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Implementation and Trial Evaluation of a Wireless Manufacturing Execution System for Industry 4.0

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***Abstract*—This paper presents the implementation framework and performance evaluation of a wireless Manufacturing Execution System (MES) for Industry 4.0. The proposed solution is based on self-configuring multi-access gateways that enable seamless transport of delay-tolerant industrial Ethernet control data traffic over LTE or Wi-Fi (or both, using hybrid-access techniques). The wireless MES solution has been deployed at the Smart Production Lab facilities at Aalborg University, allowing the removal of Ethernet cables between modules in a production line setup, and thus enabling a faster re-configuration of the production facilities. The performance of the wireless MES solution is benchmarked against the reference Ethernet case in terms of latency and packet loss. The trials revealed that, despite the increase in latency and packet loss as compared to the reference operation over Ethernet, both LTE and Wi-Fi under different conditions were able to reliably support the production control operations at MES level without discernable difference on the overall functionality of the system.**

I. Introduction

The usage of wireless communication in industrial environments and applications has received significant interest in recent years. Replacing cables by wireless offers the possibility of reduction of cost and operational expenditures as well as the promise of supporting new use cases which previously were infeasible and is seen as a key technological enabler for the 4th industrial revolution (I4.0) [1]. In general, as illustrated in Fig. 1, the different levels of automation within industrial scenarios present different communication requirements. Typically, the bottom layers include the communication between physical sensors and actuators and their associated programmable logic controllers (PLC). Above these sits the supervisory control and data acquisition (SCADA) layer which acts as interface to the higher-level management systems of the factory. This includes the manufacturing execution system (MES) which handles and monitors the overall manufacturing/production process (i.e. the progress of a specific product from raw independent components to a finished product). Finally, the top of the pyramid consists of the enterprise resource planning (ERP), which integrates the overall business management [2].

As depicted in Fig. 1, from a communication point of view, the required latency often increases as one goes up the pyramid; going from real-time (RT) communication at sensor and actuator level to delay-tolerant (DT) communication at higher levels. Currently, the majority of industrial control systems use wired schemes based on fieldbus or Ethernet technologies, where the latter is the current leading solution in the market [3]. Ethernet offers comparable reliability, latency but greater flexibility as compared to fieldbus technologies. As part of this flexibility, Ethernet allows for interoperation between multiple systems and platforms, which enables easy integration across the different layers in the automation pyramid. Therefore, any industrial wireless solution should be interoperable with Ethernet to ensure compatibility when deployed in an existing setup.

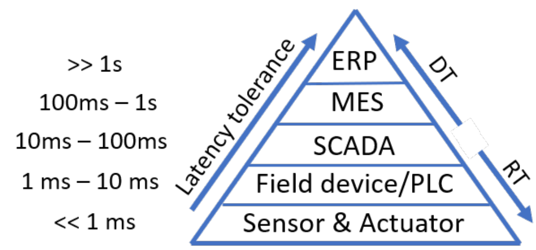

Fig. 1. Automation pyramid and associated typical communication latency requirements for each level adapted from [2].

While industrial wireless communication solutions do exist (ISA100.11, WirelessHART, WISAN, etc.) [4], they are mainly used in the context of wireless sensor networks or human machine interfaces, e.g. monitoring and analytics of the production performance but not for controlling the industrial equipment itself. Those which are more suited for the control are often based on the IEEE 802.11 radio interface such as for example Wi-Fi or IWLAN [5]. Common for all these existing wireless solutions is that they operate in unlicensed spectrum and are, therefore, prone to interference and subject to Listen-Before-Talk (LBT) mechanisms and constraints. This means that they do not scale well in environments with interference from other sources or a large number of devices [6]. While solutions have been proposed to mitigate the scalability issue of unlicensed spectrum-based technologies, they are not commercially available yet. These solutions may include for example RT-Wi-Fi [7] and [6], which proposes a modified MAC layer to better accommodate the more demanding real-time exchange of information, or MulteFire [8], which aims at providing LTE-like functionality in the unlicensed spectrum. As they are not subject to the same constraints, e.g. with regards to interference, commercial technologies operating in licensed spectrum such as 4G LTE and 5G NR can be considered as potential solutions. In particular, 5G NR will introduce features and enhancements applicable to I4.0 use cases as specified in the 3GPP Release 16 [9]. Concepts such as private network deployments and network slicing can also help to ensure the levels of reliability needed in industrial scenarios.

