On the Design of a Wireless MES Solution for the Factories of the Future

Rodriguez, Ignacio; Mogensen, Rasmus Suhr; Khatib, Emil Jatib; Berardinelli, Gilberto; Mogensen, Preben; Madsen, Ole; Møller, Charles

Published in:
2019 Global IoT Summit (GIoTS)

DOI (link to publication from Publisher):
10.1109/GIOTS.2019.8766419

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

On the Design of a Wireless MES Solution for the Factories of the Future

Ignacio Rodriguez[1], Rasmus S. Mogensen[1], Emil J. Khatib[1], Gilberto Berardinelli[1],
Preben Mogensen[1], Ole Madsen[2], Charles Møller[3]

[1]Wireless Communication Networks Section, Department of Electronic Systems, Aalborg University, Denmark
[2]Robotics and Automation Group, Department of Materials and Production, Aalborg University, Denmark
[3]Center for Industrial Production, Department of Materials and Production, Aalborg University, Denmark
Emails: {irl, rsm, ejk, gb, pm}@es.aau.dk, {om, charles}@mp.aau.dk

***Abstract*—This paper presents our vision and initial design of a wireless manufacturing execution system (MES) solution, which will be soon integrated in the fully-automated small production line in the Smart Production Lab at Aalborg University. The replacement of the current Ethernet-based control system with our wireless solution, will allow to remove all communication wires between the different stations of the production line and thus, enabling a faster re-configuration of the production facilities. The proposed solution also sets the base for the future integration of new industrial use cases requiring full mobility support.**

I. Introduction

The fourth industrial revolution - or Industry 4.0 (I4.0), will introduce major shifts in the way that products will be manufactured in the future. By integrating different cyber-physical systems (CPS), Internet-of-Things (IoT) technologies and cloud computing; the factories of the future will be equipped with highly flexible manufacturing equipment offering also a high reliability, thereby increasing the overall production output [1]. One of the key enablers for such revolution is wireless communication. By replacing existing wirelines in the current industrial equipment with wireless technologies, the overall cost of deployment will be reduced, while at the same time a faster re-configuration of the smart production facilities will be enabled. The use of wireless technologies will also allow for new industrial use cases requiring full mobility support [2], e.g., autonomous robots moving items over different workstations in the factory for the sake of manufacturing customized products.

With the aim of merging expertise across multiple domains (manufacturing, robotics, wireless communication, computer science) and demonstrating novel I4.0 concepts, a collaboration between the Center for Industrial Production, the Robotics and Automation group and the Wireless Communication Networks Section at Aalborg University (AAU) was established. Within this collaboration, and with focus on demonstrating the potential of using wireless technologies in the factories of the future, a proof-of-concept of the replacement of wired connectivity by dedicated wireless technologies is being carried out in a fully operating setup, e.g., the production line at the AAU Smart Production Lab [3]. This production line is a fully-automated line which integrates a modular and expandable transportation FESTO Cyber Physical Factory [4] together with different process modules/stations such as part dispensers, drillers, assemblers, or part inspectors, and even a dedicated robotic assembly cell [5]. The layout of the line is displayed in Fig. 1.

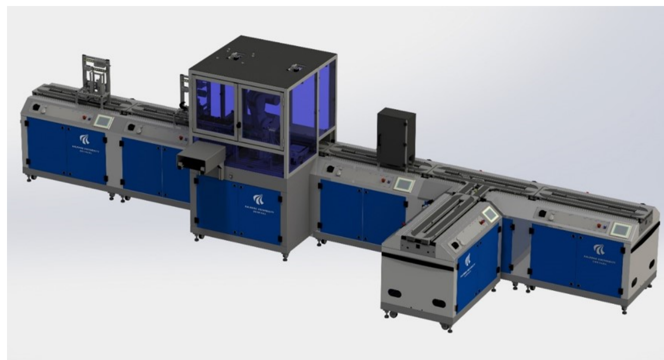

Fig. 1. Reference layout of the production line at the AAU Smart Production Lab composed of 7 interconnected modules. This number of modules translates into 14 process-specific stations as each module integrates 2 stations (one at each of the sides).

