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The authors present an overview of current Industry 4.0 applied research topics, addressed from both the industrial production and wireless communication points of view. A roadmap toward achieving the more advanced industrial manufacturing visions and concepts is defined, highlighting relevant industrial use cases, their associated communication requirements, as well as the integrated technological wireless solutions applicable to each of them.

Abstract

This article presents an overview of current Industry 4.0 applied research topics, addressed from both the industrial production and wireless communication points of view. A roadmap toward achieving the more advanced industrial manufacturing visions and concepts, such as "swarm production" (nonlinear and fully decentralized production) is defined, highlighting relevant industrial use cases, their associated communication requirements, as well as the integrated technological wireless solutions applicable to each of them. Further, the article introduces the Aalborg University 5G Smart Production Lab, an industrial lab test environment specifically designed to prototype and demonstrate different Industrial IoT use cases enabled by the integration of robotics, edge-cloud platforms, and autonomous systems operated over wireless technologies such as 4G, 5G, and Wi-Fi. Wireless performance results from various operational trials are also presented for two use cases: wireless control of industrial production and wireless control of autonomous mobile robots.

Introduction

The ongoing fourth industrial revolution (Industry 4.0) relies on the integration of cyber-physical systems, the Industrial Internet of Things (IIoT), and cloud computing technologies as a major driver for achieving highly flexible and reliable manufacturing in the factories of the future [1]. On top of this integration, optimized wireless technologies will play a pivotal role. Wireless technologies will allow the replacement of cables (favoring faster reconfiguration of production facilities and overall reduction of the cost of deployment), and also enable new industrial use cases requiring full mobility support [2].

However, under these premises, research addressing Industry 4.0 domains has typically been done in an isolated manner by vertical and horizontal sectors, without jointly accounting for all the components required to succeed in the long-term visions. For example, the industrial production and manufacturing sector has tended to focus on developing concepts and visions while somewhat overlooking the communication aspects [3], by taking reliable control data flows for granted in their advanced manufacturing system visions, even when considering cloud-based soft programmable logic controllers (PLCs) or autonomous mobile robots (AMRs) operating over wireless [4]. On the other hand, due to the lack of strong direct interaction with the vertical sectors, it took some time for the wireless communication sector to gather relevant data, such as typical traffic patterns, data rates, and tolerable latency thresholds applicable to different industrial use cases [5], which are key elements in the design of systems targeting ultra-reliable and low-latency communications (URLLC) for Industry 4.0, such as 5G. Fortunately, the situation has changed in the last few years, and the new releases of 5G targeting time-sensitive networks have had more direct impact from verticals than ever.

This proves that it is of paramount importance nowadays to have a double helix approach between the manufacturing and communication sectors, working together on the practical integration of wireless solutions into the different manufacturing use cases. Integrated wireless solutions can be optimized by having a better understanding of current and envisioned scenario-specific use cases and associated communication requirements. This will ensure that an accurate mapping between specific actions in the manufacturing process and wireless technologies capable of supporting such application requirements is done. As legacy industrial systems will continue being important, and not all industrial use cases will require URLLC, deploying 5G might be overkill in certain cases, which leaves some room in the industrial wireless ecosystem for other technologies such as 4G and Wi-Fi. In the other direction, advanced manufacturing concepts and their associated architectures or control protocols could be optimized or evolved by carefully considering the available wireless communication and cloud computing capabilities of the envisioned integrated systems. Although 5G will be able to support down to 500 μs latency with high reliability, there will still be certain industrial use cases requiring

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Step	Focus area	Actions
(1)	Wireless production	Remove cables between manufacturing line modules. Cloud-based production control. • Manufacturing target: Flexibility, reconfiguration. • Communication needs: robust low-throughput delay-tolerant wireless communication links to static units.
(2)	PLC	Remove hardware, use cloud-based soft PLCs instead. • Manufacturing target: Faster and cheaper adaptation of new functionalities. • Communication needs: reliable high-throughput low-latency wireless communication links to static units.
(3)	AMR	Move functionality (localization and navigation) to the cloud. Investigate new localization techniques. • Manufacturing target: more efficient fleet management/cheaper robots and shared world model (cloud robotics). • Communication needs: ultra-reliable high-throughput low-latency wireless communication links to mobile units.
(4)	Swarm production	Remove conveyor belts, make product carriers into small mobile robots. • Manufacturing target: More flexible and robust automation. • Communication needs: ultra-reliable high-throughput low-latency wireless communication links to both static and mobile units.

