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Comparison of 5G Enabled Control Loops for Production

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***Abstract*— Concepts such as Industry 4.0 and Industrial Internet of Things aim for a digital transformation of manufacturing companies. One aspect that is to be transformed is the shop floor, where the interconnection of machines and sensor devices plays a major role. 5G positions itself to be a key technology to enable this transformation by providing reliable, low latency, and high bandwidth communication which is required by industrial use cases. However, so far it is still unclear which role 5G will play in industrial networks and how it can be integrated into existing factory ecosystems. Therefore, this paper presents three different data flow architectures that illustrate how 5G can be integrated into the production IT and how it can coexist with a factory cloud system. Furthermore, we describe a use case that reflects typical industrial communication requirements and will be used in the future to evaluate the different architectures. We conclude by presenting a validation plan and an outlook on future work.**

Keywords—5G, Factory Cloud, Remote Cloud, IIoT, Industry 4.0, Smart Production, Wireless Sensors

I. INTRODUCTION

New trends such as Industry 4.0 or the Industrial Internet of Things (IIoT) drive digital transformations in the industrial environment. Both aim at reducing manual processes and increasing efficiency, flexibility, and versatility of smart factories for individual customer requirements. For these manufacturing systems, the interconnection of devices plays a major role [1]. For wired and wireless systems, the connectivity between devices must meet the restrictions and requirements of the industrial environment, thus creating challenges for the digitalization of the production [2].

5G proposes to be one key technology to achieve such an interconnection, allowing small and mobile devices to collaborate and to be integrated into the ecosystem created by Industry 4.0. The 5th generation of mobile communication is not only designed for mobile networks but also for machine-to- machine communication in industrial applications. For this purpose, 5G supports three different types of communication: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC) and ultra-reliable low-latency communication (URLLC). During the past years, the demand for wireless systems has increased mainly driven by the demand for high amounts of data, because more sensors and devices have to be integrated into the production area and into the processes.

To fully understand the potential of 5G in the industrial context, it is not sufficient to analyze it as a stand-alone communication medium between a sensor and a control unit, instead as an enabler of a comprehensive digitalization of the shop floor by integrating information technologies (IT) like cloud or edge systems into the control loop. Its capability of connecting devices over longer distances enables a larger distribution of the computing tasks leading to a paradigm shift of the computing architecture of future industrial applications.

For this purpose, this paper discusses the impact of 5G on the manufacturing infrastructure and presents three architecture approaches for 5G enabled smart factories. Furthermore, the validation of these kind of concepts is planned, based on a representative smart manufacturing use case and suitable metrics defined within this paper, in order to investigate the performance capabilities of different architecture approaches and determining the impact of 5G on future manufacturing systems.

II. 5G'S IMPACT ON THE MANUFACTURING INFRASTRUCTURE

In this chapter, the changes in automation control due to new technologies and three new data flow models will be elaborated. Furthermore, an overview of the AE use-case will be presented.

A. State of the Art

Communication systems for industrial applications need to meet strict requirements, such as availability and real-time execution. Due to this, most industrial environments historically build on wired solutions, with each

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one adapted for specific use cases, thus creating a wide range of field bus and Ethernet based protocols such as PROFINET, PROFIBUS or ETHERCAT. Usefullness of earlier wireless technologies such as Bluetooth, ZigBee or Wifi is very limited due to the lack of availability and reliability. The emerging 5G standard as an industrial wireless network (IWN) solution promises a real- time wirless alternative and flexible greater adaption in Industry 4.0 applications [3]. IWN provide a wide area network access for future factories enabling large scale inclusion of new IT technologies such as factory clouds, edge systems, big data analysis and digital twin implementations. 5G can be used for wireless real-time communication for both fast and reliable communication using URLLC as discussed in [4], and for large scale machine to machine communication using mMTC as discussed in [5].

B. Changes in the role of the factory cloud

Currently, automation systems follow the architecture of the automation pyramid. It consists of five levels from the field level to the enterprise resource planning. By classifying the corresponding tasks, interfaces, and communication requirements for each level, the automation pyramid gives a clear structure on how to efficiently implement an automation system [6]. But this clear structure also creates strong restrictions by losing flexibility and connectivity which is needed for IIoT and Industry 4.0. In Fig. 1 the classical automation pyramid is shown on the right side.

