D3.2

REPORT ON SYSTEM DESIGN OPTIONS FOR MONITORING OF WORKPIECES AND MACHINES

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D3.2

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Short abstract:	This deliverable contains a detailed description of the test use case systems designed and developed in 5G-SMART work package 3. This includes the requirements analysis and possible solutions to enable the trade-off required to ensure flexibility in terms of configurability, versatility for serving multiple applications and good performance of sensor system prototypes. The outcome of this deliverable will be the main input for all further developments, i.e. design of the sensor electronics, embedded system programming, factory cloud integration and planning of the validation.
Keywords:	4G, 5G, sensors, acoustic emission, multi-sensor platform, connectivity requirements, user equipment, factory cloud, M2M-communication

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Executive summary

This document reports on system design options for monitoring of workpieces and machines in the context of the 5G-SMART project. Two use case scenarios are explained which have different requirements and that lead to different system concepts. For both use cases a description of the necessity for 5G and the specific connectivity requirements is given as well as the relevance in the context of manufacturing. For the wireless acoustic emission measurement system, the principle of acoustic emission is explained, and the connectivity requirements are described, which demand a machine-near solution with low latency and fast reaction times. The multi-sensor platform on the other hand requires the acquisition and transmission of several different signals and a complex multi-signal processing like multi-variable correlation, which can be done in an on-premise edge cloud, or *factory cloud*, with virtual machines. Here the measurement quantities and its connectivity requirements are described as well. For each use case, different design options are discussed, as well as possible technical solutions. The multi-sensor platform is connected to the factory cloud using the versatile sensor data processing pipeline. With this concept, especially for multi-machine approaches, computing workload for complex elaborations can be advantageously moved to the factory cloud using virtual machines.

Contents

List of abbreviations

ADC	Analog to Digital Converter
AE	Acoustic Emission
CoAP	Constrained Application Protocol
CPU	Central Processing Unit
DSP	Digital Signal Processor
E2E	end-to-end
eMBB	Enhanced Mobile Broadband
FFT	Fast Fourier Transform
FPGA	Field Programmable Gate Arrays
GEC	*German Edge Cloud*
GEM	*Genior Modular*
GEM-VM	*Genior Modular Virtual Machine*
GPIO	General Purpose Input/Output
GPU	Graphical Processing Unit
GUI	Graphical User Interface
HMI	Human-Machine Interface
HP	High Pass
I2C	Inter-Integrated Circuit
LBO	Local Break-Out
LP	Low Pass
LTE	Long Term Evolution
M2M	Machine-to-Machine
mMTC	Massive Machine-Type Communication
MQTT	Message Queuing Telemetry Transport
MSP	Multi-Sensor Platform
M.2	Next Generation Form Factor (NGFF)
NC	Numerical Control
NTP	Network Time Protocol
OEE	Overall Equipment Efficiency
OPC-UA	Open Platform Communications Unified Architecture
PCB	Printed Circuit Board
PLC	Programmable Logic Controller
PPS	Pulse Per Second
PTP	Precision Time Protocol
RMS	Root Mean Square
SMA	Sub-Miniature Connector Version A
SPI	Serial Peripheral Interface
TSN	Time-Sensitive Networking
UART	Universal Asynchronous Receiver/Transmitter
umati	Universal machine technology interface
URLLC	Ultra-Reliable and Low-Latency Communication
UDP	User Datagram Protocol

USB	Universal Serial Bus
VFK	*Virtual Fort Knox*
VM	Virtual Machine
3DOF	Three Degrees of Freedom

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

1 Introduction

The Fraunhofer IPT trial site is one of the three trial sites within the 5G-SMART project, where a 5G communication infrastructure will be deployed in order to test and validate 5G for enhanced manufacturing applications. One of the domains for which 5G is attractive is wireless sensors which on the one hand offer new possibilities due to increased mobility of sensor solutions and on the other hand 5G can outperform and replace existing wireless transmission technologies like Bluetooth.

Two use cases will be tested and validated at the IPT trial site: the 5G-based wireless acoustic emission (AE) sensor system and the multi-sensor platform (MSP) for monitoring of workpieces and machines. While the AE use case is demanding a machine-near solution with a low latency and fast reaction times, the multi-sensor platform requires the acquisition and transmission of several different signals resulting in varying connectivity requirements in terms of latency. Furthermore, the MSP requires a complex multi signal processing like multi-variable correlation, which has to be done in an on-premise edge cloud, or *factory cloud*. Especially when using them for more than one machine, with the deployment of 5G the computing workload can be advantageously moved to the factory cloud while its virtualization approach has the potential to save energy and costs.

The objective of the document is to provide insight to the different design options for the monitoring of workpieces and machines. It contains the description of the measurement parameters, the specification of the resulting connectivity requirements and the technical description of both the sensor systems and of the factory cloud infrastructure.

The 5G communication infrastructure has been described in Deliverable 3.1 and is not part of this document.

1.1 Structure of the document

The document is structured as follows. Section 1 is an introduction to the deliverable including the objective of the document. Section 2 describes the use cases for enhanced industrial manufacturing. In section 3 the wireless acoustic emission sensor system with requirements and different technical solutions is described. Section 4 explains the multi-sensor platform for monitoring of workpieces and machines with its requirements and different technical solutions. It also includes the description of the connection from the multi-sensor platform to the factory cloud using the versatile sensor data processing pipeline.

The terminology used in this deliverable is based in the common terminology of the project 5G-SMART, which is available as a public contribution from 5G-SMART on the project website[1].

[1] https://5gsmart.eu

2 5G use cases on enhanced industrial manufacturing

The Fraunhofer IPT trial site and the associated work package WP3 of 5G-SMART deals with the application of 5G to industrial manufacturing use cases and it addresses various specific aspects of this area of production. On one hand, it focuses on various types of process monitoring. On the other hand, it supports the condition monitoring of assets in the factory, such as machines and its infrastructure.

An acoustic emission (AE) sensor system (Section 3) is being developed and prototyped to provide a high-resolution instrument of detecting and characterize the interaction between the cutting edge of the tool and the workpiece to be manufactured. The system generates a continuous stream of spectral data with average data rates in the MBit/s range. The information provided will be used to reactively control the manufacturing process and the machine tool with an ultra-low latency.

The multi-sensor platform (MSP) described in Section 4 is a versatile, multi-faceted and modular approach to monitor a wide range of process quantities in many different machining operations. It will be able to measure multiple quantities simultaneously. The configurability of the MSP will allow the adaption to different use case scenarios, delivering process and condition data with different criticality and priority. The MSP is at the same time a universal data source for different processes along the value chain acquiring different measurement quantities like acceleration, force or temperature. It may also be designed to be attached to a machine table, or even to each workpiece, following its path through different manufacturing steps in a process chain. Whether the MSP is directly fixed to the workpiece, the machine table, or the palette carrying the workpiece is a question of its size and geometry, and it will affect the design choice for the MSP. Furthermore, the MSP is also designed to be a retrofit solution for condition monitoring of machine tools with minimum set-up efforts. The Aachen trial site in 5G-SMART also exploits the interaction of 5G-enabled sensors and the factory cloud (Section 4.5.1), as well as its coexistence with the 5G infrastructure and the production IT-system.

Ultimately, Workpackage 3 demonstrates an essential contribution of 5G to resilient manufacturing, i.e., in supporting companies in various industries to increase efficiency by driving processes closer to the physical limits, and also to increase flexibility in production. In conclusion, WP3 addresses how to integrate 5G as a building block in Industry 4.0, at the heart of value creation - where chips are produced.

Both uses cases address the Ultra-Reliable and Low-Latency Communication (URLLC) feature of 5G. The following section will explain the background and motivation for the AE sensor system and the MSP in detail.

2.1 Use case scenarios for the wireless acoustic emission sensor system

There are a few different applications for the use of AE sensor systems in metal processing typically represented by cutting processes, which are explained in this subsection. If a wired sensor is not applicable because of moving machine tables and spindle heads, or if the sensor is too far away from the cutting process, then a wireless system is the only solution.

As AE-sensor heads are usually being physically attached close to the cutting tool and the cutting area, the probes are physically fixed to the workpiece. In case of collision monitoring, the AE-sensor heads are fixed to the workpiece table. During the physical contact between the cutting edge and the workpiece material, the associated mechanical deformations cause mechanical waves, which propagate in the material and finally reach the AE-sensor head. The AE-sensor measures the resulting accelerations at sampling rates in the MHz-range. This solid born sound (acoustic emission) is not in the audible range.

