D7.4

FINAL PROJECT REPORT

The 5G-SMART project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no 857008.

D7.4 Final Project Report

Grant agreement number: Project title: Project acronym: Project website: Programme:	857008 5G Smart Manufacturing 5G-SMART www.5gsmart.eu H2020-ICT-2018-3
Deliverable type: Deliverable reference number: Contributing workpackages: Dissemination level: Due date: Actual submission date:	R: Document, report D28 WP1-WP7 Public 2022-05-31 2022-05-31
Responsible organization: Editor(s): Version number: Status:	ERI-SE Leefke Grosjean, Krister Landernäs V1.0 Final
Short abstract:	This deliverable provides a summary of the major results and achievements of the 5G-SMART project.
Keywords:	Summary, 5G-SMART

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Executive summary

In this final project report of 5G-SMART the main achievements and results of the project are summarized. For all work packages, the most important accomplishments of the project are explained, and references to all deliverables are provided. The achievements include the project's work towards 5G integration into the manufacturing (new use cases, business value creation, business models, deployment options) and 5G enhancements towards manufacturing (new 5G features, end-to-end architectures, and network management), but also the significant work of the project in designing and developing, implementing and evaluating smart manufacturing use cases at the three trial sites of the project. It is evident from the report that 5G-SMART has achieved all its objectives and thereby succeeded in accomplishing its vision of showing how 5G can boost smart manufacturing.

Contents

1 Introduction

In 2019 the 5G-SMART project started its journey working towards the vision of empowering the European manufacturing sector by integrating 5G solutions into the manufacturing ecosystem, thereby contributing to an accelerated digital transformation. Through its work on industry field trials, business models, and research concepts, 5G-SMART has demonstrated how 5G can improve manufacturing.

The seven ambitious objectives of 5G-SMART are summarized below:

- **Objective 1:** To demonstrate and evaluate 5G technologies and architecture capabilities for smart manufacturing use cases by validating related 5G KPIs defined in ITU/3GPP and 5G PPP as well as 5G support of concurrent usages of network resources by different vertical domains.
- **Objective 2:** To identify, assess and propose innovative advanced "industrial" 5G KPIs with more focus on industrial characteristics.
- **Objective 3:** To identify, assess and propose new 5G features targeting connected industries.
- **Objective 4:** To identify viable business models for 5G manufacturing use cases.
- **Objective 5:** To identify regulatory aspects with a direct impact on the realization of 5G for smart manufacturing.
- **Objective 6:** To disseminate and exploit 5G-SMART outcomes and contribute to standards development organizations (3GPP/ITU-T/IETF/ETSI), regulatory forums, and scientific and industrial domains.
- **Objective 7:** To contribute to the 5G Action plan for Europe, validating 5G capabilities ("phase 1" features) in real factory environments.

In order to reach 5G-SMART's seven objectives, the diversity of the consortium of 5G-SMART has proven to be a major strength. Having partners from the entire ecosystem working towards these goals, 5G-SMART has early in the project identified the need for defining a common language and common understanding of important terms in order to facilitate the discussions. For this purpose, the document on "5G common terminology" [5GS20-CT] has been developed in the consortium, which has also been found useful outside the consortium, e.g., other 5G-PPP projects and 5G-ACIA.

1.1 Objective of the document

This document aims to summarize the main results and achievements of the 5G-SMART project. It provides an overview of the project upon its finalization and contains references to the most important outputs of the project.

1.2 Structure of the document

This document is structured as follows: Section 1 introduces the project, listing the seven objectives that 5G-SMART started out with to fulfill. Thereafter, for each work package WP1-WP6, the most important results and achievements are summarized, following the work package structure as shown in Figure 1. More specifically, Section 2 provides an overview of the work performed in WP1 on 5G integration into the manufacturing ecosystem. Section 2 also details the work of WP2, WP3, and WP4 on the 5G-SMART trials for evaluation and validation of 5G capabilities. Section 3 summarizes the main achievements and results of WP5 on optimizing 5G for smart manufacturing. Finally, Section 6 concludes the document.

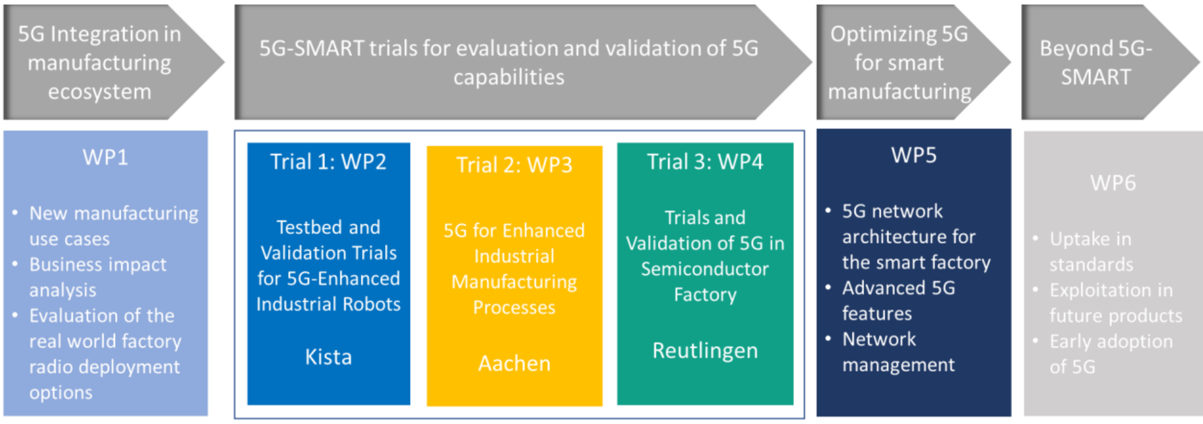

Figure 1: 5G-SMART project structure

2 WP1: 5G integration into the manufacturing ecosystem

Factories of the future will be characterized by flexible, modular production systems requiring also flexible and versatile communications and computations to enable them. 5G technologies are expected to support the requirements of factories of the future in typical application areas such as factory automation, process automation, Human-Machine-Interfaces (HMIs) and production IT, logistics and warehousing, process monitoring, advanced measurement systems for production, quality control, maintenance, etc.

2.1 New manufacturing use cases

The application areas of smart manufacturing contain a plethora of use cases with different requirements on the communication and computation infrastructure, which need to be fulfilled by the underlying 5G infrastructure. 5G-SMART has made an important contribution to better understanding the needs of the manufacturing sector with respect to 5G, with the exploration and analysis of both the trialed use cases as well as additional six forward-looking smart manufacturing use cases in WP1. For all of the use cases the state-of-the-art, benefits of using 5G as well as requirements and challenges have been investigated and documented. The full analysis is published in D1.1 [5GS20-D110]. Table 1 lists all use cases that have been investigated in 5G-SMART together with their classification according to 3GPP TR22.804 [3GPP-22.804].

The main results are summarized below:

- The analysis of the requirements and KPIs of the use cases clearly showed 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, where the local 5G network has to inter-work with traditional public cellular networks.

- Remote operations and monitoring have been identified as a key application of several use cases in smart manufacturing, demanding reliable wireless technology for their implementation. They are seen as an important driver for 5G in the future, which already became apparent during the outbreak of COVID-19. 5G technology will play an important role in realizing future Artificial Intelligence (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 enable computational offloading, thereby allowing a fast execution of the AI engines locally.

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 1: Use cases investigated in 5G-SMART

2.2 Business value creation and business models

2.2.1 Business value creation enabled by 5G for manufacturing industries

Between 2021 and 2025, Industry 4.0 technologies are expected to significantly increase the gross margins of the production industry. Applications such as closed-loop control, predictive maintenance, digital twins, augmented reality (AR), and automated guided vehicles are expected to be essential enablers. A reliable, low-latency, high-performance wireless infrastructure plays a decisive role for all these applications. While many production companies endorse the predictions of massive benefits from 5G for productivity, uncertainty is still inhibiting investments so far. The main reason is that a comprehensive framework is missing to quantify potential improvements and allow an economic evaluation of 5G-enabled benefits for specific use cases from an end-user perspective.

