.4 Requirements and Challenges

AI and data analytics have many challenges related to turning data into valuable information, however, in this section the focus will be on the challenges that this use case imposes on the 5G Network.

In order to extract and have the possibility to correlate data from the 5G network with process data, a 5G network exposure interface is required. Separation of runtime data from analytical data is also required, e.g., via network slicing. Furthermore, 5G integration with industrial LAN is required to capture brownfield installed devices and systems and interconnect with the wired industrial communication infrastructure.

High accuracy time synchronization is required in order to be able to correlate data collected across the plant. A global time across different systems is also required.

Since the data is business sensitive there is a strong requirement on security to ensure the integrity of the data.

6.7 Summary Future-looking Use cases

Building on the trial use cases for smart manufacturing, many of the future-looking use cases consider scenarios that go cross-domain and challenge the traditional supplier-producer setup. Here, 5G is seen as an enabler to create an eco-system of different companies, sharing information across company boundaries. Removing the silos between companies has the potential to unlock value to all parties in the eco-system. The challenges to realize this vision are of course many, not least on the business side. There are also technical challenges that needs to be addressed by the 5G community. With more critical infrastructure, including manufacturing sites, being connected, security and authentication to prevent unauthorized access to business sensitive data is one challenge. Another challenge is the end-to-end aspect over different wired and wireless networks. This includes roaming and mobility across non-public and public networks many times operated by different companies.

7 Summary and Conclusions

7.1 Overview of all Use cases

In total, the 5G-SMART project considers 13 use cases for smart manufacturing. Seven of these (UC1-UC7) are explored in the three trial setups. Here the project will validate 5G for factory automation, process automation, HMIs and production IT, as well as for logistics and warehousing and monitoring and maintenance, as shown in Table 20.

5G-SMART Use cases		Factory automation	Process automation	HMIs and Production IT	Logistics and warehousing	Monitoring and maintenance
UC1	5G-Connected Robot and Remotely Supported Collaboration	X			X	
UC2	Machine Vision Assisted Real-time Human-Robot Interaction over 5G	X		X	X	
UC3	5G-Aided Visualization of the Factory Floor	X		X		X
UC4	5G for Wireless Acoustic Workpiece Monitoring	X	X			X
UC5	5G Versatile Multi-Sensor Platform for Digital Twin	X	X			X
UC6	Cloud-based Mobile Robotics	X			X	
UC7	TSN/Industrial LAN over 5G	X				
UC8	5G-Enabled Remote Expert	X	X	X	X	X
UC9	5G Empowered Cross-domain and Inter-company Collaboration	X	X	X	X	X
UC10	AGV Realtime Trajectory Adaption with AI for Smart Factories	X	X		X	
UC11	5G Enabled Metrology and Process Control across Machine and Factory Boundaries	X	X			X
UC12	5G Enabled Seamless Device Plug and Play	X	X	X		X
UC13	AI-assisted Production Quality Management	X	X			X

Table 20: 5G-SMART Use case classification (according to 3GPP TR 22.804)

The trial use cases, which are described in detail in Sections 2-4, cover the application areas of 5G for "Factories of the Future", as defined in 3GPP TR 22.804 [TR22.804].

Use cases UC8-UC13 are not implemented in the trials but explored to better understand the needs of the manufacturing sector with respect to 5G and serve as input to other working streams within

5G-SMART. It is observed from Table 20 that all forward-looking use cases considered fall into several if not all categories.

7.2 Conclusions

The use cases described in the 5G-SMART project explore the benefits of 5G in smart manufacturing. The analysis of the requirements and KPIs of the use cases clearly shows the need of a reliable, low-latency, high-performance wireless infrastructure in factories of the future. This holds both for operations within a single factory or manufacturing site, which the trialed use cases have a focus on, but also for more extended deployments, going beyond a single site or company, as explored in the additional forward-looking use cases. In these cases, 5G networks deployed locally in the factory need to inter-work with traditional public cellular networks to cover a larger geographical area to support, e.g., logistics.