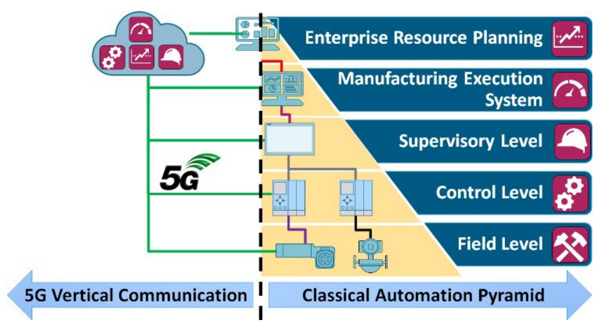

Fig. 1. Left: Vertical communication enabled by 5G. Right: Classical automation pyramid.

The new communication standard 5G aims to meet the requirements for the field level in terms of reliability, latency, and availability, but also the requirements for higher levels such as Manufacturing Execution System (MES) or Enterprise-Resource-Planning (ERP) systems. This enables vertical communication between the different levels and facilitates as shown in Fig. 1. With flexible communication infrastructure provided by 5G, cloud and edge technologies can now be integrated on all levels of the automation pyramid, thus creating a centralized system for data transmission and computing [7]. The factory cloud provides scalable access to large computing resources for outsourcing tasks from the classical allocation on the more restricted levels. Furthermore, new tasks such as online simulation, optimization, and adaptive process planning can now be used by any device especially at the field level, thus dissolving the existing structure of the automation pyramid.

In this paper, the term *factory cloud* is used for an edge cloud deployment that resides close to or at the shop floor and executes time-critical control software and retains full data ownership for the factory operator. This cloud environment can be built on specialized equipment with possibly limited resources (e.g., edge computers) or generic commodity hardware. Factory clouds may also be connected to external cloud services for non- time-critical workload. We envision that a typical deployment would run besides the 5G network stack taking advantage of minimized transmission latencies.

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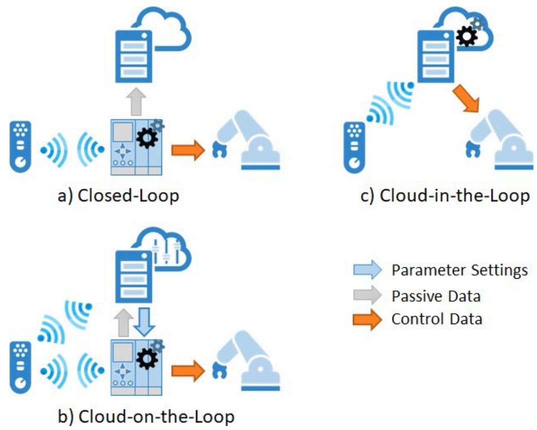

Fig. 2. Design patterns for 5G and factory cloud integration in manufactuing systems. Source: Based on [8].

Using a factory cloud and 5G communication on the shop floor enables a seamless integration of industrial applications. But how can such flexible architectures integrated into the production IT look like and which role will the factory cloud have in such a scenario? In [8] design patterns for IIoT data transfer are presented. To analyze the impact of 5G on the manufacturing data flow three patterns need to be discussed in further detail: The closed-loop, the cloud-on-the-loop and the cloud-in-the-loop pattern as presented in Fig. 2.

The *closed-loop* pattern describes the classical control loop according to the automation pyramid. The sensor sends the data directly to a controller or Programmable logic controller (PLC) situated next to the machine. The control signals can then directly be sent to the machine. The loop is realized locally on the shop floor using the cloud only as data storage, visualization and analysis tool without feedback to the shop floor. 5G can be used to integrate further wireless sensors on rotating, moving and difficult to access locations, but only as the communication medium and not as an enabler of digitalization since the other components maintain their existing roles from the automation pyramid as shown in Fig. 2 on the top left.

In *cloud-on-the-loop* pattern the sensor data is fed not only to the control unit but also to the cloud where it is being stored and analyzed. The results of the analysis can then be fed back to the control unit optimizing the control loop by changing parameters, alarms or trigger values. The path from the sensor to the actuator can still be achieved without passing the cloud but it still plays a major role enabling flexibility and remote supervision of the control loop as shown in Fig. 2 on the bottom left. 5G can be used to enable bidirectional communication to the factory cloud from the control unit and the sensor. Further the factory cloud can work as a connecting node and orchestration point for the wireless sensors and actuators.