In an attempt to fill this gap, 5G-SMART has developed an assessment framework to quantify the business value of 5G for industry applications. The focus is on brownfield investments, counting on the production planner to be able to provide data regarding the status quo of the application both from a technical and economic perspective.

The framework implements a four-step approach with the following steps:

- Requirement check: In this step, the production planner selects a use case as well as the network requirements from the end-user’s point of view.
- Goal definition: Technical and economic goals are determined. The seven technical goals are shown in Table 2 and two economic goals (net present value and return on investment) can be selected.
- Data Acquisition: In this step, the production planner enters relevant data of the use cases to be analyzed.
- Process evaluation: Finally, the evaluation result of the technical and economic potential of 5G for the users’ process is given.

Deliverable D1.2 [5GS20-D120] describes the assessment framework in detail. The main achievements of the project in this area are summarized below:

- Literature research of the impact of 5G on the behavior and performance of applications in the smart manufacturing sector,
- Development of the model including determining key KPIs and operationalizing these KPIs,
- Implementation of the model in an Excel/online tool,
- Evaluation of selected use cases to improve the tool.

The evaluation framework has been continuously updated and improved and is expected to be published and commercialized soon.

The analysis of the use cases as described in D1.1 [5GS20-D110] has been an important input to the development of the framework. The technical industry goals defined for the framework in D1.2 [5GS20-D120] and shown in Table 2 have been, on the other hand, an important input to the evaluation activities for the trials of the project.

Quality	Sustainability	Flexibility	Productivity	Mobility	Utilization	Safety
Quality rates the degree to which the output of the production process meets the requirements.	Sustainability describes the level to which the creation of manufactured products is fulfilled by processes that are nonpolluting, conserve energy and natural resources.	Flexibility describes the ability to process many different parts within the manufacturing system with minimum engineering effort and changeover time	Productivity is a measure of manufacturing system or process output per unit of input, over a specific period of time, used as a metric of the production and the engineering efficiency.	Mobility describes the ability of moving and replacing objects on the factory shopfloor.	Utilization describes the ratio of actual time the machine is used compared to the theoretically available time.	Safety describes the ability of a system to protect the operator from harm or accidents.

Table 2: Industry goals in 5G-SMART

2.2.2 Business models for smart manufacturing

5G non-public networks (NPN) are seen by the vertical industries as a real competitive advantage regarding wireless-based communication. Mobile Network Operators (MNO) are getting involved in the provisioning of 5G services for industrial customers, whose requirements may differ from the general public.

In deliverable D1.3 [5GS21-D130] 5G-SMART investigates how the relationships can be built between Industrial parties, MNOs and other third-parties, and which value MNOs can bring in this ecosystem. The analysis is performed by first defining relevant relationship models and then analyzing these based on a list of criteria identifying the main challenges to be addressed by the different stakeholders, in order to fulfill the industrial end-user's needs and to facilitate business relationships. The following categories for key value creation criteria have been considered to analyze and compare relationship models from a business perspective:

- Techno-related criteria to comply with performance requirements for industrial services,
- Business-related criteria facilitating the development of industrial activities,
- Technics- and business-related criteria towards NPN coverage extension and scalability,
- Security and confidentiality criteria, to control risks and ensure data sovereignty,
- Economic criteria, to assess needed CAPEX and OPEX investments.

While the framework for business value creation developed in D1.2, and described in the preceding section, is independent from an operation model, operational models play a key role in the analysis of business models for smart manufacturing. In order to identify business models and value proposition, the following roles concerning the ownership, deployment, operation, and management of NPNs have been defined:

- NPN Owner is the role of owning the NPN infrastructure (including both the hardware and the software components).
- Spectrum Owner is the role of having the right to transmit radio signals at a certain frequency band.

- NPN Integrator is the role of deploying and configuring the NPN according to a chosen architecture and making it ready to use.
- NPN Operator is the role of operating and managing the NPN on a day-to-day basis.
- NPN User is the role of using the services offered by the NPN.

Furthermore, three different stakeholders are identified:

- Mobile Network Operator (MNO) is the stakeholder which owns and manages a public land mobile network (PLMN).
- Industrial Party is the stakeholder which requests NPN services for performing an industrial task or a group of industrial tasks.
- Third party is a business entity whose core business is the creation of value from the 5G technology, but which is positioned along the value chain of 5G and neither at the source, nor at the end of it.

As the demand for non-public networks is growing, so is the competition to deliver accompanying services. 5G-SMART contributes in D1.3 [5GS21-D130] to a wider understanding of the different strengths and weaknesses of service providers and how different deployment options fit some scenarios better than others. Understanding and specifying the needs of the NPN User is key to target the right NPN deployment option and develop profitable business with involved parties. 5G-SMART contributes to this with the analysis on organizing who does what, understanding the strengths and weaknesses of each model and evaluating the balance between the required investment and the potential enhancement of the overall efficiency (e.g., increased flexibility, optimized maintenance, etc.), security, etc. A key conclusion is that none of the potential business and technical options can satisfy all requirements. Therefore, a trade-off has to be made, where 5G-SMART contributes with criteria and aspects that industrial players need to consider making an informed decision, and for MNOs to identify key resources required to be able to offer high-valued services.

2.3 Evaluation of radio deployment options

Wireless connectivity is increasingly becoming a necessity for business-critical services in industrial processes, such as those related to assembly lines and other modes of production. However, the specific needs and requirements can differ greatly between the different industries, and it has become obvious that the communication network offering has to be tailored for each particular deployment. While doing so, a large variety of aspects has to be considered, e.g., characteristics of the use case requiring wireless connectivity, the overall business case, spectrum regulations, characteristics of the industrial site, and so on.

Identifying the different radio network deployment options for non-public industrial 5G networks to provide the required communication services for smart manufacturing is a key first step, which has also been the starting point of the work in 5G-SMART. The project has identified and discussed different radio network deployment options for smart manufacturing, aiming at providing an overview for any desired industrial 5G scenario or service. The input data needed to select the most feasible deployment options has been identified. For the different NPN architecture options, the feasibility has been analyzed. Moreover, the impact of spectrum options available for the stakeholder deploying and operating a non-public network has been discussed. A wide range of system-level simulation studies has been performed that assess the technical performance of the identified deployment scenarios.

The detailed results from the discussions, analyses and performance evaluations related to the different radio network deployment options are summarized in deliverable D1.4 [5GS20-D140] and D1.5 [5GS22-D150], only selected key results are presented below.

5G-SMART has performed an analysis of capacity and required spectrum for smart manufacturing radio network deployment options. Evaluations are carried out through performance evaluations in link-level and system-level simulations.

- The analysis suggests that the various radio network deployment options and features can significantly impact the performance of a non-public factory network supporting ultra-reliable low-latency communication (URLLC) services. The applied Time Division Duplex (TDD) downlink-uplink pattern defines a lower bound for the achievable latency and has a clear impact on the maximum system capacity.
- Packet size also has impact on the performance of the system, which marks that a proper selection of the payload is of interest for the improvement of system performance.
- Finally, for latency critical URLLC services the downlink is more sensitive to interference increase at high load due to inter-cell interference, as compared to the uplink.

A complete trade-off analysis has been made for different bands, bandwidths, density of users and allocation of resources in TDD mode. This analysis has shown that the system limits of capacity can come from the limitation of resources and in some cases due to interference or propagation conditions.