TABLE 1. Simplified manufacturing and production roadmap toward swarm production.

In order to successfully achieve such a level of adaptable intelligent production, the integration of different technological components such as cloud-computing, 5G or B5G communications (able to provide URLLC to the different components in the system), robotics, autonomous systems and highly-accurate localization systems are essential.

much lower latencies, making some space for beyond 5G (B5G) or 6G technologies in future wireless manufacturing. Similarly, other wireless systems such as indoor positioning systems based on ultra-wideband (UWB) technologies might also be relevant in those use cases requiring precise location information in case it cannot be obtained from any other wireless source.

In this article, we present advanced Industry 4.0 visions, where the ultimate goal is to achieve and demonstrate so-called ”swarm production” where, different from current traditional manufacturing systems (based on a linear and centralized production concept), in which products are manufactured sequentially over production modules where their respective PLCs and input/output (I/O) systems are connected by wires or buses to a centralized controller, wireless is integrated into the manufacturing system, allowing production modules to be distributed across the factory hall with their PLCs and I/O systems operated in remote edge-cloud configuration, and AMRs are used to move items between them (nonlinear and decentralized production). Swarm production will allow for the maximum level of flexibility and reconfiguration of the production process, and will require robust automation and ultra-reliable cloud-based control. Thus, 5G is considered as the baseline technology for this use case. As part of the presented visions, outlined through a double helix approach between the Department of Materials and Production and the Wireless Communication Networks Section at Aalborg University, a roadmap with multiple steps is defined, addressing different sub-components of the swarm production concept, characterized by relevant related use cases that, as explained later, can be realized over different wireless technologies. To demonstrate the different steps, different prototypes are designed, built, and tested in a unique Industry 4.0 wireless testing ecosystem.

Manufacturing Industry Goals and Wireless Automation Evolution

The manufacturing industry envisions factories as highly flexible facilities, where it will be possible to cope with the increasing demand for highly customized products, while reducing or at least maintaining resource and cost efficiency [4]. Flexibility can be achieved by leveraging the swarm production concept, that is, decentralized and nonlinear production processes where products are transported by AMRs between manufacturing stations distributed across the factory hall. In order to successfully achieve such a level of adaptable intelligent production, the integration of different technological components such as cloud computing, 5G or B5G communications (able to provide URLLC to the different components in the system), robotics, autonomous systems, and highly accurate localization systems are essential.

As jumping directly from existing production schemes to swarm production might be difficult, we propose a simple reference evolution roadmap for the production process, where we define the transition path from traditional manufacturing systems to swarm production by the four steps summarized in Table 1. Such steps have been carefully selected by analyzing the specific manufacturing and high-level communication needs and the availability of technological components, and can be taken sequentially but also independently, as they have been defined around different areas of focus. In a sequential manner, the first step (1), applicable to the traditional production systems would be to replace part of the cables in the production lines with wireless communication links and set up a cloud-based manufacturing control server, replacing the current local line controllers [6]. By doing this, a first level of flexibility is achieved by enabling easier reconfiguration of the production facilities as compared to wired setups. In order to achieve this step, a robust wireless communication capable of coping with the control traffic to and from the different modules is necessary. The second step (2) targets PLCs, which are currently programmed to perform specific actions and require manual software upgrades if a change is needed. Migrating the intelligence of the PLCs to the cloud by relying on cloud-computing and the URLLC capabilities of the applied wireless technologies will add an extra degree of flexibility to the production sys-

