# D3.4

## REPORT ON 5G CAPABILITIES FOR ENHANCED INDUSTRIAL MANUFACTURING PROCESSES

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# D3.4 Report on 5G capabilities for enhanced industrial manufacturing processes


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| Short abstract: | The report describes two 5G wireless sensor solutions and their validation in the Aachen trial site. The suitability of the sensor solution has been shown successfully, and validation results have been linked to the fulfillment of industry goals. Wherever possible, measurements were carried out to quantify KPIs of the industry goals directly. |



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# Disclaimer

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This deliverable has been submitted to the EU commission, but it has not been reviewed and it has not been accepted by the EU commission yet.

# Executive summary

This report describes the validation of two wireless sensor solutions developed in the framework of the 5G-SMART project: a 5G-based acoustic emission sensor system for monitoring tool conditions in machining processes and a 5G multi-sensor platform for monitoring critical machining processes.

The report contains a short description of the use cases targeted in 5G-SMART, followed by a description of different validation scenarios. All validations were conducted for actual machining operations in state-of-the-art machines, which realistically resemble the solutions' application by end customers.

The report also contains the results of performance measurements of the 5G network at the trial site of Fraunhofer IPT in Aachen. These results show that the performance can satisfy the requirements set for the use cases, e.g., providing a latency below the cycle time of conventional process monitoring solutions. Furthermore, these results were used to assess the results of the validation tests.

The validation tests showed that the developed 5G sensor solutions are well suited for industrial operation and can interact with commercial-of-the-shelf components, making it easier to integrate into the manufacturing ecosystem. Latencies for the 5G sensors were measured between the application endpoints and were observed to comply with the cycle times of conventional monitoring equipment in the order of 10-12 ms.

Different industrial goals and KPIs were defined for the two sensor solutions. A description of the relation of the validation results to fulfilling the requirements and their meaning for the industry goals has been provided and, whenever possible, quantified. The validation cases also allowed for identifying potential improvements described in the report.

## List of abbreviations

| | |
|---|---|
| ADC | Analog to Digital Converter |
| AE | Acoustic Emission |
| APN | Access point name |
| BBU | Baseband unit |
| CAN | Controller Area Network |
| CNC | Computerized numerical control |
| CSV | Comma-separated values |
| CPU | Central Processing Unit |
| EN-DC | E-UTRA to NR Dual Connectivity |
| E-UTRA | Evolved UMTS Terrestrial Radio Access |
| FFT | Fast Fourier Transform |
| FPGA | Field Programmable Gate Array |
| *GEC* | *German Edge Cloud* |
| *GEM* | *Genior Modular* |
| *GEM-VM* | *Genior Modular Virtual Machine* |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| IRU | Indoor radio unit |
| KPI | Key performance indicators |
| LTE | Long Term Evolution |
| MSP | Multi-Sensor Platform |
| MTBF | Mean time between failures |
| NC | Numerical control |
| NPN | Non-Public Network |
| NR | New Radio |
| NSA | Non-standalone architecture |
| OEE | Overall equipment efficiency |
| OTA | Over-the-air |
| PLC | Programmable logic controller |
| PLMN | Public Land Mobile Network |
| PPS | Pulse Per Second |
| PTP | Precision Time Protocol |
| RAN | Radio Access Network |
| RMS | Root mean square |
| SA | Standalone architecture |
| SNPN | Standalone non-public network |
| TDD | Time-Division Duplexing |
| UART | Universal Asynchronous Receiver/Transmitter |
| UE | User Equipment |
| UDP | User Datagram Protocol |
| UMTS | Universal Mobile Telecommunications System |
| URLLC | Ultra-reliable low-latency communication |

Table 1: List of abbreviations (Product-related abbreviations in italics)

# 1 Introduction

The Fraunhofer IPT trial site in Aachen is one of the three trial sites within the 5G-SMART project equipped with a 5G communication infrastructure and multiple machine tools on the shopfloor of Fraunhofer IPT. Research activities in the trial site focus on enhanced manufacturing. Guaranteeing flawless machining processes is often connected with monitoring the involved assets, i.e., workpieces, machines, and the surrounding environment.

5G-SMART addresses the challenges in manufacturing by providing monitoring solutions using 5G wireless sensor systems. Furthermore, many companies are highly interested in data processing in on-premise edge-cloud systems and its integration with the 5G system and production IT. Works carried out at the Fraunhofer IPT trial site provide valuable insights for these companies.

## 1.1 Objective of the report

This report describes validation scenarios for the use cases in 5G-based process monitoring for smart manufacturing at the Fraunhofer IPT trial site in Aachen: the wireless acoustic emission (AE) sensor system and the multi-sensor platform (MSP) connected with the edge-cloud processing pipeline. Furthermore, the report introduces the industry goals addressed by these use cases and describes the various validation scenarios for the two use cases. Key performance indicators (KPIs) for various validation scenarios are given and analyzed regarding their contribution to the industry goals. The report also presents test results from use case validations and characterization of the 5G network at the Aachen trial site.

## 1.2 Relation to other documents in 5G-SMART

This report relies on descriptions and results from other deliverables released in 5G-SMART, such as D1.1 [5GS20-D110], D3.1 [5GS19-D310], D3.2 [5GS20-D320], and D3.3 [5GS21-D330], whereas D1.1 describes the use cases and D3.2 and D3.3 describe the solutions to implement them. The 5G infrastructure needed for the solutions is described in D3.1. This deliverable presents the validation of the solutions described before and analyzes the relation and contribution of the use cases to industry goals also described in the document.

## 1.3 Structure of the document

Section 2 describes the evaluation methodology and criteria used to validate the developed use cases in the 5G-SMART project at the Aachen trial site. Section 3 describes the 5G network characteristics of the Aachen trial site and related performance measurements carried out. Section 4 presents the AE use case-specific industry goals and the two scenarios used to validate the AE system. The section ends with a discussion of the results. Section 5 follows the same structure as section 4 and focuses on the multi-sensor platform, including the time synchronization solution. The report finishes with a conclusion and outlook.

# 2 Demonstration, validation, and evaluation of 5G capabilities

## 2.1 Validation and evaluation methodology

The activities described in this document aim to validate the developed solutions for the Aachen trial site of 5G-SMART. Specifically, the developed sensor solutions have been applied in relevant use cases, in which they would also be used if they would become a commercial product. Considerable attention has been put to validating the use cases in relevant scenarios in a realistic industrial manufacturing environment. Instead of an artificial lab, which does not represent a real production environment, use cases have been demonstrated and validated on an industrial shopfloor. On the other hand, the validation also happens on a quantitative basis. Specific parameters like end-to-end latency have been benchmarked and compared against the current state-of-the-art, which in most cases is a wired off-the-shelf solution with analog sensors and electronic devices, typically located in the electrical cabinet of a machine and a real-time operating system for the measurement data processing. The performance values resulting from this benchmarking can then be used to calculate additional KPIs.

## 2.2 Technical recommendations and best industry practices

Multiple guidelines describe how to evaluate the performance of industrial 5G use cases.

- 5GPPP: White paper "ICT-19 performance KPIs" [MVM+21]
- 5G-ACIA: White paper "Performance Testing of 5G Systems for Industrial Automation" [5GACIA21]
- 5G PPP: White paper "Validating 5G technology performance" [CLT+19]
- 5G PPP: Presentation "Methodologies for E2E Testing & Validation of Vertical Applications over 5G & Beyond networks - An ETSI TC INT Perspective based on EU-funded 5G-PPP Projects Contributions to Standards" [LCS+21]
- 5G PPP: White paper "Service performance measurement methods over 5G experimental networks" [MVM+21b]

Guidelines in sensor technology usually describe the terminology, functional aspects, measurement parameters, and how to calibrate sensors and characterize the measurement uncertainty, such as the Guide to the expression of uncertainty in measurements [GUM]. As the research activities in 5G-SMART are neither focused purely on mobile communication nor sensor technology, we have decided on empirical validations with case-by-case validation scenarios instead of following a general guideline. The project partners Marposs, Marposs Monitoring Solutions, and Fraunhofer IPT, with expertise in sensor technology and production technology, have defined validation scenarios.

The common methodology for all trialed use cases consists of 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 implementation and integration
4. Identification of validation scenarios and relevant KPIs for evaluation
5. Validation, evaluation, and demonstration

Detailed information on the use case characterization of step 1 and steps 2-3 can be found in the 5G-SMART deliverables D1.1, D3.2, and D3.3. The focus of this report is on steps 4 and 5 with respect to the relevant industry goals, which will be further explained in the following.

## 2.3 Industry goals

The industry goals of the Aachen trial site are aligned with industry goals relevant to machining. D1.2 [5GS21-D120] lists industry goals shown in Figure 1. These goals will be formulated in the following paragraphs from the perspective of machining and process monitoring.

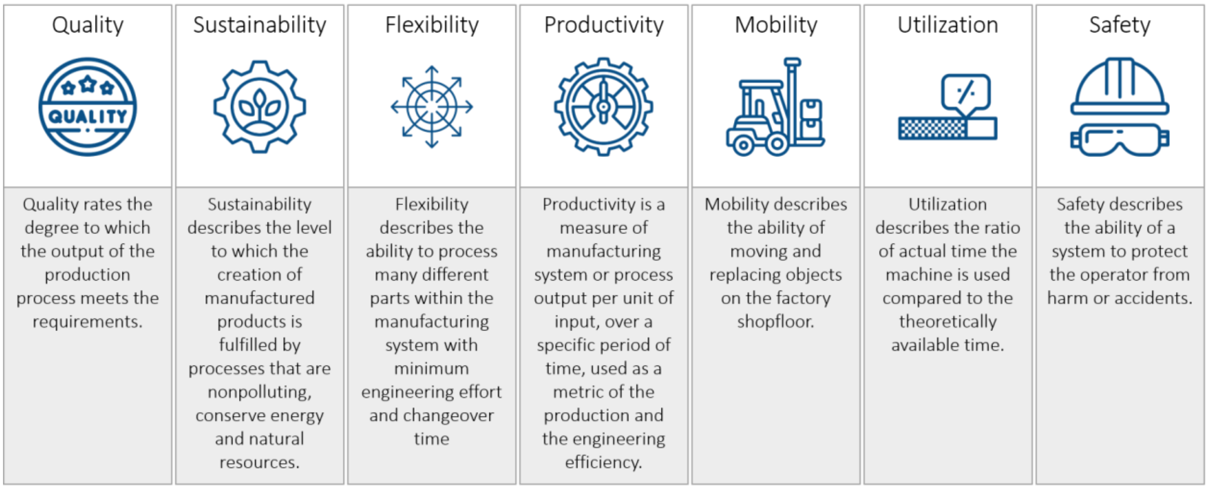


Figure 1: List of industry goals addressed in 5G-SMART

### 2.3.1 Flexibility

As stated in D1.2, flexibility describes the ability to process many parts within the manufacturing system with minimum engineering effort and changeover time required. The changeover time is the time needed to prepare a machining process, e.g., mounting and clamping the workpiece, changing the tools, loading, and initializing the numerical control (NC) program. One can also count the setup time for sensor solutions contributing to the changeover time. In our case, the changeover time is reduced as cabling efforts are no longer necessary for the sensor solutions developed in the project, owing to the wireless communication possibility. The multi-sensor platform (MSP) can easily be reconfigured, making it highly flexible to monitor the machining processes for many different parts.

### 2.3.2 Mobility

Mobility is described as the ability to move objects on a factory shopfloor. For the use cases at the Aachen trial site, the wireless sensor solutions are mobile to be moved from one measurement location to another. However, the use cases where the sensor solutions have been integrated do not require any mobility support. The only exception is the mobility of the sensors when applied on the moving machining table of a machine tool. In conclusion, we can consider that those use cases do not contribute to the industry goal of mobility.

### 2.3.3 Productivity

Productivity, according to D1.2, measures the output per unit of input over a specific period of time and therefore denotes the production efficiency. Constant monitoring of the machining processes is fundamental for detecting anomalies. A better understanding of the cutting processes is needed for its optimization. The optimization typically targets to increase productivity. In conclusion, productivity is directly affected by continuous monitoring using the developed sensor solutions.

### 2.3.4 Quality

Quality rates the degree to which the output of the production process meets the requirements. Reduced process quality can affect the quality of the product, typically specified by geometrical product specifications. These specifications can be classified into dimensional tolerances and surface qualities. In a machine tool, the dimensional accuracy is affected by the accuracy of the machine axes, thermo-elastic deformation of the mechanical machine frame, or bending of the tool. The surface quality is more affected by dynamic effects such as chatter (vibration of the tool) or vibration of the workpiece and the tool condition (tool wear, breakage) itself. The sensor solutions developed in the 5G-SMART project can acquire data relevant to detecting the aforementioned dynamic effects. Furthermore, deformations of the machine tool can be detected with the strain gauges of the MSP. Thus, the solutions developed in 5G-SMART may be well suited to contribute to the quality goal.

### 2.3.5 Safety

The ability of a system to protect itself and the operator from harm or accidents is the goal of safety measures in production. It can be clearly stated that this technical goal is not addressed in our case. As for safety, other sensor principles are used, e.g., proximity detectors.

### 2.3.6 Sustainability

Sustainability describes the level to which the creation of manufactured products is fulfilled by processes that are non-polluting and conserve energy and natural resources. Using sensor solutions for process monitoring can lead to quality improvement and the subsequent reduction of scrap production. Furthermore, monitoring tool conductions generally leads to extended tool life because a premature discarding of tools can be avoided. Using on-premise edge-clouds and virtual data processing and production control is a new paradigm that can save energy by consolidating computing resources like computerized numerical control (CNC) or programmable logic controller (PLC) by virtualization.

### 2.3.7 Utilization

According to D1.2, utilization is the ratio of actual machining time compared to the theoretically available time. In our case, utilization can be increased by reduced setup times of wireless monitoring solutions compared to wired solutions. More importantly, monitoring the manufacturing processes and equipment leads to improved knowledge and transparency of the processes. The subsequent robustness increase is connected with reducing downtimes and, thus, increased utilization.

# 3 Network characteristics at the trial site

## 3.1 5G network at Aachen trial site

The 5G network deployed at the 5G-SMART trial site at Fraunhofer IPT is part of the 5G-Industry Campus Europe [5G-ICE] in Aachen, the most significant test network of its kind in Europe for industrial use-cases development and experimentation. The network operates in the 3.7-3.8 GHz local licensed spectrum using a system bandwidth of 100 MHz allocated by the German Spectrum Regulatory Authority Bundesnetzagentur (BNetzA). The 5G-Industry Campus Europe spans over an area of approximately 1 sq. km outdoors with multiple indoor deployments, including the Fraunhofer IPT shopfloor with an area of 2700 sq. m. The outdoor and indoor networks are part of the same campus-wide 5G network providing full coverage and seamless handovers. Figure 2 shows a map of the 5G-Industry Campus Europe in Aachen. The orange dots with arrows indicate the macro sites for the outdoor network, while the green box shows the Fraunhofer IPT shopfloor area. The outdoor coverage is depicted in blue shade.

