Towards the 5G-Enabled Factories of the Future

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***Abstract*—5G is a flexible key technology for Industry 4.0. Combined with edge-computing, Industrial Internet-of-Things (IIoT) systems, and other secondary wireless technologies such as Wi-Fi and MuLTEfire, it will transform the Factories of the Future into more advanced, safer, and more flexible smart production environments. In this paper, we present our research visions, and our reference implementation of a 5G-enabled factory where industrial applications and solutions can be developed and tested in operational conditions. The paper introduces the main technological developments, including a selection of observations and performance evaluations useful for engineers in both the communications and manufacturing domains. Future research visions such as the integration of a digital twin environment are also briefly discussed.**

***Index Terms*—Industry 4.0, IIoT, 5G, Edge-Cloud, Smart Production.**

I. Introduction

One of the main objectives of the fourth industrial revolution (Industry 4.0 – I4.0) is to achieve seamless integration and automation of the different manufacturing processes. Integrating multiple Cyber-Physical Systems (CPS), Industrial Internet of Things (IIoT) devices and cloud computing is crucial for an optimized production process [1]. Additionally, the use of wireless technologies in an industrial scenario would allow the removal of cables in the factories, providing flexibility for reconfiguration, and enabling mobility for the different actors involved in a manufacturing process [2].

Among the reference wireless technologies, 5G will be the key enabler for the Factories of the Future [3]. 5G has been designed as a flexible technology able to support very different use cases in the vertical industrial sector. These industrial use cases typically present very different communication requirements, ranging from those requiring enhanced Mobile Broadband (eMBB) capabilities, massive Machine-Type Communications (mMTC), or Ultra-Reliable Low-Latency (URLLC). However, other cellular technologies such as 4G (operating in the licensed spectrum, as well as 5G), or wireless technologies such as Wi-Fi or MuLTEfire (operating in the unlicensed spectrum) should not be neglected [4]. In the end, the Factories of the Future are envisioned to be served by a combination of wireless technologies [5], which will guarantee maximum capacity, full flexibility, and reliability. In such a heterogeneous scenario, edge-cloud architectures and centralized computing schemes will facilitate both the network and industrial production process coordination and control [6].

There are other aspects that are relevant to the Factories of the Future. In industrial scenarios, where humans and mobile robotic elements co-exist, wireless indoor positioning technologies such as 5G [7] or Ultra-Wide Band (UWB) [8] will play a role in assisting the different industrial control decisions to guarantee an adequate level of human safety. Having a centralized element that combines available control, network, and positioning information will allow for the development of new digital tools providing superior optimization schemes for the industrial manufacturing process.

This paper presents an overview of our reference implementation of a 5G-enabled Factory of the Future from both conceptual and practical perspectives. We introduce an evolution roadmap and present our experimentation facilities, a small industrial research factory lab, specifically designed for validating the potential of the selected solutions in real-world operational conditions. Moreover, we include a summary of all technological implementations, including key performance results, and discuss our future research visions.

The rest of the paper is organized as follows: Section II describes the evolution roadmap from the Factories of Today to the Factories of the Future. Section III describes the industrial research lab facilities. The next three sections highlight the main current technological implementations. Section IV presents and compares wireless communication performance results, considering technologies both in the licensed and unlicensed spectrum. Section V introduces the multi-cloud environment designed for the integration of network and industrial manufacturing services. Section VI describes and compares the performance of the indoor positioning systems available in the lab. The future evolution plans and research visions are discussed in Section VII. Finally, Section VIII concludes the paper.

II. Evolution towards the 5G-Enabled Factories of the Future

Fig. 1 shows a simplified roadmap of our vision of the evolution from Factories of Today, where manufacturing systems are based on a linear and centralized production, to Factories of the Future, with a completely decentralized and non-linear production process [9]. We considered a sequential approach:

1) Removal of wires in the traditional production systems and migration of the manufacturing control to a centralized cloud server. This enables mainly flexibility and higher