In this paper, we describe our vision of a dedicated wireless solution able to provide communication control to the different elements in the production line while avoiding cables between all the stations. First, in Section II, an overview of the network architecture of the production line is presented. After that, the different high-level communication requirements for the distinct components and control levels are identified and related to the network architecture and the mode of operation of the line. Based on a dedicated measurement of control data traffic, we describe, in Section III, the specific design requirements for providing wireless communication at manufacturing execution system (MES) level and provide the reference wireless architecture for the initial proof-of-concept[1]. The paper is completed in Section IV with a discussion of future considerations, and the conclusions are given in Section V.

[1]The first LTE-based wireless MES live trials at the AAU Smart Lab are ongoing in February 2019, but unfortunately due to lack of time before the present submission, performance results are not included in this paper.

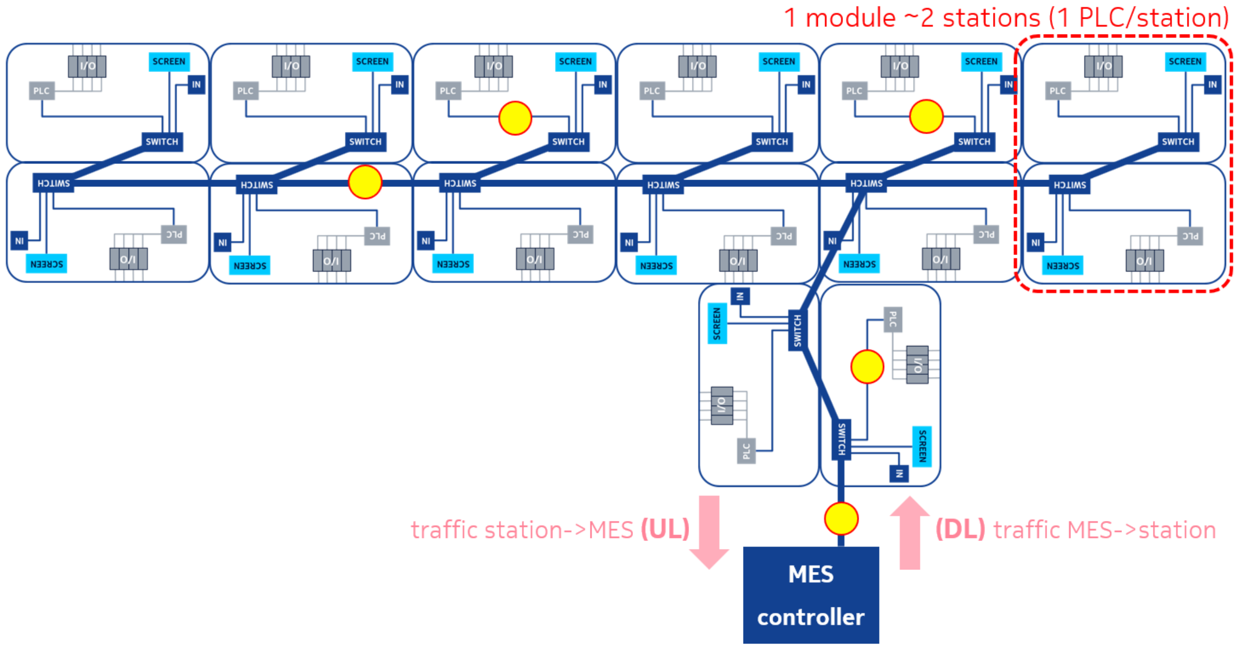

Fig. 2. Simplified reference network architecture of the production line at the AAU Smart Production Lab considering the exact same 7 modules (14 stations) displayed in Fig. 1. The yellow-filled circles indicate the interfaces selected for the control data traffic analysis.