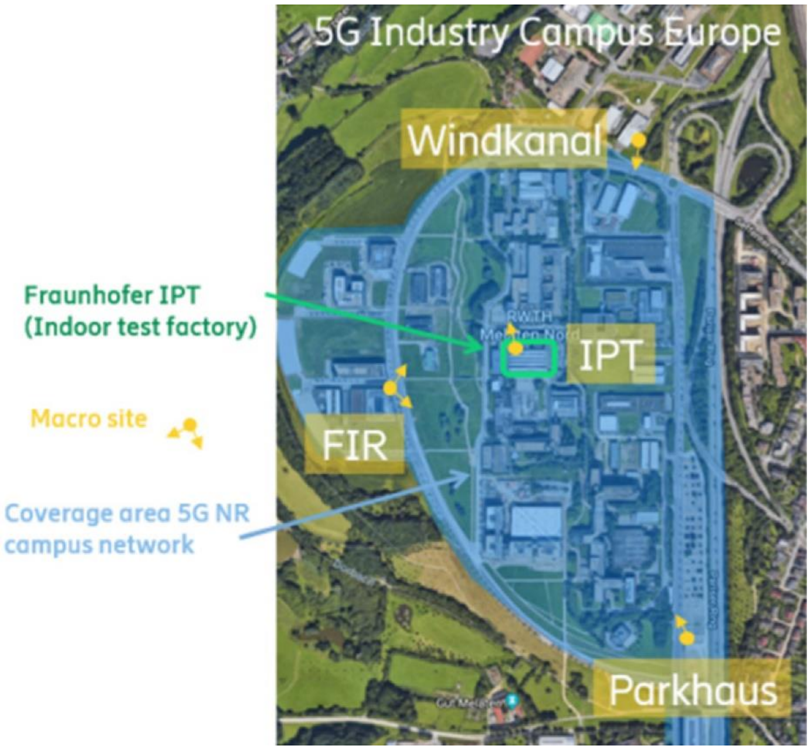


Figure 2: 5G-Industry Campus Europe in Aachen. Courtesy: GoogleMaps.

The 5G-Industry Campus Europe is based on the 5G non-standalone architecture (NSA), where an anchor LTE band is required before the transition from LTE to EN-DC (E-UTRA to NR Dual Connectivity) takes place. After the EN-DC change, all application data transmissions occur over the 5G user plane. In particular, the 5G New Radio (NR) n78 band in the 3700 – 3800 MHz and LTE band B40 at 2300 MHz are used at the 5G-Industry Campus Europe in Aachen. Besides the NSA architecture at the Fraunhofer IPT shopfloor, standalone architecture (SA) is supported in the 3700 – 3800 MHz frequency range. The two architectures deployed share the same 5G RAN and only differ in the 4G and 5G core, which can be addressed by the APN setting in the 5G device. The indoor and outdoor 5G networks are based on 3GPP Release specifications 15 and are referred to hereafter as the 5G commercial system.

In addition, a 5G prototype system operating in the high-band time division duplex (TDD) spectrum at 28 GHz (5G NR band n261) has been deployed on the Fraunhofer IPT shopfloor. This includes pre-commercial and standard-compliant ultra-reliable low-latency communication (URLLC) functionality with a standalone core network. It targets some of the more demanding and future requirements of industrial IoT use cases and will be referred to as the URLLC testbed. Please see Figure 3 for a snapshot of the URLLC testbed.


Figure 3: 5G-URLLC testbed at Fraunhofer IPT shopfloor. Source: [AAB+22]

In the 5G-SMART project, we have used both the indoor networks at the Fraunhofer IPT shopfloor and the outdoor network for our trial and experimentation activities. Table 2 summarizes the 5G-SMART trial site in Aachen.

Table 2: Specifications of networks of the 5G-SMART trial site in Aachen

| Network | Network system | 5G Architecture | 5G Frequency band | 4G Frequency band | 5G bandwidth [MHz] |
|---|---|---|---|---|---|
| **Indoor** | Mid band | SA/NSA | 3.7-3.8 GHz (n78) | 2300 MHZ (B40) | 100 |
| **Outdoor** | Mid band | NSA | 3.7-3.8 GHz (n78) | 2300 MHZ (B40) | 100 |
| **Indoor** | High band | SA | 28 GHz (n261) | - | 200 |

The indoor and outdoor networks are based on Ericsson infrastructure, including dedicated on-premises radio and core networks, as illustrated in Figure 4. The indoor network at Fraunhofer IPT uses multiple radio antennas to cover the shopfloor area with excellent 5G coverage. The indoor network uses Ericsson RDS (radio dot system), while the outdoor network uses macro antennas. The 4G radio, 4G indoor radio unit (IRU), and 4G baseband unit (BBU) are not shown in Figure 4 for simplicity and are a part of the 5G NSA setup. Please refer to [5GS-D310] for more information on the product details. The outdoors macro antennas are deployed on top of buildings at the 5G-Industry Campus Europe with the antennas facing directions as indicated in Figure 2.

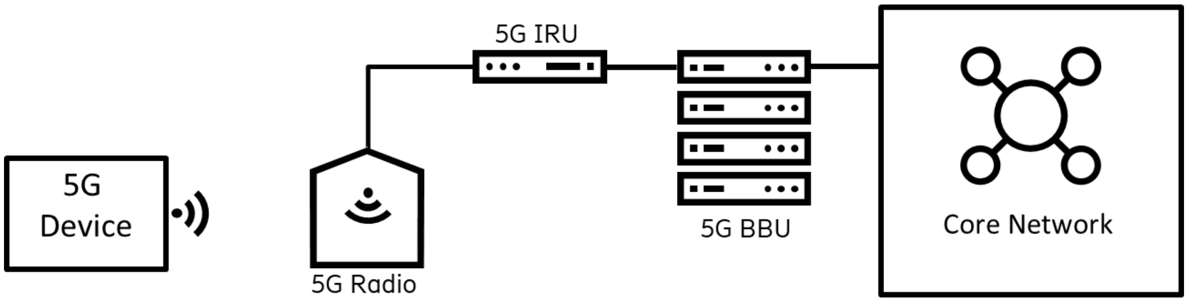


Figure 4: Simplified diagram of the 5G system deployed at 5G-Industry Campus Europe consisting of Ericsson products, including radios, indoor radio units (IRU), baseband units (BBU), and on-premises core network.

## 3.2 Performance studies and network characterization

The 5G NR n78 is a TDD spectrum where the same 100 MHz bandwidth is used for uplink and downlink transmission. The TDD pattern essentially defines the split of the transmission resources between the downlink and uplink portions. The TDD split is continuously repeated. The TDD pattern used for the outdoor network (DDDSU, where D represents a downlink slot, U represents an uplink slot, and S is a special slot for signaling) is synchronized and coherent/the same as with public networks in Germany. This is regulated to minimize adjacent channel interference effects. The indoor network TDD pattern is also configured to be DDDSU to reduce the interference effects between the outdoor and indoor networks. However, in the 5G-SMART coexistence study reported in D1.5 [5GS21-D150], we have studied the co-channel coexistence effects due to the TDD pattern variations (for instance, more uplink friendly TDD patterns) in the indoor network.

Inside the Fraunhofer IPT shopfloor, we get good coverage with signal levels greater than -70 dBm at all locations. We have used a local breakout connection behind the core network to conduct end-to-end performance measurements. The key network performance aspects studied in the 5G-SMART project include a detailed latency analysis with traffic profiles derived from the 5G-SMART use-cases (please refer to D1.1 [5GS20-D110] for more details). Besides latency measurements, throughput measurements have also been carried out in both the indoor and outdoor networks at the 5G-Industry Campus Europe in Aachen.

### 3.2.1 Latency and throughput measurements

Over-the-air (OTA) measurements have been conducted at the Fraunhofer IPT shopfloor. We have placed the test UEs at various locations, including the inside of a milling machine chamber, mounted on robots, behind cabinets, etc., and including both line-of-sight and non-line-of-sight scenarios between the 5G-UE and the 5G radio. Compared to the office and lab setups, factory shopfloors have strong multipath propagation effects with lots of metal, moving machine parts, multiple automation cells and assembly lines, workers moving around, etc. [AAB+22].

The throughput is dependent upon the TDD pattern. We have observed over 1.4 Gbps downlink throughput with TDD pattern DDDDU using standard iperf3 UDP data, while the throughput of up to 120 Mbps has been observed in uplink with TDD pattern DDDDUDDDUU. The throughput in the outdoor network has been observed in a similar range. We have also carried out detailed latency measurements in the Aachen trial site. For this purpose, we have developed a Field Programmable Gate Array (FPGA)-based tool to flexibly configure/generate application data traffic and carry out precise latency measurements. Please see Figure 5 for the setup details.

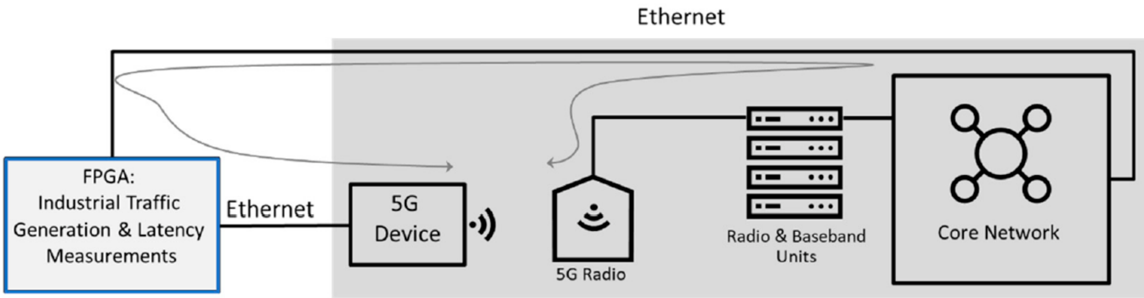


Figure 5: One-way latency measurement setup used at the 5G-SMART trial site in Aachen. The FPGA-based tool allows for generating customized/configurable automation traffic as in the 5G-SMART use-cases and carrying out accurate latency measurements. Source: [AAB+22].

Figure 6 and Figure 7 show the uplink latency results for the 5G NSA commercial system and the URLLC testbed. The figure reports that the latency in the commercial 5G system increases at higher percentile values: the larger the measurement sample, the more likely some probes will experience a latency increase. However, with the URLLC features, the latency remains bound to a very low value. Tests have been run with different devices as well as RAN configurations. One important result has been that the e2e latency depends on the 5G UE design, including the operating system and interfaces. We measured latency using two 5G devices (UE device A and UE device B), both based on the Qualcomm x55 modem chipset. The RAN configuration plays an essential role in the overall latency behavior, as shown in Figure 7 for the two 5G devices used in our tests. Here, the results obtained with a default RAN configuration are compared with those measured using an adapted configuration with tuned parameters related to scheduling and link robustness. A more detailed description of the latency and throughput measurements, including downlink performance characteristics, can be found in [AAB+22].

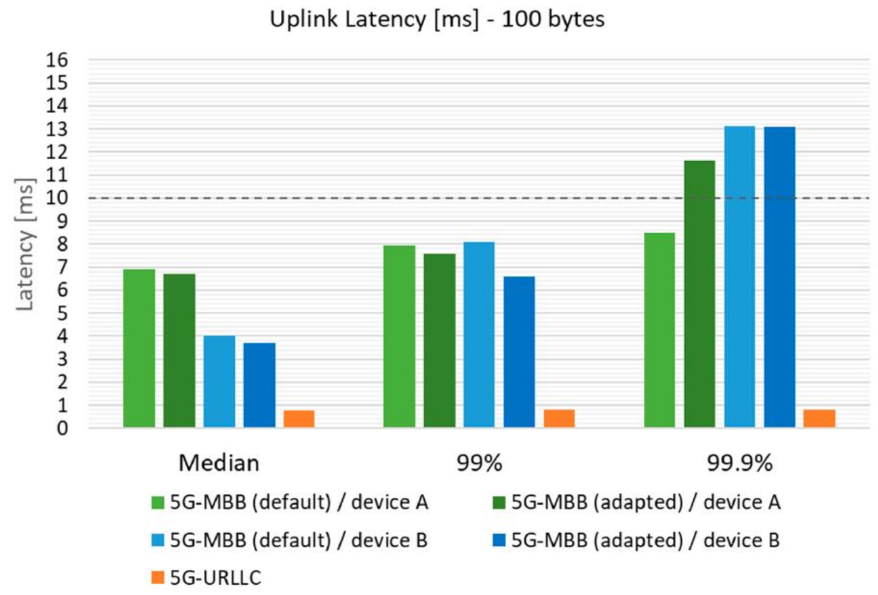


Figure 6: Uplink latency at different reliability percentiles (median, 99th percentile, 99.9th percentile) for 100 bytes message size transmitted with a period of 10 ms. Source: [AAB+22]

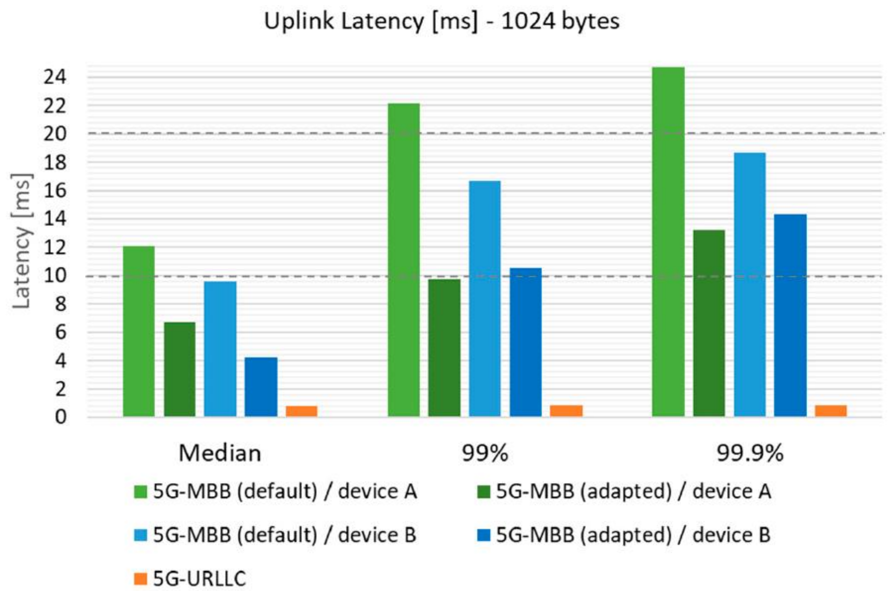


Figure 7: Uplink latency at different reliability percentiles (median, 99th percentile, 99.9th percentile) for 1024 bytes message size transmitted with a period of 10 ms. Source: [AAB+22]

### 3.2.2 Coexistence measurements

We have also carried out coexistence measurements at the 5G-SMART Aachen trial site to understand the impact on latency and throughput based on the coexistence effects. The detailed results are reported in [5GS21-D150] and [CAS+22].

# 4 5G validation of wireless acoustic emission tool condition monitoring

## 4.1 Introduction

An acoustic emission (AE) sensor system has been developed and prototyped in 5G-SMART to provide a high-resolution instrument for detecting and characterizing the interaction between the tool's cutting edge and the workpiece to be manufactured. The system generates a continuous stream of spectral data with average data rates in the range of 8 Mbit/s. The information provided is used to reactively control the manufacturing process and the machine tool with low reaction times, e.g., for interrupting the machining process and exchanging the tool based on the sensor data acquired wirelessly directly from the process zone.

There is a residual error in the computer-based planning of cutting operations due to the uncertainty of the workpiece's actual position and real dimensions. The planning is carried out under the assumption of ideal conditions. In order to consider this uncertainty and avoid a collision of tool and spindle with the workpiece, the machine operator implements safety gaps. These gaps are called *air cuts*, in which the tool is slowly approaching the workpiece. In order to save machine time, it is essential to *detect material contact* (also known as *gap control*), which is one application area of the AE measurement systems. Gap control is closely related to *collision detection*, where the purpose is not to save time but to prevent cost-intensive damages to the machine tool spindle. While a collision is an unplanned event, material contact detection is a planned event. Therefore, it is one of the validation scenarios for the AE sensor system and is described in Section 4.4.