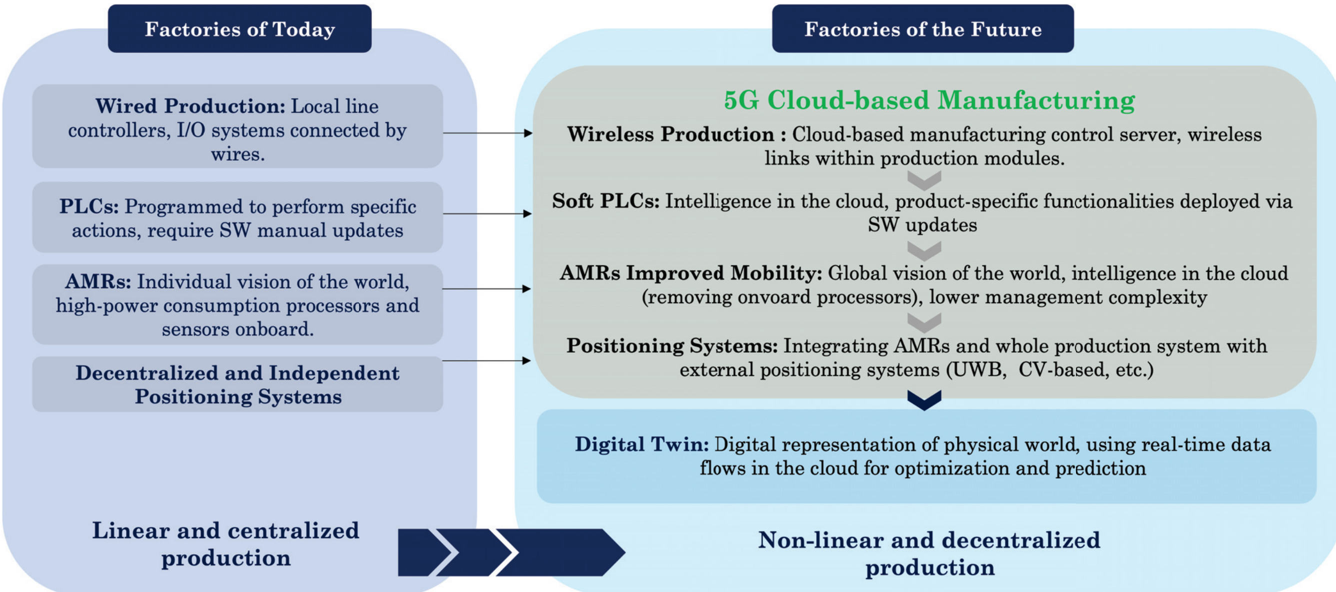

Fig. 1. Simplified roadmap from Factories of Today to Factories of the Future.

reconfigurability of the production systems in the Factories of the Future.

2) Cloudification of the Programmable Logic Controllers (PLC) product-specific hardware (HW) in both stationary (e.g., production line modules) and mobile elements (e.g., Autonomous Mobile Robots (AMRs)). This would facilitate information sharing and coordination between the different manufacturing elements.
3) Operational improvements for the mobile elements driven by centralization of intelligence. This would replace the individual vision of the world of each independent AMRs with a combined and synchronized global vision in the Factories of the Future.
4) Positioning-based optimization of the production process. Providing and combining positioning context to existing control systems assists in the coordination of stationary and mobile elements, boosting human safety while increasing production efficiency.
5) The highest level of integration and optimization can be achieved by combining all the available centralized information in the same processing element. Digital Twins (DTs) are digital representations of the physical manufacturing systems that allow for monitoring, run-time optimization, and data-driven performance modeling and prediction.

To reach the previously described levels of technological evolution, 5G and edge-cloud computing are considered the two key integration technologies. Compared to other wireless technologies, 5G will provide increased capacity, throughput, and reduced latency values, necessary for data transmission between the different production elements and the cloud. This facilitates at the same time the removal of wires, the migration of intelligence to the cloud, and the collection of further operational information (management, control, and positioning). Edge-cloud architectures and computing facilitate the optimization and control of the machinery, allowing for adaptive processing schemes depending on the use case requirements. The following sections provide further details on selected key aspects of the aforementioned technological evolution, including implementation and performance observations.

Fig. 2. Picture of part of the industrial equipment available in the AAU 5G Smart Production Lab.

III. AAU 5G Smart Production Lab

In order to implement a reference 5G-enabled Factory of the Future according to the roadmap described in the previous section, we established an industrial research lab facility at Aalborg University (AAU), where small-scale industrial use cases could be tested in realistic operational conditions. The AAU 5G Smart Production Lab [10] is a two-hall industrial

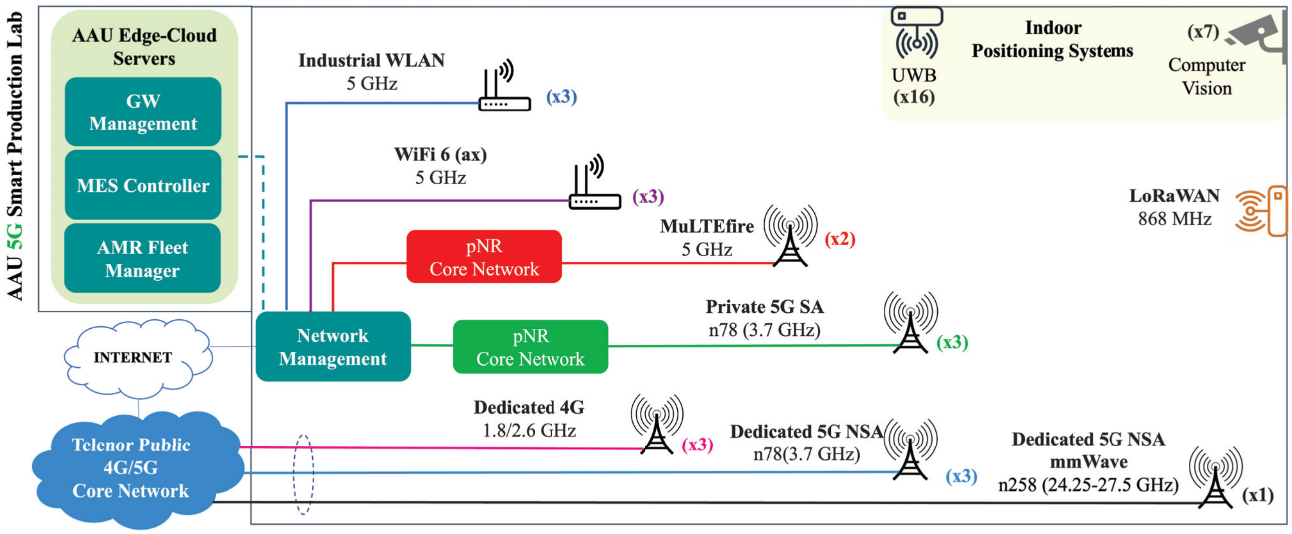

Fig. 3. High-level overview of the network infrastructure at the AAU 5G Smart Production Lab.