Use case	Research production line MES	Operational factory		AMRs		Swarm production	
		MES	I/O	Baseline	Evolution	Robots	Cloud PLC
Link	UL/DL	UL/DL	UL/DL	UL	UL	UL/DL	UL/DL
Number of devices	10	50	25	20	20	20	10
Aggregated throughput	10 kb/s	100 kb/s	1 Mb/s	20 Mb/s	0.2–2 Gb/s		
Individual user throughput				1 Mb/s	10–100 Mb/s		
Average packet size	64 B	128–256 B	128 B			256 B	128 B
Average inter-packet time	200 ms	20 ms	1 ms			100 ms	5 ms
Maximum control loop latency (survival time)	2 s RTT	*N/A — but in the order of s*	2 ms RT jitter-critical	1 s RTT	10–20 ms RTT	10 ms RTT	10 ms RTT *1 ms desired*
Applicable steps towards Swarm Production	(1) (2)	(1) (2)		(3)	(2) (3)	(3) (4)	(2) (4)
Candidate wireless technologies	Wi-Fi 4G, 5G	Wi-Fi 4G, 5G	5G B5G	Wi-Fi 4G, 5G	Wi-Fi 6 4G, 5G	Wi-Fi 6 5G	Wi-Fi 6 5G, B5G

UL: uplink; DL: downlink; RTT: round-trip time

TABLE 2. Summary of industrial use cases and associated communication requirements.

tem by enabling faster deployment of new or product-specific functionalities via software to the different production modules [7]. Architectures based on cloud-PLCs will be more scalable and will allow for having lighter production modules in terms of hardware, as now the processing power is moved to the cloud [8]. The communication needs are more demanding in this second step compared to the first one, as much more information will need to be transported from each of the industrial modules to the cloud controller.

The third step of the roadmap (3) focuses on the evolution of AMR fleets, where the main objectives are related to moving some of the robot functionalities to the cloud (similar to the previous PLC case). In particular, the interest is in having cloud-based localization and navigation. By doing this, a number of expensive and power-hungry processing onboard sensors (i.e., LiDaRs) could be removed, making the robots much more cost-efficient and easier to manage [9]. In order to achieve this, different strategies can be used, such as integrating the robots and the fleet manager server with an external high accuracy positioning system (e.g., UWB), and/or relying on the connectivity of the robots over high bandwidth reliable technologies (e.g., 5G), allowing for the transfer of real-time HD videos or pictures from each of the robots to the cloud fleet manager server. All the available information in the cloud can later be combined to create a shared world model (cloud robotics) [10]. In this case, the communication needs are even a bit more demanding than in the second step, as ultra-reliability is essential due to the safety-related critical communication aspects of the control of mobile robots. Once steps (2) and (3) are completed, the integration of both would result in (4). Swarm production is founded on the intelligent cloud control of PLCs and AMRs [11], allowing the transport of products between production modules via AMRs instead of relying on product carriers running over conveyor belts. In terms of communication needs, this step groups all the needs from the previous steps (i.e., accurate positioning, high bandwidth, as well as ultra-reliable communication) to both mobile and static units to guarantee synchronized performance between all the entities that constitute the advanced industrial manufacturing scenario. Thus, 5G is seen as a key technology for achieving this futuristic production concept.

The proposed roadmap is not universal. Not all industrial production entities consider advanced manufacturing concepts such as swarm production in their digitalization strategies. From our three years of conversations with different entities of the Danish manufacturing industry, we realized that, in general, there is huge hype about cloud control and cloud monitoring, but also that they give paramount importance to legacy machinery. Not all companies will have the chance to invest in the most advanced solutions, but still, introducing a few wireless components for specific communication needs might result in a considerable gain for them. This creates a vast diversity and heterogeneity of use cases with very specific communication needs and requirements, but also opens up the potential use of other wireless technologies, apart from 5G, in the future industrial automation ecosystem [12].