This paper focuses on how Wi-Fi and public LTE networks can facilitate the delay-tolerant communication of industrial systems at the MES level of the automation pyramid. To this extent, we build on the framework presented in [10], where we introduced our incipient vision for a wireless MES solution for industrial manufacturing, and present the implementation details of a novel multi-access gateway (MAGW) which aims at providing seamless and technology-agnostic wireless control communication, including 802.1CB like functionality that enables frame replication and elimination across disjoint communication paths. Further, this study evaluates how the solution compares to the existing wired Ethernet system in a realistic I4.0 scenario.

The rest of the paper is structured as follows. Section II presents an overview of the proposed wireless MES design, with focus on the integration with existing industrial Ethernet systems. Section III describes the implementation aspects of the multiaccess gateway. Section IV details different aspects related to the test scenario, setup and methodology used to evaluate the performance of the system over LTE and Wi-Fi as compared to the baseline Ethernet. Section V presents the results of the real-world trials in terms of packet error rate and latency. Finally, conclusions are resumed in Section VI along with future directions.

II. Integration of Wireless Industrial Ethernet

As detailed in [10], we consider the Aalborg University (AAU) Smart Production Lab assembly line as our reference scenario in this work. This is a small-scale representation, based on commercial industrial-grade equipment and interfaces, of the operational setups in real factories. As displayed in Fig. 2, the line physically consists of 5 FESTO production modules, each containing two independent stations.