The *cloud-in-the-loop* integrates the factory cloud into the control loop by using 5G to match the requirements for monitoring systems. The factory cloud now has the role of the control unit, thus leaving only the sensor and the actuator on the shop floor. The control algorithms are now digitalized and running in the factory cloud receiving raw data from the sensor and sending control commands to the actuators. The sensor can contact the actuator only indirectly via the cloud, as shown in Fig. 2 on the top right. This design pattern has the strictest communication requirements, which can only be achieved with real-time computing platforms on the factory cloud and real- time communication with 5G and Time-Sensitive Networking (TSN) [9].

C. Use Case and Application

In order to retrieve information about the condition of the work piece, the machine and the manufacturing

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processes, sensors are used to detect critical process parameters, like forces or vibration. If the machine-internal torque sensors are not sufficient for a monitoring solution, additional sensors such as vibration or acoustic emission sensors are required. Integrating these sensors into a new machine is no problem but retrofitting them will cause longer machine downtime. In addition, there are applications where the sensor must be integrated into the tool holder or on the work piece, which cannot be done due to the required wiring.

Since these sensors must be installed close to the process, wireless communication is needed, especially for demanding applications such as monitoring of a 5-axis milling machine. A communication medium that fulfills the industrial requirements in terms of reliability, data rate, and latency is the new 5G standard, which is rarely the case for existing interfaces such as Bluetooth, ZigBee or WiFi [10]. One example for such a process monitoring system is the acoustic emission sensor, which allows deep insights into industrial manufacturing processes and therefore is a promising approach for a wireless process monitoring system [11][12]. Due to the demanding requirements, such as real-time capability and fast response times, this approach requires a technology like 5G. Acoustic Emission (AE) sensors are usually being installed close to the cutting tool and the cutting area and are physically fixed to the work piece or the clamping device. The sensors measure high- frequency energy signals that are generated by the machine elements involved in the process during material removal from the work piece. The acoustic emissions, also known as structural noise, depending on the medium in which they are propagated, are inaudible ultrasonic signals. The electrical signals measured in this way consist of characteristic frequencies and sound amplitudes that are specific to the cutting processes and can therefore be used for monitoring the physical process. The frequencies range up to 1MHz, so the required sampling rates are about 1-2 MSamples/s creating data streams with up to several several-100Mb/s. In Fig. 3 an example of the usage of the AE sensor is shown.

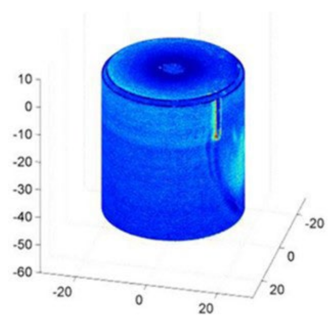

Fig. 3. Amplitude distribution of an acoustic emission measurement mapped on the cylindrical work piece geometry.

Some of the use cases for acoustic emission are detection of tool breakage, tool to material contact, and detection of inhomogeneities in the material such as cracks or variation in hardness. The advantages of the acoustic emission principle are high sensitivity, wide frequency range, robustness, and ease of installation on the machine components. Especially for very small tools with less than 1mm diameter or multi-spindle applications, where it is not possible to assign the cutting forces or power, the acoustic emission is often the only solution. In other applications wired mobile AE sensor heads are mounted temporary on the machine table in order to detect the contact from the tool on the work piece surface. This is used in precision machines to compensate thermal deviations or in very large machines for the machining of large parts, such as ship crankshafts.

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TABLE I. INDUSTRIAL REQUIREMNTS ON DATA COMMUNICATIONS FOR A TRIAL USE CASE BASED ON COMMERCIALLY AVAILABLE 5G SOLUTIONS IN 2020.