In terms of the interaction of the cutting tool, the cutting edge is subject to wear, and it may eventually break. Suppose this *tool breakage* happens during the cutting process. In that case, the AE contains characteristic spikes in a specific spectrum (typically between 150 and 250 kHz), which are constantly analyzed to detect the tool breakage and to feedback this information to the machine control system. This tool breakage detection is especially critical for drilling or milling tools with small diameters. This is reflected in the validation scenario described in Section 4.5.

A wired, commercial-off-the-shelf system (Marposs GEM AM01) was used as a benchmark to compare the wireless, 5G-based solution in both validation scenarios.

## 4.2 Relation to industry goals

The use cases *material contact detection* and *tool breakage detection* described in the previous section primarily address the industry goals of sustainability, flexibility, productivity, and utilization.

*Sustainability*

This category is mainly addressed by the use case *tool breakage detection*. In milling processes with small tool diameters where cooling lubricant is used, tool breakage can occur during the process without the machine operator noticing. This causes the milling process to continue unnecessarily, wasting machine energy and cooling lubricant. 5G sensor-based detection of tool breakage allows the machine to be stopped immediately, saving energy and resources and improving the sustainability of the process.

*Flexibility*

Both use cases address the industry goal of flexibility. The time required to install the 5G sensor is less than the wired variant. In addition, the 5G variant is much more flexible because there is no need to run a cable from inside the machine to a computer outside the machine. For example, some machines are not designed in such a way that a cable can be routed out of the machine.

*Productivity*

Both use cases address the goal of productivity. For the *material contact detection* use case, productivity can be increased by reducing the processing time when no material is being cut. For example, the time for approach and retract movements can be reduced by increasing the feed rates based on the sensor signal. In the *tool breakage detection* use case, productivity increases if the machine stops immediately after tool breakage, and a new tool can be clamped. This also prevents potential damage to the workpiece.

*Utilization*

Both use cases address the goal of utilization. As explained in the categories above, the idle time of the machine is reduced, as running processes with broken tools can be stopped immediately, and approach and retract movements are accelerated.

## 4.3 Validation KPIs

In order to validate, evaluate and demonstrate the use case of wireless acoustic emission tool condition monitoring, two validation scenarios have been defined, and the relevant KPIs for evaluation have been determined.

Table 3 summarizes the KPIs identified as relevant together with their definition.

Table 3: Validation KPIs for the acoustic emission sensor system

| KPI | KPI Definition | Industry goal category |
|---|---|---|
| **Resource consumption** | Consumption of electricity for the machine tool, milling tools, and lubricant | Sustainability |
| **Setup time** | Time needed to set up the equipment (e.g., 5G wireless acoustic emission sensor) | Flexibility |
| **Process time** | Time needed for milling a workpiece | Productivity |
| **Idle time** | Time in which the machine is down or the tool is not in contact with the material | Utilization |
| **Response time** | Time needed to detect and react to a critical event (e.g., interrupting the machining process after a tool breakage) | Utilization |

## 4.4 Validation scenario 1: Material Contact Detection

### 4.4.1 Description of the scenario

The material contact of the tool with the workpiece can be determined using the acoustic emission sensor system. When the tool interacts with the workpiece, it induces the acoustic waves, which are detected by the sensor. When the spectrum of the captured data is plotted, a time-increasing peak can be seen, indicating that the tool has interacted with the workpiece.

The KPI determined in the validation is the difference in response time between the wired and the 5G solution. The GEM CPU receives both the data streams, one from the GEM AM01 via CAN and the other from the KBox as UDP packets, as illustrated in

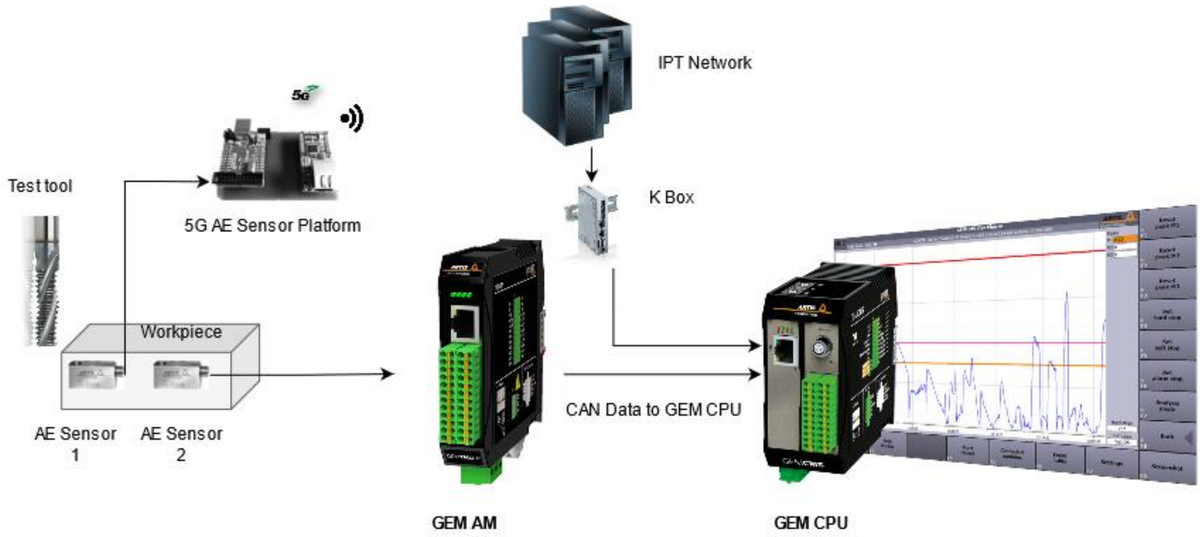


Figure 8. During the tests, the GEM CPU operated at a sampling rate of 2ms for maximum delay measurement accuracy. However, with this setup, it is only possible to determine how much slower the data transmission from the 5G-based AE sensor is compared to the data from the AM01 module. However, this is not a problem because the duration of data processing in the AM01 is well below the 2 ms sampling rate, so the AM01 data can be considered as a time reference. These data streams are then plotted using the GEM Visu software.

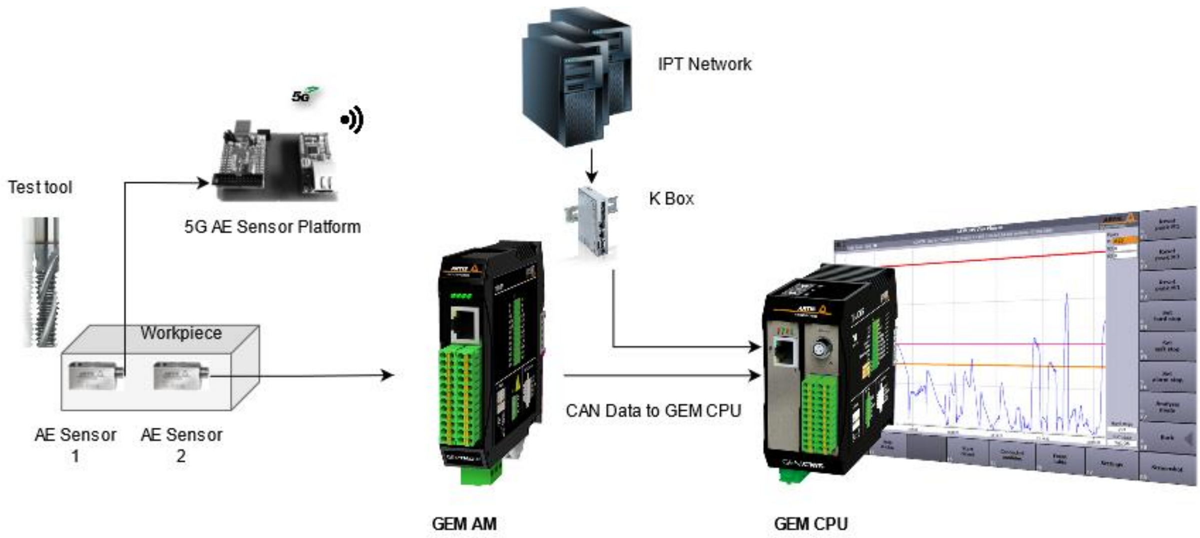


Figure 8: Measurement setup of the 5G AE sensor and the MMS Monitoring system.

The setup uses a prismatic solid workpiece made of titanium alloy as the validation workpiece. Two AE sensors are connected to the workpiece, equidistant from the edges of the workpiece. One of the sensors has a cabled connection to the Marposs GEM AM01 module, which pre-processes the AE signal and extracts features such as peaks and Fast Fourier Transform (FFT). This data is then sent to the GEM-CPU via CAN-bus, where monitoring takes place. The data can be visualized using the GEM Visualization (GEM-Visu) software to keep track of the monitoring.


Figure 9: Measurement setup with the AE sensors, FPGA, and 5G box

The other AE sensor is connected to the wireless 5G AE sensor system (Figure 9). The 5G AE sensor calculates the FFT spectrum using an FPGA and identifies the peaks on the selected frequency bands of the sensor. This peak information is then sent using a housed 5G-UE over the 5G network at the Fraunhofer IPT to the Kontron K-Box A330-RPI (K Box). The K Box acts as a gateway for the data transferred from the Fraunhofer IPT and the CNC machine networks. Both AE sensors and the 5G-based system are placed inside the DMG Mori DMU 65 monoBLOCK 5-axis milling machine, as shown in Figure 9. Figure 10 shows the AM01 module, GEM-CPU, and the K Box in the control cabinet of the machine tool.

The GEM-CPU receives both data streams, one from the GEM AM01 via CAN and the other from the 5G-based version via KBox as UDP packets. The GEM-CPU is operated at a sampling interval of 2 ms for maximum delay measurement accuracy during the tests. With this setup, the resolution is only 2 ms to determine how much slower the 5G data is compared to the data from the AM01 module. However, this is not a problem because the duration of data processing in the AM01 is well below the

2 ms interval so that the AM01 data can be considered the time reference. The two data streams are then plotted using the GEM Visu software. The data is recorded and can be exported as CSV files.

The CNC of the machine tool is used to control the tool position and the material contact, which can be detected by both AE sensors simultaneously.

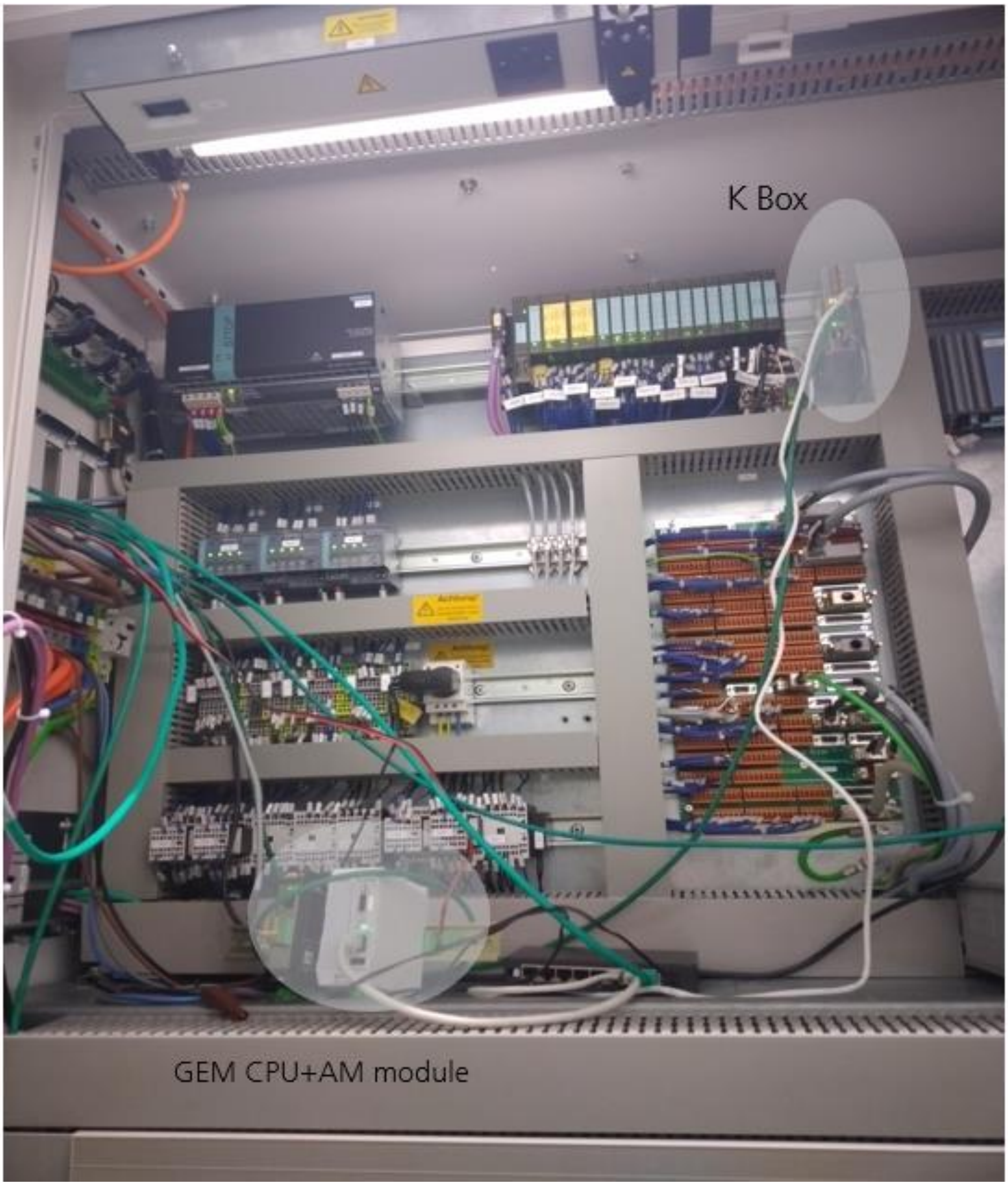


Figure 10: The machine's control cabinet, where the GEM-CPU is integrated.

### 4.4.2 Validation results

A high amplitude spike is detected in the GEM Visu monitoring software when the tool approaches physical contact with the workpiece to measure the time of material contact. The following snapshots were taken, showing the event at which the software detected the contact. The following screenshot in

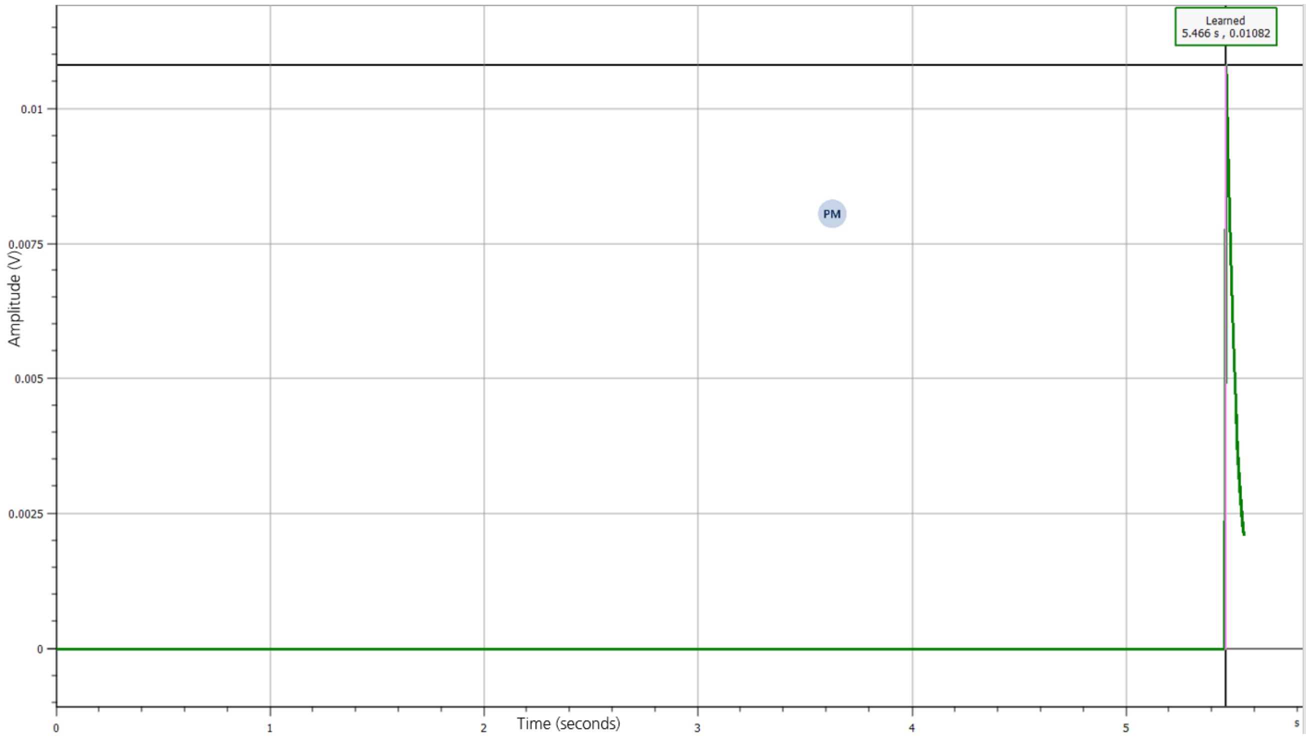


Figure 11 shows the material contact acquired from the GEM AM01.