In order to illustrate the heterogeneity of applicable wireless technologies, Table 2 gathers a number of industrial use cases and associated communication requirements mapped over the applicable technological candidates and roadmap steps. The table considers the following use cases: the manufacturing execution system (MES) links between the centralized manufacturing controller and PLCs of a FESTO CP Factory research production line [6], the MES and PLC-I/O links of an operational setup in a real factory, the MiR200-based AMRs control links between the fleet operation manager and the PLC in the robot, and the envisioned swarm production, orchestrated over optimized robot communication and cloud PLC architectures. All communication-related parameters in the table are based on measurements over operational industrial-grade manufacturing equipment for the research production line MES, MES, and I/O in the operational factory, and current baseline AMRs, while the rest, those related to evolution of the current systems and the targeted swarm production, are based on our own visions and educated research analysis. The presented use cases serve as references to illustrate the applicability of the roadmap steps. The current implementations of both the research production line and the production line at the operational factory can be evolved by applying the roadmap steps (1) and (2): replacing cables with wireless and moving intelligence from the lines to cloud control. In the case of the AMRs, steps (2) and (3) would be applicable as the desire in this case is improving the current wireless navigation control and moving most of the robot intelligence to the cloud. Finally, in the swarm production case, all previous use cases could be combined and optimized as part of steps (3) and (4), coordinating and synchronizing the operation of production line modules and AMRs by making use of advanced automation algorithms. Clearly, based on the different requirements, some of the use cases can be operated over wireless technologies other than 5G, for example, the PLCs' and AMRs' current control schemes, which could be operated reliably over 4G or Wi-Fi, as illustrated later. On the other hand, it should be noted that some of the evolution use cases will require B5G technologies as control closed loops in some I/O cases demand stringent deterministic sub-millisecond latencies, which are not achievable over 5G [13]. In general, we believe that Wi-Fi 6 will also play a role in some of these use cases mainly in the static ones, while in those requiring mobility, its suitability will be subject to tight coordination between access points in order to ensure reliable handover management.

The AAU 5G Smart Production Lab

With the aim of building and demonstrating the swarm production concept and the associated use cases in realistic industrial environment conditions, an advanced Industry 4.0 wireless playground was established at AAU. The AAU 5G Smart Production Lab is a 1200 m^2 factory industrial lab, with access to a wide range of operational industrial-grade manufacturing and production equipment from different vendors, including production line modules, robotic arms, AMRs, and so on. The lab is currently equipped with multiple networks from different wireless technologies, ranging from local private deployments of 4G LTE, 5G NR, and different flavors of Wi-Fi (including the last version, Wi-Fi 6) to dedicated operator-managed network slices of 4G LTE and 5G NR, and a dedicated positioning system based on UWB radio technology. A summary of all available wireless technologies is given in Table 3, along with a few technical details.

Figure 1 depicts the high-level architecture of the research testbed, exemplifying how the different industrial components, such as production modules and AMRs, can be connected and controlled over the multiple available wireless networks. Integration between the machinery and the different networks is achieved via wireless multi-access gateways (GWs), which also allow for simultaneous multi-connectivity over multiple networks [14]. Quite some effort has been made in designing the network management back-end that integrates all the deployments with the local edge-cloud, where the management of the production systems, AMR fleets, and GW devices is centralized. Such architecture allows to monitor the different networks and configure them as controlled test environments, with the possibility of recording network traces during the testing of the different use cases, enabling the opportunity of optimizing the network for the specific traffic and mobility patterns associated with that particular use case. This setup also allows benchmarking the performance of the different use cases under different 4G/5G licensed spectrum radio access network and core combinations by comparing the performance of private network solutions with dedicated edge-cloud servers to that from a dedicated network slice operating over a public core, for example. Moreover, the same use case could be tested over different Wi-Fi settings, providing a benchmark of the performance over unlicensed spectrum technologies.

Network type	Wireless technology	Details
Local private network	5G NR Private (pNR)	Private 5G NR mini-core + pico BSs. 3.7 GHz SA, 100 MHz, TDD, 3 cells.
	4G LTE Private (pLTE)	2x Private mini-core + micro BSs. 3.5 GHz, 20 MHz, TDD, 3 cells each.
	Wi-Fi 6	2x Coordinated IEEE 802.11ax deployment. 5 GHz, 3 cells each, cloud management.
	Wi-Fi 5	Uncoordinated IEEE 802.11ac deployment. 2.4/5 GHz, 3 cells.
Dedicated operator network slice	5G NR Dedicated (dNR)	Public core + dedicated APN/BS setup. 1.8/2.1/2.6 GHz, FDD, 3 cells.
	4G LTE Dedicated (dLTE)	Public core + dedicated APN/BS setup. 2.6 GHz, 20 MHz, FDD, 3 cells.
Positioning	UWB	Enterprise TDOA positioning solution. 8 anchors, <10 cm accuracy.

TABLE 3. AAU 5G Smart Production Lab wireless capabilities.