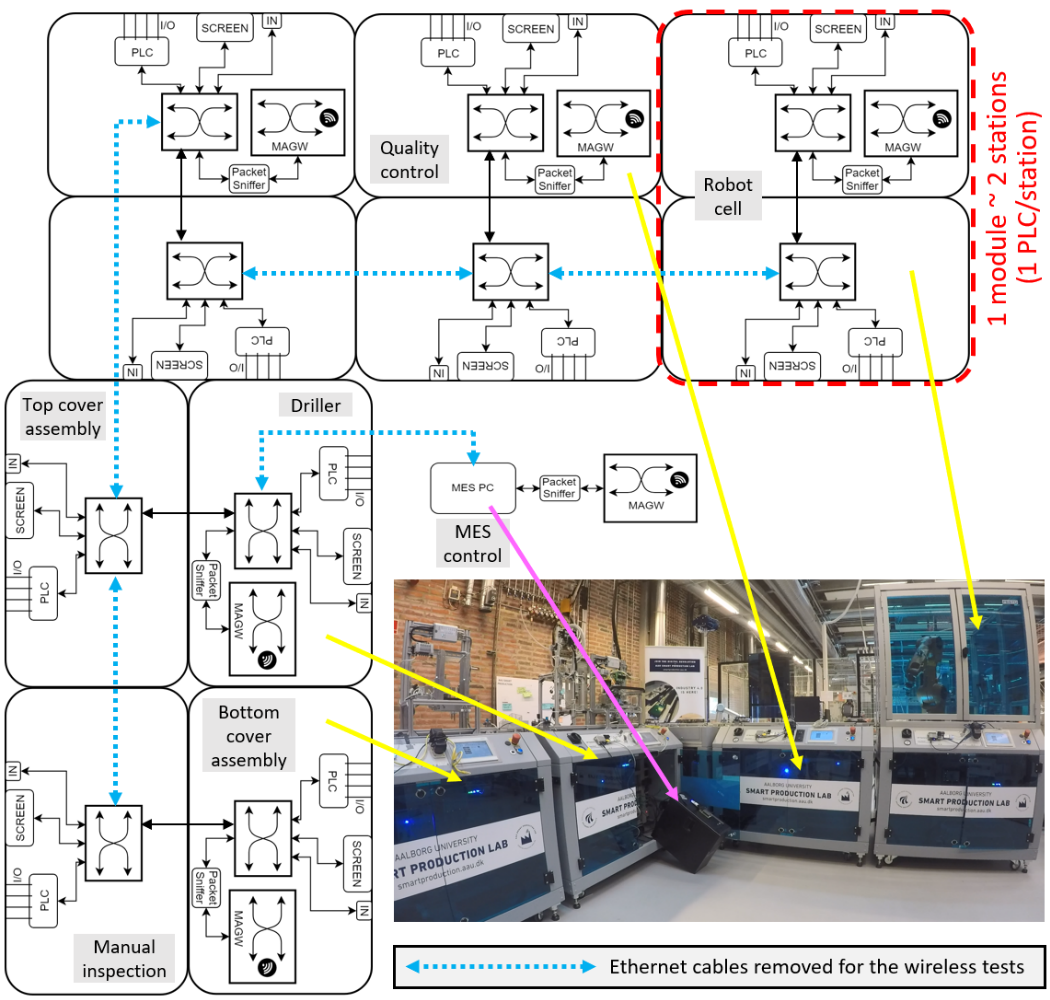

Fig. 2. Overview of the fully-automated test assembly line at the AAU Smart Production Lab composed of 5 modules (10 process-specific stations), including reference network architecture and picture of the real setup.

Each station consists of a PLC with different input/output (I/O) capabilities (analog, digital, fieldbus etc.), a display screen and an extension port (IN), all of them interconnected via a switch. They are equipped with different industrial-grade components which are in charge of performing different actions or tasks within the manufacturing process. Such components are connected to the integrated PLC either using Ethernet or the I/O. All these modules are daisy chained by Ethernet via the internal switches, to which the MES PC is also connected to orchestrate the overall operation. When operational, the system system can be configured to manufacture different variants of mock smartphones, each consisting of three main components: a bottom cover, a circuit board with fuse holders and a top cover. During the assembly process, these phones are transported on trays via conveyor belts from station to station where different operations are performed. The MES keeps track of the specific products in progress based on RFID tags placed on the product trays. When a tray enters a station, the RFID is read, and then the PLC reports the associated product ID to the MES. Then, the MES replies by issuing a command according to the action to be performed over the product at the particular station, according to its current state. The production of a singular product consists of 7 steps: 1) bottom cover placement at stack magazine, 2) hole drilling, 3) placement of a circuit board and fuse at robot cell, 4) video-based quality assurance, 5) top cover placement at stack magazine, 6) final product manual inspection and packaging. As a safety feature, even if they are not busy, the stations continuously check their connection status towards the MES PC, verifying whether the communication is active and reliable. In the case that the maximum survival time period of 2 s is exceeded, the station is stopped, and an alert is displayed at the MES. It should be noted that the described system tolerates a slightly higher latency than the one described for typical systems in Fig. 1.

From a communication perspective, the only time-sensitive communication is the one happening at PLC I/O and fieldbus level. In contrast, the overall inter-module and MES communication is the delay-tolerant [10]. Therefore, in this paper, we focus only on providing communication at MES level between the different modules and MES controller PC by replacing the Ethernet connection with wireless, while keeping the internal components of the modules wired. By doing this, both greater flexibility and re-configurability of the production line is enabled.