In terms of the interaction of the cutting tool, the cutting edge is subject to wear and it may eventually break. If this *tool breakage* happens during the cutting process, the AE contains characteristic spikes in a certain spectrum, which is constantly analyzed in order to detect the tool breakage and to feedback this information to the machine control system. This tool breakage detection is especially critical for small drilling or milling tools.

Furthermore, the physical contact of the worn cutting edge induces a characteristic fingerprint in the AE spectrum. This fingerprint is highly dependent on the geometry of the cutting edge, the material of the workpiece and the process parameters. Therefore, the assessment of *tool wear* is generally possible with AE measurement systems, but it requires dedicated signal processing for each application. The application of machine learning approaches is subject of current research to correlate key parameters or indicators of the acquired spectral fingerprint to the quality quantities of the machining process. There are known approaches, where specific frequencies of the AE-spectrum can correlate to the condition of the tool.

In the computer-based planning of cutting operations, there is a residual error due to the uncertainty of the real position and real dimensions of the workpiece, because the planning is carried out under the assumption of ideal conditions. In order to take this uncertainty into consideration and to 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 another 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.

An additional AE application is the *detection of inhomogeneities* in the workpiece material, like cracks, other structural damages or variations in the material hardness. AE measurement systems are capable of detecting these inhomogeneities. In case of position-synchronized measurements, it is possible to map the data to the workpiece geometry for advanced diagnostics, as shown in Figure 1. In the figure, local changes in the materials hardness of a bearing roll are induced by a heat treatment. These changes cause a variation in the cutting conditions. Furthermore, the bearing roll contains a scratch on the surface. The position information of the turning lathe axes are recorded synchronized to the AE sensor signal generating a map indicating the surface condition.

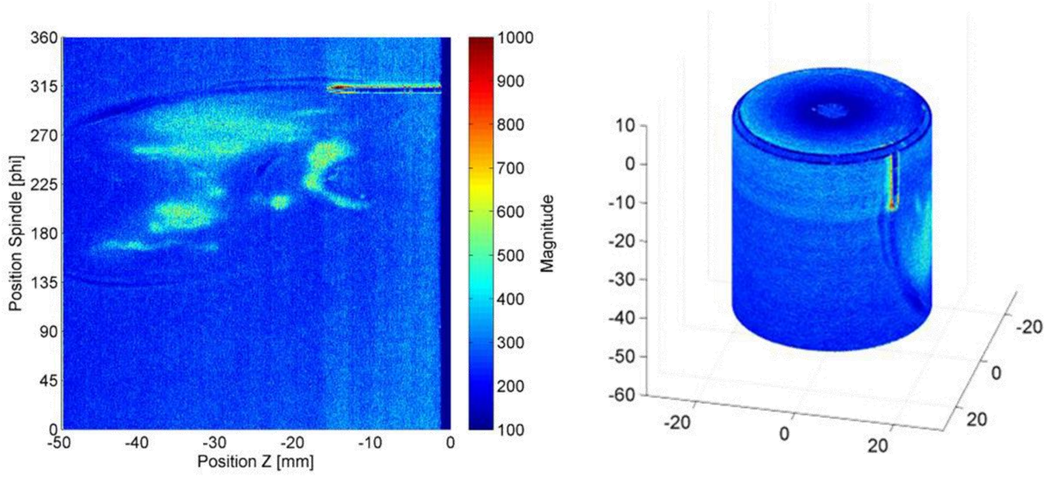

Figure 1. Left: Position-resolved amplitude distribution of an AE measurement acquired during the machining process of a bearing roll, which has been heated up locally in order to induce hardness changes. Right: measurement data mapped onto the cylinder.

2.2 Use case scenarios for the multi-sensor platform

The MSP is intended to be applicable as a versatile solution for measuring different parameters and to connect a wide range of sensors in a production plant. These measurement parameters can be described as measurands, which can be quantified with a measurement frequency and resolution.

In order to derive the connectivity requirements, it is important to understand, that depending on the application, a different number and different types of sensors of the MSP are used and also the measuring rates may depend on the application. Therefore, in the following sections there will be a description of different characteristic use case scenarios. Regardless of the requirements addressing the specific use case scenarios, there are general requirements independent from the use case the MSP is applied to.

For a better understanding of the performance requirements, a brief description of different use case scenarios is essential. One of the main application domains of the MSP will be the *workpiece and process monitoring*. It will be used, ,for the monitoring of cutting processes, i.e., cutting force or material contact detection. The latter monitoring is required for all cutting processes. The availability of wireless sensors results in a better accessibility of the sensors to the workpiece, which also allows for measurements on rotating elements (e.g. machine C-axis). 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 for a proper process modelling. Subsequently, these insights serve for a constant optimization of the machining processes in order to achieve optimal results in terms of costs, time and quality. Furthermore, the MSP will consistently deliver information of the processing history, contributing to *digital twin*, while following the workpiece along steps in the process chain. Thus, a continuous monitoring helps companies to constantly increase the production efficiency, e.g. calculated as the overall equipment efficiency (OEE). The OEE quantifies the percentage of manufacturing time that is truly productive taking into consideration quality, performance and availability of production processes.

The application of the MSP to *machine condition monitoring* is attractive in order to assess lifetime data from multiple machines on a shop floor or even 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 to 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 also for 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 a high reliability or low latency. Therefore, the application of the MSP can also be associated with the massive machine-type communication (mMTC) service category. Nevertheless, 5G-SMART will not implement and exploit the last use case scenario, because they do not represent a specific challenge towards 5G transmission in the context of manufacturing.

3 Wireless acoustic emission sensor system

Figure 2 shows the concept for the architecture use case including the wireless AE system. This is a machine-near approach with a high grade of communication efficiency to bring the data from the sensor to the analysis and monitoring hardware, via the 5G network with low latency. The monitoring hardware (the GEM monitoring unit in Figure 2) is connected to the machine with a reliable and safe automation bus system. The machine is being monitored and controlled based on a smart AE sensor mounted on the machine table near the machined part. The electronic circuitry includes components for amplification, filtering and sampling with high rates. The raw data or the pre-processed data will be passed through the signal processing unit to the 5G transceiver. This pre-processing allows a high grade of flexibility to adapt to the uplink bandwidth requirements and calculation of Fast Fourier Transform (FFT), peak values and so on. Therefore, the pre-processing may be carried out by an embedded systems, e.g. microcontroller, FPGA or DSP. Thus, events like the first contact from the cutting edge of the tool with the work piece material can be evaluated very fast.

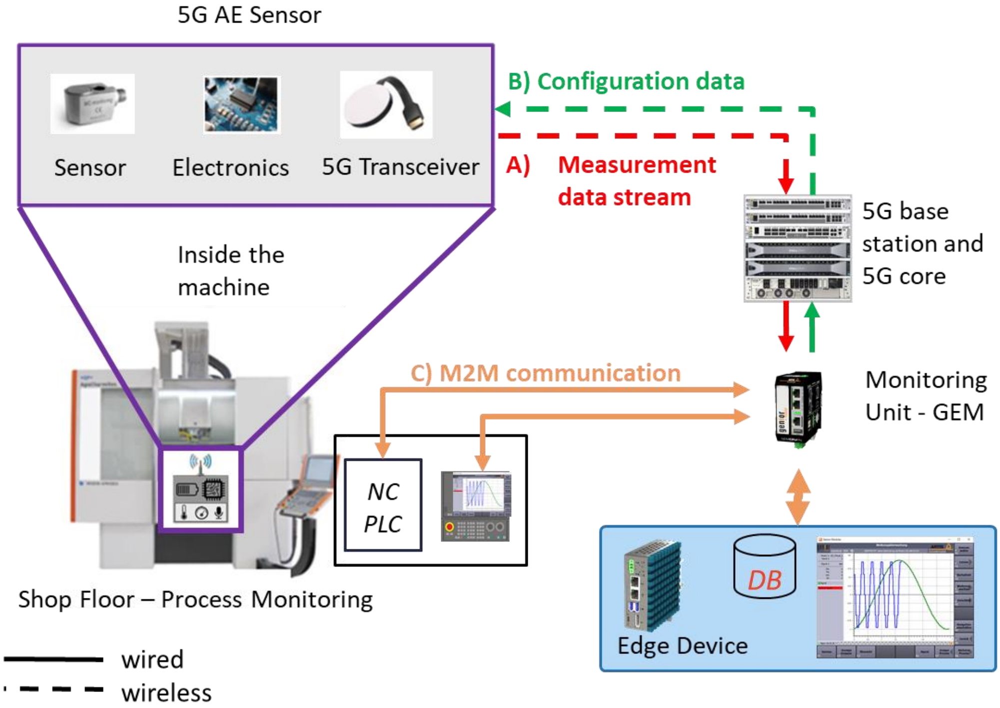

Figure 2: Design option for a 5G wireless Acoustic Emission Sensor system

On the other end of the link, the 5G base station with the 5G core receives network receives the data and forwards it to the monitoring hardware (Monitoring Unit – Genior Modular (GEM)), which is based on a real-time system to guarantee reproducible evaluation. Here, the automated monitoring algorithms can detect deviations in the process and send the results like alarms, material contact, tool change, and override control via the machine bus system, like PROFINET or Profibus, to the machine control. The Numerical Control (NC) and the Programmable Logic Controller (PLC) are connected to the monitoring hardware to synchronize the signal elaboration with the machining of the parts. The data is also delivered to an edge device, which is usually an industrial PC integrated into the machine. The Human Machine Interface (HMI) is the user interface to the machine and the monitoring unit for setup and local visualization. For validation and elaboration, the processed data can be stored on that local edge device in a database for documentation and later analysis.