5G radio transmission is based on electromagnetic waves that are created at the transmitter and are then propagating through the transmission medium. It is desirable that a strong signal is received at receiver to achieve reliable communication at high date rates. However, the signal also propagates to other locations where other equipment may be located and may there create interference. Co-existence describes the impact of such interference on another system, or the mutual interference among multiple systems on each other. 5G-SMART has assessed empirically the coexistence between a wide-area outdoor network and an indoor NPN both operating in the same channel. The results can be summarized as follows:

- Under some conditions, the transmission in the outdoor network can create interference to the indoor NPN and, therefore, increase the transmission latency of the indoor NPN. Such interference can in particular appear in a (practically uncommon) situation, when an outdoor User Equipment (UE) is located right outside an unshielded window of a factory. This can lead to an increased NPN latency, which may be very small for the median values but can impact the 99th and 99.9th percentile of the latency distribution, especially if the two networks use un-synchronized TDD configurations with strong cross-link interference over very short distance.
- It has been shown that such cross-link interference can be avoided by an indoor TDD configuration that avoids Downlink (DL) transmission slots during Uplink (UL) transmission slots of the outdoor network, while still allowing for a separate TDD configuration for the NPN.
- When the outdoor UE is located further away from the factory wall, the interference on the indoor NPN becomes negligible independent from the used TDD pattern.

Finally, a realistic performance evaluation in the Bosch factory deployment has shown the feasibility of defining micro-exclusion zones via the usage of a proper planning plus the use of selective beamforming. Results show that it is possible to isolate a certain area while maintaining on average good levels of service. However, URLLC type of service cannot be deployed together with micro-exclusion zone solution due to significant signal quality degradation. Careful planning of the radio network deployments and agreeing on appropriate emission limits should be applied to control the level of the interference.

3 WP2, WP3, WP4: 5G-SMART trials for evaluation and validation of 5G capabilities

For all of the trials, special focus has been brought to understanding the specific requirements and needs of the use cases, with the objective of identifying and assessing innovative advanced industrial KPIs with more focus on industrial characteristics. To this end, all trials have been evaluated with respect to the seven industrials goals, shown in Table 2, that have earlier been identified as essential for understanding the business value creation of 5G in smart manufacturing.

The common methodology for all trialed use cases can be summarized into the following steps:

1. Use case characterization and identification of relevant industry goals.
2. Radio planning and 5G deployment at the trial site.
3. Use case design, implementation and integration.
4. Identification of validation scenarios and relevant KPIs for evaluation.
5. Validation, evaluation and demonstration.

In the following sections the use cases and key results are summarized per trial site and use case. It is important to note that 5G-SMART covers with its trial deployments all relevant 5G system options of today, that is non-standalone architecture (Kista, Aachen) and standalone architecture (Reutlingen) and mid-band New Radio (Aachen, Reutlingen) and high-band New Radio (Kista).

3.1 WP2: 5G-enhanced industrial robots

At the Kista trial site, the testbed demonstrates, evaluates, and validates 5G capabilities for 5G-enhanced industrial robotics inside the Ericsson smart factory. Robotics is a vital part in modern manufacturing. 5G wireless communications and edge-cloud computing are two technical trends that may disrupt the way in which industrial robots are deployed and used in the future. The 5G-enhanced industrial robotics testbed validates novel design of industrial robotics, where part of the robot control is moved from the robot hardware to a central location, e.g., a control room in the factory. This puts stringent requirements on 5G in terms of reliable and low-latency communication for connecting the robot to the controller.

The use cases investigated are:

- Use case 1 on 5G-connected robots and their collaboration,
- Use case 2 on vision-supported real-time human-robot interaction, and
- Use case 3 on advanced visualization for the factory floor.

These new use cases bring several advantages. By off-loading computational tasks, the hardware of industrial robots can be simplified, become cheaper and occupy less space on a factory floor. This is achieved by hosting control functionality in an edge cloud – a local computing infrastructure of the factory, rather than follow today's design. A typical design has the control placed in an embedded processor on the industry robot or in a dedicated control hardware that is in proximity of the robot and connected to it via cables. By reducing the cabling, the flexibility of redesigning the factory floor is improved. 5G wireless connectivity allows increasing the number of mobile robots in a factory, which can take over more diverse tasks in a flexible production process. A key component of the testbed is the machine vision system that is being used to detect and track objects on the factory floor as well as assist operations of both mobile and stationary robots. An overview of the use cases' setup is illustrated in Figure 2. Details of the design and implementation of the testbed can be found in D2.1 [5GS20-D210] and D2.2 [5GS22-D220].

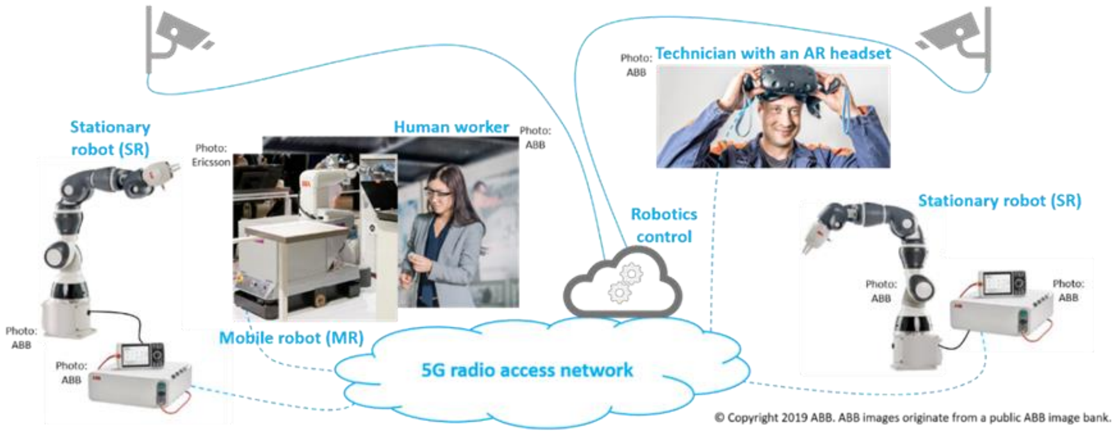

Figure 2: The use cases' setup for WP2, Source: ABB

3.1.1 5G-connected robots and their collaboration

This use case focuses on a very common task in manufacturing, namely the scenario of autonomously transferring goods and other items between production lines. The task has been realized relying on the collaboration between different types of robots, namely a mobile robot and a stationary robot arm. The project has successfully implemented a setup where the mobile robot transfers an object between workstations with ABB's robot arms, thereby navigating the mobile robot in an environment shared with human workers and having the stationary robot arms grasp and move the object. Other two distinctive features of the use case instantiation are machine-vision-assisted docking of the mobile robot to a precise pose next to the robot workstation and vision-assisted execution of the object pick-and-place operation by each of the stationary robots. All these operations are controlled from an edge cloud and over 5G. An overview of the implementation, highlighting the main equipment and functions delivered across all three WP2 use cases, is shown in Figure 3.

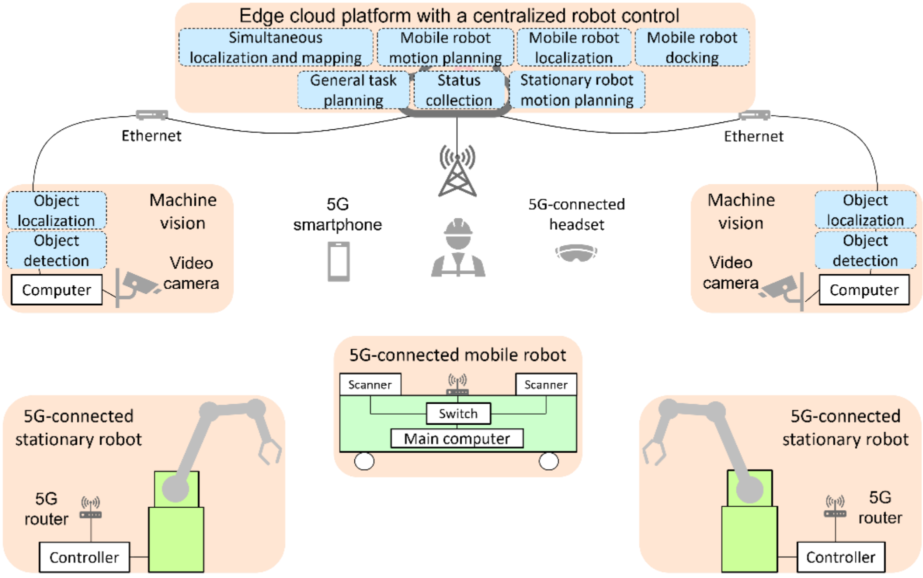

Figure 3: Use case overview, Source: ABB

3.1.2 Vision-supported real-time human-robot interaction

Workers in a factory need to have safe and efficient ways of interacting with machines and robots. In this project, we explored and implemented a novel approach to robot programming. The use case is instantiated by a human worker (e.g., commissioning engineer) programming a stationary robot arm to autonomously execute the object pick-and-place operation through the means of demonstration. Instead of writing a robot program, the worker mimics grasping and moving the object through application on a mobile device (in our case, a 5G-enabled smartphone), which the stationary robot arm then executes as seen in Figure 4.