Performance of Industrial Wireless Use Cases

Two of the industrial use cases described in Table 2 have already been demonstrated over the testbed: the wireless control of industrial production and the control of AMRs. These tests were performed based on the testbed elements depicted in Fig. 2, and their associated wireless perfomance results are presented in Fig. 3, in terms of control-loop latency empirical complementary cumulative distribution functions (CCDFs). This metric is of paramount importance for understanding whether the communication requirements of a given use case can be fulfilled (i.e., its control-loop latency operated over a certain wireless technology is contained within the communication protocol bounds specified by its survival time) at high levels of reliability. For further details, values of average latency, jitter, and packet error rate (PER) are also given in the legend of the figure for each of the tests.

Wireless Control of Industrial Production

For the first use case, step (1) of the roadmap was demonstrated. The cables between modules in the FESTO CP Factory research production line were removed and wireless GWs were installed instead to provide control communication from the centralized MES controller deployed in an edge-cloud configuration. More details about this specific use case are given in [14]. This industrial static use case has been evaluated over different Wi-Fi 5 configurations, 4G, and also more recent-

We have put in practice some of the steps of the roadmap, and have successfully demonstrated the wireless control of industrial production, as well as the control of mobile autonomous robots in a dedicated industrial wireless research setup, the AAU 5G Smart Production Lab, considering multiple technologies such as Wi-Fi 5, Wi-Fi 6, 4G and 5G.

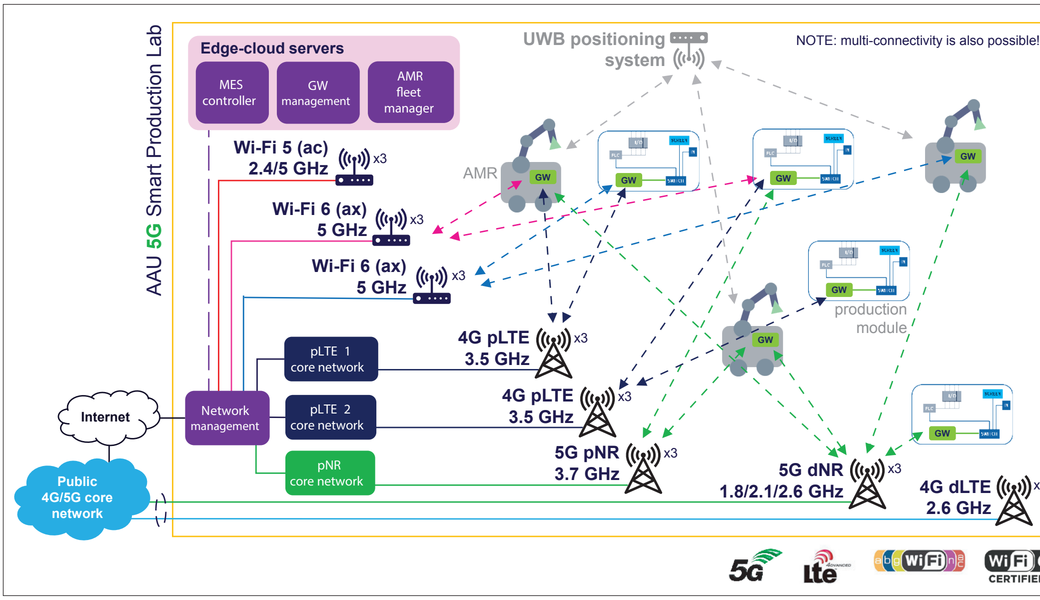

FIGURE 1. High-level overview of the Industry 4.0 wireless production testbed deployed at AAU, illustrating the swarm production concept with production modules and AMRs distributed over the production facilities, and the dedicated network infrastructure available for the testing of industrial use cases.

ly, 5G and Wi-Fi 6. The performance results presented in Fig. 3 for this case consider the full line individually operated over the different technologies with all its seven modules connected over wireless, and compared to the results obtained when the line was operated over its standard Ethernet-based control configuration.