3.1 Connectivity requirements

This section describes the functional and performance requirements and it indicates the demands towards 5G connectivity.

3.1.1 Functional requirements

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

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

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

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

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

3.1.2 Non-functional requirements

Traffic requirements come from three different communication streams, as shown in Figure 2: (A) measurement data stream, containing the AE spectra on the uplink of the AE sensor system, (B) configuration data on the downlink for deploying updated configuration parameters to the sensor system, and (C) Machine-to-machine (M2M) communication between the factory cloud and the machine. The monitoring hardware is connected to the Local Break-Out (LBO) of the 5G network by a wired connection, e.g. Ethernet cable or optical fiber. M2M communication makes use of standard industrial communication protocols, e.g. PROFINET. Since the wired M2M-communication does not affect the 5G requirements, their performance requirements will not be further described here, while (A) and (B) are specified separately. Due to different uplink and downlink characteristics of (A) and (B), the traffic for the AE sensor system is asymmetrical. Traffic characteristics for streams (A) and (B) are summarized in Table 2. For measurement data, traffic is categorized as non-deterministic, since missing or jittered sensor data is not critical. Nevertheless, upon event detection, a quick reaction and process control is required imposing low latency requirement on communication link.

Communication streams	Periodicity	Determinism	Symmetry	Transfer interval [ms]	User data length [kByte]
(A) Measurement data	Periodic	Non-deterministic	Asymmetrical	1	1 - 100
(B) Configuration data	Aperiodic	Non-deterministic	Asymmetrical	<1000	>1

Table 2: Characteristics of the communication streams for the AE measurement system

Performance requirements of the streams (A) and (B) are listed in Table 3. For communication stream (A), as a first step, the current system will deliver a limited data rate, comprising FFT spectrum data up to 8 Mbit/s using the built-in ADC converter. In a next stage, an optimized system will be developed with the flexibility to increase the effective data rate, for higher sampling rate and higher ADC resolution in order to increase the data quality. This will require a more powerful processing FPGA platform for the application. Then, the effective data rate can increase significantly. Also, the low-latency (from sensor to machine) support is needed in order to react immediately to critical events such as tool breakage or collision. Jitter requirements will be normally non-critical up to 1 ms. If plotted as a waterfall diagram (time vs. spectral distribution), a jittered signal transmission would result in non-equidistant spectra or (if FFT calculation is executed after wireless transmission of raw data) in increased noise level. Since the amplitudes of the different frequencies in each spectrum are most relevant for the detection of tool wear or breakage, e.g. by threshold or pattern recognition, the jitter conditions are less critical.

In addition, time synchronization is required particularly if the end-device operates in coordination with others, e.g. machines. In that case, a low time synchronization error between machine numerical control (NC) and sensor is required in order to map AE spectra to positions of the tool on the workpiece surface as a digital twin. Here the synchronization error is the maximum difference between the time stamp of the measurement on a certain machine coordinate and the time stamp of the sensor data measured at that coordinate. In order to calculate this tolerated synchronization error, the required position error of the part has to be divided by the feed rate of the tool. For example, in order to achieve a position error of 10 µm for a feed rate of 100 mm/s, the synchronization error needs to be below 100 µs. In order to calculate this tolerated synchronization error, the required position error of the part has to be divided by the feed rate of the tool. For example, in order to achieve a position error of 10 µm for a feed rate of 100 mm/s, the synchronization error needs to be below 100 µs.

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

Communication	Data rate [Mbit/s]	Latency [ms]	Jitter [ms]	Time Synchronization Error [ms]	Communication Service Reliability
A) Measurement data	≥ 8	< 10	< 1	< 0.1	≥ 99.999 %
B) Configuration data	Low	< 1.000	Not relevant	Not relevant	≥ 99.999 %

Table 3: Performance requirements of traffic streams for the AE measurement system

Table 4 reflects the operating conditions at the trial site at Fraunhofer IPT. In terms of communication range, there is the 15 m maximum distance between sensor and next 5G radio antenna. Altogether, there will be 8 radio antennas positioned equally spaced in a shop-floor size of 3000 m². The overall setup is described in Deliverable 3.1. During transmission, the sensor can be moved by the machine with a velocity of up to 0.5 m/s in a volume of 1 m³. Communication density corresponds to one sensor per machine, which has an average footprint of 15 m². In terms of the mobility requirements, we have to note that the given value relates to the movement of the sensor inside the machine, and therefore it is not relevant for the 5G system design. Requirements for other shop floors may differ due to a different size and antenna density required to reach a sufficient coverage.

Performance requirement metric at Fraunhofer IPT	Value
Communication range [m]	< 15
Communication density [device/m²]	0.067
Velocity [m/s]	< 0.5
Localization/positioning accuracy [m]	Not relevant

Table 4: Complementary performance requirements for AE measurement system at the Fraunhofer IPT trial site

3.2 Technical solution description

3.2.1 Architecture of the wireless acoustic emission sensor system

A 5G AE sensor system is being developed and evaluated. To be able to perform a pre-processing on the sensor module, a signal processing unit has to be integrated.

The wireless AE sensor system is a dedicated, low-latency, high-processing-intensive system capable of performing on board signal processing before transmission. The structure of the sensor platform is described below, see Figure 3.

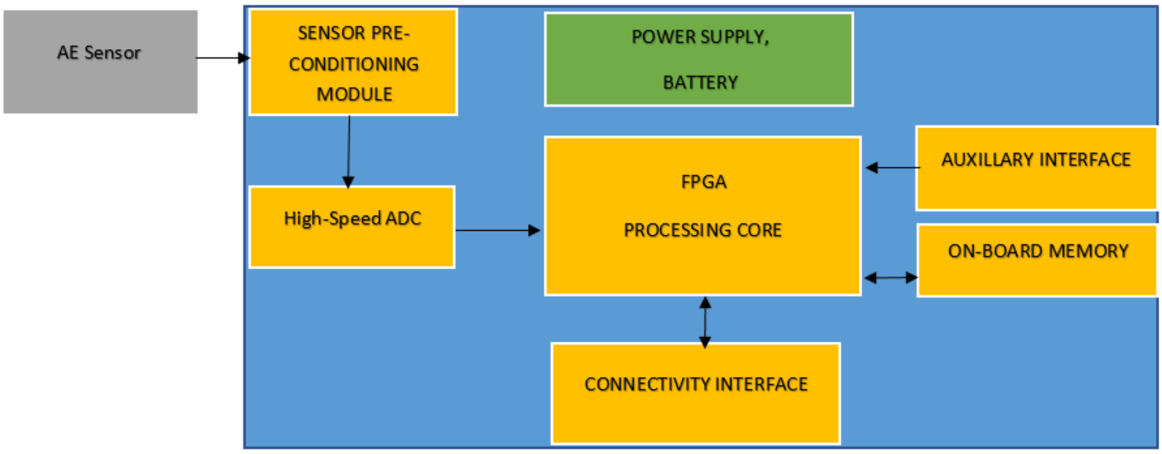

Figure 3: AE-sensor system hardware architecture.

The AE sensor data is fed into a pre-conditioning module. The integrated signal pre-conditioning module for the AE sensor can perform suitable signal amplification and filtering. Due to the nature of the acoustic emission, a high-speed ADC is integrated so as to achieve the necessary resolution (≥ 12 bits) and sampling condition for the acoustic emission (≥ 1 MHz) achieving in the prototype the data rate of 12 Mbit/s, which is reduced to 8Mbit/s after pre-processing. In the future, for higher data rates and higher resolution, a suitable external ADC at high sampling rates has to be used. That would require also a powerful processing core to handle the higher data rates.