II. Overview of the Production Line

The communication network within a production line plays a key role in the overall manufacturing and production process as it enables the control and supervision of the different stations from a centralizes location.

A. Reference Network Architecture

As displayed in Fig. 2, the communication network architecture of the production line at the AAU Smart Production Lab, which can be seen as a specific small-scale representation of what can be found in larger industrial production lines in real factories [6], is mainly composed of a number of switches (one per station) interconnected via Ethernet cables. As also shown, one of the switches placed at the end of such network is directly connected to a centralized control unit, where all specific module/station parameters as well as the overall product manufacturing orders are managed at manufacturing execution system (MES) level [7]. Eventually, this central control unit could be placed in a different network than the production line itself or even in a remote cloud location. For our proof-of-concept, we focus on the existing local deployment, but only minor adjustments would be needed to adapt our designed wireless solution to the other two cases.

As shown in the previous figure and highlighted in Fig. 3, the internal network inside each of the individual stations is generally composed of three different Ethernet connections from the switch to the programmable logic controller (PLC), to the station display screen and to an extra Ethernet port (IN) - which can be used for plugging extra components on a particular station. In our production line, the PLC, who centralizes all the operational logic of a particular station is connected to the input/output (I/O) sensors/actuators by means of dedicated wired communication buses.

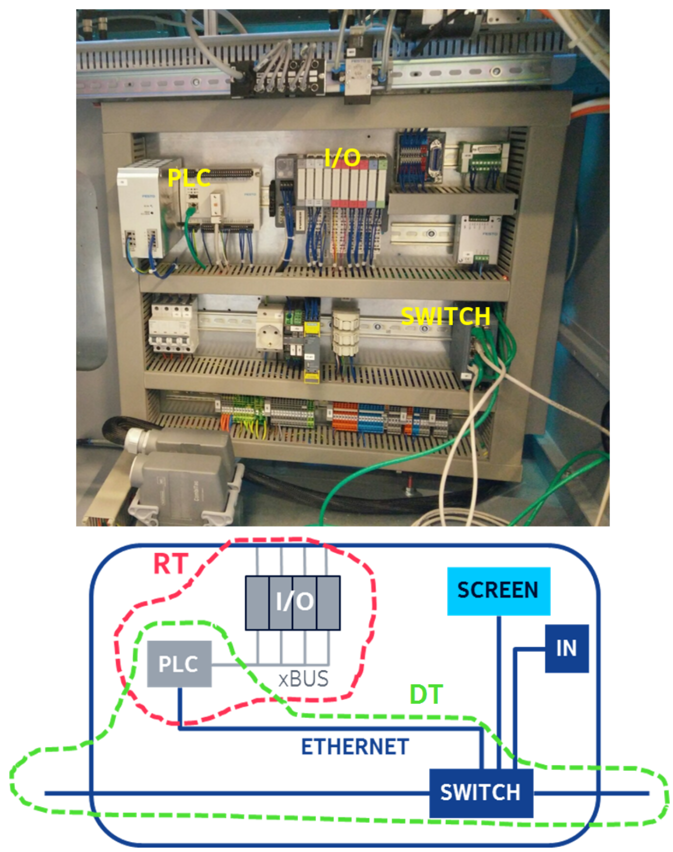

Fig. 3. Overview of the internal composition of one of the production line stations (above) and its associated reference architecture (below).