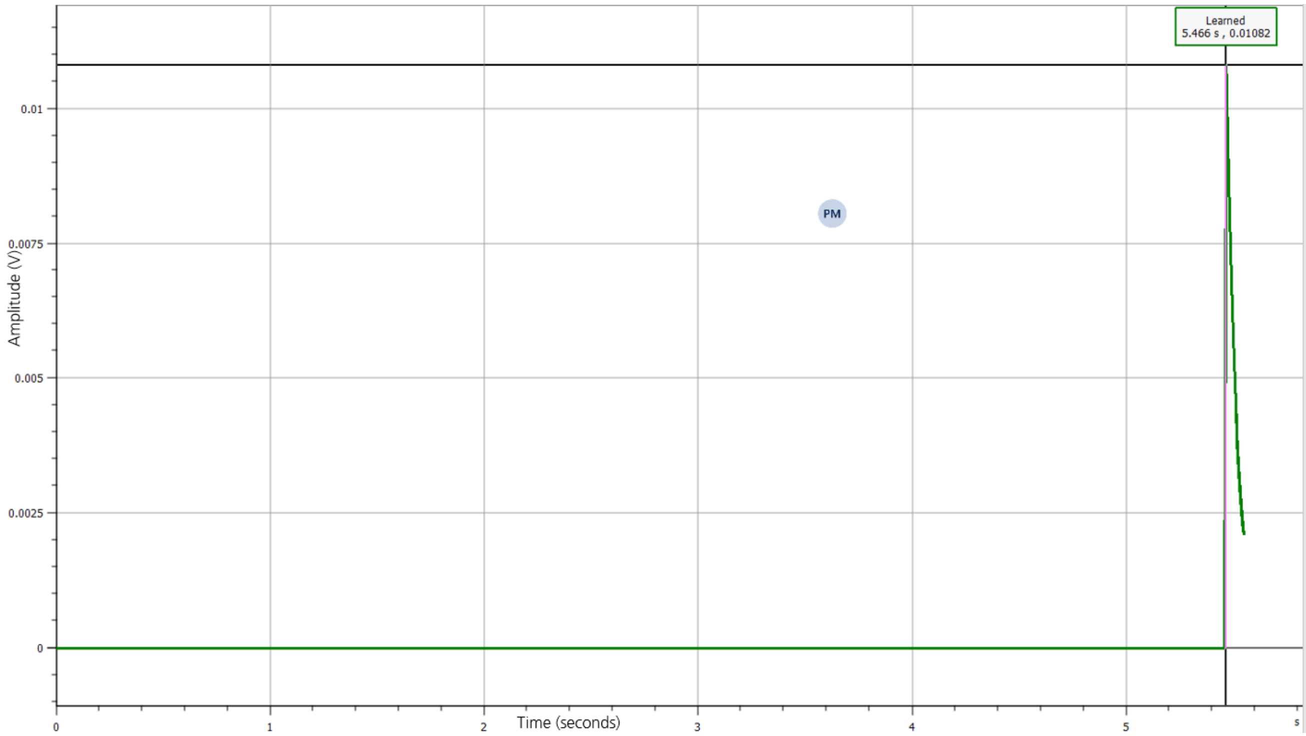


Figure 11: Material contact acquired from GEM AM01

The same event has been acquired with the 5G AE sensor, shown in Figure 12:

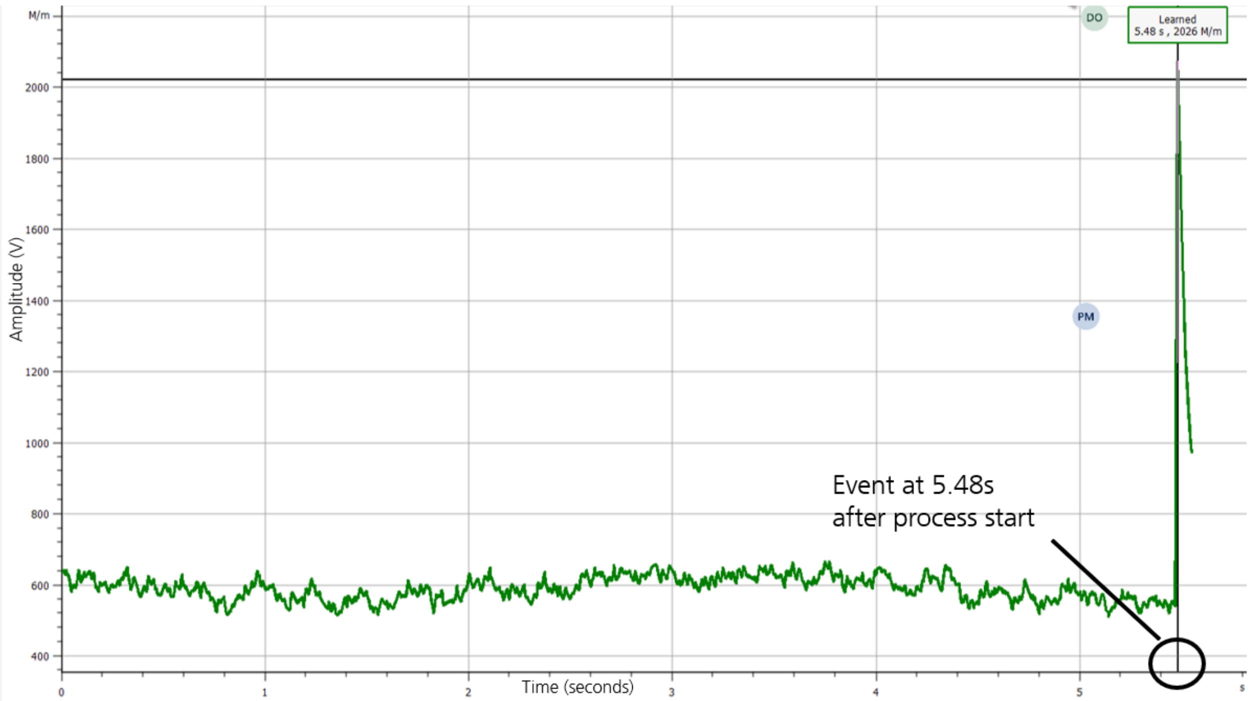


Figure 12: Material contact acquired from the 5G AE sensor

Table 4: Normalized amplitude values recorded from the material contact event using GEM AM01 (cabled) and 5G AE sensor (wireless)

| Time Stamp | GEM AM01 | 5G |
|---|---|---|
| 2021-11-24 10-48-17.544 | 0 | 0.02484076 |
| 2021-11-24 10-48-17.546 | 0 | 0.02356688 |
| 2021-11-24 10-48-17.548 | 0.88314904 | 0.02292994 |
| 2021-11-24 10-48-17.550 | 0.99932563 | 0.02165605 |
| **2021-11-24 10-48-17.552** | **1** | **0.02038217** |
| 2021-11-24 10-48-17.554 | 0.96739 | 0.01974522 |
| 2021-11-24 10-48-17.556 | 0.92869218 | 0.34394905 |
| 2021-11-24 10-48-17.558 | 0.89154634 | 0.65605096 |
| 2021-11-24 10-48-17.560 | 0.85588504 | 0.77070064 |
| 2021-11-24 10-48-17.562 | 0.82164916 | 0.88535032 |
| **2021-11-24 10-48-17.564** | **0.78878327** | **1** |
| 2021-11-24 10-48-17.566 | 0.75723194 | 0.96815287 |
| 2021-11-24 10-48-17.568 | 0.72694251 | 0.93630573 |
| 2021-11-24 10-48-17.570 | 0.69786511 | 0.9044586 |
| 2021-11-24 10-48-17.572 | 0.66995076 | 0.87261147 |

Generally, it can be observed that the sensor signals have different noise levels because of the different analog/digital processing paths and the different hardware components used for that.

To retrieve the exact timestamps of the event, it is necessary to look at the recorded data. Table 4 shows an example of the normalized values of these plots so that the peak values are clearly visible.

GEM AM01 data shows the material contact event at 10:48:17.552, while the event in the 5G data is at 10:48:17.564. So, the latency of the 5G data is 12 ms.

### 4.4.3 Discussion

The sampling interval of the GEM-CPU influences the measured latency of 12 ms, which during the validation measurements was decreased to 2 ms. In terms of measurement uncertainty, this corresponds to a rectangular probability density function with a half-width $a = 1\,ms$. This is comparable to the reading error or aliasing in digital instruments. According to [GUM], the measurement uncertainty for the measured latency is $u_l = k \cdot {}^{a}/_{\sqrt{3}} = 1.15\,ms$, with a coverage factor $k = 2$. So, the resulting measured latency is $\mu_l = 12\,ms \pm 1.15\,ms$.

It has to be added that the default sampling interval of the GEM-CPU is 10 ms. Furthermore, the measured latency $\mu_l$ is composed of several elements:

- processing time of the 5G AE sensor electronics,
- transfer interval of the 5G AE sensor system of 1 ms, in which data is aggregated into UDP packets, and the

- total end-to-end transfer time of the UDP data via the 5G system, the local breakout to the Fraunhofer IPT network, and K Box to the GEM-CPU.

The packet size of the 5G AE system is 1024 bytes. The one-way latency given in Section 3.2.1 for this packet size is between 4 ms (median, Device B, adapted configuration) and 13 ms (99.9% percentile, Device A, adapted configuration). As indicated in the evaluation results on the prototype system (cf. Figure 6 and Figure 7), latency will decrease with 3GPP Release 16 and URLLC functions when available on the commercial track.

In conclusion, the 5G AE sensor system's suitability for material contact detection can be positively answered. Even if the measured e2e latency was $\mu_l = 12\ ms \pm 1{,}15\ ms$ and above the usual sampling rate of the monitoring system, it is clear that with URLLC coming with Rel. 16 of the time-critical-communication feature of Ericsson, the latency of the 5G communication will decrease.

*Relation to KPIs and industry goals*

Given the suitability of the 5G-based version, one can compare the *setup times* of the 5G-based vs. the wire-based version. The wired version requires extensive cabling effort, for which parts of the machine tool have to be dismantled. Once installed, there is no flexibility to change the setup, e.g., use the system for different use cases. The setup time for the wired version is estimated to be one day.

In contrast, the wireless version's setup time is max. 10 mins. The wireless version has the additional advantage that the AE sensing probe can be flexibly attached to the workpiece rather than the machine, providing valuable new data for monitoring. However, the power consumption of the 5G UEs has to be reduced to have reasonable battery runtimes and device sizes. We have measured the power consumption of various 5G UEs used at the 5G-Industry Campus Europe in the range of 2.5-3 W.

It is also worth mentioning that the maintainability of a 5G-based AE sensor system may reduce service efforts. The mean time between failures (MTBF) for conventional AE sensor systems is approx. ten years. The 5G-based system may receive OTA software updates, saving two days of service personnel.

*Idle-time* decreases as AE-based material contact detection reduces air cuts saving up to one minute per cutting procedure. On average, this method saves 5-10% for each NC program and decreases the *process time,* consequently positively influencing *productivity*.

## 4.5 Validation scenario 2: Tool Breakage

### 4.5.1 Description of the scenario

The AE sensor system can also be used to detect tool breakage. The tool, upon breakage, inhibits an impulse of high-frequency burst on the workpiece, which the system can sense. The GEM monitoring solution has an integrated learning algorithm that learns the AE data and determines the mathematical statistics of the tool condition. An anomaly is detected when the tool breaks, deviating from the learned parameters and triggering an alarm.

To evaluate the performance of the 5G for Tool breakage detection, the same setup as described in Section 4.4.1 for contact detection is used. The software is modified to analyze the AE data for tool breakage. The 5G AE sensor sends the root mean square (RMS) value of its FFT. The monitoring solution uses these values to train its breakage statistics model.

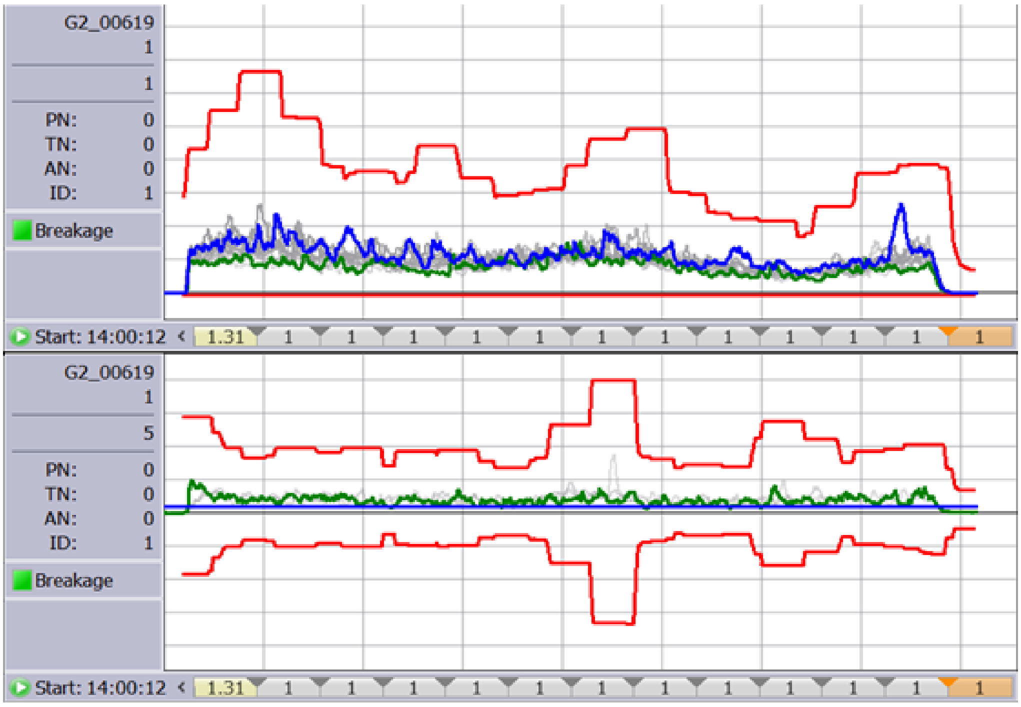


Figure 13 depicts the learning mode of the monitoring software. The data of the reference (first cut) are plotted in green, the signal of the current machining is plotted in blue, and the red lines are the limits that trigger an alarm when exceeded. Tool breakages were intentionally caused by increasing the feed rate of the spindle without increasing the spindle speed, thus increasing the pressure on the tool.