Test Case	***Data Rate [Mbit/s]***	***Latency [ms]***	***Jitter [ms]***	***Transmission Reliability [%]***
Scenario 1	< 10	< 5	< 1	≥ 99.999
Scenario 2	Several 100	< 10	< 1	≥ 99.99

Depending on the use case, the requirements for the 5G communication can differ. For time critical applications with short reaction times, for example stopping the machining upon tool breakage detection or adapting the machining process in case of critical resonance vibration of the work piece, URLLC communications is needed for a real time communication between sensor and control unit. An example set of requirements is shown in TABLE.1 scenario 1, taken from a currently running activity [13]. Furthermore, some kind of synchronization between the sensor data and the machining process is needed.

For large data applications, like analysis or tool path optimization, eMBB can support the large data volumes from the AE sensor. The requirements for these use cases can be found under scenario 2. Both URLLC and eMBB requirements originate from the industrial perspective, and we will examine which of them can be realized with 5G during the validation.

III. DATA FLOW MODELS OF FACTORY SYSTEMS WITH 5G We aim to evaluate the applicability of 5G systems within smart factory architectures represented by the example use-case presented above by comparing three main data flow architectures. The three designs correspond to the data flow models of Fig. 2 and are described in detail in the order of compute workload being moved increasingly from specialized hardware equipment to the factory cloud.

A. 5G as communication medium – "Closed-Loop"

The closed-loop architecture is a machine near approach with a high grade of communication efficiency to bring the data from the sensor via the 5G network to the analysis and monitoring hardware with low latency and less delay times. The monitoring hardware is connected to the machine with a reliable and safe automation bus system. The following Fig. 4 shows the closed-loop design concept with a machine being monitored and controlled based on a smart AE sensor module mounted on the machine table near the machined part. The amplified and filtered AE-signals are sampled with high rates and passed to the signal conditioning unit. The raw data can be passed through the signal processor board to the 5G module. With a high grade of flexibility, the data can be pre-processed for reducing the bandwidth requirements or calculating key performance indicators like Fast Fourier Transform (FFT) or peak values, such that events like the first contact from the cutting edge of the tool with the work piece material can be evaluated very fast.

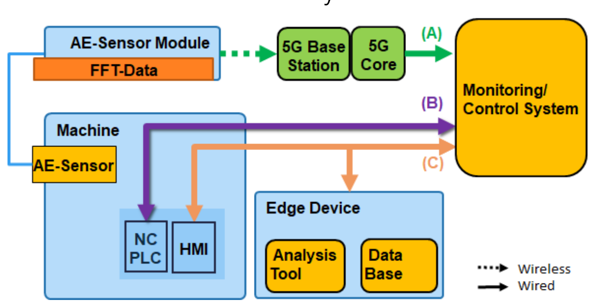

Fig. 4. Closed Loop Architecture with 5G communication. (A) Measurement data - (B) Control data via Fieldbus - (C) Interface and Analysis Data

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On the other end, the 5G base station with the 5G core receives the data and forwards it to the monitoring hardware, 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. Here the Numerical Control (NC) and the PLC are connected to the Monitoring unit to synchronize the signal elaboration with the machining of the parts. The Humane 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 a local edge device in a database for documentation and later analyzation.

B. 5G for data analysis – "Cloud-on-the-Loop"

The cloud-on-the-loop data flow architecture is a hybrid approach, where critical communication continues to only flow through the shop floor and 5G network, while integrating the cloud for monitoring and analysis purposes. The central component is a proxy that is located in/at the edge of the shop floor and 5G network as shown in Fig. 5. The data collection continues to be performed by the machine integrated sensors. They either communicate directly, or through the proxy, with the monitoring/control system that is responsible for the closed- loop control of the process. Additionally, through the proxy, they allow the cloud system to collect process data which can then be used in supervision tasks.

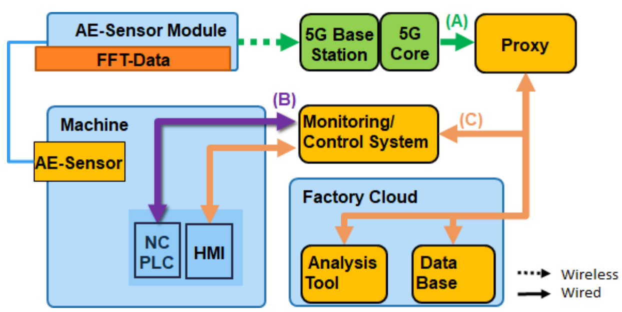

Fig. 5. Cloud-on-the-Loop Architecture with 5G comunication. (A) Measurement data - (B) Control data via Fieldbus - (C) Interface and Analysis Data