Figure 4: Robot programming using 5G-enabled smart phone, Source: ABB

To perform the operation, the robot arm needs to learn two tasks, trajectory generation and object pick/drop. In the trajectory generation task, the human worker manipulates the robot motion by contactless lead-through using the smartphone. The pick/drop task is taught by opening and closing the robot arm's gripper. The successful implementation illustrates the potential of advanced means of human-robot interaction on the factory floor, which would positively impact flexibility.

3.1.3 Advanced visualization for the factory floor

This use case is characterized by employing AR-based means to remotely manipulate robot motion and to visualize operational robot information in an efficient way. It also illustrates how novel technologies such as AR can be exploited to create new ways for human workers to access and maintain factory-floor machinery. Like in the other two use cases, machine vision support is used to detect and distinguish between different objects, i.e., stationary robot arms for which operational information is collected.

The implemented scenario is shown in Figure 5. It contains two separate locations inside a factory premises, one where an AR-headset-equipped human technician is and another one where an ABB single-arm robot is located. Via the headset, the human technician can retrieve and visualize status information of the robot, which would aid her/his inspection and maintenance responsibilities.

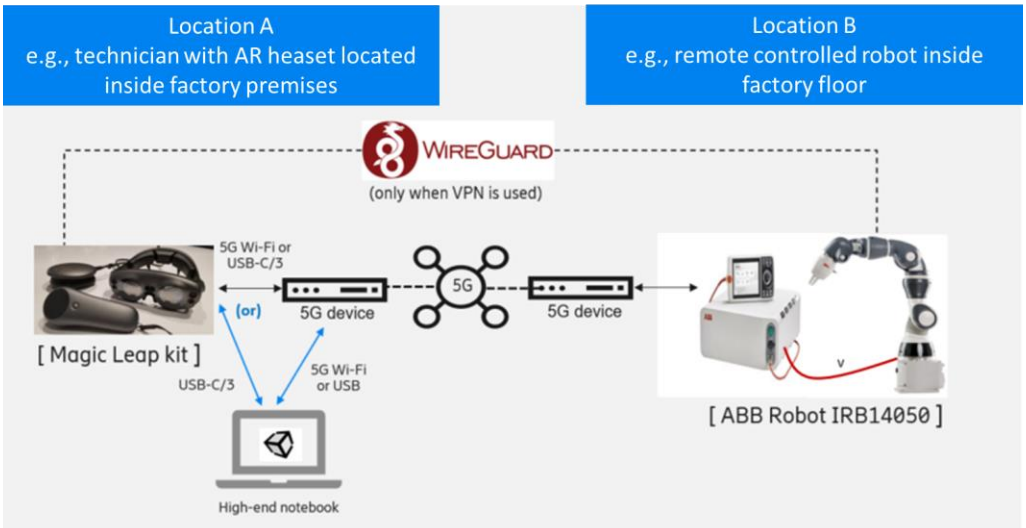

Figure 5: The AR-based use case implementation, Source: Ericsson/ABB

3.1.4 Summary of main findings and results

The use case validations showed that the mobile robot navigation, the mobile robot docking, and the pick-and-place by the stationary robot arms are feasible to implement with high-level robot control functionality being moved to an edge-cloud node, while running communication over 5G. Furthermore, both the lead-through teaching and AR visualization were validated to work well using subjective evaluations.

It is to be noted that all test results and measured KPIs should be seen in the light that the functional design and implementation for the industrial robotics use cases were prototyped, and that the 5G network was based on MBB services, without functionality for, e.g., bounded latency. Despite this, the overall conclusion is that 5G supports the implemented use cases, which is also an important learning of the project.

All details of the validation of the 5G capabilities at the Kista trial site can be found in D2.3 [5GS22-D230].

3.2 WP3: 5G for enhanced industrial manufacturing processes

At the Aachen trial site, there are two use cases trialed. These are (1) 5G for wireless acoustic workpiece monitoring and (2) a 5G versatile multi-sensor platform for creating a digital twin.

3.2.1 5G for wireless acoustic emission tool condition monitoring

In the first use case trialed within the testbed, an acoustic emission (AE) sensor has been developed and integrated into a 5-axis milling machine, to monitor the condition of cutting tools. Acoustic workpiece monitoring is a technology that makes use of AE sensors for collecting relevant data for the monitoring system. AE sensors are widely applied for monitoring cutting processes, in particular for performing the following items in real-time:

- Monitoring of tool wear,
- Detection of tool breakage,
- Detection of collision of the machine spindle,
- Detection of inhomogeneities of the workpiece material.

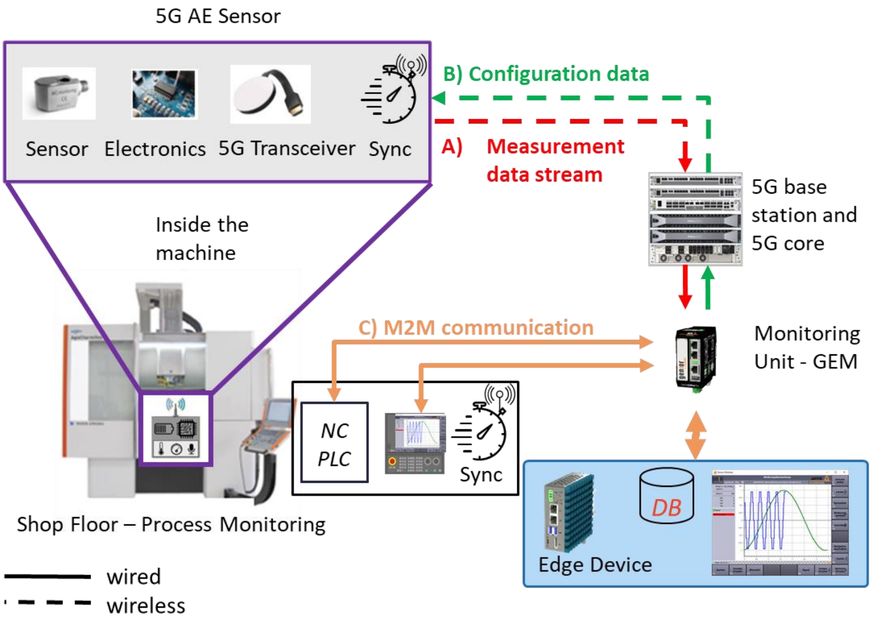

Figure 6: 5G wireless acoustic emission (AE) system, Source: Fraunhofer IPT

A timely detection of any of the above disturbances is highly desirable as it allows an intervention into the process, to optimize the fabrication process, as well as to reduce the production costs due to decreased failure rates.

In 5G-SMART, the following setup has been implemented, as illustrated in Figure 6: a wireless acoustic emission sensor with 1 MHz sampling rate has been integrated with a 5G device. The sensor is connected to the workpiece during the machining process to provide measurements from the machine to a monitoring unit, e.g., located in an edge cloud. The raw signals are preprocessed on the wireless device using a Field-programmable gate array (FPGA) and then transmitted via 5G as User Datagram Protocol (UDP) packets with a data length of 1024 bytes and one message being transmitted every 1ms. The measurements are analysed inside the Monitoring Unit – Genior Modular (GEM)[1], and the observations are fed to the machine control to steer the machining process. The entire loop of acoustic emission measurements, data collection and analysis in the monitoring unit, and adaptively steering the machining process from the machine control needs to take place in real-time.