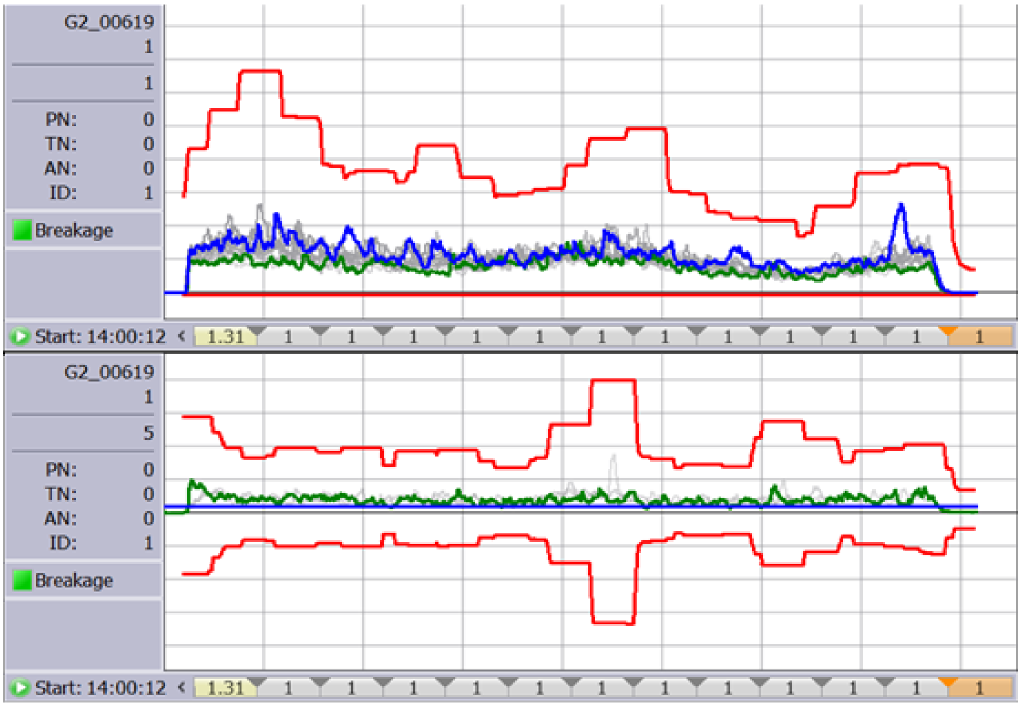


Figure 13: Tool breakage learning mode with limits (in red)

### 4.5.2 Validation results

After the training phase is complete, monitoring allows detecting signal deviations from the reference process. The monitoring solution keeps track of the statistics and updates them after every measurement cycle. The tool gradually wears off, and as the tool reaches the breakage point, a sharp increase in the RMS value exceeding the threshold is detected. This event causes an alarm by the software. Figure 14 shows such an event.

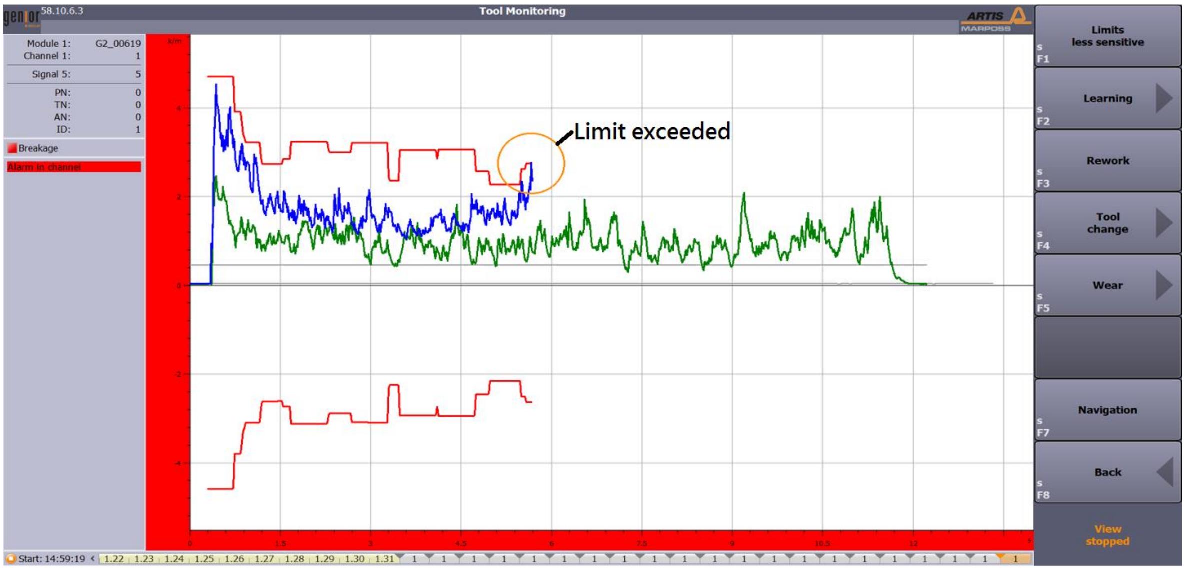


Figure 14: Plot of the tool breakage alarm from the 5G AE sensor.

In addition, the tool breakage was recorded using an external force measurement system to determine the bending moment of the tool. It is measured with a tool holder with integrated strain gauges. Figure 15 shows the 5G AE and the bending moment measurements in one plot. It can be seen that the AE signal disappears with the tool breakage because it stops the interaction of the cutting edge with the workpiece. The bending moment sensor indicates the increase of the pressure onto the tool induced by the milling strategy described at the end of Section 4.5.1. Figure 16 shows the broken tool inside the machine.

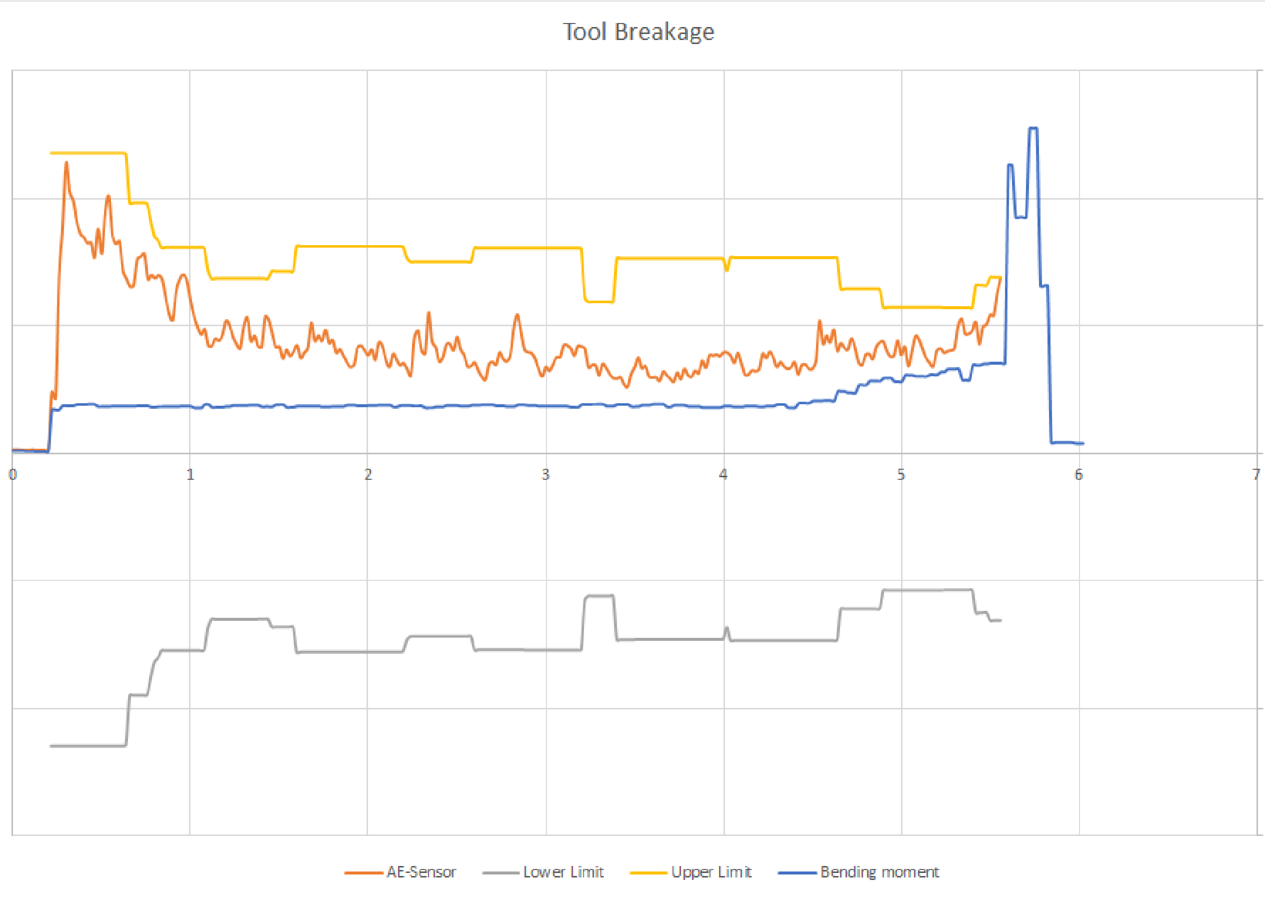


Figure 15: Plot of the CSV data from the GEM module and machine data with bending moment. [X-axis: seconds, Y-axis: a.u.]


Figure 16: Broken tool during the 5G-SMART trial at the Aachen site.

### 4.5.3 Discussion

The validation measurements showed that integrating data transmitted via 5G into a state-of-the-art monitoring system like the GEM used in the trials is possible. The signals transmitted via the 5G system could be processed the same way as in a wired sensor system, including applying the trained model for alert creation based upon that model. Thus, with its onboard signal conditioning and feature extraction, the wireless 5G AE sensor for tool breakage is comparable to the current industrial solution. The feature where the sensor is directly integrated close to the workpiece means that it can be used in almost any complex machining without additional cabling effort. The trial also indicates that the solution can be easily integrated with slight software modification into the application. On the one hand, the modifications could lead to a better configurability of the sensor solution regarding measurement parameters like sampling rate, integration time, or the spectrum of interest to be analyzed. On the other hand, automated feature detection could be integrated into the FPGA program. Furthermore, the integration of the GEM into the machine's CNC would offer the possibility of recording position-resolved measurements for creating Digital Twins.

In case of tool breakage, it is essential to detect the breakage as soon as possible. When detected, the machine user has to exchange the broken tool against a new one, find the broken part in the machine, and rewind the process to restart it at the point of the breakage. Before the restart, the workpiece needs to be inspected to determine whether it has to be discarded or still can be used. In the latter case, the tool has to be approached to the workpiece again.

*Relation to KPIs and industry goals*

The relation to the KPIs for this validation scenario is identical for the 5G-based vs. the wire-based version *setup times*. Also, the statement regarding the application of the 5G-based AE sensor, battery runtime, and maintenance can be copied here from validation scenario 1.

*Idle-time* decreases as AE-based tool breakage detection reduces the time of the NC program rewind and restart procedure by up to five minutes per tool breakage incident because the AE-based detection will generate a timestamp that needs to be compared with the logfiles of the CNC controller. After a tool breakage, the machine operator must set up a new tool and recalibrate it. This can take up to 5 minutes. Then the NC program in which the tool breakage occurred is started from the beginning. Depending on the duration of the NC program, this can lead to a further delay of up to 15 minutes. In the case of a BLISK, an undetected tool breakage can lead to a delay of between 5 and 12 minutes. On average, the AE-based tool breakage detection method saves 5% for each NC program, positively influencing *productivity*.

## 4.6 Conclusions on 5G validation of wireless acoustic emission tool condition monitoring

Both validation scenarios for the 5G-based AE sensor system show this solution's suitability for machining applications. One main result is that the performance of the 5G-Non-public network (NPN) is sufficient not to compromise the application for both validation scenarios, *material contact detection,* and *tool breakage detection*. Thus, we can state that 5G-connectivity for the AE sensor is capable of real-time data transmission since it does not delay conventional process monitoring solutions, i.e., the total e2e latency between application endpoints is on the order of magnitude of state-of-the-art systems.

Furthermore, the use cases benefit the KPIs, namely *setup time* and *idle time*, resulting from the wireless nature of the 5G-based AE sensor and the short reaction times compared to conventional machining operations without any AE sensor. The reduction of the KPI *idle time* directly relates to decreased *process time* and *resource consumption* since these KPIs feed into each other.

Regarding the KPIs mentioned above, applying a 5G-based AE sensor system to machining operations contributes to the industry goals of flexibility, productivity, utilization, and sustainability.

A limitation of the current implementation can be seen in the energy consumption of the AE sensor system, not in terms of a disadvantage for sustainability because the energy consumption is still low compared to a machine tool. As mentioned in Section 4.4.3, the energy consumption of the 5G UE requires the use of batteries with sufficient capacity to achieve a reasonable wireless runtime of the overall sensor system. It also has to be added that the FPGA, as the central processing unit of the AE sensor system, runs on the same battery and is also quite energy-intensive. Larger capacities usually come at the cost of a larger footprint of the overall sensor system limiting its applicability and versatility for machine-integrated use cases.

In the future, 5G UEs with new specifications may allow for lower energy consumption but still sufficient capacity on the uplink and low latency, e.g., Reduced Capability New Radio (RedCap NR) devices with 3GPP Release 17 can be exploited in this context. The FPGA is energy-efficient compared to platforms that could potentially provide the required computing capacity, like Beaglebone or Jetson Nano. Thus, the most probable approach to decrease the energy consumption is to offload computation to a device not running on battery, e.g., an edge device or an edge-cloud. The edge-cloud has the advantage of taking over computation for multiple AE sensor systems while offering the potential for consolidating the computation requirements and saving energy. At the same time, an AE sensor system operated only with a microcontroller responsible for ADC and packet generation would require less energy and subsequently have a smaller footprint.

# 5 5G validation of versatile multi-sensor platform for digital twin

## 5.1 Introduction

The multi-sensor platform (MSP) is a versatile solution for measuring different parameters and connecting a wide range of sensors in a production plant. Depending on the application, different numbers and types of sensors of the MSP are used and configured flexibly depending on the application.

The MSP can be applied in various use case scenarios. One of the main application domains of the MSP is the *workpiece and process monitoring*. It can be used for monitoring the cutting processes. The availability of wireless sensors results in better accessibility of the sensors to the workpiece, which also allows for measurements on moving elements (e.g., machine axes). Furthermore, new applications are possible, such as the measurement of the dynamic behavior of the workpiece (e.g., vibration). The process information acquired is essential for a comprehensive understanding of the physical effects and a proper process modeling. Subsequently, these insights serve for constant optimization of the machining processes to achieve optimal results in terms of costs, time, and quality.

The MSP will consistently deliver information on the processing history, contributing to the *digital twin*, while following the workpiece along with steps in the process chain. Thus, continuous monitoring helps companies constantly increase production efficiency, e.g., calculated as the overall equipment efficiency (OEE). The OEE quantifies the percentage of manufacturing time that is truly productive, considering production processes' quality, performance, and availability.

The application of the MSP to *machine condition monitoring* is attractive in assessing lifetime data from multiple machines on a shop floor or across multiple sites. In these use case scenarios, the MSP serves the versatile, continuous monitoring of multiple parameters from within the machine. The MSP will be a resident installation inside the machine, i.e., it will not be changed after each workpiece. This solution allows for easy retrofit without the need for cabling efforts. The measurement data acquired by multiple MSPs can be used for centralized data analytics, comparison of different machine conditions, pattern analysis, and ultimately predictive maintenance.