Several aspects must be considered when integrating a cloud system. As there are possibly many sensor devices in the 5G network, functionalities need to be provided, that make them discoverable on application level and describe their functionality programmatically so that they can be automatically integrated into a larger software system. Furthermore, the requirements for the communication protocols in the 5G network and in the cloud system are likely to differ. In a wireless IIoT network, many sensors will likely run on battery and try to minimize the amount of data that is sent as they need to conserve energy. Therefore, a 5G network will probably prefer using binary protocols, for example the Constrained Application Protocol (CoAP), and binary encoding schemes, for example the Concise Binary Object Representation (CBOR). On the other hand, in cloud systems, Hypertext Transfer Protocol (HTTP) and JavaScript Object Notation (JSON) are established technologies which are both text-based. Hence, it might be required to perform a translation. Another approach to reduce the communication is by using a cache at the border of the 5G network. Repeated requests can then be answered directly and subscriptions can be bundled. Our cloud-on-the-loop architecture uses a proxy service that combines all these functionalities into a unified communication gateway.

Its primary function is to facilitate discovery of network devices and their resources. Whenever a new device joins the network, it will send a multicast message to discover the proxy. It then sends the information

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about its resources to the proxy, which records them in the resource directory. Software running in the factory cloud can then discover devices and resources by querying the proxy instead of each individual device. This significantly reduces the required communication and shifts the heavy lifting to the proxy service that can run on much more capable edge hardware than the 5G sensor devices.

The secondary function is the transparent translation of protocols and encodings between the cloud services and the 5G network devices. For example, in case of semantic similarities of resources in CoAP, resources in HTTP, and topics in Message Queuing Telemetry Transport (MQTT), the proxy is able to perform a transparent translation. Furthermore, it can re-encode binary encodings like CBOR messages lossless into JSON messages. As a result, cloud services can communicate using established technologies through the proxy with the 5G devices without needing to understand binary protocols and encodings. An added benefit is that the proxy can perform caching for requests and multiplexing for subscriptions. If two cloud services request or subscribe to the same resource, the proxy can answer both by performing a single request to the 5G device respectively by subscribing only once to the resource of the 5G device. This further decreases the required communication with the sensor, and thus its energy consumption.

C. 5G digitalized production – "Cloud-in-the-Loop"

Building on the increased performance provided by 5G connectivity, digitalization of manufacturing processes can be taken one step further. The architecture concept of cloud-in-the- loop, illustrated in Fig. 6 moves all computation tasks of the closed-loop manufacturing control application to the local factory cloud deployment. Sensors and machining elements on the left-hand side, connectivity through 5G, and the gateway remain the same as in the previous two models. The difference is that critical software is executed in the factory cloud: raw measurement data is delivered to the fully cloudified control applications, which process it and send back the control commands.

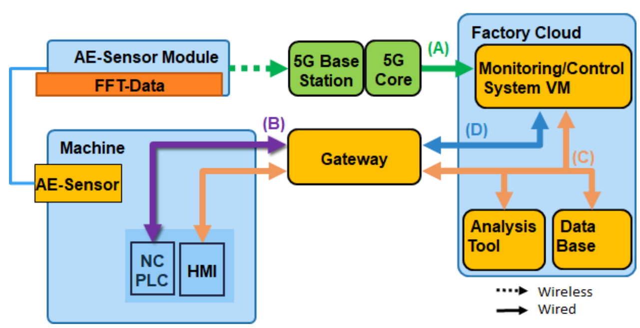

Fig. 6. Cloud-in-the-Loop Architecture with 5G communication. (A) Measurement data - (B) Control data via Fieldbus - (C) Interface and Analysis Data - (D) Control Data via Ethernet

Benefits of this concept are twofold. On the one hand, computing resources and therefore energy consumption of embedded sensors are minimized allowing for longer uninterrupted machining phases. On the other hand, computations carried out in a full-fledged cloud deployment can take advantage of compute solutions like increased parallelism of execution and robustness through replication as well as capitalize on a richer set of external data, like large knowledge bases of historical profiles. Neither of this would be feasible to employ in the limited environment of an embedded device. As a result, the software complexity of factory shop floor elements is decreased and shifted to a cloud environment allowing for a simplification of the former while at the same time avoiding problems of the latter to be addressed with the tool set developed and enjoyed by the web-scale industry.