The benefits of remote operations and monitoring are addressed in several of the use cases. Whether the use case is remote control of a mobile robot or aiding a plant worker doing maintenance, the need for a reliable wireless technology like 5G is clear. This need has become even more apparent during the outbreak of the Corona pandemic and will likely become an important driver for 5G in the future.

The project envisions that 5G technology will play an important role in realizing future AI solutions for factory automation. Here, the bounded latency and scalability of 5G will enable easy and reliable connectivity to a large number of sensors in the factory. Edge cloud deployments will enable fast processing close to the data sources allowing AI engines to execute locally.

The project acknowledges the importance of the work done in 5G-ACIA, 3GPP, NGMN and other bodies in terms of identified smart manufacturing use cases, requirements and KPIs, but tries to go beyond the existing work by looking into the details of concrete implementation of use cases. Valuable insights as well as further requirements and challenges are expected to be identified during the implementation phase of the trial use cases.

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Appendix

List of Abbreviations

AE	Acoustic Emission
AI	Artificial Intelligence
AR	Augmented Reality
AGV	Automated Guided Vehicle
BBU	Baseband Unit
C2C	Controller to Controller
CNC	Computerized Numerical Control
CSI	Communication Service Interface
DL	Downlink
E2E	End-to-End
eMBB	enhanced Mobile Broadband
EPC	Evolved Packet Core
ESD	Electrostatic discharge
FPGA	Field Programmable Gate Array
gNB	gNodeB
GPS	Global Positioning System
HMI	Human-Machine Interfaces
ICT	Information and Communications Technology
I-LAN	Industrial Local Area Network
I/O	Input/Output
IoP	Internet of Production
IT	Information Technology

KPI	Key Performance Indicator
LiDAR	Laser imaging, detection and ranging
LTE	Long Term Evolution (3GPP technology)
MEC	Multi-access Edge Computing
ML	Machine Learning
mMTC	massive Machine-Type Communications
MSP	Multi-Sensor Platform
MTTF	Mean Time To Failure
NFV	Network Function Virtualization
NR	New Radio (5G radio interface)
NSA	Non-Standalone Architecture (5G deployment option)
OPC UA	Open Platform Communications - Unified Architecture
OEE	Overall Equipment Effectiveness
OT	Operational Technology
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
QoS	Quality of Service
RAN	Radio Access Network
RRH	Radio Remote Head
SA	Stand-alone Architecture (5G deployment option)
SDN	Software-Defined Networking
SLAM	Simultaneous Localization and Mapping
TCO	Total Cost of Ownership
TSN	Time-Sensitive Networking
UAV	Unmanned Aerial Vehicle

UC	Use case
UDP	User Datagram Protocol
UE	User Equipment
UHD	Ultra-High Definition
UL	Uplink
UPF	User Plane Function
UTM	Universal Transverse Mercator
URLLC	Ultra-Reliable Low Latency Communications
VR	Virtual Reality

Terminology and Definitions

The aim of this section is to clarify the key concepts, definitions and terms used throughout the project so that we have a common understanding on the language used during the project discussions and deliverables. This is a living document for internal project use that is expected to evolve during the project lifetime as new needs of clarification and common understanding arises.

Note that for most of the terms, we have adopted the definitions that are widely used and accepted in the ecosystem, and for some others we have proposed modifications to the existing ones or proposed totally new ones. Some existing definitions come from the NGMN 5G White Paper [NGMN15] as well as the 3GPP documents TS 22.261 [TS22.261] and 3GPP TS 22.104 [TS22.104]. The reference framework is mostly based on the NGMN document "Verticals URLLC Use Cases and Requirements" [NGMN2019] but adopted for a 5G smart manufacturing context. For data traffic models, the 5G-ACIA white paper on traffic models [5GACIA] is used, and for Mobile Edge Computing, ETSI documents are taken as a basis.

Reference Framework

An **application service** represents an application that is provided within a use case and scenario with particular characteristics in terms of key performance indicators (KPIs). Examples of an application service are Augmented Reality (AR), Virtual Reality (VR), Ultra-High Definition (UHD) video, real-time control, etc.

To realize an application service that involves distinct connected objects, a **communication service** must be set up and may need to fulfill specific requirements to allow proper operations of these connected objects. Principal requirements and performance metrics are explained in Subsection 2.3.3 and the different traffic flow types of such communication services are described in Subsection 2.3.4.