The best wireless performance for this use case was achieved over optimized Wi-Fi 5/6, with an average control loop latency only 2–2.5 ms higher than the reference one achieved over Ethernet. These results were obtained with single access point deployments with non-interfered Wi-Fi channels dedicated to the particular use case, which is usually not the case in operational factory scenarios. Operational factory scenarios are better represented by the non-optimized Wi-Fi 5 case, which exhibits a good average performance, but also presents much longer unbounded tails, reaching even 1 s at the lower percentiles. The performance over 4G is much more contained over both the dLTE and pLTE configurations, ensuring a more deterministic low-jitter communication pattern with control-loop latencies below 35 and 20 ms at median level, and 55 and 40 ms at the 99.99th percentile, respectively. The very similar shape of the dLTE and pLTE distributions can be explained by the use of equipment from the same vendor in the radio access, and the offset difference between them is due to the core network configuration: the dLTE relies on the public core of the operator, while the pLTE is based on a local core, which reduces the overall latency. The 5G pNR configuration, also based on a local core network, offers better control-loop performance than 4G, with less than 10 ms median and 22 ms at the lower percentiles, achieving the same reliability as the optimized Wi-Fi configurations at the tails. It should be noted that the 5G used in the test was a first out-of-the-box release, and thus there is still plenty of room for optimization. In any case, as the control-loop latency requirements dictated by the maximum survival time (2 s) were always fulfilled, the wireless manufacturing system operated reliably (without interruptions) over all Wi-Fi, 4G, and 5G technologies. This was the case even when packet loss was observed, meaning that the higher-layer mechanisms were able to correctly handle the communication errors. From a manufacturing performance perspective, it is difficult to evaluate the impact of the increased latency introduced by the wireless technologies without the use of simulation tools. Based on the wireless performance numbers observed in the reported tests, it is expected that the degradation in production throughput will be maximum 0.01–0.41 percent, depending on the exact line configuration and technology chosen [15].

Control of Industrial Mobile Robots

For the second use case, the baseline for step (3) of the roadmap is demonstrated. In this initial exercise, the AMRs run a lightweight control communication algorithm with feedback to the cloud-edge fleet manager server, but most of its localization functions remain operating locally at the AMR. This mobile use case has been evaluated, for the moment, only over Wi-Fi 5 and 4G, considering a single controlled AMR, while roaming at default speed (maximum 0.8 m/s) around the multiple cells deployed in the industrial hall following pre-configured mobility patterns (based on waypoint definitions).

For this mobile use case, the best control-loop performance was achieved over the pLTE configuration. As compared to the non-optimized Wi-Fi 5 case, 4G outperforms Wi-Fi at both the median (20 vs. 35 ms, respectively), and low percentiles (157 ms vs. 4.2 s, respectively). As the maximum latency tolerable by the control-loop in this use case was 1 s, the operation over Wi-Fi resulted in sudden interruptions in the normal operation of the robot during 0.14 percent of the time. By comparing the performance of the mobile use case and the static use case over pLTE and non-optimized Wi-Fi 5, it is possible to quantify the effect of mobility and handover management for both technologies, with the impact on the order of 1–117 ms for 4G and 4 ms–3.2 s for Wi-Fi. It is clear that, due to their operation in dedicated licensed spectrum and in-built scheduling and handover mechanisms, the cellular technologies (4G, 5G) offer much more contained and deterministic control-loop latency with lower packet error rates than Wi-Fi.

Conclusion

The factories of the future will be equipped with flexible manufacturing equipment enabling the mass production of highly customized products. In order to achieve the maximum level of flexibility, a complete transformation of the traditional sequential centralized production paradigm is needed. In this respect, we envision the swarm production (nonlinear decentralized production) enabled by the integration of advanced wireless technologies, cloud computing, and autonomous mobile robots, which can be made a reality by following a simple roadmap and implementing the different steps and associated use cases. We have put in practice some of the steps of the roadmap, and have successfully demonstrated wireless control of industrial production, as well as the control of mobile autonomous robots in a dedicated industrial wireless research setup, the AAU 5G Smart Production Lab, considering multiple technologies such as Wi-Fi 5, Wi-Fi 6, 4G, and 5G.