B. Mode of Operation and High-level Communication Requirements

In a simplified manner, the production line at the AAU Smart Production line operates as follows. Once the stations are powered up, and the carriers (support pieces carrying a product being manufactured) begin to circulate over the conveyor belt:

1) When a carrier arrives to a particular station, its identification (ID) is read by a near-field (NF) or radio frequency identification (RFID) sensor and notified to the PLC.
2) The ID of the specific carrier is transmitted from the PLC to the centralized MES controller to query about the operations to be carried out at that station for that particular item.
3) The MES replies back to the PLC with the set of specific actions to be performed.
4) The PLC coordinates the different I/O actions to be performed over the product. These station-specific actions may include, for example, drilling, assembly of pieces, manipulation by a robotic arm, camera inspection, etc.
5) Once all the actions have been done over the product at the particular station, the PLC notifies the centralized MES controller about the finalization of the work.
6) The MES updates the status of the product in the overall production management registry and notifies the PLC that the product can continue to the next production stage.
7) The PLC sends the order to the conveyor to transport the carrier to the next station.

It should also be mentioned that, throughout most of the above detailed steps, the PLC also sends operational information to its associated display such as, for example, the ID of the product being operated at the station and the status associated operations to be performed.

By putting in perspective the described mode of operation together with the overall architecture details, it is possible to understand that the high-level communication requirements for the described operations are different from one another. All the MES-PLC control-related actions happen in a triggered/on-demand asynchronous way (initialization and production 1-3, 5-7) and are not excessively time-critical. In fact, they are delay-tolerant (DT); so a minor delay in this communication will result in a slower reaction time, but it will not impact the manufacturing quality of the product. On the other hand, the specific I/O actions performed by the different sensors and actuators orchestrated by the PLC (production 4) must happen in real-time (RT). In the case that this time-critical and not-delay tolerant communication between PLC and I/O is not reliable, a mismatch between the actions of sensors and actuators could happen, putting in risk the quality of the product or even the entire manufacturing process.

These identified high-level requirements can be also described in terms of the well-known automation pyramid[2] [8] as depicted in Fig. 4. The lower the process is in the pyramid, the more time-critical it is. The same color code (red for time-critical and green for non-time-critical) has been used in the previous Fig. 3 to further illustrate that there exists a direct relation between the control processes and their associated communication requirements, and the wired technologies used in the current production line architecture. While the Ethernet technology is enough guarantee to the required multiple access level of service between MES and PLCs, a dedicated fieldbus-based technology is used between PLC and I/O to ensure a reliable performance. This is due to the need of a highly time-synchronized and time-deterministic exchange of information, which the standard Ethernet technology is not able to provide [6].

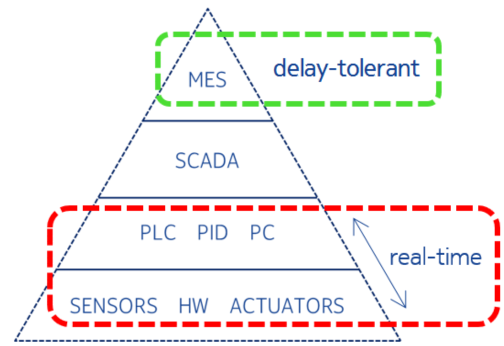

Fig. 4. Automation pyramid with an overview of the different levels of control communication within the production line and their associated high-level communication requirements.

Other more advanced Ethernet-based wired technologies such as PROFINET or EtherCAT are also in use nowadays for the control of industrial manufacturing processes [9]. However, it should be noted that our particular target system also represents one of the most common architectures used in real operation industry (mostly due to legacy and interface standardization constraints) and thus, we still consider of interest to address its evolution into wireless, not only as a practical demo, but also as of great relevance for the manufacturing industry.

As the main target of the proof-of-concept is to replace the communication wirelines between the different modules/stations with wireless to ensure a faster re-configuration of the production line, we set our initial target on designing an interface able to provide wireless control at MES level between the different stations and the centralized control unit, keeping all other intra-station communication interfaces unaltered.

C. MES Control Data Traffic Measurements

In order to design the above-described wireless interface, a deeper understanding than the high-level communication aspects is needed. To gain further knowledge on the MES control data traffic characteristics, a dedicated measurement

[2]The standard representation of the automation pyramid has been adapted to the particular use case presented in this paper. Above levels of the pyramid, e.g. enterprise resource planning (ERP) are omitted.