environment of more than 1200 m^2, combining workshops, production areas and storage areas. A picture of the industrial lab is displayed in Fig. 2. The lab is equipped with a wide range of devices and equipment that could be found in any operational factory. This includes a production line, multiple AMRs, robotic arms, an autonomous forklift, welding machines, etc. Furthermore, a series of advanced wireless technologies are available in the research lab, allowing us to test and evaluate their integration in an industrial framework. A total of three *communication islands* cover the two halls of the AAU 5G Smart Production Lab. Generally, it is possible to find an Access Point (AP) or radio head unit for every communication technology at each communication island. Specifically, the following wireless technologies are available:

- Technologies in the licensed spectrum:
  - **Private 5G Standalone (SA):** private 5G mini-core with a 3 pico cell Base Station (BS), operating at 3.7 GHz FR1 with 100 MHz bandwidth, Time Division Duplexing (TDD).
  - **Dedicated 5G Non-Standalone (NSA):** public evolved packet core with dedicated dark fiber to the BS infrastructure inside the lab, operating in FR1 at 3.7 GHz with 100 MHz bandwidth, TDD; and in the FR2 *mmWave* band at 26 GHz with up to 400 MHz bandwidth, TDD.
  - **Dedicated 4G:** public evolved packet core with dedicated dark fiber to the infrastructure inside the lab, 3 pico cells, operating at 1.8, 2.1, and 2.6 GHz with 20 MHz bandwidth, TDD.
- Technologies in the unlicensed spectrum:
  - **Wi-Fi 6:** IEEE 802.11ax coorinated deployment with 3 cells, operating in the 5 GHz ISM band and managed through vendor's cloud.
  - **MuLTEfire:** private core with 2 radio cells, operating in the 5 GHz ISM band with 20 MHz bandwidth.
  - **Industrial WLAN:** Industrial Wireless Local Area Network (IWLAN) deployment with 3 cells, operating in the 5 GHz ISM band.
- Technologies for IoT and massive deployment of sensors:
  - **LoRaWAN:** Low-power Wide Area Network with 1 gateway, operating in the 868 MHz ISM band.

All these technologies, with 5G as the main one, conform a very advanced communication ecosystem, the baseline for wireless automation research activities. The diagram in Fig. 3, illustrates this network ecosystem deployed at the AAU 5G Smart Production Lab, including also its integration to the Edge-cloud. All networks are inter-connected and have access to both Internet and the edge-cloud servers with as minimum latency as possible. Additionally, the 5G Smart Production Lab counts on two different indoor positioning systems: an RF-based UWB and a Computer Vision (CV)-based system. The specific role of these two technologies will be further addressed in Section VI.

IV. Reliable Wireless Communication

Reliable wireless communication is essential for mobile and flexible production in Industry 4.0. Getting rid of cabled connections while maintaining high communication performance would provide the mobility and flexibility required for the next generation of manufacturing facilities. In order to understand better the capabilities of the different wireless technologies in operational conditions, a comparison study was carried out, benchmarking the performance of the main technologies operating in licensed and unlicensed spectrum:

- Private 5G SA FR1: as the key reference cellular technology in the licensed spectrum, it is expected to deliver superior reliable performance as compared to the other technologies, providing ultra-reliable low latency communication for safety-critical applications, industrial control loops, and autonomous robots.

- IEEE 802.11ax: also known as Wi-Fi 6, the most widespread technology operating in the unlicensed spectrum currently used in factories due to its cost-effectiveness and reduced latency compared to previous generations of Wi-Fi.
- MuLTEfire: as one of the new and promising alternatives to current technologies operating in the unlicensed spectrum. Its synchronized and coordinated nodes, enable robust radio links and optimal support for mobility, making it an attractive technology for operating Industry 4.0 applications.

The combination of these technologies is already becoming part of the digitalization strategies of industrial manufacturers [11].

A. Performance Comparison of Technologies Operating in Licensed vs. Unlicensed Spectrum

The performance evaluation considered latency and throughput measurements. The latency tests are performed using the Linux ping tool, sending 64 B packets from a connected User Equipment (UE) to a server located in the edge cloud. For the throughput performance evaluation, we used the *iperf3* tool [12], configuring a different target bandwidth for each technology depending on its capabilities (i.e., 1 Gbps for 5G SA, 200 Mbps for Wi-Fi 6, and 50 Mbps for MuLTEfire). The UE used for testing was mounted on an AMR, emulating an industrial 5G-connected robot. Tests under static and mobility conditions were performed for all technologies. For static measurements, the AMR was left stationary at a given position. For the mobile case, the AMR was configured to self-navigate the factory floor at a constant speed (1 m/s), covering several times the same measurement route from one end of the lab to the other one, roaming across the multiple cells of the different technologies.