For real-time low-latency signal processing, the core is chosen as a FPGA because of its higher processing capabilities as compared to a traditional microcontroller. The platform has a memory module and it supports advanced type of memory access and data buffering. The platform also has some auxiliary interfaces such as generic general- purpose input/output inputs/outputs (GPIOs), external memory card, etc., for additional add-on modules or sensors (if necessary). For connectivity, the platform has a Gigabit Ethernet interface through which the 5G modem can be connected. Additionally, a USB interface is also provided for connecting to next generation modules that may become available during the project lifetime. Regarding the power supply, the platform is equipped with a battery pack with the necessary conversion modules to provide proper biasing to the FPGA core, the AE sensor and the connectivity module. Considering the machining process environment, the module will be mounted in a water-proof enclosure (preferably made of anodized aluminum) with antenna connectors for the connectivity module.

3.2.2 Solution options

In order to gain experiences and to provide a testable system as soon as possible, a prototype should be setup first. For the design of this prototype, the standard signal processing chain of an AE system is considered (Figure 4).

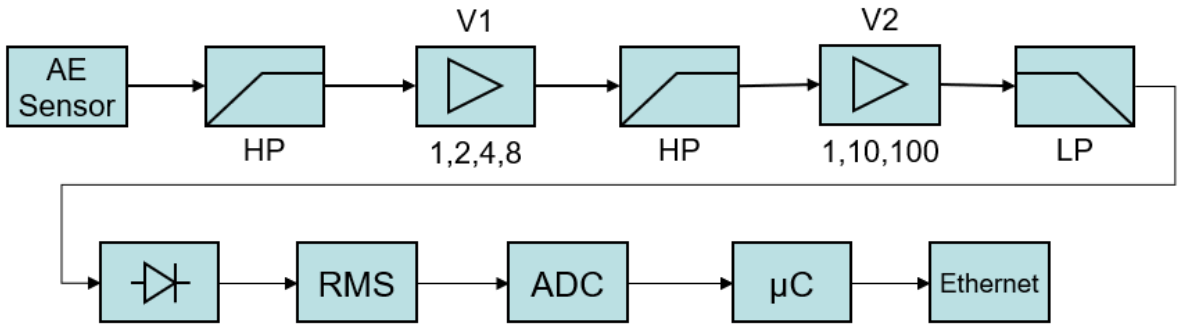

Figure 4: Example for a typical signal processing chain for acoustic emission.

The sensor is driven by a current source, the signals are decoupled, amplified and filtered. The filters are tunable and they can normally adapt to the application. The rectified signal passes through an root mean square (RMS) detector, then it is converted by an ADC and finally evaluated by a microprocessor (µC).). Such boards are readily available, but flexibility is limited.

Another option with more flexibility is the usage of a standard FPGA board, like an ARTY or CORA-7. These boards include an ARM controller for data communication, an Ethernet®® interface, an SD-card slot, a USB port, a SPI (serial peripheral interface (SPI) , and others.

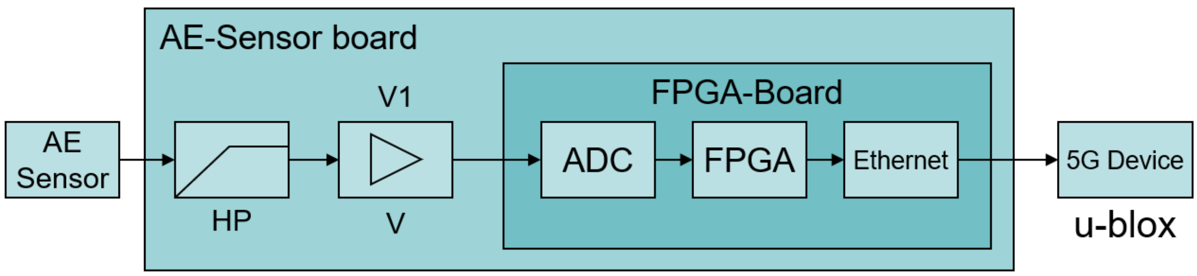

Figure 5: AE-sensor board with an FPGA board module.

Even if such test boards are more expensive, have larger form factors and require more power, it is an advantageous and flexible approach for the fast evaluation of the planned design before building the final system.

4 Multi-sensor platform for monitoring of workpieces and machines

The MSP offers great flexibility to cover a large variety of applications due to the multiple sensors. Furthermore, the 5G connection enables an installation on rotating, mobile and -difficult--to-access places, making it useful for many industrial applications. To benefit from all of its advantages and to use it on a large scale, e.g. hundreds of devices per shop floor, the data flow model and the correspondent infrastructure need to support this.

In Figure 6, the integration of the MSP in three use case scenarios is illustrated: The MSP for factory-internal logistic tracking through the shop floor, the MSP installed on a work piece during processing, and the MSP installed in machines as addition to existing sensors. In order to support potentially large number of devices and the different use cases, it is necessary to have a centralized solution in the production site, i.e., the factory cloud.

The data flow model for all three use cases, as well as the tasks and applications hosted in the factory cloud are also depicted in Figure 6. Starting from the MSP, data from the sensors is sent via 5G to the base station, and then it is forwarded to the factory cloud. Afterwards, in the factory cloud the data is processed for different purposes, like creating a digital twin or monitoring the productions processes. For process monitoring the data needs to pass two stages. At first the data needs to be structured and fused in order to be sent to the monitoring unit, since the connection of several sensors with different characteristics to the MSP creates a large variety of data formats that may differ, for example, in frequency, measurement unit, data quantity and quality.

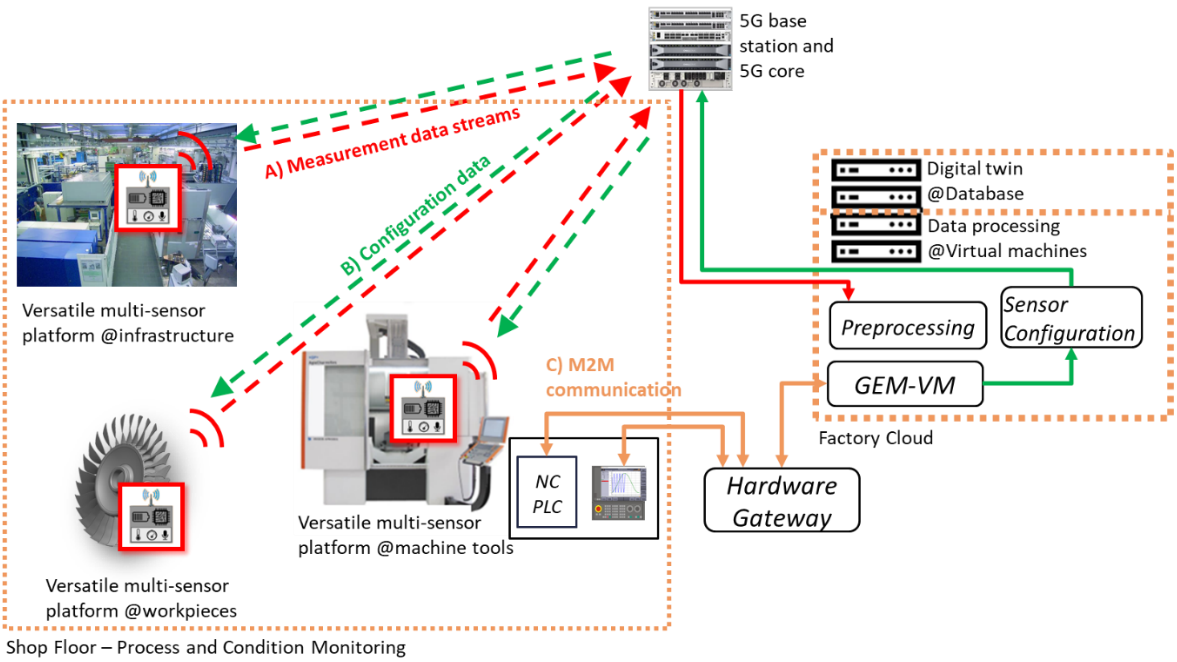

Figure 6: Data flow model for three MSP use cases

After the normalization of the data, it can be used for monitoring of the process. This is done in the GEM-VM, Genior Modular deployed on a virtual machine (see Section 4.5.1). The GEM-VM is only software-based component and therefore it needs a hardware gateway connecting the factory cloud to the machine. Using a virtualized version of the Genior Modular increases the scalability. The gateway can communicate with the NC and the HMI of the machine for the control and interaction purposes. Finally, the configuration of the MSP is also done in the factory cloud with a sensor configuration application.

This data flow model reduces the computing demand on the shop floor equipment, and it increases the flexibility and coverage of sensors across the factory.