For both use case scenarios described above, the MSP targets all industries associated with metal processing, e.g., tool and die making, aviation, automotive, etc. A third use case scenario is *infrastructure monitoring*, which serves to gain information about the condition of facilities, such as temperature, humidity, noise levels, etc. From the connectivity perspective, the associated measurement parameters are not acquired with high sampling frequencies or user data rates, and they do not require high reliability or low latency. Therefore, the application of the MSP can then also be associated with the massive machine-type communication (mMTC) service category. Nevertheless, 5G-SMART has not implemented and exploited the last use case scenario because it does not represent a specific challenge regarding eMBB or URLLC 5G transmission in manufacturing as addressed in 5G-SMART.

## 5.2 Relation to industry goals

This section focuses on *process monitoring for critical machining* and *strain measurement*. These use cases can be assigned to the industry goals of quality, sustainability, productivity, and utilization.

*Quality*

This category is addressed by both of the use cases. The use case *process monitoring for critical machining* is to detect and avoid high vibrations (e.g., chatter) within a milling process. This improves the resulting surface quality of the machined surfaces and thus the workpiece quality. The use case *strain measurement* enables the measurement of a workpiece's strains during the milling process. This can be used, for example, to evaluate the workpiece deflection that can lead to dimensional deviations. Based on the measured strains, process parameters can be optimized to compensate for the workpiece deflection to achieve the required tolerances. A wireless solution supports an easier deployment and thus strengthens the widespread use of sensor applications in monitoring, whereby the accessibility of the measuring spot is also improved in the case of wireless sensors.

*Sustainability*

Both use cases contribute to an increase in sustainability: the vibration detection and reduction decrease tool wear and the failure rate of workpieces. The strain measurements can further reduce the failure rate of workpieces. Wireless sensors can make the accessibility for measurements of these quantities easier and reduce scrap production, leading to material and energy savings.

*Productivity*

Both use cases increase the productivity of the machining process. As described above, both the use cases contribute to a reduction in the failure rate of machined workpieces. In addition, optimization of the process parameters in terms of productivity as a function of the measured vibrations and strains is feasible.

*Utilization*

Analogous to Section 4.2, the two use cases discussed in this section also reduce the idle time of the machine. In addition, the ramp-up time is reduced because optimized process parameters can be found quicker. Constant optimization parallel to the process can be facilitated by continuous monitoring using the MSP.

## 5.3 Validation KPIs

In order to validate, evaluate and demonstrate the use case of the multi-sensor platform, three validation scenarios have been defined, and the relevant KPIs for evaluation have been determined.

Table 5 summarizes the KPIs identified as relevant together with their definition.

Table 5: Validation KPIs for the multi-sensor platform

| KPI | KPI Definition | Industry goal category |
|---|---|---|
| **Surface quality** | Quality of a machined surface measured as roughness | Quality |
| **Shape and dimensional deviation** | Shape and dimensional deviations of a machined workpiece (e.g., profile deviations of a blade) | Quality |
| **Resource consumption** | Consumption of electricity for the machine tool, milling tools, and lubricant | Sustainability |

| | | |
|---|---|---|
| **Setup time** | Time needed to set up the equipment (e.g., 5G multi-sensor platform) | Flexibility |
| **Process time** | Time needed for milling a workpiece | Productivity |
| **Idle time** | Time in which the machine is down or the tool is not in contact with the material | Utilization |

## 5.4 Validation scenario 1: process monitoring for critical machining

### 5.4.1 Description of the scenario

For condition monitoring of machining processes, parameters such as bending moment or strain of the workpiece on tool interaction and natural frequency vibration of a workpiece are monitored. This allows maintaining the workpiece in the working threshold to get the desired quality. This data must be sent in real-time to monitor and control the process if specific parameters exceed the operating limits. One key performance measure is the latency when the data is sent to the end application to detect the alarm after the parameter reaches the threshold. The 5G-MSP is equipped with an accelerometer and a strain gauge for the validation trials, while it can be flexibly equipped with up to three different sensor modules, as described in [5GS21-D330] and [MPZ+22]. The strain gauge is compared with the standard cabled industrial sensor strain gauge solution to validate its performance.

The measurement setup for the MSP latency performance is shown in Figure 17. The setup comprises two sensors. One of the sensors is integrated into the MSP with its sensor conditioning module, and the other is connected to the Marposs GEM Modules. For the strain sensor, the GEMGP (Genior modular general purpose) module is used. This module contains the bridge amplifier circuit for the strain gauge.

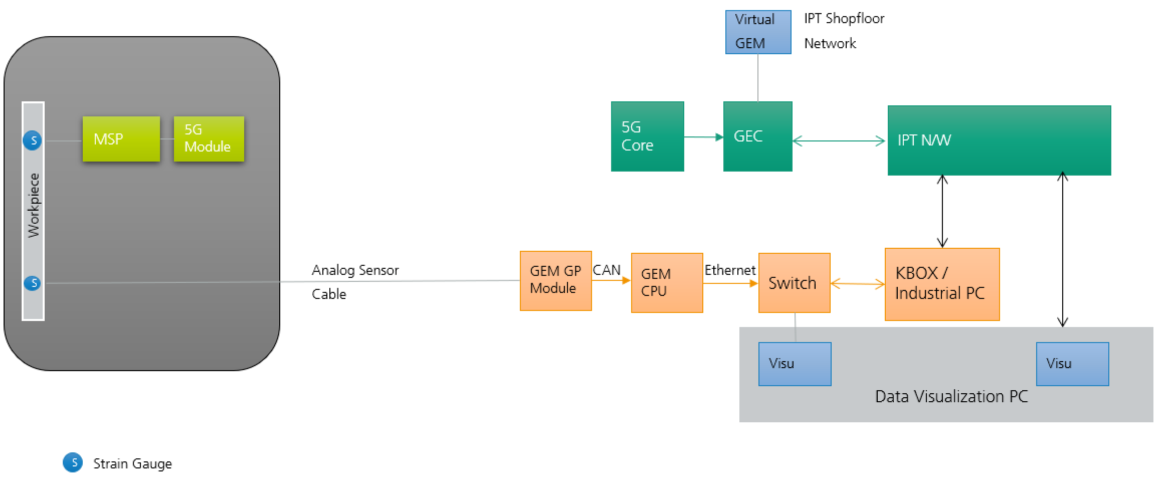


Figure 17: Measurement setup for the MSP sensor and industrial sensor solution

These modules send the data to the GEM CPU module via the CAN bus. The data aggregated by the GEM CPU can be accessed and processed for applications such as live monitoring and tool breakage detection, etc. The monitoring solution is viewed using the special visualization tool called GEM-Visu. The GEM-Visu software running on the PC is interfaced with the GEM CPU via an Ethernet switch.

The data from the 5G-MSP (see Figure 18) is sent to the edge-cloud gateway over the 5G network. The gateway processes the timestamp and forwards the corresponding data to the Virtual-GEM (GEM-VM) hosted in the German Edge Cloud (GEC). This GEM-VM can be accessed remotely from the Fraunhofer IPT network with the GEM-Visu.

An industrial PC accesses both visualization tools with access to the machine network and the German Edge Cloud. To synchronize the trigger for starting the acquisition, a script was developed to start the visualization. The process is continuously monitored by recording and analyzing the data.

Figure 18 illustrates the learning procedure needed to trigger the alarm when the strain on the workpiece exceeds the limit. The red lines represent the limits to trigger the alarm, and the green line represents the past data used for the training algorithm. The blue line represents the current data. The previous iteration of the trained data is represented as a grey line. The graph represented in Figure 18 shows the data stream coming from the 5G MSP.

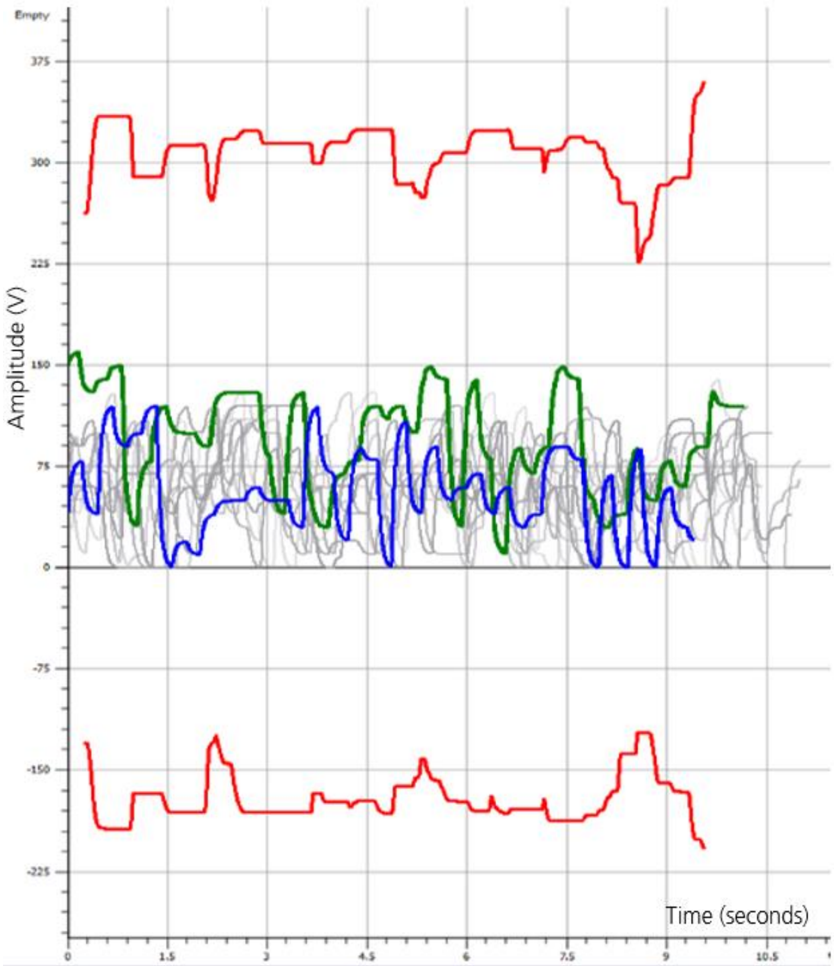


Figure 18: Strain gauge data from 5G-MSP with the learned model for alarm trigger

The same learning procedure was executed in parallel for the data stream from the analog sensor processed by the GEM hardware. This is illustrated in Figure 19.

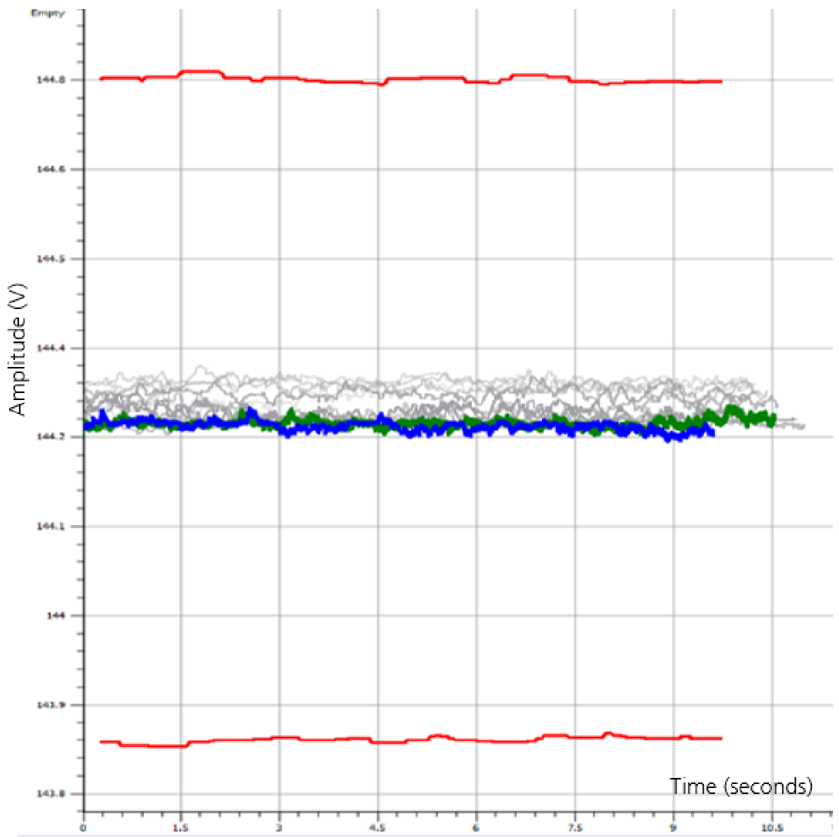


Figure 19: Learned model for strain gauge data based alarm trigger for Analog GEM module

Both the graph values do not have the same range of values. This is because of the analog signal conditioning such as filters and amplifiers in the GEM Module. The MSP does not have analog signal conditioners and sends only raw data. This results in more smoothened voltage values in Figure 19 and spiked values for the 5G-MSP data in Figure 18. Although the range is quite different, the learning algorithm uses the incoming data stream for learning, and hence the difference in the range of values does not impact the detection of the tool breakage alarm.

### 5.4.2 Validation results

The workpiece with strain gauges was used for the first trial to measure the latency between the bending data from the industrial wired system and the 5G system. During the process, the bending forces were detected by the strain gauges. The GEM-Visu visualizes these values, as shown in Figure 20 below. The plot on the left corresponds to the data from the GEMGP module. The plot on the right corresponds to the data received from the UDP socket in the virtual GEM.

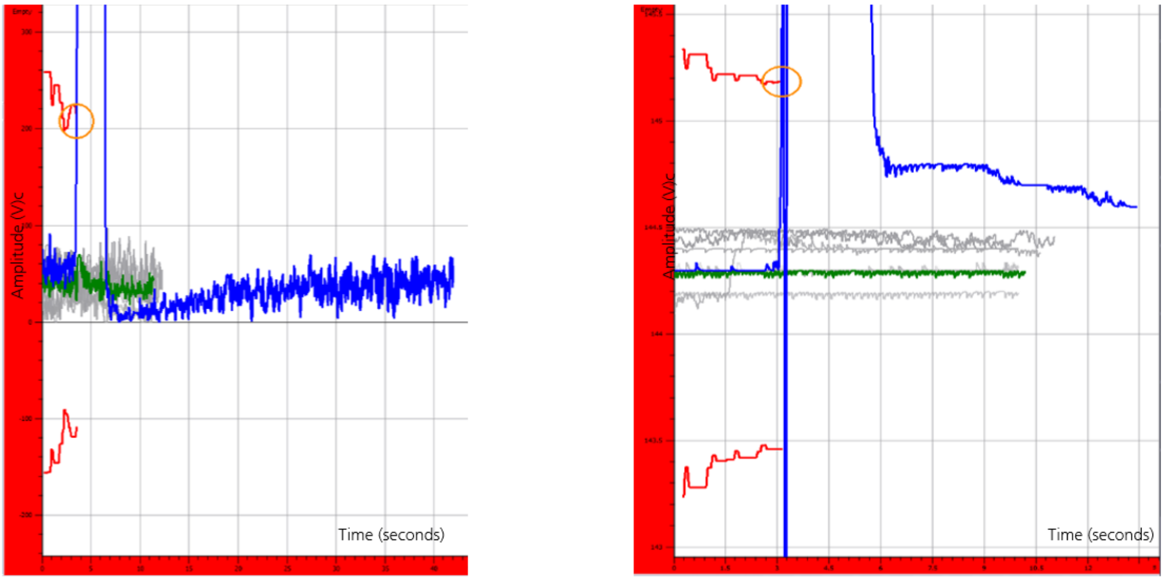


Figure 20: Alarm triggered from both GEMGP (left) and 5G-MSP (right)

As shown in Figure 20, the alarm is triggered when the bending force reaches the threshold. The latency between the alarm is analyzed from the recorded log file of this data. Table 6 shows a snippet of the data log stored in GEMGP and the virtual GEM. These logs are integrated concerning timestamps and show the alarm status. Each entry is recorded every one millisecond.