As previously mentioned, an important aspect to be considered, from an industrial network architecture point of view, is backwards compatibility and seamless integration such that no existing equipment needs to be modified or replaced to enable wireless connectivity. This is an essential aspect, especially when dealing with legacy industrial setups (which are the vast majority in the current real-world operational deployments). This requires that the wireless network is self-contained and configurable independently from the wired network. To achieve this, we introduce our proposed multi-access gateway (MAGW) solution, which is presented in detail in Section III. To integrate our wireless setup in the system, the cables between modules are removed and a total of 6 gateways are installed in the system (as depicted in Fig. 2): one of them is connected to the MES PC, while the other 5 are installed at each of the 5 modules (serving two stations each).

The gateways provide seamless connectivity at MES level over both LTE and Wi-Fi. LTE connectivity is provided by one of the major mobile operators in Denmark via its commercial wide area network, optimized for mobile broadband use. A dedicated access point name (APN) is deployed at the operator's core network allowing for inter-communication between gateways based on static LTE IP configurations. Under such configuration, the traffic between gateways is routed at the core without being forwarded to the public internet. In other words, a "private network slice" is created using the public infrastructure, similar to what 5G NR will consider for the support of vertical use cases, but without prioritized resource allocation in the radio access network (RAN). With respect to the Wi-Fi connectivity, it is provided through dedicated infrastructure, in a similar way to what it is done nowadays in any enterprise deployment. Our gateways have the further capability of providing transport layer hybrid access (or multi-connectivity) by combining the connections over both technologies. Combining LTE with Wi-Fi provides the additional benefit of having fallback options in case of network errors, thereby increasing the availability and reliability of the overall system [11].

III. Multi-access Wireless Gateway

As previously stated, the purpose of the multi-access gateway is to provide seamless wireless connectivity via LTE, Wi-Fi or both. To create these multi-access gateways, the functionality and components depicted by the block diagram in in Fig 3.a, were implemented on UP-boards equipped with

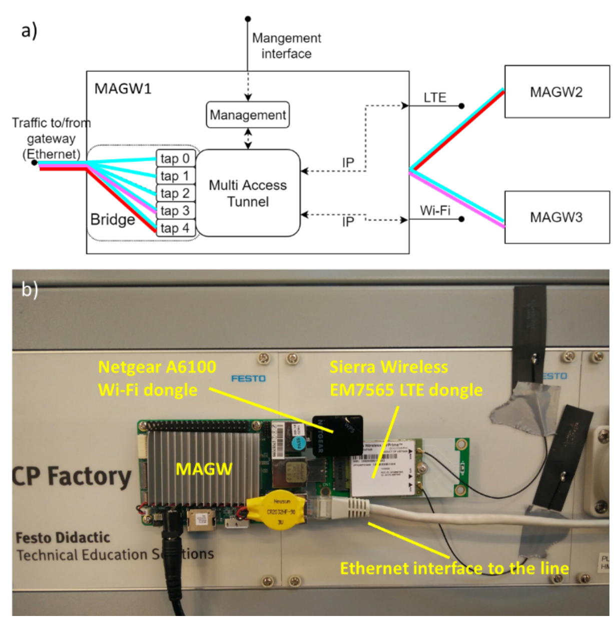

Fig. 3. Overview of the multi-access gateway: a) block diagram including the internal components, b) picture of the prototype implementation illustrating the different Ethernet, LTE and Wi-Fi interfaces.

TABLE I
HARDWARE AND SOFTWARE DETAILS FOR THE MAGW AND TRAFFIC SNIFFERS.

HW/SW	Details
Gateway	UP-Board, intel x5-Z8350, 4 GB RAM
OS	Ubuntu 18.04 LTS
SW	Custom Multi-access Tunnel
NIC model	RealTek 8111G, 1 Gb/s
Wi-Fi dongle	Netgear A6100, 802.11ac
LTE dongle	Sierra Wireless EM7565, Cat 12
Sniffer	Raspberry Pi Model 3B, Broadcom BCM2837, 1 GB RAM
OS	Raspbian Stretch
SW	Tcp-dump v4.9.2
NIC model	Apple 10/100 USB ethernet adapter

LTE and Wi-Fi dongles via USB ports (as illustrated in Fig. 3.b). Details on the specific hardware and software used are summarized in Table I.