During the testing, the configuration of the different technologies was as detailed in Table I. It should be noted that, for unlicensed spectrum technologies, the spectrum is fully managed by us. There are no other networks operating in the upper part of the 5 GHz band and we can configure the allocations as we would like for the testing. Further, independent APs are configured to different non-overlapping frequencies to avoid inter-cell interference, ensuring an as-good-as-possible performance from these technologies.

TABLE I
WIRELESS NETWORK SETTINGS FOR PERFORMANCE TESTING

Technology	No. cells	Bandwidth	Allocations
5G SA	3	100	FR1, 3.7 GHz, TDD 3/7
Wi-Fi 6	3	20	5660, 5680, and 5700 MHz
MuLTEfire	2	20	5520, and 5560 MHz

Figs. 4 and 5 illustrate the throughput test results for Downlink (DL) and Uplink (UL), respectively. The statistical results are displayed in terms of Cumulative Distribution Functions (CDFs) for the three different technologies, and the

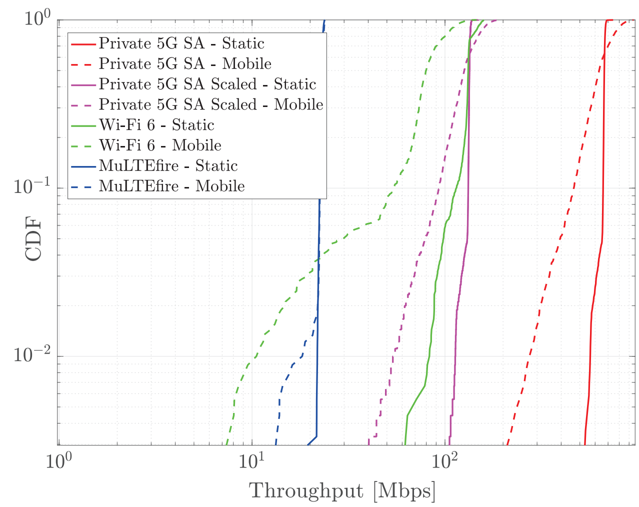

Fig. 4. Downlink throughput test results for 5G SA, Wi-Fi 6, and MuLTEfire.

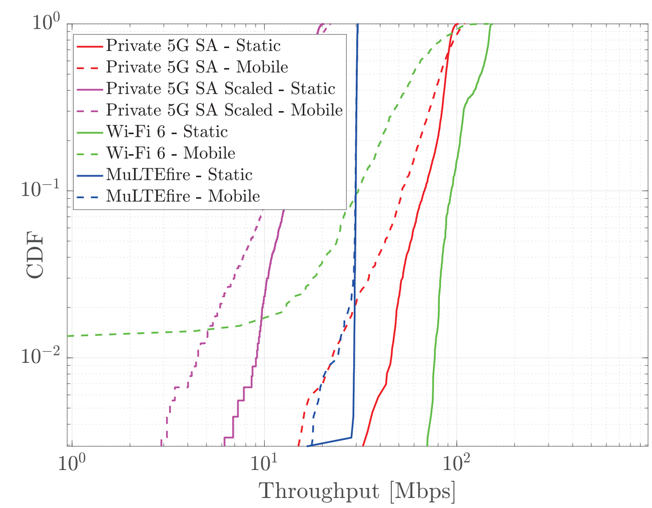

Fig. 5. Uplink throughput test results for 5G SA, Wi-Fi 6, and MuLTEfire.

two operational conditions. In order to make the results for 5G SA (100 MHz bandwidth) comparable to those from Wi-Fi 6 and MuLTEfire (20 MHz bandwidth), both the raw 5G SA results with 100 MHz and scaled 5G SA results with 20 MHz are displayed.

For the DL, it is observed how 5G SA outperforms the technologies in the unlicensed spectrum for both static and mobile conditions. While in the static case, the performances of 5G SA scaled and Wi-Fi 6 are very similar, reaching median DL throughput values of approximately 130 Mbps, the MulLTEfire one is limited to 23 Mbps. The DL throughput performance for 5G SA scaled is slightly degraded in the mobility case in comparison to the static tests, with median value similar to the static case (125 Mbps), but with a reduction from 100 to 50 Mbps in the lower tail of the distribution. The performances of Wi-Fi 6 and MuLTEfire are also degraded in the mobility case, Wi-Fi 6 being the most affected by mobility and roaming procedures, reducing