From the table, the alarm from the GEMGP is triggered first at time 2022-03-25 14-12-05.22, followed by the alarm triggered in the virtual GEM-VM at time 2022-03-25 14-12-05.33. Hence, there is a difference of approximately 11 milliseconds.

Table 6: Time series of logged alarms from GEMGP and GEM-VM

| Timestamp | Alarm Status from GEMGP | Alarm status from GEM-VM |
|---|---|---|
| 2022-03-25 14-12-05.14 | FALSE | FALSE |
| 2022-03-25 14-12-05.15 | FALSE | FALSE |
| 2022-03-25 14-12-05.16 | FALSE | FALSE |
| 2022-03-25 14-12-05.17 | FALSE | FALSE |
| 2022-03-25 14-12-05.18 | FALSE | FALSE |
| 2022-03-25 14-12-05.19 | FALSE | FALSE |
| 2022-03-25 14-12-05.20 | FALSE | FALSE |
| 2022-03-25 14-12-05.21 | FALSE | FALSE |
| 2022-03-25 14-12-05.22 | TRUE | FALSE |
| 2022-03-25 14-12-05.23 | TRUE | FALSE |
| 2022-03-25 14-12-05.24 | TRUE | FALSE |
| 2022-03-25 14-12-05.25 | TRUE | FALSE |
| 2022-03-25 14-12-05.26 | TRUE | FALSE |
| 2022-03-25 14-12-05.27 | TRUE | FALSE |
| 2022-03-25 14-12-05.28 | TRUE | FALSE |
| 2022-03-25 14-12-05.29 | TRUE | FALSE |
| 2022-03-25 14-12-05.30 | TRUE | FALSE |
| 2022-03-25 14-12-05.31 | TRUE | FALSE |
| 2022-03-25 14-12-05.32 | TRUE | FALSE |
| 2022-03-25 14-12-05.33 | TRUE | TRUE |
| 2022-03-25 14-12-05.34 | TRUE | TRUE |
| 2022-03-25 14-12-05.35 | TRUE | TRUE |
| 2022-03-25 14-12-05.36 | TRUE | TRUE |

### 5.4.3 Discussion

The logging interval of the GEM-CPU, which was set to 1 ms during the validation measurements, influences the measured latency of 11 ms. The same approach as described in Section 4.4.3 leads to a latency of $\mu_l = 11\ ms \pm 0.58\ ms$.

As already mentioned, the default sampling interval of the GEM modules is 10 ms. Furthermore, the measured latency $\mu_l$ is composed of several elements:

- processing time of the 5G-MSP sensor electronics,
- transfer interval of the 5G-MSP sensor system of 1 ms, in which data is aggregated into UDP packets, and the
- total roundtrip time of the UDP data via the 5G system, the local breakout to the Fraunhofer IPT network,

- processing of measurement data in the GEM-VM as part of the edge-cloud pipeline,
- transfer from K Box to the GEM-CPU.

The packet size of the 5G-MSP is 6 bytes for strain and temperature data and 1029 bytes for vibration data. The one-way latency given in Section 3.2.1 for this packet size is between 4 ms (median, Device B, adapted configuration) and 13 ms (99.9% percentile, Device A, adapted configuration). As indicated by the tests on the URLLC pre-commercial prototype system, it is expected that this latency will decrease with 3GPP Release 16 and URLLC features when available in the commercial 5G products.

In conclusion, the 5G-MSP's suitability for monitoring critical machining processes can be positively answered because the measured e2e latency is close to the default sampling interval of today's monitoring systems.

*Relation to KPIs and industry goals*

Given the suitability of the 5G-based version, one can compare the *setup times* of the 5G-based vs. the wire-based version. Both solutions have in common that the strain gauge needs to be fixed to the workpiece, e.g., gluing or soldering. The sensor solutions are then connected with wires to the sensor electronics.

The wired strain gauge system version requires extensive cabling effort, for which multiple cables have to be fed from the strain gauge inside the machine to the sensor electronics outside of the machine. This increases the cable length, whereas longer cable lengths increase susceptibility to external disturbance effects like electromagnetic interference. Furthermore, long cables increase the risk of cable damage. Once installed, there is no flexibility to change the setup, e.g., use the system for different use cases. The setup time for the wired strain gauge version can be estimated at half a day.

In contrast, the wireless version's setup time is max. 120 mins in our validation. The strain gauge can be connected to the MSP's electronics with comparably short cables so that the electronics of the MSP can be placed on the machine table close to the workpiece. This setup has a significantly lower risk of cable damage because the machine's movement does not bend the cable. However, the power consumption of the 5G UEs has to be reduced for this use case as well, as the MSP electronics are operated with a microcontroller at relatively low power.

*Idle-time* decreases because the setup time for the strain gauge (as part of the setup time for each workpiece) attached to the 5G-MSP is less than 50% of the time needed for the cabled version. This drastically increases *productivity*.

*Shape and dimensional deviation* improve because of the improved knowledge about bending and deflection effects during the machining and the ability to compensate for the machining process.

Reduction of *idle-time* and controlled processes with reduced *shape and dimensional deviation* can lead to an overall reduction of the *process time*.

## 5.5 Validation scenario 2. closed-loop control of machining processes

### 5.5.1 Description of the scenario

In this scenario, the closed-loop performance of the 5G Multi-Sensor Platform and the edge-cloud pipeline is evaluated.

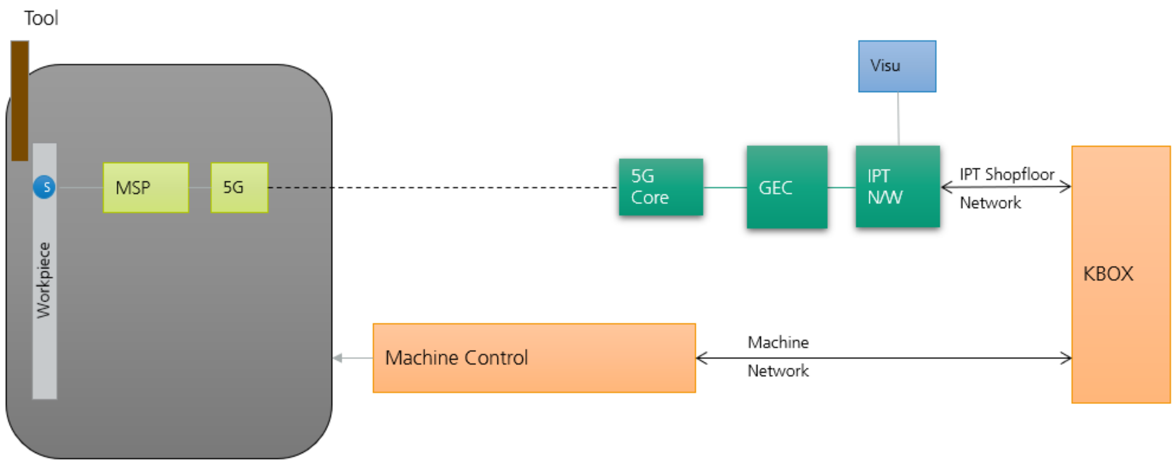


Figure 21: Setup for 5G-MSP in a closed-loop machine control

The setup is shown in Figure 21. The workpiece is mounted with the strain gauges and the vibration sensor. These sensors are then connected to the MSP, which sends the data to the pipeline. The pipeline consists of a data processing pipeline in the GEC that computes features such as FFT and forwards the data to the virtual GEM (GEM-VM). This pipeline and the GEM-Visu are containerized and deployed in the GEC. With its monitoring software, the GEM-VM is trained for the cutting process to identify a threshold for triggering an alarm. The training is done with the sensor data coming from the MSP over 5G. The GEM software has the 'Adaptive Control' feature, which can control machine parameters such as the speed spindle or the feed rate based on measurement data. In our validation, this feature is enabled to control the process based on the data coming from MSP.

With the training done, the machining process is started and allowed to continue. The cutting process, as it continues, induces strain and vibration on the workpiece. When the induced strain reaches a threshold or the vibration frequency reaches the eigenfrequency (natural frequency), the GEM-VM detects the anomaly and triggers the K Box to adopt the process. The K Box acts as a gateway to pass commands to the machine to adapt the process according to the alarm event, e.g., by increasing the spindle speed. These measures relate to keeping *shape and dimensional deviation* low.

### 5.5.2 Validation results

For the adaptive control feature, the vibration data of the MSP is used. Figure 22 illustrates the adaptive control by the GEM monitoring software, in which the green line represents the learned data from the previous cyles. The adaptive control analyses the vibration pattern and accordingly increases the feed rate to the machine to reduce the air cuts. The blue line, representing the current data, shows how the adaptive control reduced the time to finish one cutting process. The vibration value represented by the blue line drops just before that of the green line, indicating the end of the process.

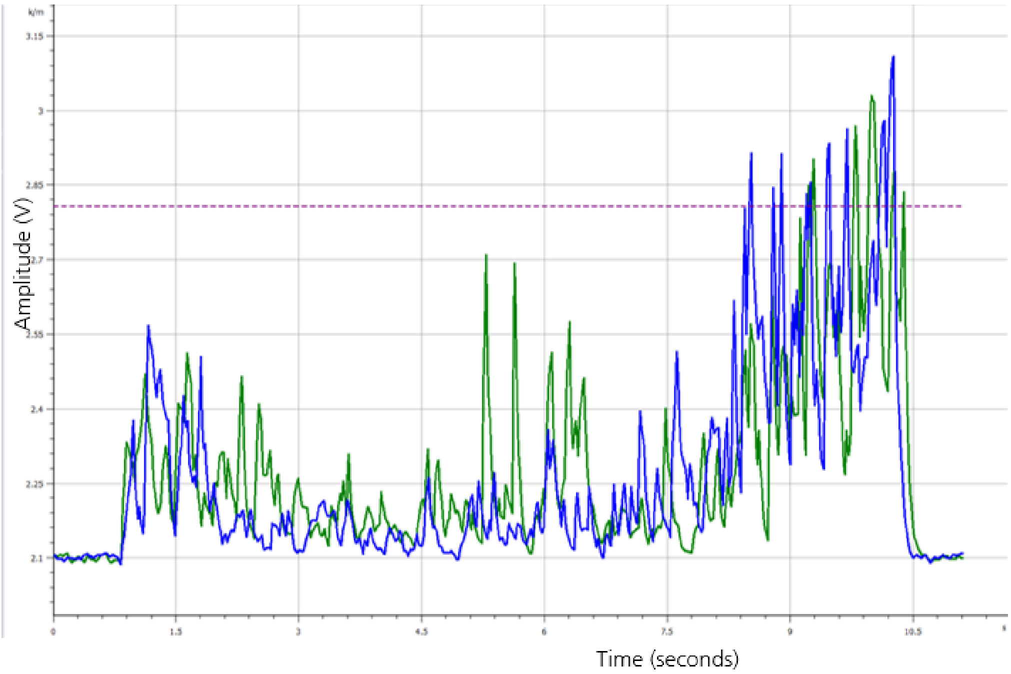


Figure 22: Adaptive control process by the GEM software based on MSP Vibration data (iteration 1).

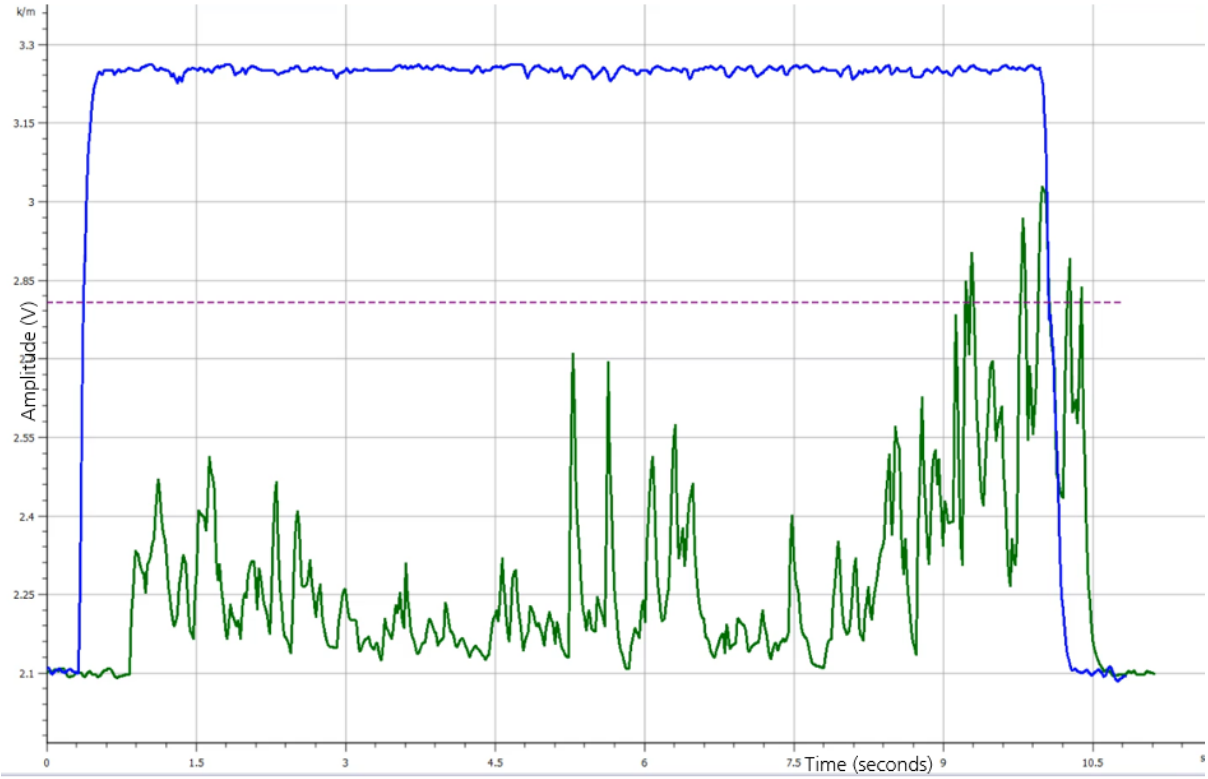


Figure 23: Adaptive control process by the GEM software based on MSP Vibration data (iteration 2).

The blue line vibration data drops much faster than in the previous cycle in the next iteration of the same process, as illustrated in Figure 23. It can be seen that the adaptive control routine results in a constant force, represented by the blue line in Figure 23.

### 5.5.3 Discussion

The developed MSP and the data processing pipeline proved to be a complex system consisting of hardware and software with many different interfaces and services. Achieving stable end-to-end connectivity from the MSP via 5G and the edge-cloud pipeline to the K Box acting as machine gateway was challenging as all components besides the 5G system were a prototype. However, in the end, it was successfully validated in the adaptively controlled machining operation.

Given that the solution is operational during manufacturing, auto-compensated machining allows high process and product quality with low *shape and dimensional deviation* and high *surface quality* with low roughness and waviness by vibration compensation. The user can set its custom thresholds for any quality-related measurement parameter. The GEM-VM allows applying learning routines for the threshold, which can be trained to avoid tedious try-and-error and process optimization. Finding the proper machining parameters in the ramp-up phase can take one day or more for complex parts, which could be saved with the developed solution. This is a significant benefit in terms of *utilization* and thus *productivity* and helps the user reach high quality in the shortest time.

Furthermore, the adaptive control can speed up the overall machining process, which benefits a shorter *process time*, leading to increased *productivity* and *utilization* without compromising the product quality.