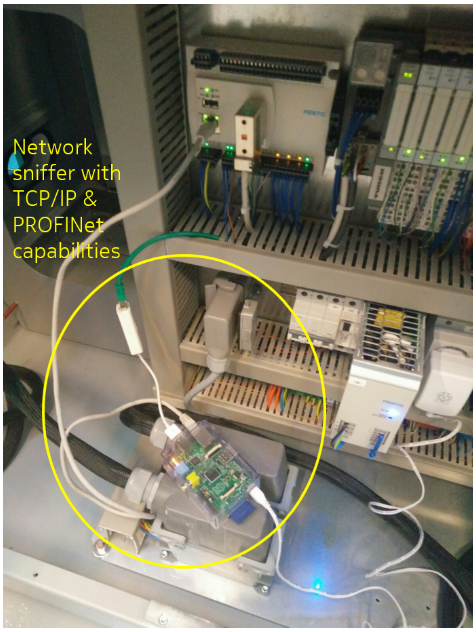

Fig. 5. Illustration of one of the Raspberry Pi-based network sniffers interfaced with the production line during the data traffic measurements.

was performed. Measurements were performed by probing different interfaces of the production line (see yellow-filled circles in Fig. 2 for reference) with the Raspberry Pi-based network traffic sniffers depicted in Fig. 5. Such devices, equipped with two Ethernet ports, were designed to perform a machine-in-the-middle ”attack” over the chosen link and log all traffic passing through it by using tcpdump packet capturing software [10]. A third Ethernet interface in the devices was used as dedicated network time protocol (NTP) synchronization port to ensure that the measurements from all probes have a common time reference with an accuracy in the order of a few ms [11].

A data throughput trace resulting from more than 1 hour of measurement over the operational production line is displayed in Fig. 6. The figure shows the results from the probe situated between the MES and the first switch in the network, considering downlink (DL) traffic between the MES control unit and all PLCs in the different stations and uplink (UL) traffic between the PLCs and the MES central unit (see pink arrows in Fig. 2 for further reference). The traces are further classified according to the different layer 4 data protocols: transmission control protocol (TCP) and user datagram protocol (UDP). Different phases, related to different actions being executed by the line, can be distinguished in the illustrated results:

1) Initialization: all stations in the line are sequentially powered on. Only background UDP DL data is detected (it is not shown here, but there is also some address resolution protocol (ARP) traffic in layer 2 which is essential for the overall system to operate).
2) ”Single product” test: the line is configured with the order of manufacturing a single product. Once the transportation carrier enters the conveyor line, the product will be sequentially manufactured by passing through all the stations. As there is a single carrier and single product, and due to the asynchronous operation nature of the line, no two stations are generating simultaneous traffic in this test. The results show how, in the moment that PLCs and MES need to exchange critical information, both DL and UL TCP traffic is being generated.
3) ”Line saturation” test: the line is configured with the order of manufacturing several dozens of products. In order to track the increase in data traffic generated by the production demands, one transportation carrier is introduced to the line each minute (up to a maximum of 13 carriers). As displayed in the results, the amount of TCP traffic increases as compared to the ”single product” test. Eventually, the production line reaches a saturation state and no higher data traffic is generated. In our particular case, this happens when the buffer at the robotic arm assembly station, with a capacity of 3 carriers, is fully occupied. This creates a bottleneck and causes that all other carriers just wait their turn to be operated by the robotic arm station by circulating around the line without performing any action at other stations.