4.1 Measurement Quantities

The MSP is being designed to acquire a variety of different measurement quantities dependent on the specific use case. The sensors listed below are planned to be supported and measure quantities as follows:

- *3 degree of freedom (3DOF) force sensors* measure the cutting force and they are used to optimize and control the process, for example to limit the tool deflection.
- *Acceleration sensors* measure the vibration coming from the workpiece or the tool and their mechanical interaction with the machine. This is essential to avoid effects like vibration marks or chatter marks that affect the overall part quality, ultimately even leading to a rejection of parts.
- *Microphones* measure the sound emission and they can be used to evaluate the tool and machine condition.
- *Thermal sensors* are used to prevent the overheating of the parts or of the machine components.
- *Torque and force sensors* are employed to setup the cutting process parameter in order to avoid damages to tools and workpieces.
- *Strain sensors* correlate the strain with the force load leading to deformations, e.g. they are often integrated in the spindle of a machine.
- *Position sensors* can be used to monitor the workpiece orientation, in order to detect clamping errors which can lead to tool and material damages.
- *Internal temperature and humidity sensors* can be used to detect overheating of the electronics or liquid ingress.

4.2 Performance and other non-functional requirements

As mentioned in Section 2.2, the definition of measurement parameters which affect the performance requirements can be differentiated into general parameters and use case related parameters. The general parameters contain requirements towards the resolution of all sensors and for the MSP as a device and can be described as follows, see also Table 5 and Table 6,

- Resolution of measurement data should be ≥ 16 bit
- Battery driven, intelligent energy management for consideration of optimal running times for different application workloads
- Small footprint (for example 50 mm x 30 mm)
- Robust against environmental effects (≤100G shock, ≤9G RMS, temperature: -20-60°C)

- Latency: <10ms for process monitoring and control
- Communication range: up to 100 m x 100 m (e.g. for internal logistic tracking)
- Velocity: ≤1m/s in an area of ≤100m²
- Different communication service reliability levels:
  - High: 99.999%
  - Medium: 99.99%
  - Low: 99.9%
- Capability to measure internal quantities with sensors inside the housing of the MSP to monitor the condition:
  - Temperature: ~1Hz measurement frequency, 100 ms latency, low-level transmission reliability (e.g. detection of printed circuit board, or PCB, overheating)
  - Humidity: ~ 1Hz measurement frequency, 100 ms latency, low-level transmission reliability (water ingress and box intrusion detection, e.g. by cooling lubricant)
- Generic sensor interfaces:
  - Digital Inputs: configuration cycle time ~1 s, setting time ≤1 s (connection of external sensors (e.g. liquid sensor), encoder signals (e.g. from machine axes)
  - Digital Outputs: gate signal, PLC-standard type e.g. 24 V, 40 mA (set voltage to start/trigger external sensor or synchronize events, configuration of smart sensors)

5G-SMART aims at investigating and evaluating what ranges of the use case requirements can be supported with which concepts and features. In other words, the objective is to investigate the trade-offs between use case requirements and needed 5G system resources, such as the compute power, battery life and 5G system resource usage. However, the small footprint requires a miniaturization of all components and, therefore, it is out of the scope of 5G-SMART. Such effort should rather be part of a product development.

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

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

Table 5. Parameter sets for use case scenario ‘workpiece and process monitoring’’.

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

Table 6. Parameter sets for use case scenario ‘machine condition monitoring’.

4.3 General requirements

Independently from the connectivity requirements described above, general requirements can be defined, which do not affect the connectivity solution, but they are important for the overall integration into the manufacturing ecosystem. The requirements are listed in Table 7.

Category	Requirements	Comments
5G-interfaces	• Integration of 5G module (e.g. over M.2 interface) • Communication between application and 5G transceiver via Ethernet®®	
Interfaces	• Usage of standardized communication protocols	*umati is in the definition phase and based on OPC-UA

	(CoAP, MQTT, OPC-UA, TSN, umati*) • Usage of standardized field buses (e.g. PROFINET) • Need for security concept for communication "sensor-data analysis" • Connected to factory cloud solutions, e.g. SINUMERIK Edge, Fanuc Field, SAP Cloud	Machine parameters should be available in real time
Synchronization	• Synchronization between multiple MSPs or between one MSP and a machine • UTC timestamping for global time sync	Built-in synchronization features provided by u-blox as a workaround as long as TSN over 5G is not ready
Sensor interfaces	• Auto discovery for sensors: configuration self-descriptive, manual configuration possible	
Data pre-processing	• Close to machine • Additional latency and energy consumption to be considered • Standardized data format for data serialization and aggregation • Reduction of data rate by data compression or FFT	

Table 7: General requirements towards applications of the multi-sensor platform

4.4 Technical solution options

4.4.1 Architecture options

The concept of the MSP consists of three interconnected sub-systems: a set of sensors to be attached to the workpiece or integrated into the machine, a device that collects the signals from the sensors and that delivers the information to the 5G network, and the factory cloud that processes the information and generates different outputs, potentially also to be fed back to the shop floor. Figure 7 shows this structure, including the possibility to deploy the sensors in the plant infrastructure; that would be another valuable source of information about the production processes as a whole, but it is not going to be trialed in the 5G-SMART project.

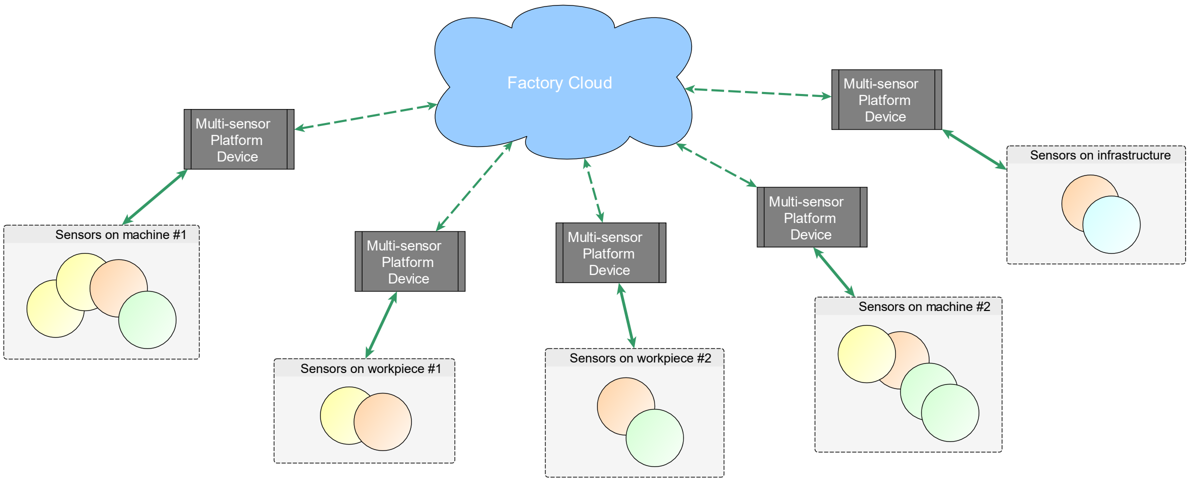

Figure 7. Architecture of the MSP.

Ideally, the multi-sensor device should be a compact embedded device, for the purpose of the easiest and most adaptable integration into the many different machines and workpieces, as well as of being as close as possible to the sensors. As a matter of fact, the multi-sensor device should be integrated with sensors in a single unit without the need of connections; cables and connectors require space and they are a potential weakness from the point of view of reliability. The ideal architecture of this hardware device would be the one in Figure 8.

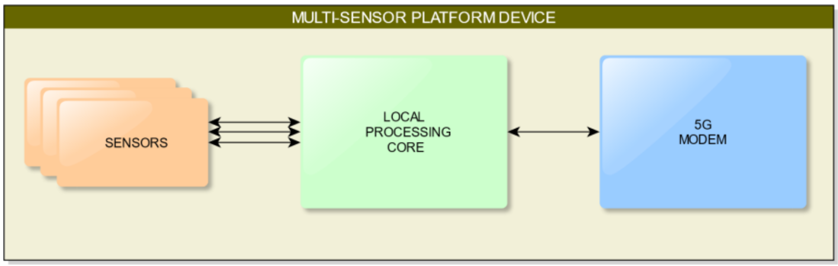

Figure 8. Ideal architecture of the MSP device.

In this architecture option, the field sensors are tightly integrated into the device, together with a microprocessor and the 5G modem. Even though it is not explicitly shown, the power supply would be also integrated in the form of a battery, so that such wireless embedded system can be truly mobile.

Notwithstanding this ideal architecture, in order to effectively support several different sensors and their specific way of interacting with the machine, workpiece or plant infrastructure, some of the field sensors may be physically separated from the embedded unit and connected externally, even though always in close proximity.