The key results obtained by 5G-SMART from the Aachen trial are:

- The AE sensor system can be successfully realized over 5G. Several benefits are observed with respect to the industry goals of flexibility, productivity, utilization, and sustainability.
- A limitation of the current implementation can be seen with respect to energy consumption. A need for the development of 5G UEs with reduced power consumption to allow reasonable battery runtimes or sizes has been identified.

3.2.2 Versatile multi-sensor platform for digital twin

The second use case trialed at the Aachen trial site, the wireless 5G versatile multi-sensor platform (MSP), aims to address and solve the limitations of current sensor-systems. We envision a fine-grained system of widespread sensors and transducers, whose heterogeneous data is collected, transferred via 5G and aggregated in a local cloud close to the shopfloor, that we call the Factory Cloud. The general concept can be seen in Figure 6: on the shop floor, multiple machines and workpieces as well as the infrastructure, are equipped with MSPs, and are connected via 5G to the Factory Cloud, where measurement data can be processed and stored. Some extracted information can then be fed back as process parameter adjustment or control to the machines. Sensors are tuned and orchestrated in form of configuration data.

Many diverse physical quantities can be measured or sensed across a factory, relating to machines, workpieces, and the infrastructure as well. Each of those may have different requirements, especially regarding reliability and latency that can potentially be rather challenging. Critical process parameters in machining are for example accelerations or forces, which are an indicator of unforeseen behavior of the workpiece to be machined. Chatter marks or tool deflection may be the result, leading to insufficient quality of the final product. To instantly react on such incidents, a latency less than 10 ms may be required to adopt the machining parameters. This requirement is typically associated with the URLLC (Ultra Reliable and Low Latency Communication) feature of 5G.

[1] https://www.marposs.com/eng/product/tool-and-process-monitoring-system-2

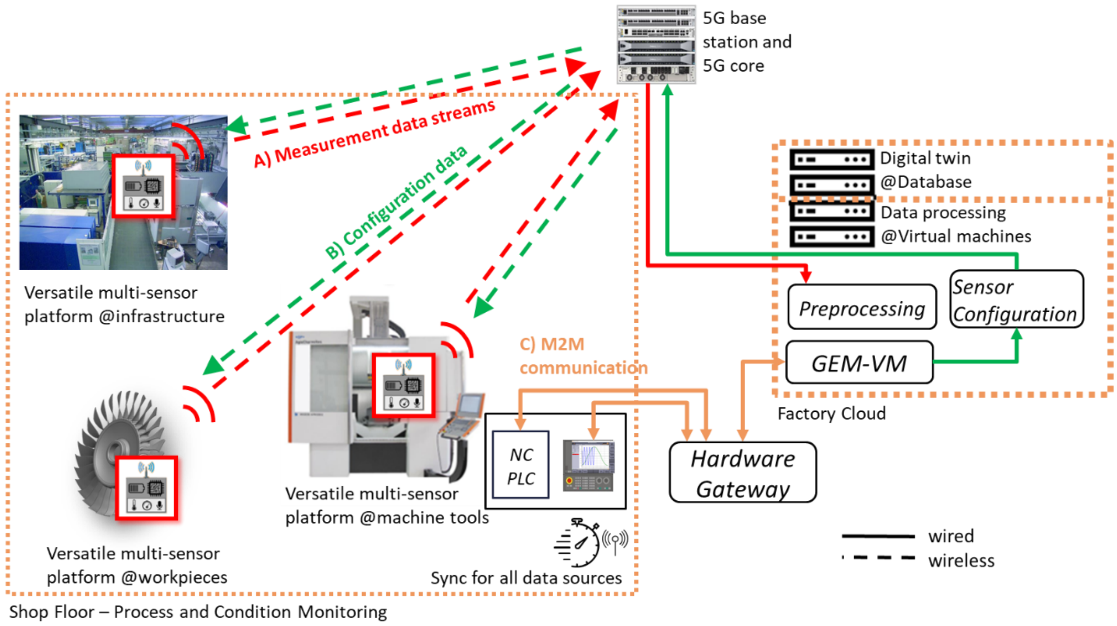

Figure 7: Process and shopfloor monitoring with the 5G multi-sensor platform, Source: Fraunhofer IPT

The key results obtained by 5G-SMART from the validation and evaluation of the multi-sensor platform are:

- The MSP can be realized via 5G and will provide a valuable tool to rapidly ramp up new processes and achieve a high product quality in a short time, thus saving time and energy.
- The 5G-communication of the MSP can be successfully interfaced with state-of-the-art monitoring equipment.
- The value of precise time synchronization over the 5G network has been shown, which enables industrial users to assign different wired and wireless data sources with ultra-high accuracy timestamps and thus put them into a common time zone. This has been demonstrated by means of the CellTime™ solution integrated into the MSP.

Detailed results and discussions of the Aachen trial site can be found in D3.4 [5GS22-340].

3.3 WP4: 5G for semiconductor factory automation

At the Reutlingen trial site, 5G has been validated in a Bosch semiconductor factory environment from two different perspectives. First, 5G-SMART focused on 5G radio propagation in the production environment to ensure that 5G can provide the required stable connectivity and coverage throughout the factory floor, and that it provides the electromagnetic compatibility (EMC) levels as required in the semiconductor factory. Considering the learnings from the wireless channel measurements and EMC tests, the 5G system testbed has been designed and deployed at the Bosch semiconductor factory in Reutlingen to validate 5G-based factory automation. This activity led to significant learnings with respect to the design and integration of a 5G network into the existing Bosch-network in fulfilling requirements of IT-security. The 5G network deployed at the trial site is a dedicated, on-premises, and standalone (SA) 5G network based on 3GPP Release 15 specification. More details about the network deployment as well as the trial site constraints can be found in the 5G-SMART's deliverable D4.1

[5GS20-D410]. Second, 5G has been validated on the application-level, by realizing two use cases on the factory shop floor: a cloud-based mobile robotics use case and a Time-Sensitive Networking (TSN)/Industrial Local Area Network (LAN) over 5G use case, as illustrated in Figure 8. These are further explained in the following subsections, together with more details on the EMC and channel measurements.