To setup the inter-gateway network, a list containing the address and port information from all gateways in the network is distributed via the management interface (logical interface used for configuration that can be accessed either physical via USB port or over any of the wireless networks when connected). To establish the actual communication, each gateway creates a virtual port that is bridged to each of the remote gateways. Thereby, a gateway is seen as a switch port with a set of devices (MAC addresses) behind it from the perspective of the Ethernet network. This means the physical Ethernet traffic is automatically routed through the correct gateway based on the destination MAC address, as illustrated in Fig. 3.a. Each of the taps illustrated in the figure corresponds to a unique remote gateway. As an example, the traffic flow associated with the taps with destinations MAGW2 and MAGW3 are color-coded in red and magenta, respectively. The cyan flow indicates broadcast traffic and is therefore routed to all remote gateways.

When an Ethernet packet is routed to the correct virtual port, the multi-access tunnel module will extract the Ethernet frame, and encapsulate it in a user datagram protocol (UDP) packet along with a sequence number and a unique ID used to

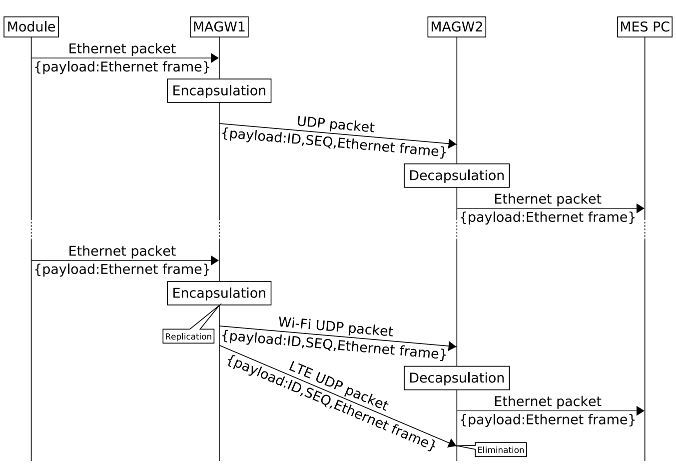

Fig. 4. Module to MES PC sequence diagrams. The top one illustrates the single connectivity case, while the one in the bottom shows the multi-connectivity case.

identify which virtual port it should be routed to at the remote side. Once received at the remote side, the received UDP packet is decapsulated into an Ethernet packet and forwarded to the Ethernet interface of the gateway. A complete sequence diagram is depicted at the top part in Fig. 4.

If the distributed network configuration specifies that both the local and remote gateways have multiple connection options available between them (hybrid access is enabled), the encapsulated packet is replicated across all specified connections, i.e. the same packet is sent over LTE and over Wi-Fi. At the destination gateway, packets with the same origin network are identified by the unique ID and potential duplicates are eliminated based on the sequence number of the packet. This mechanism is similar to the 802.1CB FRER [12] but at IP-level. An example of this multi-connectivity sequence is illustrated in the bottom part of Fig. 4.

IV. TEST SETUP

To evaluate the performance of the wireless MES communication over LTE and Wi-Fi and benchmark it against Ethernet, we have examined the following cases:

1) Ethernet (reference MES performance).
2) Public LTE: the system operates over the wireless gateways, being these connected to the commercial Telenor LTE network. The network operates at 2.6 GHz with 20 MHz bandwidth. The closest macro base stations are placed outside the test lab at an approximate distance of 1 km. The performance in this case is subject to the LTE network load.
3) Wi-Fi: the system operates over the wireless gateways, being these connected to a dedicated Wi-Fi infrastructure based on an 802.11n TP-Link N750 AP (with customized OpenWrt 18.06.2 OS) located inside the lab in the vicinity of the production line at approximately 5-10 m distance. The dedicated Wi-Fi network is operated in the 5 GHz band over the unoccupied channel 161 with 20 MHz bandwidth. This setup emulates an enterprise industrial deployment with strict frequency channel planning.
4) Wi-Fi with interference (w.i.): the system operates over the wireless gateways connected to the dedicated Wi-Fi infrastructure described in 3. However, in this interference case, the dedicated Wi-Fi network is operated in the 5 GHz band over channel 132 with 20 MHz bandwidth. This network overlaps with the Aalborg University Wi-Fi network, which was loaded by starting different traffic flows from 5 devices (streaming service, file download and periodic traffic) while the manufacturing line is running. This setup emulates a non-optimized Wi-Fi case, where the network in charge of controlling the equipment is affected by external interferers.
5) Hybrid access (HA) over public LTE and Wi-Fi: the gateways are simultaneously connected to the networks detailed in 2. and 3.

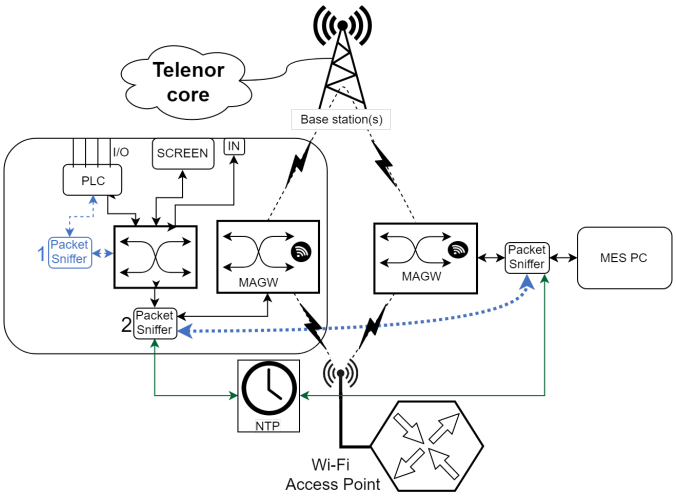

Fig. 5. Simplified measurement setup between MES and a single station, considering the Ethernet reference case (blue dotted line) and both wireless cases: LTE and Wi-Fi.

6) Hybrid access over public LTE and Wi-Fi with interference: the gateways are simultaneously connected to the networks detailed in 2. and 4.

Each case is evaluated by configuring the production line to manufacture several products during a period of 30 minutes, where actions are continuously occurring according to the flow presented in Section II. In terms of generated data traffic in the reference configuration operating over industrial Ethernet, this corresponds to 17k-20k packets sent between the MES controller and the FESTO modules, with an average load of 6.7 kb/s, when aggregating all the samples to and from the modules. In terms of transmission behavior, no distinction between TCP and UDP traffic was done, and 75 % of the traffic is unicast, while the remaining is multicast/broadcast traffic. The average packet size is 63-70 bytes, which will translate into 88-108 bytes when considering wireless MES access over the gateways (excluding the technology-specific MAC/PHY overhead for Wi-Fi and LTE). On average, the modules (grouping two stations/PLCs) and MES PC produce one packet every 148 ms and 112 ms, respectively. A similar behavior was observed for all modules, with minor variations mainly in the upper bounds (above 99%-iles). It should be noted that similar traffic patterns have been observed in larger systems in real factory scenarios. These are not very demanding numbers in terms of data traffic nature, which further back up our view with respect to the potential of using existing wireless technologies as LTE or Wi-Fi for provisioning this delay-tolerant communication at MES level.