A communication **service category** represents a set of communication services that share some common characteristics in terms of connectivity. eMBB, mMTC and URLLC are examples of service categories. The services within each category may not have the same KPIs but share some basic connectivity parameters, like, e.g., the need to provide reliability and low latency in URLLC.

Two fundamental perspectives are considered to evaluate the performance of a practical 5G system deployment [TS22.104]: i) the **application perspective** of the communication services, which is related to the application using the communication service (e.g., a robot motion controller) and ii) the **network perspective**, which sustains this communication service. In between, the **Communication Service Interface** (CSI) connects the application system to the underlying 5G system, as depicted in Figure 10, and serves as the principal reference point for defining metrics and evaluating performance. In this figure,

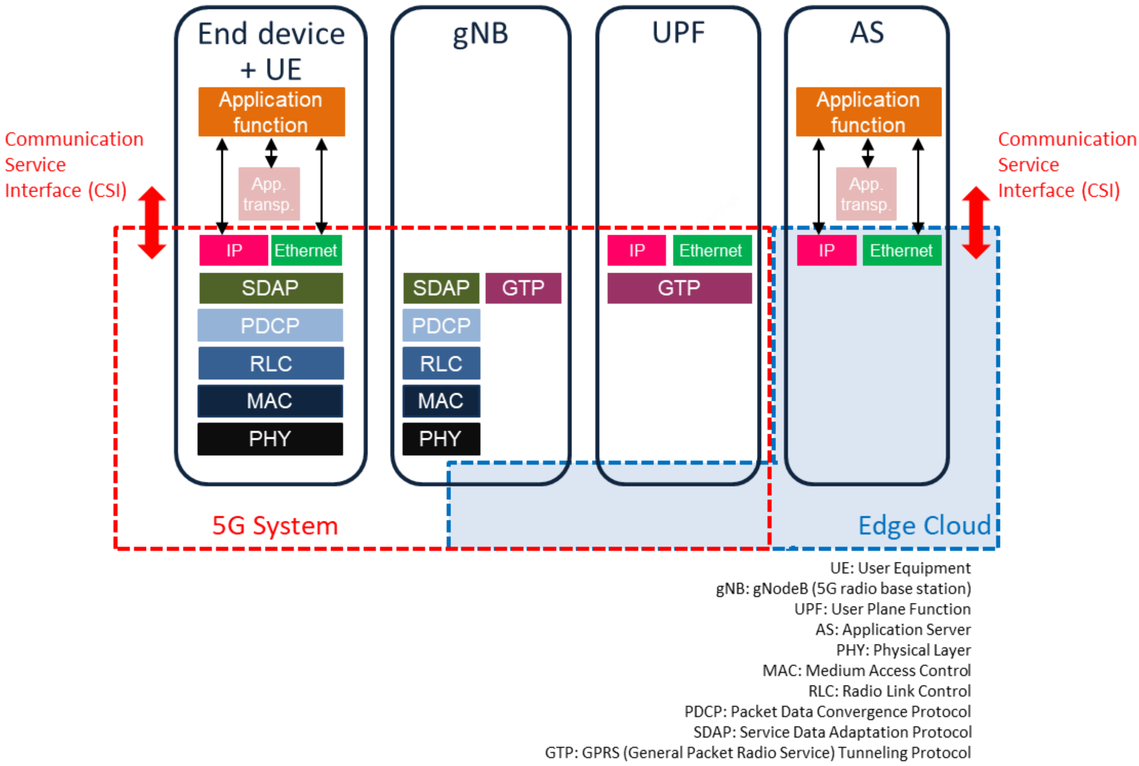
- **Application Server** (AS) refers to a server specifically designed to run applications. The "server" includes both the hardware and software that provide an environment for programs to run.

- **User Equipment (UE)** refers to the 5G functionality in a (mobile) end device that provides the connectivity to the 5G network.
- **Application function** refers to the functionality that realizes/enables the application service.
- **Application transport** refers to different protocol options for transferring data units of an application service in an end-to-end manner, such as TCP/UDP over IP, and TCP/UDP over IP and over Ethernet.