Such an architecture would be particularly suited to the design of a product, but it offers some disadvantages in the context of the applied research of 5G-SMART trials. Besides the significant design effort, a tight integration of the electronics would be a limitation in the possibilities of rapidly evaluating different options in terms of sensors, as well as of 5G connectivity. Furthermore, since each sensor has its own specific physical interaction with the measured target, a tightly integrated unit would require a nearly custom mechanical fixture. What is more, dedicated electronics are often needed in order to maximize the sensor performances. Finally, this architecture would require a compact silicon integrated 5G modem with the performances and features for industrial applications; unfortunately, 5G devices with suitable form factor are unavailable at the time of this development, and likely at the time of testing as well. Nevertheless, testing has to be performed in a real 5G network, even if not with integrated devices.

As a result, a second architecture option consists in adopting a highly modular approach for the MSP device, as depicted in Figure 9. Some sensors may be integrated, but an external connectivity is also provided to allow for a flexible choice. The 5G modem is also externally connected, in order to keep track of any devices that may come onto the market and be flexible to connect to it without changing the MSP device.

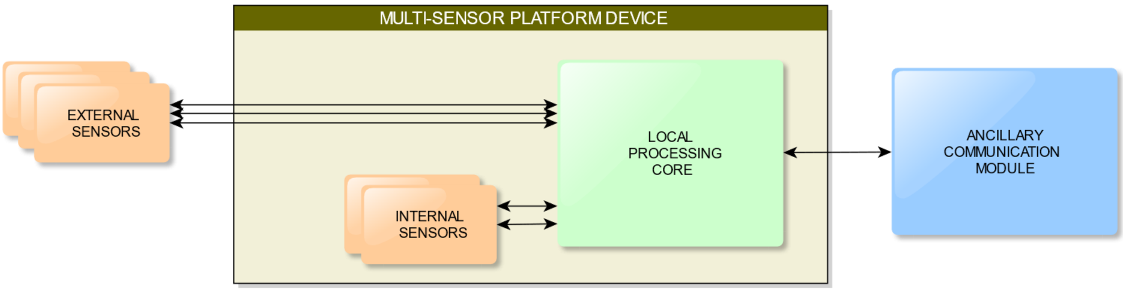

Figure 9. Modular architecture for the MSP device.

An ancillary communication module is designed and connected to the core electronics of the MSP device. This module will not be representative of the concept of the platform, but it would rather be a technical mean for flexibility regarding the availability of suitable 5G devices.

The main disadvantage of this approach is the significant impact of the size of the device, which will hardly meet the specifications of a realistic product. On the positive side, it lets us expand freely the coverage of the tests, both from the sensors point of view and from the wireless connectivity, even at a later time. In this case, even though a battery power supply can be foreseen, this feature would require a further design effort despite of unclear benefits. In fact, since the total dimensions would limit and affect anyway the installation of the device, providing a wired power supply does not appear to be a substantial limitation. Instead, an unlimited source of energy would be more convenient for the tests; the very high reliability requirements demand potentially long times of recording for the evaluations to be statistically significant.

4.4.2 Sensors connectivity options

In the framework of the MSP, each sensor measurement needs to be digitalized so that its information can be aggregated with the others. Since a lot of commercial analog sensors are available and still in wide use, a design option would be to include a dedicated analog signal chain in order to support them. Even though it would be possible, such choice would be a further complication from the design point of view, without bringing any advantage from the point of view of the purposes of the trials.

From the point of view of the local processing core of the MSP device, the sensor signal has to be digitalized, so that they can be readily acquired, processed and forwarded to the ancillary communication module. In case a particular analog sensor is deemed really interesting for the trial, a suitable conditioning and analog-to-digital conversion path will be included in a sensor sub-system that includes both the sensor and its conditioning electronics. A digital signal on a digital bus will then enter the MSP device.

The same reasoning can be applied to the internal sensors; however, nowadays digital semiconductors exist for any physical quantity of interest, therefore the choice will be limited to those.

4.4.3 Local processing core

The local processing core of the MSP consists of the typical real-time embedded system, as depicted in Figure 10. Several trade-offs are present which have to be evaluated.

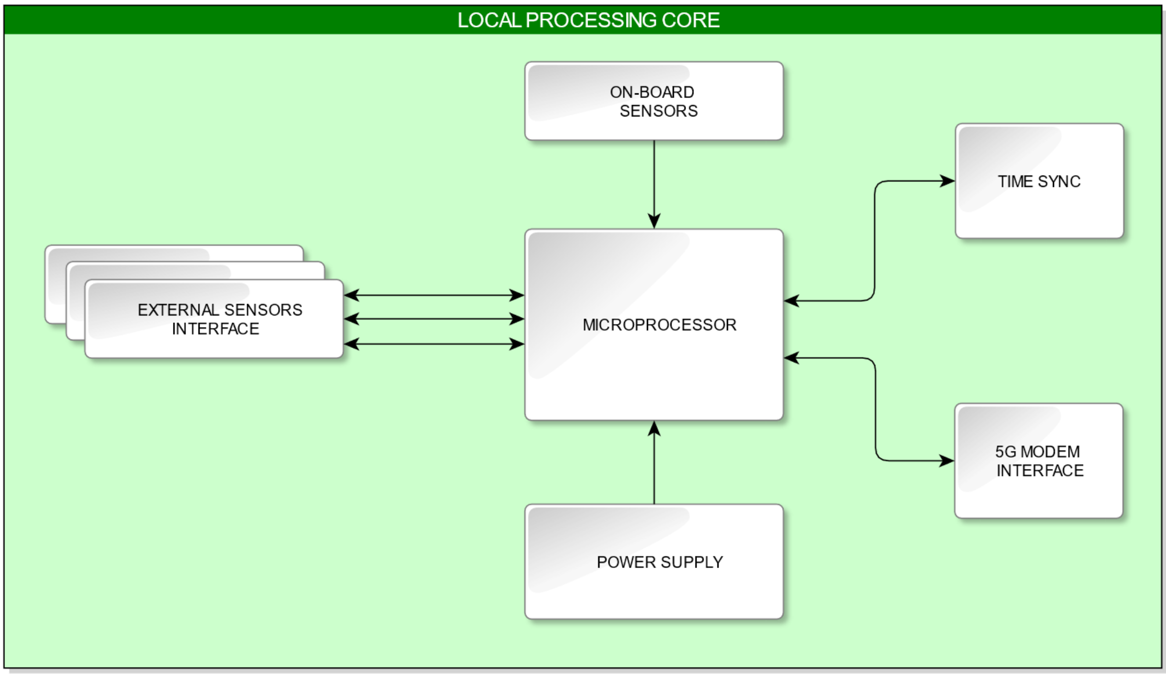

Figure 10. Block diagram of the processing core within the MSP device.

Microprocessor

The optimum selection of the microprocessor is a trade-off between processing power and power consumption. Even if a wired power supply scheme is selected for the trials, the current consumption of the whole system should be considered in view of a product design. As a matter of fact, even the otherwise best performing solution could be useless, if its energy figures were significantly off the customer’s expectation. The options range from ultra-low power microcontrollers running at a few MHz like ARM Cortex-M®,®, to high-level embedded microprocessors like ARM Cortex-A®® running at hundreds of MHz, to a Digital Signal Processor (DSP) like Analog Devices Blackfin®® running at a wide range of clock frequencies. The energy consumption is substantially directly related to the clock frequency, which will be selected based on the processing required by the sensors to be employed.

The selection of the microprocessor will also depend on the peripherals that will be needed for communicating with the sensors.

Given the nature of 5G-SMART trials and the required versatility of the MSP platform, the energy figures will be considered, but they might not be taken to their (lowest) extreme, in favor of more integrated peripherals and computational power.

On-board sensors

In representation of a real application, some sensors are installed on-board. They include internal environmental diagnostics, like humidity and circuit board temperature, as well as monitoring sensors, like a gyroscope and an acceleration sensor.

The implementation of the internal environmental sensors is straightforward compared to the external sensors, since they typically exist in the form of an integrated silicon device with simple and common digital interfaces like Inter-Integrated Circuit (I2C) or SPI.

The choice of the sensors may have a significant impact on the mechanical design. As an example, in order to sense an acceleration or a vibration, the integrated silicon device needs to be rigidly connected to the external body of the unit, rather than to the circuit board. A special gluing procedure is typically followed, while providing the electrical connection to the other electronics circuits. Finally, the whole unit has to be rigidly connected to the part to be monitored, therefore with a suitable fastening system. In general, the mechanical design will have to be coherent to the usage of the sensors, so that the measured physical quantities will be as much representative as possible, despite of the demonstrative nature of the MSP platform.

External sensors interface

The exact number of external sensors will be selected according to the trial setup and the selected sensors, with a trade-off between flexibility of the platform and the size of the complete unit.