To evaluate the performance of the system under the different configurations, the key performance indicators (KPIs) are the packet error rate and one-way latency [13]. The latter can be related to system survival time i.e. the maximum time over which the system can function without new control information being received (in this case commands to and from the MES controller), which is configured to be 2 s in the analyzed setup. To compute the KPIs, we use the measurement method presented in [10] and illustrated in Fig. 5. This method considers a synchronized measurement setup consisting on packet sniffers that are placed at the Ethernet interfaces of the multi-access gateways on each module and the MES controller PC, logging all the incoming and outcoming traffic passing through. During the measurements, these sniffers synchronize (with an accuracy of 8 µs on average) to a common network time protocol (NTP) server via a dedicated external network. This allows us to extract the precise departure and arrival time of each packet in the network with respect to a common reference. Further details about the hardware and software of the sniffers are given in Table I.

V. Performance Results

The empirical complementary cumulative distribution function (CCDF) of one-way MES communication latencies is displayed in Fig 6 for the 6 different test cases along with a summary of the latency values for different percentiles in Table II. As expected, the reference system over Ethernet presents the best performance (low latency, low jitter), presenting a maximum one-way latency of 0.43 ms. This indicates that such system and particular configuration could even cope with the more demanding latency requirements of the lower layer systems dictated by the automation pyramid in Fig. 1.

Communications via public LTE experiences higher latency than the dedicated Wi-Fi case: 47.6 ms median one-way latency with LTE vs 2.81 ms for Wi-Fi. This can be explained from the fact that the considered LTE network was a public network, optimized for mobile broadband, and without control of the load; whereas the considered dedicated Wi-Fi configuration operated over unoccupied non-interfered spectrum and with a small number of devices (modules + MES controller). The behavior of the wireless MES over Wi-Fi with interference is, in general, also better than LTE with a median one-way latency of 4.43 ms. However, for the higher percentiles, it presents a degraded performance due to the interference from the external co-channel network. This degradation resulted in a maximum latency of 1.1 s (still lower than the allowed survival time within the system). This has a large impact on the jitter (σ), reaching up to 43 ms, which is much larger than the one from LTE (17.9 ms) and Wi-Fi without interference (1.42 ms). Without external interferes, Wi-Fi latency lies well below the most demanding MES communication requirement (100 ms) and could provide such service with a 99.99+% of reliability. The tested public LTE connection, however, would only be suitable for such demanding MES deployments if the required reliability level is below 99%.

When examining the packet error rate (PER) behavior during the various tests, LTE presents a significantly higher rate than Wi-Fi with and without interference (0.5% and 0.02-0.06%, respectively). LTE and Wi-Fi with and without interference present mostly sporadic single packet losses. However, the wireless MES communication over LTE also present larger bursts of losses in some cases, reaching up to 2-5 consecutive lost packets. As the LTE is a public network, it is difficult to determine the exact cause of these burst of errors since the

TABLE II

SUMMARY OF ONE-WAY LATENCY AND PACKET ERROR RATE MEASUREMENT RESULTS FOR THE 6 TEST CASES.

Technology	**Selected latency statistics**								**Packet loss burst size**					**PER [%]**
	Min [ms]	**Median [ms]**	**99%-ile [ms]**	**99.9%-ile [ms]**	**Max [ms]**	**σ [ms]**	**[%] <100 ms**	**[%] <1s**	**1**	**2**	**3**	**4**	**5**	
1. Ethernet	0.09	0.18	0.31	0.36	0.43	0.04	100	100	-	-	-	-	-	0
2. Public LTE	27	47.6	105	234	468	17.9	98.41	100	500	29	4	5	1	0.5
3. Wi-Fi	1.67	2.81	4.35	10.5	88	1.42	100	100	15	1	-	-	-	0.02
4. Wi-Fi w.i.	1.74	4.43	217	488	1187	43	97.07	99.98	71	1	-	-	-	0.06
5. HA over Public LTE & Wi-Fi	2	3.2	5	9	44	0.8	100	100	1	-	-	-	-	0.001
6. HA over Public LTE & Wi-Fi w.i.	1.8	3.1	31	59	217	5.25	99.99	100	32	-	-	-	-	0.03