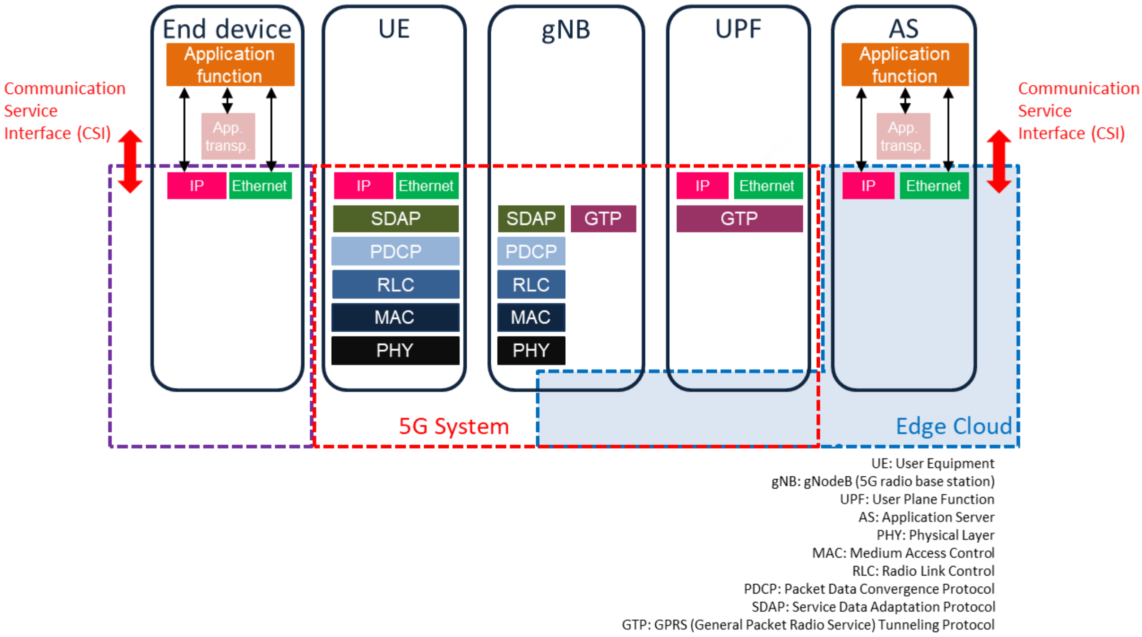
For most of the smart manufacturing deployments, the UE is not embedded in the end device (like in a smart phone) but connected via a separate L3/L2 connection (there may even be several end devices behing a 5G UE). For those cases, the reference framework looks like in Figure 10.

Edge Computing

Edge computing is a generic term encompassing a variety of different approaches to putting computing and storage resources at the edge of the network close to the customer rather than in remote data centers. It includes approaches like fog computing, cloudlets and others, which are not based on the cellular network. As illustrated in Figure 11, each segment of Edge computing has its own characteristics, potentially addresses different requirements and comes at a different cost, as distributing resources may significantly increase the complexity of integrating, operating and maintaining the overall infrastructure.



(a)



(b)

Figure 10: Reference framework of communication systems in smart manufacturing: (a) embedded UE, (b) UE over a L3/L2 connection