If the sensors are defined in type and number before the implementation, then each external interface can be customized specifically for such sensor; they could be significantly different from each other, requiring a dedicate circuitry, but in this way standard, commercially available sensors can be connected.

An alternative option consists of a modular architecture where the external interfaces are all identical, with a selected standard, so that different combinations of sensors can be employed at the time of the trials or even changed during different repetitions of a test. In this case, either all types of sensors have the same electrical and mechanical connection, or they have to be encapsulated in a sensor sub-system in order to uniform them.

There are some common electrical standards for interfacing a wide range of sensors, like the traditional “4-20 mAmA” or the more recent IO-Link®.®. Every time a standard is adopted, a trade-off arises between modularity and optimization: it happens quite often that the highest level of optimization of a particular transducer can be reached only by customizing its electronics, connection and mechanical interface; adopting a standard may then result in a limitation to the optimization. However, if a standard is chosen so that most of the sensors are commercially available, then some special ones can be integrated in a dedicate sensors sub-system that realizes the very same connection.

Finally, a completely different approach consists of building the selected sensors from the ground up, i.e., by mechanically integrating the transducer and the electronics into one device. In this case, the mechanical and electrical interface can be selected quite freely to suit the peculiarities of the 5G-SMART trials, like the deployment in the harsh environment of a machining center. This approach requires more design effort, but it has the benefit of matching the sensors to the application at the best.

5G radio interface

The connection of the microprocessor to the 5G radio module can be internal or external to the unit, depending on which architecture option is chosen. Usually, high speed modems for cellular networks have one or more of the following interfaces: UART (Universal Asynchronous Receiver Transmitter), USB®® (Universal Serial Bus), or Ethernet®.®. The first one is typically used for control operations of the modem and it is supported by one of the other two for data transmission; given the current uncertainty on which 5G modem will be used, and given that the existing 5G demonstrator has an Ethernet®® connection, it seems advisable to include all of them in the design from the electrical point of view.

If the architecture option with an external ancillary module is selected, then a robust water-proof mechanical connection is required; however, a disadvantage of selecting such option is that high speed serial buses like USB® and Ethernet® require special design care, since their standard connectors are by no means water-proof.

Power supply

If the architectural option of a completely integrated device is chosen, then the power supply design will follow by integrating a Lithium-ion battery or battery pack, which will be regulated to the specific voltages required by the different parts of the electronics. The battery can be primary (i.e., disposable) or secondary (i.e., rechargeable): in the first case, the mechanical design of the unit will need a water-proof opening, while in the second case, a recharging circuit is required. The first option usually requires a careful mechanical design for safe operation in the foreseen environment. The second option, an energy source needs to be available at times: the solution can be either wired, with another water-proof connector, or wireless. In the last case, the simplification in abiding to the water-proof requirement comes in change of the electromagnetic design of the enclosure, which cannot be completely shielded.

If the modular architecture with an external ancillary communication module is selected, then the same connector of the ancillary module may also route the power to the recharging circuit.

Time synchronization

The MSP aggregates a potentially large number of data sources spread over of the factory. For the fused data processing to be meaningful, the information streams must have a well-known time correlation. Each of them needs to be time-stamped by the MSP device, which, therefore, needs time synchronization. 5G is expected to support these features, but at the writing of this deliverable the devices are not available. As a result, an alternative has to be implemented.

The most common source of time information is a GNSS module, but it requires a nearly constant access to the sky satellites. Unfortunately, this condition cannot be guaranteed in most production sites.

An alternative is the integration of a 4G-LTE modem from u-blox, that provides a CellTime™ feature. Whenever two or more of u-blox´s modems are connected to the same 4G-LTE base station, they provide two options for time synchronization: a PPS (Pulse Per Second) digital output or a time-stamping digital input. One of the two modems, either SARA-R5 or LARA-R3, will be connected to the microprocessor.

This module requires an antenna on its own. If the module is completely integrated in the unit, then it either provides an external RF port for connecting an antenna, or it provides a suitable electromagnetic opening for correct antenna operation. The first option limits the robustness of the device, since a protection for such antenna or a long RF cable can hardly be provided. On the contrary, the second option requires a dedicated design effort and it may further increase the size of the device.

4.4.4 Ancillary communication module

If the architecture option with an external ancillary module is selected, then a second device has to be designed. The benefit of such architecture would be the possibility to perform some testing in advance with available solutions like 4G-LTE and later with 5G modems.

A first design may, for instance, include the u-blox TOBY-L4 platform[2], which supports the spectrum band available at the trial site. This module is a 4G-LTE Cat 6, which provides enough bandwidth for the use cases for the Aachen trial site, especially the wireless AE system. However, its bandwidth and power consumption are significantly over-sized for the MSP. As a result, the device has to be encapsulated in an external unit, which will be supplied either by large batteries or by a wired connection. This second option is particularly interesting, because it can be used to supply the recharging unit inside the MSP device, without being a limitation for the purposes of the trials. In Figure 11, a block diagram of ancillary communication module is sketched.

[2] www.u-blox.com

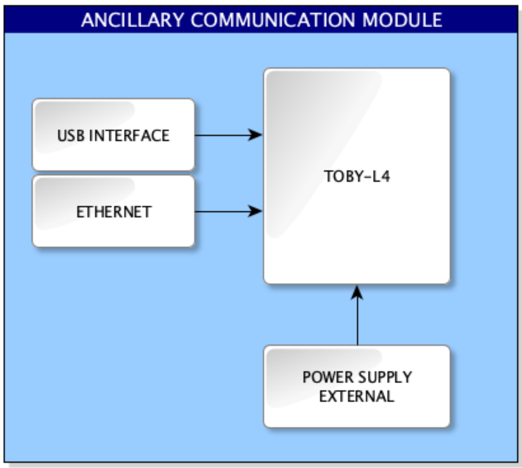

Figure 11: Ancillary communication module.

From a mechanical point of view, a simpler enclosure should be designed as compared to the MSP device, eventually made of plastics in total or in part. This ancillary unit does not need to be placed strictly close or inside the machine environment, because it is not representative of the general platform design.

4.5 Versatile sensor data processing pipeline

The concept for the MSP use case in Section 2.2 puts the compute workload in the *factory cloud*, an edge cloud equipment and software stack , that runs physically close to the machining equipment it is serving. Hardware-wise, factory clouds may be installed separate from, but in close proximity to, the 5G network equipment. They can, in general, be built on specialized computer solutions, but we envision them to run on commodity servers, typically rack-mountable units with an x86 CPU architecture, with possible hardware-accelerated networking and GPUs to increase parallel computing efficiency. Time-critical software, especially closed-loop control running in the factory cloud, can take advantage of the bounded one-way latency thanks to the minimized transmission distance. Moreover, developing and maintaining control software becomes easier and more accessible thanks to the possibility to use programming methods and tools from the web-scale IT industry. Factory clouds give the option for constraining critical data to stay within the physical confines of the operating enterprise, but can also be connected to external services, e.g., for data enrichment or lengthy offline analysis.

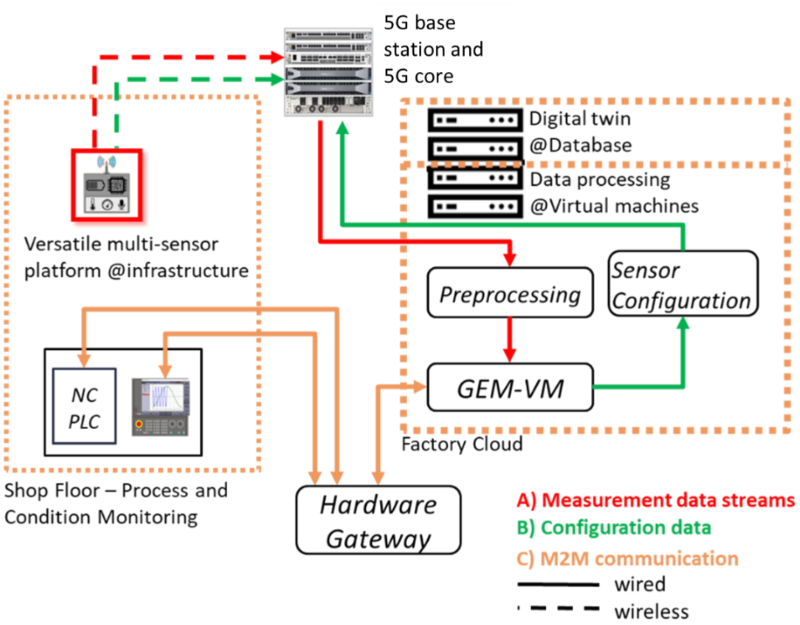

Figure 12: Factory Cloud Computing Architecture for the MSP

An important aspect of cloud technologies is virtualization of computer resources, to isolate components of the full workload for both responsibility-separation and protection from each other's malfunction. Two popular virtualization technologies that we have considered are virtual machines (VMs) and containers. VMs offer easier moving of pre-existing software from specialized hardware into the cloud, while containers are more flexible to manage and expected to use less total compute resources due to the finer granularity of their design.