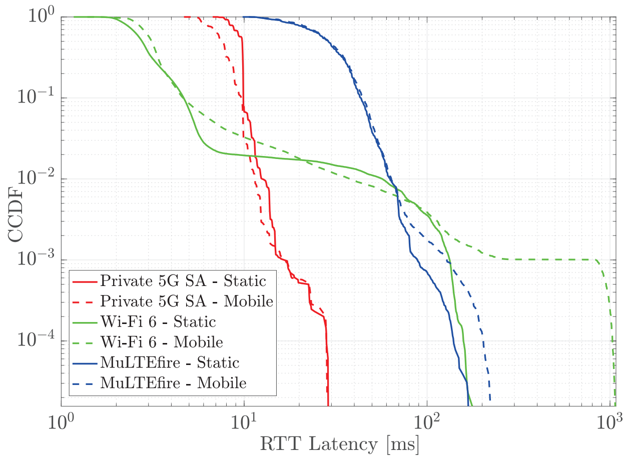

Fig. 6. Latency test results for Wi-Fi 6, MuLTEfire, and 5G SA

its performance from 80 to 8 Mbps in the lower tails. Even though MuLTEfire presents the lowest number (23 Mbps) in terms of median DL throughput, its performance is not so degraded at the tail (13 Mbps), which illustrates the higher robustness of this technology for mobility support as opposed to Wi-Fi 6.

In the UL case, the 5G SA scaled UL throughput is lower than the DL one. This is due to the 3/7 UL/DL ratio configured. 5G SA scaled presents a median UL throughput of approximately 20 Mbps for both the static and mobile cases. In the lower tail, its performance is degraded to 8 and 3 Mbps in the static case and mobile scenarios, respectively. In this case, WI-Fi presents the best UL throughput performance in static conditions with a stable delivery of 80-110 Mbps. However, a large degradation is observed in the mobile case, with median UL throughput values of 55 Mbps and 0 Mbps at the lower tail. This indicates that the UL transmission was in outage (service discontinuity) due to mobility and roaming between APs while the robot was navigating the factory. MuLTEfire, on the other hand, exhibits a very stable performance, delivering UL throughputs of 30 Mbps in both static and mobile conditions.

Latency performance results are presented in Fig. 6 in terms of Complementary Cumulative Distribution Functions (CCDFs) for the different technologies and deployment cases. The results illustrate that Wi-Fi 6 provides the best performance for approximately 96% of the samples in the static case and 98% of the samples under mobility conditions. However, this technology exhibits the largest tails, especially when evaluating mobility, with latency values of up to 1000 ms due to handover from one AP to another one. MuLTEfire shows a more robust performance, very similar for both the static and mobile cases, with a median value of 50 ms and bounded tail latencies of approximately 200 ms. This illustrates the better mobility management in MuLTEfire as compared to Wi-Fi 6. The 5G SA latency performance is the more deterministic of all technologies. Despite providing higher latency than Wi-Fi 6 at the median value, a stable performance of 7-30 ms was observed throughout all the tests in both static and mobile conditions. These results highlight why 5G SA technology is a key enabler for the Factories of the Future: it is proven to be capable of providing bounded low latency with high reliability and, thus, supporting industrial latency-critical use cases.

It should be noted that the performance reported for Wi-Fi 6 and MuLTEfire considers optimal deployment configurations and, thus, it is representative of the best achievable performance. In the case of 5G SA, the reported performance is only an initial baseline reference, as 5G SA will continue its evolution by means of new Releases, which will improve further the performance, especially in terms of latency.

V. Multi- and Edge-Cloud Computing

To fully exploit the performance of the technologies presented in the previous Section, and guarantee a minimum latency to operate delay-critical industrial applications, edge-cloud design is paramount. Due to the high level of efficiency, flexibility, and interoperability demanded by the Factories of the Future, it is essential to centralize real-time information regarding the different actors involved in the manufacturing processes. This can be achieved through the use of cloud computing, which would not only allow data centralization but would also increase production efficiency. As global remote cloud environments, accessed via the Internet, would suffer from high network latencies [13], edge-cloud computing, where the servers are deployed at the network's edge, should be considered for industrial use cases, allowing for near-real-time operation of the connected industrial manufacturing equipment [14]. Additionally, redundant multi-cloud environments offering alternative clouds with different resources and network statuses might be an interesting capability to guarantee that delay-sensitive industrial applications can be

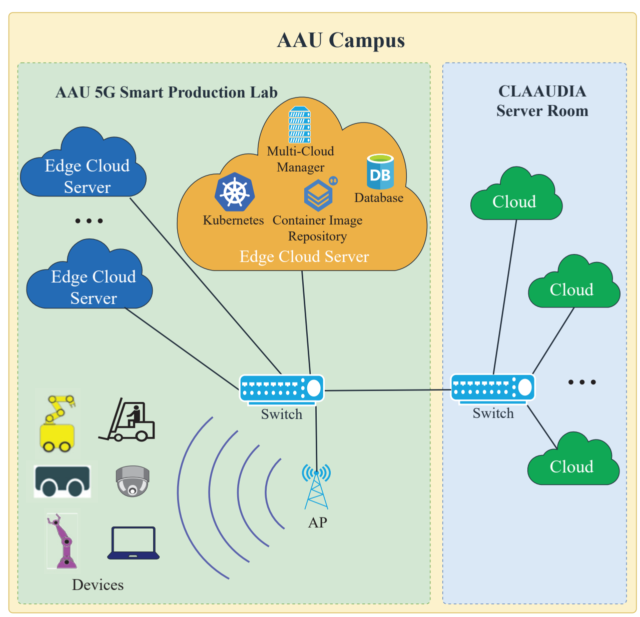

Fig. 7. Target architecture of the multi- and edge-cloud environment.