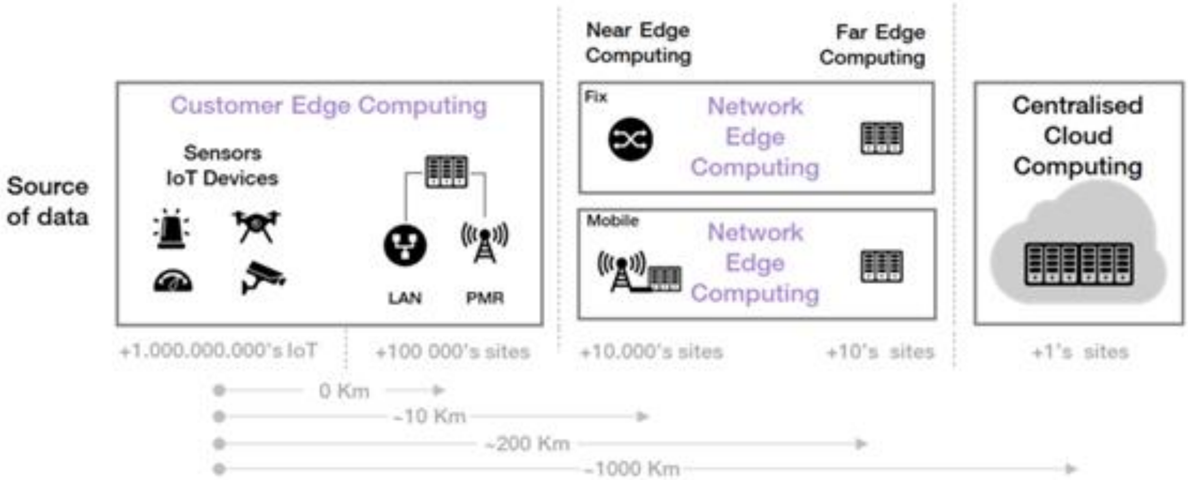


Figure 11 Different types of edge computing (source: Orange)

Initially, this notion was introduced and used for mobile networks, hence the term **Mobile Edge Computing**. Later, the European Telecommunications Standards Institute (ETSI) defined the term **Multi-access Edge Computing (MEC)** as a generalization of Mobile Edge Computing to any network. Although the concept of Edge computing applies to any type of network, in the context of 5G-SMART, the term **Edge Computing** is used to refer to a mobile network architecture model that enables a business oriented, cloud computing platform within the radio access network at the close proximity of the users/devices of the mobile network to serve delay-sensitive, context-aware applications. It also enables Network Function Virtualization. Those edge-based capabilities can be provided to internal network functions, in-house applications run by the operator or the network customers, or potentially third-party partners / developers (Figure 12). ETSI White Paper No. 28 on “MEC in 5G networks” [ETSI5GMEC] offers a good overview of the model.

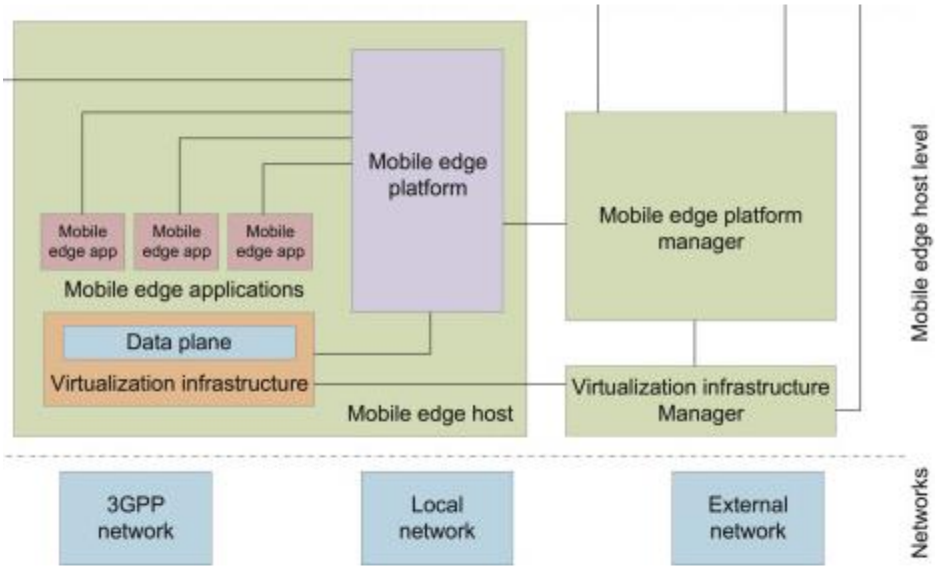


Figure 12: Integrated MEC deployment in 5G network [ETSI5GMEC]

Different Edge compute deployments are possible (e.g. factory cloud, on-premise Edge cloud, telco Edge cloud etc.), the details of which are out of the scope of this document. For more details on the deployment options, one can refer to [ETSI5GMEC] or [SKTW20]. For illustration purposes, a mobile Edge host could be a virtual machine on the same hardware as a 5G radio base station (gNodeB) and a mobile Edge app could be a robot controller software running on this host (Figure 12).