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Usability of the concept relies on two aspects: throughput and latency of the connectivity, and reliability and latency of computations. Connectivity is provided by 5G for wireless and TSN for wired data transmission. For computations a 5G factory cloud is used, a specialized form of edge cloud computing where all components of the cloud software stack run as close to the factory shop floor as possible, in order to minimize transmission latency overhead and make it negligible compared to the millisecond range of other typical time constants in the loop. The factory cloud deployment is otherwise built of and managed via the same tools as its public counterparts and can be connected to such for long timeout data storage and offline analytics, for example.

IV. Validation Plan

Three different approaches for the same task have been presented, each architecture integrating the factory cloud and the computing tasks in a different way. For the validation and comparison of these concepts, all architectures will be implemented in parallel performing the same milling task on a real machine. Each architecture will be benchmarked against each other finding the disadvantages and advantages of each design pattern. For this purpose, four Key Performance Indicator (KPI) are defined: reaction time, resilience, scalability and effective data rate. These KPIs are crucial for industrial applications and especially reaction time was promoted as the main advantage of 5G over other wireless standards [14], which needs to be verified in the context of this project. The trial verification will be done with the AE sensor system integrated into a 5-axis milling machine. The complete monitoring and control chain from sensor to machine is checked for functionality.

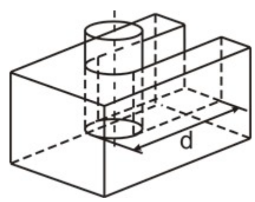

Fig. 7. Reaction Time validation with material contact detection test.

Reaction Time: One of the most important characteristics that needs to be determined during the validation tests is the reaction time of the system. This is not only defined by the round-trip time from the sensor to the machine, but from the sensor until changes in the mechanics of the machine occur. The most accurate way to measure this is to set sensitive monitoring limits that stop the machine at the first material contact. Then the milling tools moves with a fixed feed rate towards the work piece and at the first touch the sensor sends a signal to the monitoring unit which than triggers a stop signal. With the distances travelled in the material (marked with "d" in Fig. 7), the resulting reaction time of each architecture can be determined from the distance travelled and the feedrate.

Even if the results are satisfactory, not only the round-trip time but also the response time of each step in the control loop should be determined as well. Five major steps can be found for all architectures: the sensor input, the monitoring unit, the hardware gateway, the PLC, and he mechanics of the machine. Between each of these steps the communication characteristics can be determined and used to identify problematic components for improvement of each architecture.

Resilience: If the communication between components is lost, the system should be able to restore normal operation as soon as the connection is restored. This behavior can be verified by intentionally switching the sensors or factory cloud applications off. In addition, a failure of individual components must be detected and

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reported to a technician as during this time monitoring does not work and the machining is not protected.

Scalability: Future manufacturing will consist of many wireless devices. Each needs to be orchestrated and integrated in the overall production process. To test the scalability of the different approaches and the 5G network, several wireless acoustic emission sensors will be integrated in the shop floor together with several machines. Especially the wireless acoustic emission sensor needs a lot of bandwidth, which can cause an overload of the wireless network. By testing all three concepts, it can be checked how much of the data processing needs to be shifted to the edge or the embedded side to achieve scalability without overloading the 5G network.

Effective data rate: For reliable operation of the 5G network, it is a good idea not to operate the medium at the limit but to maintain free capacity to avoid package loss due to burstiness of scheduling. For this reason, the effective data rate will be lower than the maximum possible data rate. The effective data rate and the amount of package loss needs to be determined within the project. This can be done by comparing the amount of send bytes with the amount of received bytes.

V. Conclusion And Future Work

In this position paper the integration of future technologies such as 5G, cloud, and edge systems into smart factory infrastructures has been discussed based on three main data flow models. The difference between the models is in task allocation and the role of the factory cloud in the control loop. For each of these models a high-level architecture has been presented designed for the AE sensor use case. Furthermore, we have presented a validation plan for each architecture focusing on the connectivity between the sensor and the machine. This validation uses four KPIs to compare the different approaches: reliability, latency, scalability and effective data rate.