TABLE II
SPECIFICATIONS OF THE 12 SERVERS USED FOR THE MULTI- AND EDGE-CLOUD ARCHITECTURE IN THE AAU 5G SMART PRODUCTION LAB

Server ID	CPU Logic Cores	RAM	Storage
01	128	440 GiB	894 GiB
02		503 GiB	
03	56	125 GiB	932 GiB
04			
05			
06			
07			
08			908 GiB
09			814 GiB
10			1.4 TiB
11	40	62 GiB	872 GiB
12			894 GiB

TABLE III
FLEET MANAGER RESOURCE UTILIZATION IN THE EDGE-CLOUD

Storage Usage	2.5 GiB
Memory Usage	1001 GiB
CPU Usage	0.000075 Logic Cores
Avg. Downstream BW	0.014 Mbps
Avg. Upstream BW	0.002 Mbps

deployed on the servers that are providing the best network performance [15].

To attain the most optimal performance, we target to build the multi- and edge cloud environment described by the architecture shown in Fig. 7. The setup in AAU 5G Smart Production Lab, consists of 12 servers with the specifications summarized in Table II. The network is designed to support up to 10 Gbps speeds on all interfaces. We installed Proxmox in each of the servers, which is an open-source virtualization hypervisor that allows generating clouds and virtual server clusters [16]. Additionally, we also count on several OpenStack-based remote clouds [17] provided by AAU Research Data Services [18]. These clouds are used to build the multi- and edge-cloud environment, which provides cloud services that can be accessed by industrial devices through different wireless communication technologies.

We use Kubernetes to manage the installed applications and, since it only supports containerized applications, we deploy a container image repository in this environment to store users' images [19]. In order to manage the edge-cloud, the remote clouds, and Kubernetes, we designed and developed a Multi-Cloud Manager, which is the core of this architecture. The Multi-Cloud Manager can use an Application Programming Interface (API) to monitor the resources and network statuses of all clouds and edge-cloud and maintain this information in a database. When the Multi-Cloud Manager receives a user request to deploy an application, it will run a scheduling algorithm designed by us to choose a suitable cloud to deploy this application. This choice will be made according to the requirements of the application and the resources and network statuses of every cloud in the environment. This scheduling algorithm will maximize the performance and optimize the whole manufacturing process.

This architecture is currently under development, so we are in the process of monitoring the performance of the already-available containerized industrial applications to verify their correct operation and use of computing resources. Examples of these edge cloud-deployed applications, illustrated in Fig. 3, are the Manufacturing Execution System (MES) controller (for production line control), the wireless multi-access gateway manager (for UE management and control) [20], or the AMRs' fleet manager. The latter, which handles the missions and routes programmed to each of the lab AMRs, utilizes the computing and network resources summarized in Table III. The amount of resources is low and reasonable for this application. In view of this level of performance and the number of resources available in our multi-cloud environment, we anticipate a huge potential for operation once the Multi-Cloud Manager and the scheduling algorithm are fully functional. The multi- and edge-cloud environment is expected to bring an optimized orchestration of the different elements of the industrial scenario, adapting the service to the specific application requirements.

VI. INDOOR POSITIONING SYSTEMS FOR HUMAN SAFETY

As detailed in the previous Section, one of the target uses of the developed multi- and edge-cloud computing environment is to centralize status information from the different actors in the factory: networks, production line modules, AMRs, forklifts, humans, etc. Apart from enhancing manufacturing and production efficiency, the setup can be further leveraged for other relevant purposes such as, for example, ensuring human safety, by collecting and centralizing in the edge-cloud run-time location information from both industrial equipment and factory employees. If the location of all humans on the factory shop floor is known, this information could be used to inform the mobile elements, e.g., AMRs, so that they could adapt their performance accordingly. For example, they could reduce their velocity when they are approaching a human, and speed up if there are no humans obstructing their route. Currently, AMRs are able to detect close human presence based on their inbuilt Light Detection and Ranging (LiDAR) system and other proximity sensors and cameras. However, knowing in advance about the potential presence of workers would allow for early re-routing and optimized path planning, resulting in a production gain from the overall manufacturing process point of view.

In order to obtain information about human presence in the production areas, external monitoring systems are needed. In our case, two technologies are considered for the indoor positioning of humans (also illustrated in Fig. 3):

- **Ultra-Wide Band (UWB):** this RF-based technology uses the Time Difference of Arrival (TDoA) of the signals transmitted from the different *anchors* deployed around the scenario towards the *tags* mounted on the target element subject to be localized. The UWB deployment at the AAU 5G Smart Production Lab is based on commercial DecaWave DW1000 equipment [24]. A total of 16 UWB anchors are

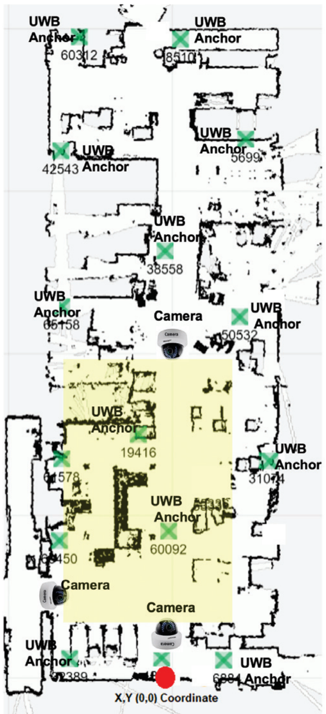

Fig. 8. Floorplan of one of the halls of the AAU 5G Smart Production Lab indicating critical production area (in yellow) and deployment of indoor positioning systems.