Another model for managing distributed cloud environments in mobile networks, from central cloud computing to edge cloud computing, is defined by the **Open Networking Automation Platform** [ONAP], which is an open source project with wide industry support [ONAP-WP]. ONAP allows to orchestrate and manage network functions and application functions in a distributed computing environment. This enables to provide flexible realizations for different services where applications are embedded into the communication infrastructure according to network characteristics and service needs [BSK18] [SKTW20], see Figure 13.

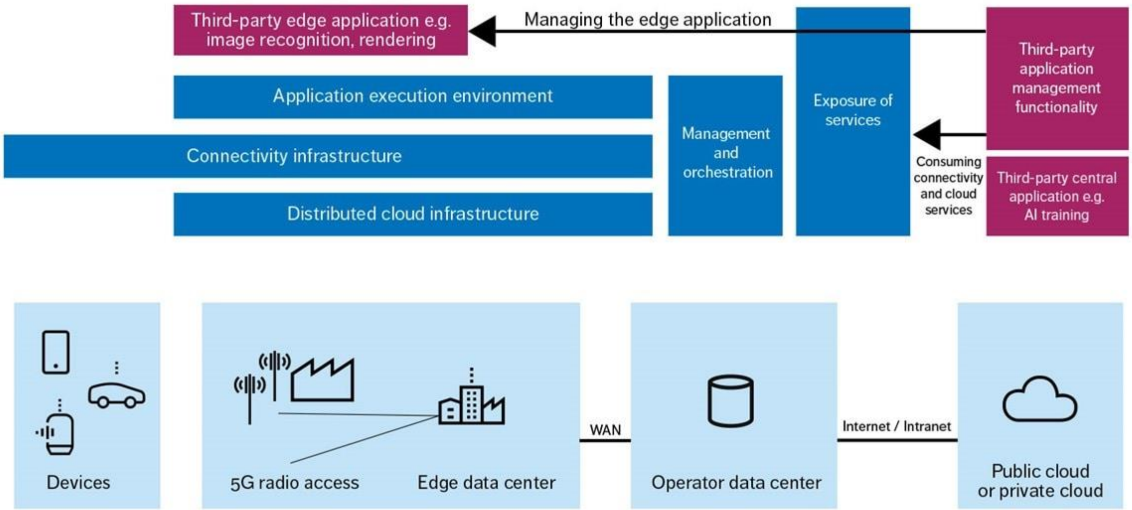


Figure 13: High-level architecture of an edge-computing solution (source: [SKTW20])

NOTE: **Edge cloud** is another term for edge computing, not necessarily only on MEC as defined above but also on other edge architectures. In 5G-SMART, the term **Edge cloud** is used synonymously with **Edge computing**.

Local BreakOut (LBO): defines local termination of the 3GPP-standardized user-plane connectivity close to the base station. This enables to locate time-critical applications in proximity, for example in an edge cloud, and provide access to advanced 5G capabilities (e.g., 5G support for LAN and TSN connectivity) at the local site. LBO combined with 5G URLLC RAN support enables bounded low latency for control loops on the factory shop floor that connect machines and sensors.

Metrics and Key Performance Indicators (KPIs)

Data rate, timeliness and dependability are key parameters to evaluate the performance of a communication service for smart manufacturing. Related KPIs are further explained in the following.

Data Rate

The **user data rate** is defined as the minimum value of the number of bits transmitted or received over time, typically expressed in Mbit/s, which is expected to be measured at the CSI shown in Figure 10. This definition excludes scenarios for broadcast-like services, where the given value is the maximum that is needed [TS 22.261].

For uneven or bursty traffic, the **average (respectively peak) data rate** is defined as the average (respectively maximum) number of bits transmitted or received at the CSI over a time window. The specific size of this time window depends on the communication service characteristics (such as traffic, performance requirements) and the application that uses this communication service.