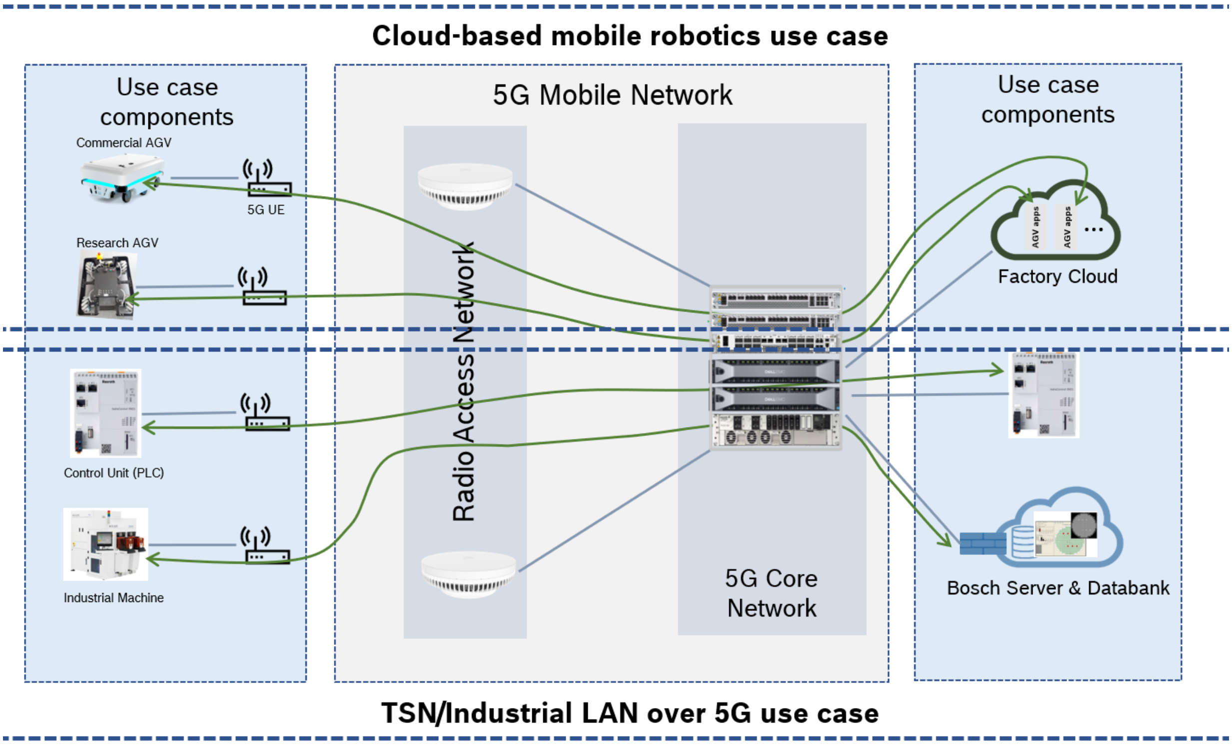

Figure 8: Illustration of the use cases at the Reutlingen trial site, Source: Ericsson/Bosch

3.3.1 Channel measurements and EMC tests

The semiconductor factory floor is a challenging environment in terms of radio propagation, not only due to its layout consisting of narrow corridors and high walls, but also due to the large amount of reflective material/equipment. Therefore, attention needs to be given to how to provide a reliable coverage throughout the factory. Factory floors are usually environments characterised as rich scattering with various tools and machines, which contribute to shadowing effects and are in different ways interacting with the radio signals. In addition to that, moving people and robots introduce dynamic changes in the environment. 5G-SMART has designed channel measurement campaigns to study the effects of these aspects, measuring signal properties, such as signal strength, impulse response, delay spread, etc. Different scenarios and locations have been determined to obtain a comprehensive picture of the radio propagation characteristics in the factory. The results show that providing coverage at mid-band frequency looks promising. Deliverable D4.2 [5GS22-D420] describes the performed tests and analysis in detail.

A major requirement in order to install 5G in industrial environments is that 5G is electromagnetically compliant with the industrial equipment on site. It is therefore crucial to make sure that 5G signals do not have any negative impact on the production processes. To address this issue, 5G-SMART has analyzed and evaluated the impact of 5G signals on semiconductor production using a test setup developed by the project. The setup makes use of a vector signal generator generating uplink or downlink 5G NR signals at 3.7 GHz with 20 MHz and 100 MHz bandwidths, which are amplified and transmitted via a horn antenna. The impact of the electromagnetic fields created due to the 5G signals is then investigated for different devices under test.

Based on the EMC test results, it has been concluded that with the actual tested samples, deploying a 5G network in the final test and the sensor backend areas can be considered without any concerns, while the wafer test area cannot be considered unless actions are taken to ensure EMC. It is important to mention that negative effects of 5G signals on untested devices, or in future test processes, cannot be fully excluded. For the details on the EMC tests and the results, we refer the reader to 5G-SMART deliverable D4.2[5GS22-D420].

3.3.2 Cloud-based mobile robotics use case

This use case focuses on the feasibility, flexibility, and performance of wirelessly controlled mobile robots in a manufacturing shop-floor equipped with 5G technology. A 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 an edge cloud execution environment (i.e., a factory cloud) while sustaining the Key Performance Indicators (KPIs), like sufficiently low execution latency and adequate fault-tolerance. Moving the control logic into the cloud benefits from scaling of the workload when changing the tasks for the robots, ease of maintenance of the control software and improved resiliency to software and hardware failures. Furthermore, decoupling the control logic from the mobile robot or Automated Guided Vehicle (AGV) enables innovative control solutions such as collaboration between individual AGVs by, e.g., facilitating the creation and sharing of up-to-date common maps. For instance, 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. Moving the control of the robot into the cloud however comes with stringent requirements on the communication in form of low-latency and reliable radio connectivity.

5G-SMART has successfully implemented the use case, where a hybrid solution was chosen using two AGVs, a so-called *Research AGV*, and a commercial one, to demonstrate different aspects of AGV cloudification. The research AGV has been entirely built up and implemented by the 5G-SMART project and is used to show how we can leverage 5G and cloud technologies to enable novel collaborative control solutions based on the cloud-native realization of the AGV control. The certified commercial AGV platform is connected over the 5G system to show the benefit of collaborative knowledge collected in the factory cloud (e.g., using the common map for AGV trajectory planning), we refer to this *as 5G-enhanced commercial AGV*. A detailed description of the selection of robot platforms, necessary sensors, and other equipment, as well as on the implementation of the hardware and software architectures is provided in 5G-SMART deliverable D4.3 [5GS21-D430]. In Figure 9, the functional architectures of the state-of-the-art commercial AGV (left side), the 5G-enhanced commercial AGV (middle), and our custom-built Research AGV (right side) are illustrated. As can be seen, more and more components are offloaded from the hardware device to the local factory cloud when moving from the commercial AGV towards the Research AGV. For the latter one, the project has implemented all software blocks in the cloud. Even the safety functions are executed in the cloud, but they are also kept onboard to be in-line with the safety regulations of the factory. This means that in principle the entire intelligence of the research AGV is removed from the platform itself, reimplemented and extended in a cloud-native manner to the edge cloud.

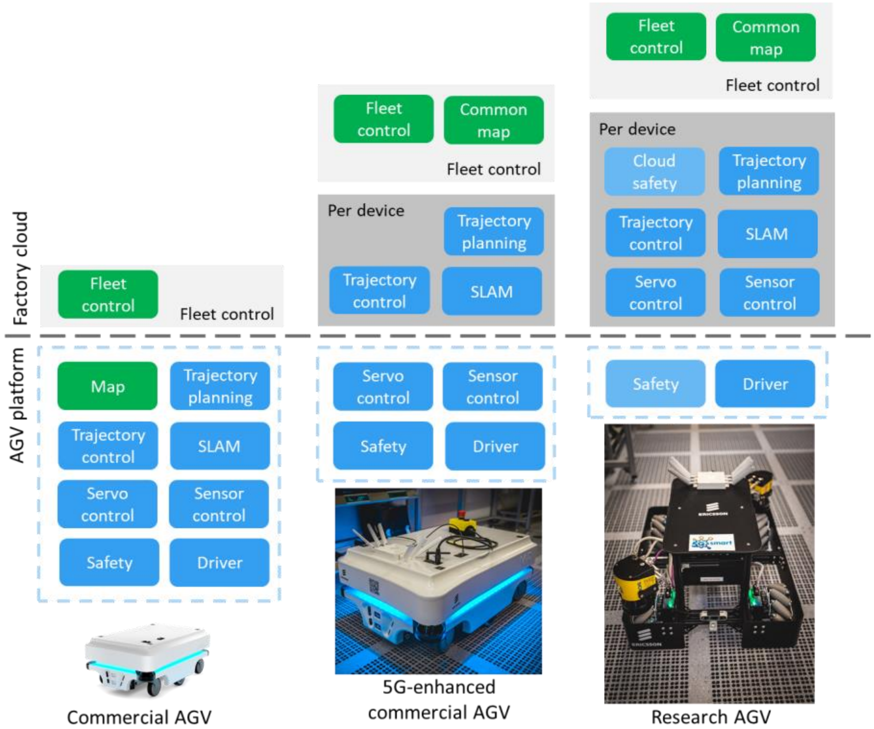

Figure 9: Functional architecture of the AGVs

The evaluation of the cloud-based mobile robots use case showed that cloud-controlled mobile robots can be successfully realized via 5G and opens for novel opportunities.