In the future we plan to implement these architectures on the shop floor using 5G and a factory cloud system as described in this paper. This enables comprehensive validation not only of 5G but also of IIoT and Industry 4.0 systems. Although these concepts offer many advantages in terms of flexibility and efficiency, they do not come without problems. The usage of these large amounts of data, and also safety, security, and reliability aspects need to be investigated in further details using measured data from a real implementation on the shop floor.

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References

[1] M. Wollschlaeger, T. Sauter and J. Jasperneite, "The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0," in IEEE Industrial Electronics Magazine, vol. 11, no. 1, pp. 17-27, March 2017, doi: 10.1109/MIE.2017.2649104.

[2] T. Lennvall, M. Gidlund, and J. Akerberg, "Challenges when bringing IoT into industrial automation," in 2017 IEEE AFRICON, Cape Town, Sep. 2017 - Sep. 2017, pp. 905–910.

[3] Li, X., Li, D., Wan, J. *et al.* A review of industrial wireless networks in the context of Industry 4.0. *Wireless Netw* **23,** 23–41 (2017). https://doi.org/10.1007/s11276-015-1133-7

[4] M. Khoshnevisan, V. Joseph, P. Gupta, F. Meshkati, R. Prakash and P. Tinnakornsrisuphap, "5G Industrial Networks With CoMP for URLLC and Time Sensitive Network Architecture," in *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 4, pp. 947-959, April 2019, doi: 10.1109/JSAC.2019.2898744.

[5] J. S. Walia, H. Hämmäinen and H. Flinck, "Future scenarios and value network configurations for industrial 5G," 2017 8th International Conference on the Network of the Future (NOF), London, 2017, pp. 79- 84, doi: 10.1109/NOF.2017.8251224.

[6] S. Y. Nof, Springer Handbook of Automation. Berlin: Springer, 2009. [Online]. Available: http:// dx.doi.org / 10.1007/ 978- 3- 540-78831- 7

[7] X. Xu, "From cloud computing to cloud manufacturing," Robotics and Computer-Integrated Manufacturing, vol. 28, no. 1, pp. 75–86, 2012, doi: 10.1016/j.rcim.2011.07.002.

[8] G. Bloom, B. Alsulami, E. Nwafor, and I. C. Bertolotti, "Design patterns for the industrial Internet of Things," in 2018 14th IEEE International Workshop on Factory Communication Systems (WFCS), Imperia, Italy, Jun. 2018 - Jun. 2018, pp. 1–10.

[9] J. L. Messenger, "Time-Sensitive Networking: An Introduction," in IEEE Communications Standards Magazine, vol. 2, no. 2, pp. 29-33, JUNE 2018, doi: 10.1109/MCOMSTD.2018.1700047.

[10] J.-S. Lee, Y.-W. Su, and C.-C. Shen, "A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi," in IECON 2007 - 33rd Annual Conference of the IEEE Industrial Electronics Society, Taipei, Taiwan, Nov. 2007 - Nov. 2007, pp. 46–51.

[11] X. Li, "A brief review: acoustic emission method for tool wear monitoring during turning," International Journal of Machine Tools and Manufacture, vol. 42, no. 2, pp. 157–165, 2002, doi: 10.1016/S0890-6955(01)00108-0.

[12] H. A. Kishawy, H. Hegab, U. Umer, and A. Mohany, "Application of acoustic emissions in machining processes: analysis and critical review," Int J Adv Manuf Technol, vol. 98, 5-8, pp. 1391–1407, 2018, doi: 10.1007/s00170-018-2341-y.

[13] K. Landernäs (ed.), "Forward looking smart manufacturing use cases, requirements and KPIs", in deliverables of H2020 project 5G-SMART, 2020, https://5gsmart.eu/wp-content/uploads/5G-SMART-D1.1.pdf

[14] A. Frotzscher et al., "Requirements and current solutions of wireless communication in industrial automation," 2014 IEEE International Conference on Communications Workshops (ICC), Sydney, NSW, 2014, pp. 67-72, doi: 10.1109/ICCW.2014.68811.