Timeliness Aspects

Timeliness aspects are essential when it comes to URLLC communication or to synchronized industrial processes. Latency, jitter and synchronization accuracy are defined as follows:

- **(End-to-end) Latency** is the time that it takes to transfer application data of a given size from a source to a destination, from the moment it is transmitted by the source to the moment it is successfully received at the destination (one-way latency). In other words, the end-to-end (E2E) latency, typically expressed in ms, is measured from the CSI on the UE side to the same interface on the application server side (Figure 10), or vice versa.

- **Jitter** is the variation of a time parameter, typically the end-to-end latency. The jitter value is specified by the application service.

- **Time synchronization error** is defined as the value of the time difference between a synch master (that is used as the timing reference) and any device operating on time-sensitive applications. For example, a time synchronization error of ≤ 1 µs is equivalent to having a time difference equal to at most ± 1 µs offset between the sync master (for example global positioning system, GPS) and any device in an industrial network, resulting in two times this value as the maximum absolute time difference between any two devices in the network (i.e., 2 µs).

Dependability

Dependability involves the following components:

- The **survival time** indicates the maximum time period the communication service may not meet the application's requirements before there is a failure on the application layer, such that the communication service is deemed to be in an unavailable state. Such a situation occurs when the communication with the network is lost, the application crashes and an alarm is raised.

- In the context of network layer packet transmissions, **reliability** is 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 [TS 22.261]. In order to well differentiate reliability from communication service reliability (defined below), we will use the term **network packet transmission reliability**.

- The **communication service availability** relates to the ability to allow correct operation of the application. It 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 according to the specification in a specific area" [TS 22.104]. The service is unavailable if the messages received at the target are impaired and/or untimely (e.g. latency > stipulated maximum), resulting in survival time being exceeded.

- The **communication service reliability** relates to the ability to continuously operate as required by the application, without failure, for a given time interval and under given conditions (e.g. mode of operation, stress levels, and environment). It can be quantified using metrics such as **mean time**

between failures (MTBF) or the probability of no failure within a specified period of time. MTBF is the mean value of how long the communication service is available before it becomes unavailable. For instance, a mean time between failures of one month indicates that a communication service runs without any failure for one month on the average before a failure makes the communication service unavailable. Note that the failures shorter than the survival time remain unnoticed by the application. This KPI is an end-to-end reliability metric comprising the reliability of several sub-segments, such as the equipment (including hardware and software) reliability as well as the network packet transmission reliability.

- **Resilience** can be defined as "the intrinsic ability of a system to adjust its functioning prior to, during, or following changes and disturbances, so that it can sustain required operations under both expected and unexpected conditions".

Note that some of the components of dependability relate to the application perspective, while others relate to the network perspective. The relationship and mapping between these views is explained in the Appendix.

Communication Characterization

A communication service may involve different types of sources and destinations, e.g. humans and/or different types of machines such as stationary or mobile robots, controllers, actuators or sensors.

Machine-to-Machine (M2M) communication stands for the predominantly automated exchange of information between technical equipment such as machines, vending machines, vehicles or measuring systems (e.g. electricity, gas and water meters) or to a central data processing system. M2M communication includes, among other things, remote monitoring, remote control and remote maintenance of machines, equipment and systems, traditionally referred to as telemetry. Communication can be either wired or wireless. A human being is usually not involved in the communication, although a limited human involvement does not prevent the classification as M2M communication. M2M technology combines information and communication technology. Automated communication between technical equipment is predicted to be a major growth driver in the telecommunications industry in the coming years. Growth rates are expected to be many times higher than those of voice communication. The number of possible M2M devices and M2M services offered will also increase sharply in the next few years according to current expectations [BUN].

The nature of the communicating entities affects the geographical characteristics and the overall shape of the resulting traffic.

Geographical Characteristics

The **communication area** is defined as the given area where a communication service should operate, under given conditions and requirements.

The **communication density** is the number of devices performing a given communication service per area unit, within the communication area. It may be specified in terms of minimum, maximum or average. The communication area, range and density may also be defined per volume, depending on the considered use case.