- The deployed 5G network could support all of the tested validation scenarios without any deterioration on the performance of the robots.
- In the evaluations towards the industry goals, a positive impact on flexibility, productivity, mobility and safety was found.
- As an example, efficiency could be significantly increased by optimizing AGV routes in real factories when cloud-based control is realized over the 5G network. The project succeeded in quantifying the gain in terms of mission execution time in real environment with obstacles and multiple paths, which can be directly exploited when the use case is applied in the real production flow.

The detailed analysis of the cloud-based mobile robots use case can be found in Deliverable D4.4 [5GS22-D440].

3.3.3 TSN/Industrial LAN over 5G use case

This use case focuses on investigating and validating the applicability of 5G for transporting the traffic of TSN/industrial LAN (I-LAN) applications. Nowadays, due to the stringent requirements of the industrial applications, 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. Introducing 5G comes with the potential of reducing the cables and connectors wear and tear, for the mobile machines/controllers, resulting in reduced maintenance costs. Additionally, replacing the cables for communications between controllers and machines with 5G communications results in a greater 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.

Partially replacing fixed interconnections between TSN/I-LAN nodes with 5G mobile communications puts, however, very stringent requirements in terms of latency and reliability on the communication system.

In order to validate the applicability of TSN/Industrial LAN traffic over 5G, diverse validation scenarios have been designed and tested for the applications in this use case. More specifically, the performance of these application has been evaluated under various load conditions at the RAN by also investigating options of prioritizing different types of traffic. Moreover, several KPIs have been defined and used to evaluate industry goals such as flexibility, productivity, etc., defined by the plant management in different validation scenarios.

The key results are:

- Controller-to-controller (C2C) applications can be realized via 5G, although the C2C communication performance over the wired Ethernet network outperforms that over the 5G network due to shorter round-trip time.
- It has been demonstrated that without traffic prioritization for the C2C as well as the machine-to-server communication, the background traffic may have an impact onto the controller traffic and the machine traffic in terms of increased delay. While an increased delay affects the C2C communication efficiency, it does not have any negative impact to the machine's efficiency. A conclusion is that depending on the application, traffic prioritization may be needed.
- In the evaluations towards the industry goals, a positive impact on flexibility, mobility, and sustainability was found.

The detailed analysis of the TSN/I-LAN use case can be found in Deliverable D4.4 [5GS22-D440].

4 WP5: Optimizing 5G for smart manufacturing

5G-SMART has carried out an extensive investigation into various technical aspects of the 5G systems beyond those that are already standardized or currently under standardization. The project focused on aspects that have a strong business value for the manufacturing ecosystem and investigates needed enhancements and their integration into the ecosystem. Three dimensions play a major role here as detailed in the following sections. These are: Advanced 5G technical features, novel 5G network architecture options and an industrial-centric network management of the 5G system.

4.1 Advanced 5G technical features

The project has identified three novel technical features (as shown in Figure 10) important for the smart manufacturing, which were evaluated, namely 5G-TSN integration, 5G-based positioning, and time synchronization (5GS20-D51).

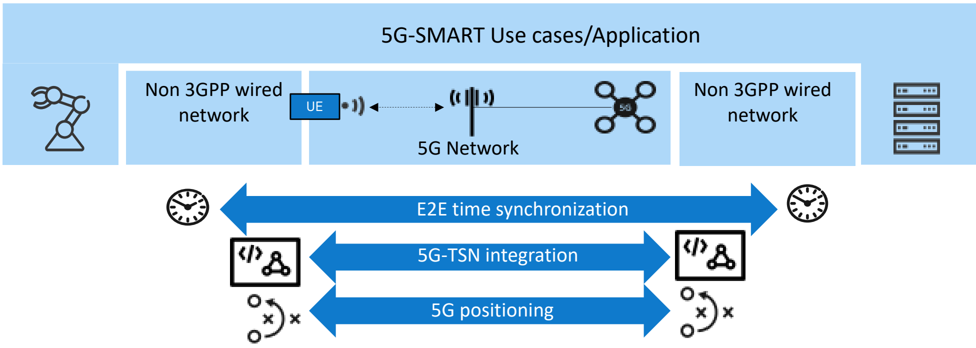

Figure 10: Selected 5G features to support the 5G-SMART use cases, Source: Ericsson

Time Sensitive Networking (TSN) is the open standard for deterministic communication services over IEEE 802.1 Ethernet network; it is set to become the future industrial communication network technology, which is so far dominated by a plurality of incompatible “real-time” Ethernet variants and fieldbus technologies. To adapt 5G well to industrial networks, it needs to interwork and integrate well with Ethernet and TSN. The project has made significant contributions on how the 5G system can support Ethernet-based industrial networking including support for TSN functionality. Building on the functionality to support TSN, the project has further developed an integration architecture of 5G with DetNet, the IETF standard for IP-based deterministic networking. The outcome of the project has been brought to 5G standardization in 3GPP, where 5G support for TSN has been standardized and work to support DetNet is currently ongoing. Furthermore, results have been brought to different activities in 5G-ACIA, where both TSN and DetNet are investigated in combination with 5G. Overall, the project has made a significant impact in the uptake of the results in the current standards and solutions.

The project undertook development of the overall system concept to enable time synchronization supported with 5G system in an integrated 5G-TSN network. From finding gaps in the standards and solutions to support time synchronization, 5G-SMART has analyzed the E2E time synchronization chain in an integrated 5G-TSN network for typical smart manufacturing scenarios and undertook an in-depth analysis in terms of the analytical and simulation evaluation. This investigation provided details on how a 5G system can support the time synchronization error budget for a typical smart manufacturing scenario. As a result of the work, several contributions on enhancements and validations were made towards 5G-ACIA, 3GPP and ITU-T.

In addition, the project also evaluated 5G radio-frequency-based positioning in a realistic industrial environment of a 5G-SMART trial site. The environment was modelled by means of the 3GPP statistical radio propagation channel and with a geometric 3D ray tracing channel. Comparing the two methods and taking future standardization efforts into account it was concluded that the standardization direction and performance targets for Industrial IoT positioning in 3GPP Release 17 look promising as it provides additional support for industrial IoT use cases which demand positioning with high accuracy. However, similar to legacy positioning solutions, given the diverse factory settings and various signal propagation conditions, there is no one-size-fits-all solution. Hence to commercially deploy those solutions, tight eco-system collaboration is essential to ensure practical deployment success.

To summarize, 5G-SMART has done significant work from gap analysis to concept development and evaluation of highly relevant 5G technological features, aiming to support smart manufacturing applications. At the same time, it has also ensured successful uptake of the findings in relevant standardization bodies and industry fora.

4.2 Novel 5G network architecture options

5G NPNs deployment models are set to become prominent network architecture options for the 5G system integration with the smart manufacturing eco-system. From an end-to-end perspective, there are several aspects important to consider fulfilling the functional requirements of the smart manufacturing application. In these directions, the work by 5G-SMART covers in-depth investigation of device to edge cloud aspects for several non-public network deployment models, in order to allow the adoption of cloud technologies for industrial applications. In addition, systematic investigations of the NPN architecture from the deployment and operational point of view have been performed. Overall, the work included investigations on architecture concepts on devices, Edge cloud, Quality of Service (QoS), and resiliency.

A set of nine plausible NPN operation models have been analyzed. These models provide an understanding on how the roles involved in operating a 5G NPN deployment can be assigned to different stakeholders in the smart manufacturing eco-system. To evaluate such NPN operation models, a framework was proposed for systematic analysis of different NPN operation models.

Given the importance in manufacturing of 5G System integration with Ethernet-based networks and Time-Sensitive Networking (TSN), a device architecture was proposed that incorporates interaction with Ethernet end points (Ethernet bridge/end-station).