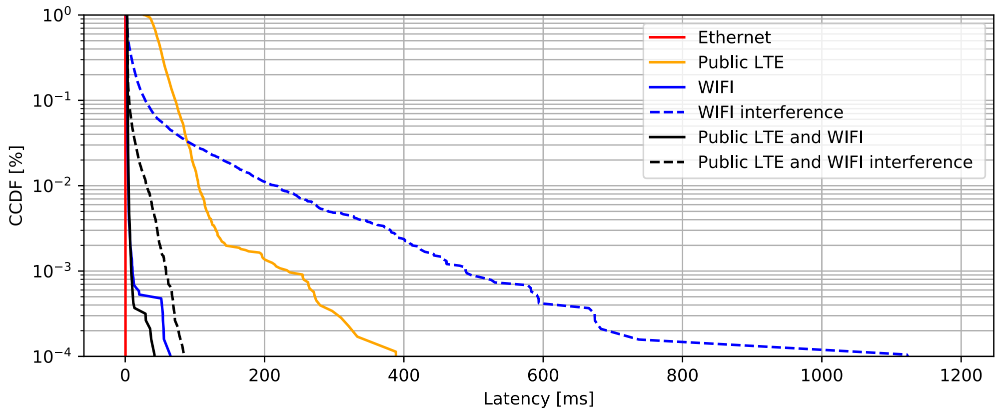

Fig. 6. One-way latency distributions from the trials for the various technologies.

connection is not only subject to the radio channel but also to any optimizations and specific configurations made by the operator.

Combining the two technologies through hybrid-access or multi-connectivity, yields to a significant improvement in terms of both latency and PER, even in the case where Wi-Fi is subject to interference. The best performance of the wireless MES system was achieved with configuration 5 (combination of public LTE and dedicated Wi-Fi) with a maximum latency of 44 ms and a single packet loss (resulting in a PER or 0.001%). Multi-connectivity techniques help in both tested scenarios, even in the highly interfered scenario of case 6 (where multi-connectivity over public LTE and Wi-Fi with interference was tested), achieving a much better performance than the LTE-only or interfered Wi-Fi-only cases. This is due to the fact that the access over each technology is highly uncorrelated, which leads to high diversity gain.

The evaluated wireless configurations experienced higher latencies than the reference wired Ethernet case. However, the latency can still be contained below 100 ms on average, and as the considered industrial traffic can tolerate delays of 100-1000 ms [2], using wireless is nevertheless attractive from a flexibility point of view.

VI. CONCLUSIONS

In this paper, we evaluated the suitability of wireless technologies such as public LTE and Wi-Fi in supporting communication at Manufacturing Execution System (MES) level in industrial scenarios. The study is carried out in a production line at the Smart Production Lab at Aalborg University. Wireless connectivity is obtained via our designed multi-access gateway that seamlessly leverage LTE, Wi-Fi and their combination via hybrid access with frame replication and elimination. For Wi-Fi, both cases of free and busy operational channels are considered, reflecting the cases of strict frequency planning and non-optimized deployment, respectively. Measurement results reveal for all the studied solutions one-way latencies significantly below the 2 s survival time set by the MES of our setup and fitting to the 100-1000 ms range of typical MES. Wi-Fi provides lower median latencies than public LTE, although the presence of interference increases 99.9 %-ile latencies up to 490 ms, whereas public LTE offers 230 ms. The usage of hybrid access leveraging both LTE and Wi-Fi via packet duplication leads to 99.9 %-ile latencies lower than 100 ms, thus coping even with the stricter delay communication requirements seen in MES deployments.

Next research steps include testing Wi-Fi scalability for larger MES deployments, deploying and optimizing a private LTE network for industrial automation, and assessing the impact on production capability by looking at trade-off among higher latency and better flexibility of wireless.

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