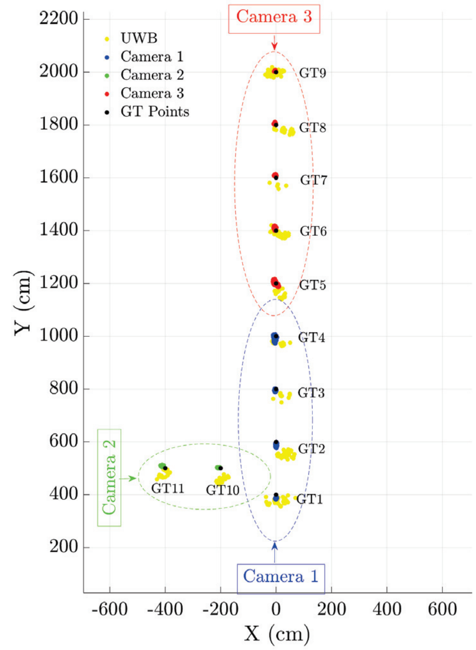

Fig. 9. Scatter plot including the Ground Truth points and the samples obtained through the two indoor positioning systems.

located at next-to-the-ceiling locations depicted in Fig. 8 with green crosses.

- **Computer Vision (CV)-based:** this image/video-based technology allows detecting humans by runtime processing of snapshots obtained from cameras located at key areas of the production area. Once humans are detected, associated spatial coordinates are estimated [25]. In our industrial research lab, the CV system is based on three thermal/RGB cameras strategically placed to survey the critical production area in the lab, as illustrated in Fig. 8.

The main idea behind having two systems for the same purpose is to have a certain level of redundancy in the case that, for example, a worker forgets to wear its UWB *tag*, or one UWB *tag* runs out of battery. Then the CV system is still there to capture the location of the worker. Having the UWB system and multiple cameras provides at the moment several position readings for the same human entering the production area. We are applying sensor fusion to get the most accurate human position possible by combining all available data from the different systems, ensuring also that there are no false positive readings or multiple readings from the same person.

The initial step prior to applying sensor fusion is to understand the individual performance of both systems in operational conditions. Thus, a performance evaluation test was proposed. In order to do that, twelve Ground Truth (GT) points were established across the critical production area, and measured using a total station theodolite that provides absolute position with mm accuracy. Then, we collected a series of static measurements at each of the twelve GT locations with each of the two positioning systems and evaluated their accuracy by calculating the Euclidean distance between the GT points and the measurement samples. The UWB positioning system provides an output single value for the target *tag* at a 50 Hz rate. However, for the CV case, three different readings are available for the target (one from each camera). A calibrated algorithm was developed to establish confidence areas for each of the three cameras and reduce the output to a single camera. These confidence areas are illustrated in Fig. 9 together with the GT points, and the measurement samples collected by each positioning technology. The median accuracy and maximum error observed in the measurements for each of the systems are summarized in Table IV. According to the results, when operated independently, the UWB system presents lower accuracy and higher maximum error than the CV-based system. While the information from the individual systems available at the edge cloud is a good starting point for human-AMR coordination, having higher accuracy sensor fused data from both technologies will allow for further improved human safety in the Factories of the Future.

TABLE IV
SUMMARY OF ACCURACY RESULTS OF UWB AND CV-BASED POSITIONING SYSTEMS

Performance Parameters	UWB System	CV-based System
Median Accuracy [cm]	35.2	12.9
Max. Error [cm]	87.9	27.6

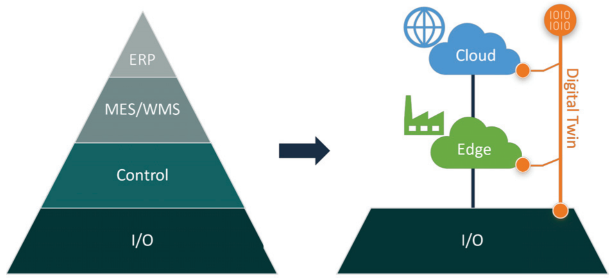

Fig. 10. Illustration of the envisioned industrial automation system evolution towards cloud-based physical and digital environments.

VII. Future Visions

The above Sections presented our initial efforts in fulfilling the roadmap explained in Section II. Now, the evolution continues, and further testing will be done for the installed wireless technologies considering, for example, new equipment, new releases, new features, new protocols; or new test conditions such as scalability under heavy load conditions. Further understanding of the performance of the available technologies will allow for developing guidelines for the Factories of the Future operators.