Concerning the Edge cloud architecture, an extensive analysis of different Edge cloud integration options with NPN deployment models was performed. Several learnings are listed from this analysis and were provided as contributions towards 5G-ACIA. The investigation showed how the 5G system with URLLC features, TSN support and integration with Edge cloud can provide E2E deterministic communication services for a wide range of smart manufacturing use cases. It also highlighted the main open challenges of adding support for TSN features such as redundant transmission via FRER

(Frame Replication and Elimination for Reliability) in an Edge cloud platform which interworks with the 5G network.

A network reliability analysis showed all the relevant physical and virtual components involved in 5G NPN operations. It was concluded that, along with ensuring reliability of 5G connectivity, one needs to ensure high availability of the hardware and software components involved in an E2E NPN architecture. Furthermore, our analysis showed the benefits of having parallel redundancy of the components in order to fulfil the demanding requirement of the smart manufacturing applications.

4.3 Industrial-centric network management of 5G system

Along with architectural and technical features, it is important to align the 5G network management with existing network management and industrial applications. 5G-SMART has developed an industrial centric network management framework which helps industrial application and network management solutions to leverage functionality of the 5G system in a simplified manner.

The framework provides standardized Application Programming Interfaces (APIs) to leverage 5G infrastructure functionality (e.g., group management, location, time synchronization) with minimal efforts as shown in figure 10. The essential functional blocks of the framework are based on the 3GPP-defined common API Framework (CAPIF) and Service Enablement Architecture Layer (SEAL) architecture as reported in Deliverable D5.5 [5GS20-D55. The proposed network management framework implements an application enablement architecture based on the CAPIF and SEAL components defined by 3GPP. The interaction on the northbound interface is via standardized API defined by 3GPP. Industrial applications such as Robot Operating System (ROS) and the existing wired network management framework acts as an API invoker and can implement the API interaction with the framework. This functionality can be easily triggered via standardized APIs from the OT network management applications and industrial applications. The essential building blocks of the framework are further discussed in the report deliverable D5.5[5GS20-D55].

The learnings and insights from the development of the conceptual network management framework was provided as input towards 5G-ACIA.

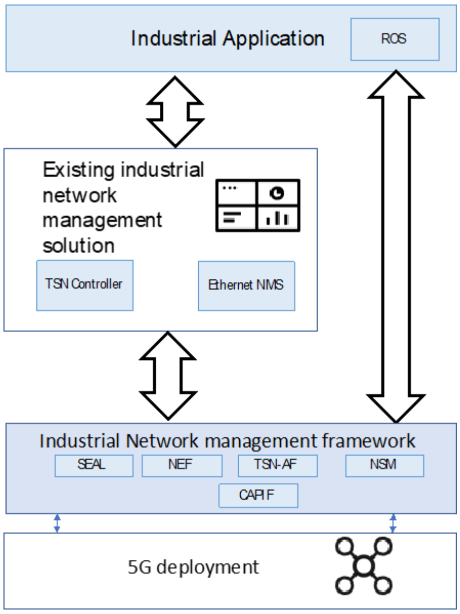

Figure 11: Network management framework developed in 5G-SMART, Source: Ericsson, NEF = Network Exposure Function, NMS = Network Management Function, AF = Application Function

Additionally, the 5G-SMART project has successfully prototyped an Industrial Network Slice Management Service (INSMS) that allows in an intuitive way to create and manage network slices. The framework was designed with the aim to hide slice management complexity from industrial applications as much as possible, thus simplifying interaction and implementation of the industrial applications and 5G system over the north-bound interface. The analysis showed how different configurations can be enabled for plug and produce use cases with such a network management framework.

5 WP6: Dissemination, communication, and exploitation

Communication, dissemination, and exploitation have been tasks of high importance in 5G-SMART, as it is recognized that they are crucial elements to increase visibility and the impact of the project. With the outbreak of the Covid-19 pandemic, severe adjustments had to be made to the original plans of 5G-SMART for communication and dissemination. Deliverable D6.3 [5GS22-D630] summarizes the dissemination, communication and exploitation activities of the project.

5G-SMART prepared and attended a significant number of workshops, conferences and events, all based on the main technical objective of the performed research, i.e., the 5G system design for the industrial adoption of this technology. In doing so, 5G-SMART cooperated with the organizations in charge of the promotion of this technology, mainly 3GPP, ITU, 5G-ACIA and 5G-PPP. 5G-SMART has contributed to several work items and whitepapers of 5G-ACIA, and all three 5G-SMART testbeds have been endorsed by 5G-ACIA in 2021, confirming the relevance and interest in the results of the project.

5G-SMART has achieved the goals that were outlined at the start in terms of exploitation and dissemination plans of the consortium and all the partners. More than 20 papers, 13 press impacts, 30 contributions to standards, 3 keynotes in major conferences, the participation in 20 5G industrial events, 3 workshops, 5 demos and 8 webinars, show the high implication of the project in the dissemination of achieved results. The achievements per partner as well as exploitation opportunities show the important impact of the project. The final project results and deeper insights to the trials have been presented at the end of the project in the Trial Open Day in Kista.

6 Conclusion

In summary, 5G-SMART has been successfully showcasing 5G for manufacturing industries, by

- Bringing 5G deployment to real manufacturing shopfloors and factory floors, and demonstrating, validating and evaluating novel use cases, thereby contributing to a wider understanding of the specific requirements of the manufacturing sector.
- Performing EMC and channel measurements for 5G deployment in real production facilities, thereby contributing to a wider understanding of radio signal propagation and suitability of 5G deployments in manufacturing factories.
- Performing coexistence evaluations between public and private 5G network deployments.
- Evaluating 5G radio network deployment and spectrum options.
- Developing and evaluating new 5G features as well as network architecture options for 5G to be used in smart manufacturing.
- Developing an industrial-centric framework for network management and configuration for industrial use cases.
- Advancing and developing new 5G enabled sensors and factory cloud solutions tailored for the manufacturing sector.
- Analyzing the business value creation enabled by 5G for manufacturing industries as well as the different business models relevant in the new ecosystem landscape.

Therefore, it is concluded that 5G-SMART has succeeded in fulfilling its objectives. Moreover, the project has set the foundation for further exploitation, future research and development, and a tighter collaboration between the ecosystem partners. Overall, the project has contributed to an accelerated digital transformation in the manufacturing sector.

Appendix

List of abbreviations

3GPP	3rd Generation Partnership Project https://www.3gpp.org/
AE	Acoustic Emission
AGV	Automated Guided Vehicle
API	Application Programming Interface
AR	Augmented Reality
AI	Artificial Intelligence
C2C	Controller to Controller
EMC	Electromagnetic Compatibility
ETSI	European Telecommunications Standards Institute https://www.etsi.org/
FRER	Frame Replication and Elimination for Reliability
ITU	International Telecommunication Union https://www.itu.int/en/Pages/default.aspx
KPI	Key Performance Indicator
LAN	Local Area Network
LTE	Long Term Evolution
MBB	Mobile BroadBand
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MSP	Multi-Sensor Platform
NPN	Non-Public Network
NR	New Radio
NSA	Non-Standalone
INSM	Industrial Network Slice Manager
PCB	Printed Circuit Board
RAN	Radio Access Network
SA	Standalone
SEAL	Service Enablement Architecture Layer
SLAM	Simultaneous Localization and Mapping
TSN	Time-sensitive Networking
URLLC	Ultra-reliable and Low-latency Communication
VM	Virtual Machine
WP	Work Package
UC	Use case
5G-ACIA	5G Alliance for Connected Industries and Automation
DL	Downlink
UL	Uplink

I-LAN	Industrial LAN
FRER	Frame Replication and Elimination
PLMN	Public Land Mobile Network

Table 2: List of abbreviations

References

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5GS-SCS	https://5gsmart.eu/standard-contributions/
5GS-TWI	5G-SMART, Twitter account, https://twitter.com/5G_smart
5GS-YOU	5G-SMART, YouTube channel, https://www.youtube.com/channel/UCdhRYuUuSfT97tIivMGLRIg