In the following, we describe options for control software realization for the MSP use case in a factory cloud.

4.5.1 Factory cloud application architecture

In accordance with cloud software terminology, we use the term *service* for the elementary components that together make up the control software. Services are separate packages that can be individually started, stopped, or *scaled* (have their resource usage and, thus, processing performance increased or decreased). Moreover, for each service it is important to consider reliability aspects, i.e., how a possible failure or other availability issues regarding a service would affect the rest of the control software's correct behavior.

The services defined for the MSP use case, and their reliability and scalability considerations are planned as follows:

- *Data processing service:* Both critical and non-critical sensor data may be created by multiple orders of magnitude more frequently than what data processing functions (GEM hardware or GEM-VM, see below) in the control loop can handle. This service would limit the forwarded data rate, and enable novel data processing algorithms to be implemented based on the factory cloud concept.

Reliability: This service should be run in active-standby configuration to allow for fast recovery in case of a container or a VM failure, in the range of 5-10ms. This can be achieved via both in-rack or intra-rack distribution of instances.
Scalability: It is assumed that data pre-processing pertaining to a single sensor can be executed in a single instance of this service, and depending on the workload, a single instance can handle multiple sensors. If this is not the case, the service will need to be split into multiple modules that can be scaled individually (i.e., it is for further study if new use cases are added later).

- *GEM-VM* service: The pre-existing GEM virtual machine implements the main business logic of the control software. GEM-VM reads pre-processed measurement data, creating alarms or other actuator events (e.g., emergency stop), and generally monitors and provides visualization input for the machining hardware. This is the only service that will run in VMs, not containers, as it is based on a heavily customized operating system image provided for the 5G-SMART project.
  Reliability: This service is critical for the use cases and is planned to be run in two parallel instances, to protect from the single VM failure case, without service discontinuity. Scalability: One instance of the service can control multiple sensors, therefore the number of instances should be set according to the total workload. Instances do not inter-communicate, so no issues are expected to arise from their multiplicity.

- *Data storage* service: Processed raw data from sensors may be persisted for a configurable time period (e.g., 1 week for FFT) and GEM-VM output for a longer time (e.g., 1 year), for offline processing or post-mortem analysis. This service is to support extension of the use cases in the future.
  Reliability: This service is not critical, its failure detection is health-check-based, and it is planned to be restarted with a sub-minute timeout.
  Scalability: The service should store data in a per-sensor manner, e.g., data file naming convention.
- *GEM GUI* service: The visualization of GEM-VM monitoring data is planned in a web service that can be connected to or from clients inside the factory.
  Reliability: It is a non-critical service, and it should be health-checked and restarted upon failure with a sub-minute outage.
  Scalability: Depending on workload, the service may be scaled out to multiple instances using standard web-scale technologies.
- *Sensor configuration* service: Run-time change of sensor parameters is planned to be provided by this service. Clients in the factory would be able to connect to, monitor, and change these parameters of each sensor module.
  Reliability & scalability: Same as for the *GEM GUI* service.

Data communication between instances of the different services will need to be separated in the networking overlay to avoid mixing or duplication. The orchestration of data paths of the processing pipeline will account for the above described redundancy requirements. For instance, the UDP-based stream from *Data processing* to the *GEM-VM*'s duplicate instances will need to be replicated via multicasting.

Scalability of the whole data processing solution is planned to be demonstrated by using a multitude of simulated sensors. These will appear as additional data sources for *Data processing*, and *GEM-VM* output related to them should not be forwarded to the GEM hardware. The number of simulated sensors will need to be changed in runtime to emulate changing activity level in a factory and measure the performance of the solution in such dynamic situations.

4.5.2 Deployment options

The way the individual services defined in Section 4.5.1 are handled as a whole software solution includes *a)* how the services should be executed and maintained during the life-time of the production, and *b)* how they are connected to each other and to the two-way data flow of the sensors on the factory shop floor. The aspects of the deployment are:

- Cloud platform: For the deployment of application components, a factory cloud system at Fraunhofer IPT will be used. Performance and utilization of virtual service instances, data pipelines, and network connections can be monitored and supervised in real-time on-site or remotely through a secure management interface for the development, testing, and production deployment purposes. Two cloud platforms will be tested, Virtual Fort Knox (VFK)[3] and German Edge Cloud (GEC)[4]. VFK provides an open, scalable cloud IT platform for the efficient delivery of production-related software solutions developed by Fraunhofer IPA in Stuttgart. GEC is a start-up which belongs to the Friedhelm Loh Group, and in cooperation with Fraunhofer IPT, new potentials for the integration and use of real-time edge control systems will be tested. The uniqueness of the developed factory cloud platform is its real-time capability. Both VFK and GEC allow use of VMs and containers, and the final environment will be selected during the development phase.
- Application orchestration: For services in Section 4.5.1 Docker[5] containers are planned to be used as hosts for reasons of flexibility and exchangeability. Docker containers provide convenient encapsulation, isolation and portability of applications, which can be used to create scalable and updatable clusters. Further, they can be stopped and (re)started very quickly so that the cluster can be adapted to the resources needed by the shop floor, but without blocking network capacities when they are not required. For orchestration of the cluster, a solution based on Kubernetes[6] and Helm[7] tools will be tested, as the de-facto standards in container orchestration. Should any performance or usability issues be detected, the project will propose alternate solutions, both provided by the partners and external from other 3rd parties. Kubernetes is a container-orchestration software automated for deploying, scaling and managing containerized applications. Helm is a package management extension to Kubernetes. Helm charts install, create and upgrade complex Kubernetes clusters for reliable, scalable and redundant container clusters. Kubernetes handles each service by

[3] https://research.virtualfortknox.de/en/
[4] https://www.gec.io/
[5] https://docs.docker.com/reference/
[6] https://kubernetes.io/docs/reference/
[7] https://www.consul.io/docs/platform/k8s/helm.html

monitoring their individual performance, and starting or stopping instances to adapt their number to the current workload. It also provides name resolution and a virtual networking overlay, where services can look each other up using symbolic names and communicate over IP addresses. Measurement data from and configuration information towards the sensors are provided for the services over IP as well.

- Sensor management: Control of sensors will be realized through a configuration service that can query and instruct sensors on the shop floor regarding their current or expected runtime parameters, such as sampling frequency or unit of measurement. This control should be highly reliable to guarantee that the current states of sensors corresponds to that of the machining process. Lightweight M2M[8] is chosen for configuration and control of the sensors, which a light and compact device management protocol for sensor networks. It offers a secure and efficient way for device configuration, which is suitable for fixed and mobile devices.

[8] https://omaspecworks.org/what-is-oma-specworks/iot/lightweight-m2m-lwm2m/

5 Summary and outlook

This document reports on system design options for monitoring of workpieces and machines in the context of the 5G-SMART project. The wireless acoustic emission measurement system with its principle of acoustic emission is explained and the connectivity requirements are described, motivating a machine-near solution with low latency and fast reaction times. The multi-sensor platform, on the other hand, handles the acquisition and transmission of several additional sensor signals to augment the process monitoring with further valuable data. The third signal source type will be the machine internal signals, which will not be transferred via new wireless technologies such as 5G, but via established fieldbus and Ethernet connections. The complex multi-signal elaboration can be done directly in the acoustic emission measurement system, in the multi-sensor platform, or in the factory cloud with virtual machines.

The implementation and validation of the use cases is an ongoing work in 5G-SMART, and further details and results of the study will be made available continuously during the project. In the following months, the discussion on the different design options for the two sensor solutions will converge, so that implementation work can be started, i.e., PCB design, embedded system programming, and sensor integration.

Furthermore, hardware-based (GEM) and factory cloud-based (GEM-VM and GEC) data processing solutions are being established. The latter requires a dedicated security concept and routing scheme that allows integration into the shop-floor IT at the Fraunhofer IPT with optimal latency and throughput.

While both sensor solutions are mainly exploiting the ultra-reliable and low-latency communications (URLLC) features of 5G, the performance evaluation of the sensor data processing pipeline involving the factory cloud requires an elaboration of a validation plan. This validation plan must take into account, that the end points of the overall data transfer are the sensor and machine, and that the processing pipeline relies on both wireless and wired communication.