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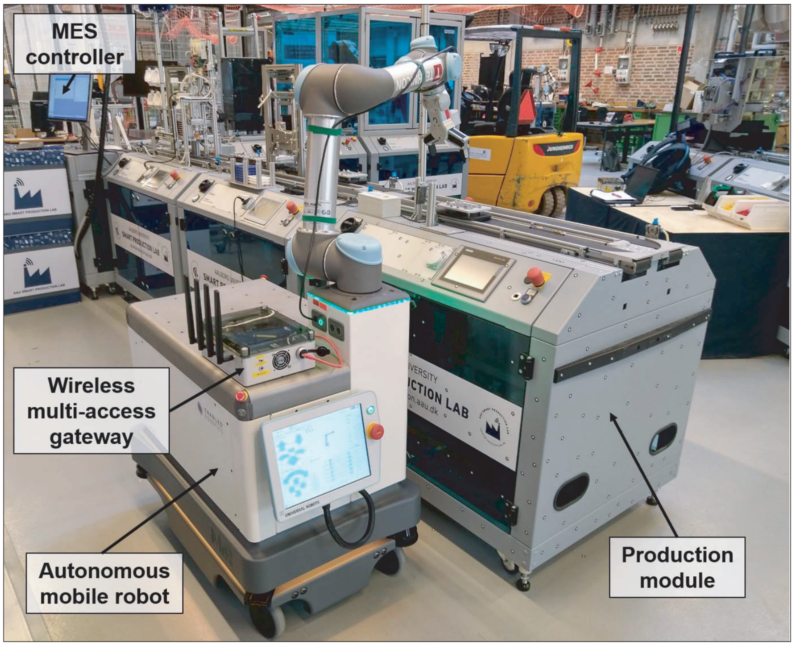

FIGURE 2. Picture of some of the industrial machinery elements of the testbed, including the FESTO CP Factory production line in its standard wired configuration and one of the MiR200-based AMRs. The picture also depicts one of the wireless multi-access gateways used in the various experiments to interface the industrial equipment to the different networks.

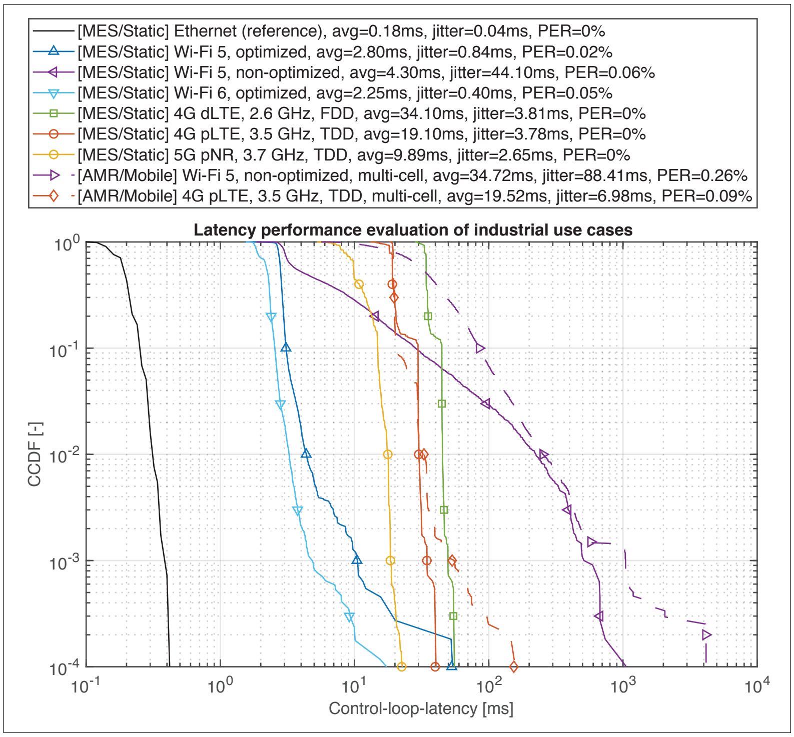

FIGURE 3. Wireless performance results for the wireless control of industrial production (MES/static) and for the control of AMRs (AMR/mobile) industrial use cases over different communication technologies.

Biographies

Ignacio Rodriguez received his Ph.D. degree in wireless communications from Aalborg University, Denmark, in 2016. Since then, he has been a postdoctoral researcher at the same institution, working in close collaboration with Nokia Bell Labs. His research interests include radio propagation, 5G, URLLC, and IIoT.

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