Localization/positioning error (typically expressed in m) is defined as the value of the difference between the estimated position of an object with respect to its real location, according to a reference coordinate system (which is specific for each country). Finally, knowing device **mobility aspects** is important in the design of a mobile radio network to model, among others, the handover probability, the load variation across cells or the receive power variation in both uplink and downlink [5GACIA1]. Some devices might be restricted to move in predefined corridors, as this is most commonly the case for AGVs, while humans with connected augmented reality (AR) glasses are expected to move with less restriction. Therefore, the description of mobility aspects includes parameters related to the device size, velocity, motion capabilities and trajectory (predefined or not, restricted or not, pause time, etc.) as well as average distance between mobile devices. Ideally, a statistical motion model is provided (for example, the distance between vehicles is modelled as an exponential random variable with the average equal to the average distance between mobile devices).

NOTE: The moving and/or rotating sensors/actuators in a motion control system of a machine are also excluded from the mobility modelling, since typically they have little impact on the handover probability, load variation across cells, or the receive power variation [5GACIA1].

Traffic Models

Within the context of this document, traffic is said to be **symmetrical** between two nodes A and B if the average date rate from A to B is equal to that from B to A.

Communication in industrial automation has two major characteristics: **periodicity** and **determinism**.

Periodicity refers to transmitting messages with a certain transmission interval in-between messages. If that transmission interval is known and repeated, then the traffic is said to be **periodic**, otherwise it is **aperiodic**.

Determinism refers to the boundedness of the time between the transmission and the reception of a message. If this time is bounded, then the communication is said to be **deterministic**, otherwise **non-deterministic**.

Three different traffic models may be used for industrial communication, each with distinct constraints and requirements.

First, **periodic deterministic communication** is periodic with stringent requirements on timeliness and availability of the communication service. Applications producing this traffic pattern are sending messages at a fixed time interval, the transfer interval [TS22.104].

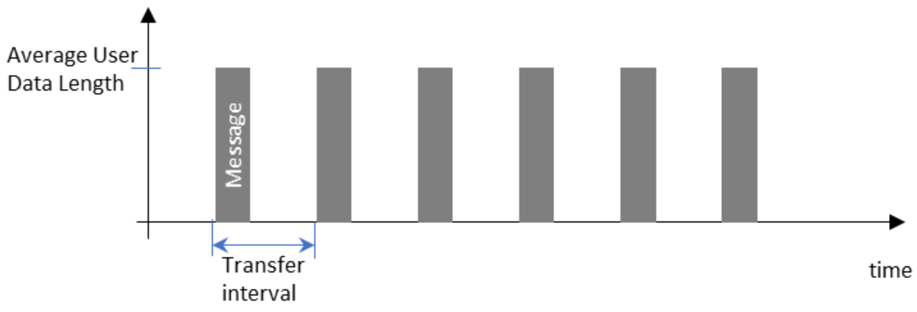


Figure 14: Periodic deterministic communications and the transfer interval [5GACIA]

The **transfer interval**, as depicted in Figure 14, is the time difference between two consecutive transfers of application data from an application to the 5G system via the CSI. Deterministic periodic traffic can be specified using the attributes of user data length (i.e., application payload size) and transfer interval [5GACIA].

Second, **aperiodic deterministic communication** consists of messages that are sent regularly but aperiodically, i.e., there is no fixed transfer interval between messages. Even without a pre-set sending time, requirements on timeliness and availability of the communication service are still stringent [TS22.104]. Applications consuming this type of traffic are still expecting to receive messages within a predictable latency [5GACIA1].

Finally, **non-deterministic communication** subsumes all other traffic types than periodic/aperiodic deterministic communication. This includes periodic/aperiodic non-real-time traffic [TS22.104].

Bursty traffic is characterized by a sequence of successive messages that are sent in a burst, for example to transmit images. Bursts can occur periodically or aperiodically. It is not expected that the messages of a burst are received at the target end-point within a specified time frame [5GACIA1].

Production/Manufacturing related Terms

A **digital twin** is a complete and operational virtual representation of an asset, subsystem or system, combining digital aspects of how the equipment is built (PLM data, design models, manufacturing data) with real-time aspects of how it is operated and maintained [GAN18].

A **control loop** can be defined as all functional components used for automatically regulating the actual state of a process that is being controlled to match a desired state.