As already explained, computation offloading to an edge-cloud has the potential to save energy due to the consolidation of computing resources. This also applies in this case. The virtualization of the physical GEM module as a virtual GEM-VM can be seen as a blueprint for virtual PLCs because it contains a virtualized real-time operating system. A net energy saving in the single-digit kW range was calculated for a shopfloor of 100 machines by scaling up this scenario and virtualizing the CNC controllers of machine tools. Energy consumptions of 5G UEs, TSN switches, the GEC edge cloud, and the 5G system were included in this calculation. Therefore, the paradigm implemented in this scenario is also a blueprint for contributing to production sustainability.

## 5.6 Validation scenario 3: time synchronization

### 5.6.1 Description of the scenario

The MSP contains a SARA-R5 module of u-blox. In our case, this module is needed to create timestamps via the u-blox' CellTime™ solution over the LTE-M network, as described in deliverable D3.3 [5GS21-D330]. The timestamps are needed to fuse sensor data with data from other sources. One example is the fusion of sensor data from the 5G-MSP with machine position data, which may be extracted via a cabled Ethernet connection. A precise correlation of the sensor data to the positions, e.g., on the workpiece, is essential to creating Digital Twins.

To measure the accuracy of the timestamps received by the SARA-R5 module, the setup shown in Figure 24 was used.

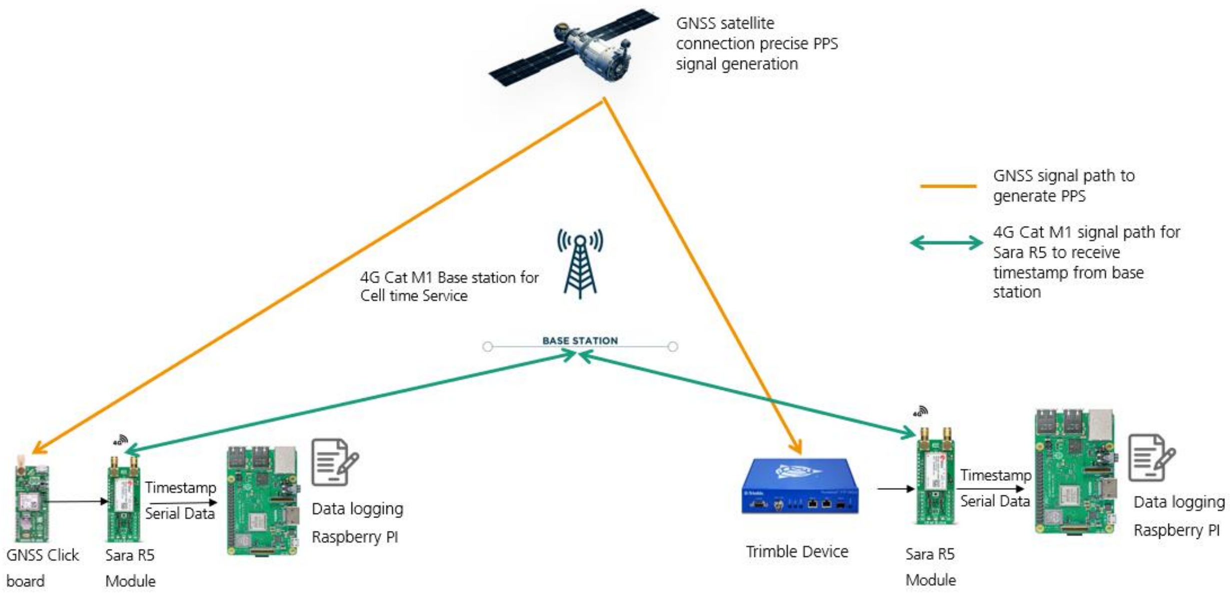


Figure 24: Measurement setup for the time synchronization via SARA-R5 modules

The setup consists of two SARA-R5 modules interfaced to a Raspberry Pi, each using the UART interface. These SARA-R5 modules are configured to receive an external trigger to capture timestamps extracted from CellTime™. To trigger the modules, one of them is connected with a Thunderbolt PTP Grandmaster Clock GM200 from Trimble, and the other one is connected to a u-blox Global Navigation Satellite System (GNSS) module. These modules are connected to the GNSS satellite to generate a PPS output. These outputs trigger the SARA-R5 modules for writing a timestamp. The timestamp is sent out as a string to the Raspberry Pi, logged over a long period. The modules are placed far apart but still in the same public LTE-M cell and started simultaneously to trigger timestamping. The measurement was carried out for 22 hours.

### 5.6.2 Validation results

The logged data was stored as CSV files and then put in a spreadsheet. Values of the timestamps were subtracted from both Raspberry Pi units. The absolute value of these differences is plotted over time, shown in Figure 25.

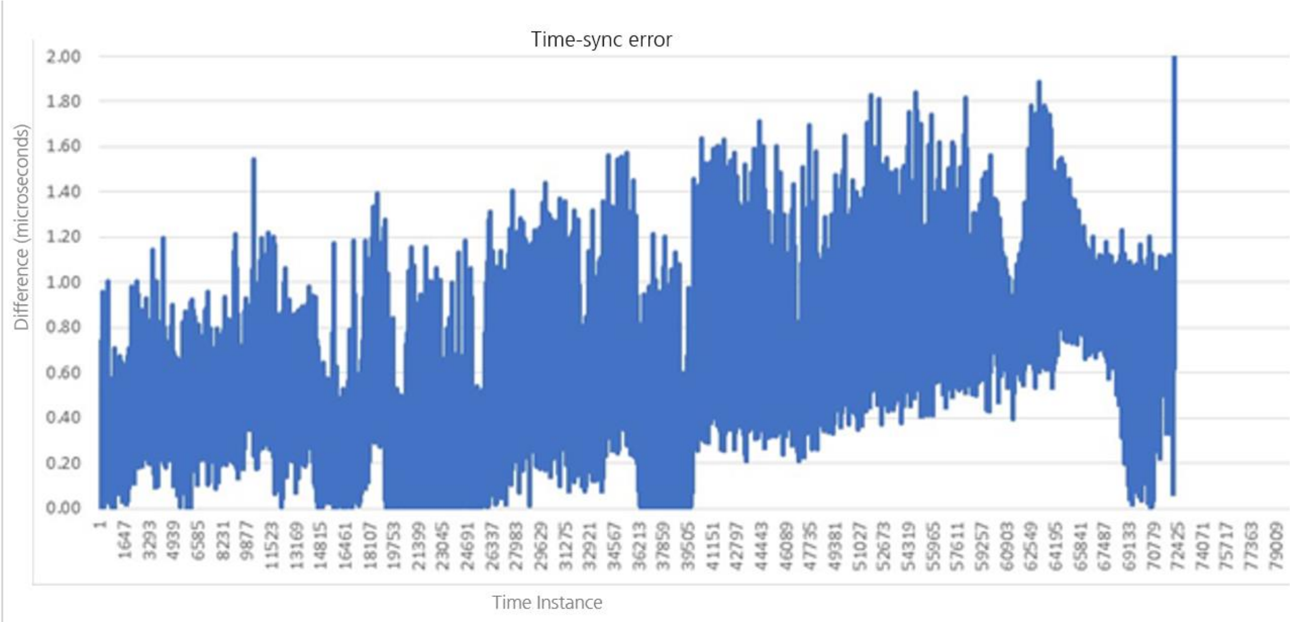


Figure 25: Plot of the time-sync difference between the two SARA-R5 modules

### 5.6.3 Discussion

The plot shown in Figure 25 shows the performance of the CellTime™ feature of the new SARA-R5 module in synchronizing to a reference time over the mobile network. The two SARA-R5 Raspberry Pi data acquisition modules placed far apart show that a time-sync error of less than 2 microseconds is achieved over a long duration of the trial measurement. As time goes by, there is a drift, but it is well within 2 microseconds. This is highly beneficial for using the module for time synchronization of SARA-R5-enabled devices. The CellTime™ service provides synchronization without GNSS visibility, which traditional synchronization devices use. 3GPP has specified a time synchronization solution for 5G allowing 5G UEs to be time-synchronized to any external time reference with less than 1 microsecond time error, see [5GS20-D510, 5GS21-D530, GLR+20]. The CellTime™ feature of u-blox demonstrates the time synchronization capabilities of mobile networks that will become available in 5G networks as a standardized capability.

This scenario is not directly a use case scenario, but this synchronization solution may offer quasi-real-time capabilities for industrial customers, even if they use a public 5G network. With this help, distributed sensing might be an application area for multiple sensors. Furthermore, it also enables to create Digital Twins with position-synchronized data.

## 5.7 Conclusions on 5G validation of versatile multi-sensor platform for digital twin

Various use case aspects have been investigated for the MSP. Like the 5G-AE sensor system, the 5G-MSP showed good performance, not compromising the performance of the industrial use case. For the industrial user, e.g., the machine operator, the MSP 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. Furthermore, we have shown that the 5G-communication of the MSP can be successfully interfaced with state-of-the-art monitoring equipment. At the same time, 5G is beneficial because of its wireless nature and provides benefits with ubiquitous IP connectivity and flexible routing capabilities compared to conventional sensor solutions running on, e.g., Bluetooth. Integration of time synchronization over 5G directly into the MSP or a standalone module (as demonstrated with u-blox CellTime™ in the trial setup) enables industrial users to extract ultra-high accuracy timestamps, which can be used to put wireless and wired data sources into the same time zone. It can be used for an a-posteriori synchronization for use cases operated in standalone non-public networks (SNPN) and public land mobile networks (PLMN), especially for cases with no GNSS/GPS (Global Positioning System) coverage.

As mentioned above, the 5G-based solution can be improved in energy consumption to reach longer battery runtimes or smaller footprints.

# 6 Summary, conclusions, outlook

The 5G sensor solutions developed within 5G-SMART were successfully validated in an experimental context. The acoustic emission sensor system has been validated in the two relevant scenarios *material contact detection* and *tool breakage detection*. The multi-sensor platform has been investigated for *process monitoring* and *closed-loop control operations* and the ability to provide *time-synchronized data acquisition*. The validation cases chosen exploited the relevant aspects that can be expected in the daily routine machining operation.

Performance measurements in the 5G network of the Aachen trial site showed the uplink and downlink performance for different traffic profiles covering the packet sizes and packet generation rates in the two use cases. The results of the performance measurements were fundamental for the interpretation of the end-to-end latency of the two 5G sensor solutions.

The most important outcome was that the performance of the two solutions matched the requirements set in deliverable D1.1 [5GS20-D110] at the beginning of the 5G-SMART project. It has been shown that the 5G system provided good coverage in the deployment area, enabling the flexible realization of the use cases on the shopfloor. The required latencies and data rates could be achieved with the 5G network. It was further shown that the capability to provide time synchronization with high precision over the 5G network provides high value to industrial use cases, like the investigated industrial sensor systems.

The sensor solutions were validated in a realistic environment and with validation cases, which allowed for testing of relevant properties, but were close to real applications. The findings help estimate the suitability for new use cases, which rely on wireless communication with high reliability and low latency like the two developed use cases for the Aachen trial site.

The relevance of the validation scenarios has been analyzed, and the chosen scenarios address aspects of quality, sustainability, productivity, utilization, and flexibility. KPIs matching these industry goals have been defined and quantified whenever possible. As a conclusion of the validation results, it could be shown that 5G-based sensor solutions can provide a value-add to enhanced manufacturing.

In a follow-up activity, a detailed analysis of the latency budget between the endpoints, i.e., from the sensor to the machine, could be investigated, e.g., with active network performance monitoring systems like Hawkeye. This would be helpful for the understanding of issues (also in the wired network) to improve the overall application performance. Furthermore, with more resources, the 5G network's performance could be investigated when operating many 5G sensor systems simultaneously.

To improve the applicability of the sensor solutions, a decrease in energy consumption will be helpful for the battery-powered operation, especially since the consumption of the 5G UE needs to be decreased in the future.

Further investigations of the edge-cloud pipeline will be necessary because only a single MSP device has been used in the validation. So, it is yet unclear what happens, especially when simultaneously using multiple MSPs with multiple sensing probes of different types.

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# Appendix

## A1 – Industry goals from D1.2

| | | | |
|---|---|---|---|
| **Flexibility** | Machine Flexibility (MF) | $\frac{Potential\ Product\ Variants}{Machines}$ | Max |
| | Setup Ratio (SUR) | $\frac{Actual\ Unit\ Setup\ Time}{Actual\ Unit\ Processing\ Time}$ | Min |
| **Mobility** | Material Handling Mobility (MHM) | $\frac{Paths\ Supported\ By\ System}{Total\ Number\ of\ Paths}$ | Max |
| | On-Time Delivery (OTD) | $\frac{On-Time\ Customer\ Orders}{Total\ Customer\ Orders}$ | Max |
| | Space Productivity (SP) | $\frac{Total\ Plant\ A.-Rework\ A.-Storage\ A.-Manufacturing\ A.}{Total\ Plant\ A.}$ | Max |
| **Productivity** | Effectiveness (E) | $\frac{Planned\ Runtime\ \cdot Produced\ Quantity}{Actual\ Application\ Production\ Time}$ | Max |
| | Throughput Ratio (TR) | $\frac{Produced\ Quantity}{Actual\ Application\ Execution\ Time}$ | Max |
| | Worker Efficiency (WE) | $\frac{Actual\ Personnel\ Work\ Time}{Actual\ Personnel\ Attendance\ Time}$ | Max |
| **Quality** | First Pass Yield (FPY) | $\frac{First\ Time\ Good\ Quantity}{Inspected\ Quantity}$ | Max |
| | Quality Ratio (QR) | $\frac{Good\ Quantity}{Produced\ Quantity}$ | Max |
| | Rework Ratio (RR) | $\frac{Rework\ Quantity}{Produced\ Quantity}$ | Min |
| | Scrap Ratio (SR) | $\frac{Scrap\ Quantity}{Produced\ Quantity}$ | Min |
| **Safety** | Accident Ratio (ACCR) | $\frac{Number\ of\ Accidents}{Actual\ Personnel\ Attendance\ Time}$ | Min |
| | Mean Operating Time between Failures (MTBF) | $\frac{Time\ between\ Failures}{Number\ of\ Failure\ Events+1}$ | Max |
| | Mean Time to Repair (MTTR) | $\frac{Time\ to\ Repair}{Number\ of\ Failure\ Events+1}$ | Min |
| **Sustainability** | Carbon Weight (CW) | $Total\ Energy\ Consumption\ \cdot Convergence_{(kWh\rightarrow CO_2)}$ | Min |
| | Compressed Air Consumption Ratio (ACR) | $\frac{Compressed\ Air\ Consumption}{Produced\ Quantity}$ | Min |
| | Electric Power Consumption Ratio (ECR) | $\frac{Electric\ Power\ Consumption}{Produced\ Quantity}$ | Min |

| | | | |
|---|---|---|---|
| | Gas Consumption Ratio (GCR) | $\frac{Gas\ Consumption}{Produced\ Quantity}$ | Min |
| | Water Consumption Ratio (WCR) | $\frac{Water\ Consumption}{Produced\ Quantity}$ | Min |
| **Utilization** | Allocation Efficiency (AE) | $\frac{Actual\ Application\ Busy\ Time}{Planned\ Application\ Busy\ Time}$ | Max |
| | Availability (A) | $\frac{Actual\ Application\ Production\ Time}{Planned\ Application\ Busy\ Time}$ | Max |
| | Technical Efficiency (TE) | $\frac{Actual\ Application\ Production\ Time}{Act.Appl.Production\ Time + Act.Appl.Delay\ Time}$ | Max |
| | Utilization Efficiency (UE) | $\frac{Actual\ Application\ Production\ Time}{Actual\ Application\ Busy\ Time}$ | Max |