Our efforts will continue in the direction of achieving a fully cloudified production environment, where the full integration with external technologies and the collection of operational data from sensors, machinery, and robots, will enable the development of Machine Learning/Artificial Intelligence algorithms for further optimization of the manufacturing procedures while enhancing human safety. With the current edge- and multi-cloud computing environment as a base, our end goal vision, considers also the development of a digital twin, as illustrated in Fig.10. This digital twin will collect data from the physical world, to analyze it and leverage predictive maintenance schemes or perform runtime optimizations; but also to model it and perform future production performance.

VIII. Conclusions

The Factories of the Future will be equipped with a mixture of 5G and other wireless technologies operating in unlicensed spectrum, in order to enable flexibility, reconfigurability, and reliable support for mobile robotic elements. These communication technologies will guarantee multi-Gbps capacity and close or below ms level latency values, which combined with edge- and multi-cloud computing environments will leverage the industrial ecosystem, allowing for virtualization and containerization of control applications, and collection of operational data for production optimization purposes. This will also allow for the integration of complementary intelligent external systems, such as positioning systems, or digital twins, setting a reference for fully digitalized and automated production environments.

Acknowledgments

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References

[1] Sanchez, M., et al., 2020. Industry 4.0: survey from a system integration perspective. International Journal of Computer Integrated Manufacturing, 33(10-11), pp.1017-1041.
[2] Varga, P., et al., 2020. 5G support for industrial IoT applications—challenges, solutions, and research gaps. Sensors, 20(3), p.828.
[3] Mogensen, Preben, and Ignacio Rodriguez. ”5G for smart production.” In The Future of Smart Production for SMEs: A Methodological and Practical Approach Towards Digitalization in SMEs, pp. 327-333. Cham: Springer International Publishing, 2022.
[4] Cuevas, R. M. (2020). Ph.D. Thesis. Radio Resource Management Techniques for Ultra-Reliable Low-Latency Communications in Unlicensed Spectrum.
[5] Kourtis, M.A., et al., 2022., 5G NPN Performance Evaluation for I4. 0 Environments. Applied Sciences, 12(15), p.7891.
[6] Xiong, G., et al., 2015. Cloud operating system for industrial application. In 2015 IEEE International Conference on Service Operations And Logistics, And Informatics (SOLI) (pp. 43-48). IEEE.
[7] Mogyorósi, F., et al., 2022. Positioning in 5G and 6G networks—A Survey. Sensors, 22(13), p.4757.
[8] Schjørring, A., et al., 2022. Performance Evaluation of a UWB Positioning System Applied to Static and Mobile Use Cases in Industrial Scenarios. Electronics, 11(20), p.3294.
[9] Rodriguez, I., et al., 2021. 5G swarm production: Advanced industrial manufacturing concepts enabled by wireless automation. IEEE Communications Magazine, 59(1), pp.48-54.
[10] Virtual Tour of AAU 5G Smart Production Lab. Available online: https://www.5gsmartproduction.aau.dk/virtual-tour/.
[11] Peter Raggam, 2021. ”Wi-Fi 6 accelerates adoption of Industry 4.0”. NXP.
[12] “iPerf - The TCP, UDP and SCTP network bandwidth measurement tool.” [Online]. Available: https://iperf.fr/.
[13] Chang, H., et al., 2014. Bringing the cloud to the edge. In 2014 IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS) (pp. 346-351). IEEE.
[14] Xu, M., et al., 2021. From cloud to edge: a first look at public edge platforms. In Proceedings of the 21st ACM Internet Measurement Conference (pp. 37-53).
[15] Hong, J., et al., 2019. An overview of multi-cloud computing. In Web, Artificial Intelligence and Network Applications: 33rd International Conference on Advanced Information Networking and Applications (WAINA-2019) 33 (pp. 1055-1068). Springer International Publishing.
[16] Proxmox. Open-source virtualization platform. [Available Online:] https://proxmox.com/en/.
[17] Sefraoui, O., et al., 2012. OpenStack: toward an open-source solution for cloud computing. International Journal of Computer Applications, 55(3), 38-42.
[18] CLAAUDIA Research Data Services at Aalborg University. [Available Online:] https://www.claaudia.aau.dk/.
[19] Kubernetes K8s. An open-source system for automating deployment, scaling, and management of containerized applications.[Available Online:] https://kubernetes.io/.
[20] Rodriguez, I., et al., 2021. An experimental framework for 5G wireless system integration into industry 4.0 applications. Energies, 14(15), p.4444
[21] 5G-SMART. Design of 5G-Based Testbed for Industrial Robotics. Deliverable D2.1. Available online: https://5gsmart.eu/wp-content/uploads/5G-SMART-D2.1.pdf (accessed on 19 October 2021).
[22] Mahmood, A., et al., 2021. Industrial IoT in 5G-and-beyond networks: Vision, architecture, and design trends. IEEE Transactions on Industrial Informatics, 18(6), pp.4122-4137.
[23] Ansari, J., et al., 2022. Performance of 5G trials for industrial automation. Electronics, 11(3), p.412.
[24] Pozyx. [Available online:] https://pozyx.io/products-and-services/enterprise/
[25] Ambolt AI. ”Mobile robots must learn to drive nicely among people”. [Available Online:] https://ambolt.io/en/mobile-robots-must-learn-to-drive-nicely-among-people/.