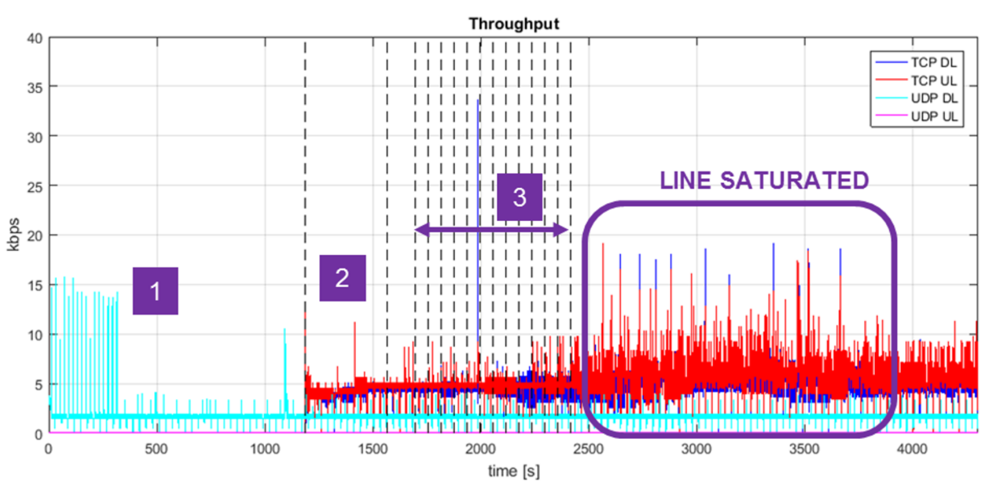

Fig. 6. Throughput trace recorded at the central MES controller for different performance tests carried out over the AAU smart production line.

TABLE I
SUMMARY OF RESULTS FROM THE DATA TRAFFIC MEASUREMENT

Data Traffic Key Performance Indicator	UL (PLC $\rightarrow$ MES)	DL (MES $\rightarrow$ PLC)
avg. UDP throughput	-	1.5 kbps
max. UDP throughput	-	15.4 kbps
avg. TCP throughput	5.0 kbps	4.6 kbps
max. TCP throughput	18.9 kbps	33.8 kbps
avg. TCP inter-arrival time	2.5 s	200 ms
avg. packet size	70 B	63 B

Table I provides a summary of selected data traffic key performance indicators. There is only UDP traffic in DL, with an average throughput of 1.5 kbps. The maximum TCP throughput is higher in DL than in UL due to the more frequent transmissions in this direction, but due to the smaller packet size, they both exhibit a quite symmetric average throughput behavior of about 5 kbps (slightly lower in DL). The end-to-end latency and jitter between the probe close to the MES and the ones close to the PLCs was also analyzed from the measurement, finding similar distributions for DL and UL with a latency close to zero with a few ms of jitter. These distributions are a bit artificial due to the time synchronization accuracy of the measurement system over NTP, but the main message is that the end-to-end delay in the wired production line is very small. From analyzing the measurements from the other probes, we could observe that the data traffic generated in both UL and DL exhibits a similar pattern in all analyzed stations (which makes sense from the on-demand nature of the data and the similar structure of the MES data being transmitted to all stations). From the same measurements, it was also possible to observe that stations do not communicate to each other. The only traffic outgoing of a particular station is the one directed to the MES central unit. Intra-station data traffic was also measured, detecting mainly UDP traffic between PLC and screen.

III. PROPOSED WIRELESS MES SOLUTION

Based on the high-level requirements and the analysis of key performance indicators presented in the previous section, it can be concluded that the control communication of the production line at MES level is not very demanding in terms of end points (tens of nodes), traffic patterns (very similar in all nodes), payload size (short packets of a few bytes), and overall throughput (moderate, in the order of a few kbps). Moreover, due to the nature of the MES control actions, the communication at this level is delay-tolerant (some delay fluctuations and jitter are tolerated), which makes it suitable for wireless provisioning by using some of the existing technologies such as WiFi or cellular 4G Long Term Evolution (LTE) [2].

The initial wireless MES interface solution designed for the production line at the AAU Smart Production Lab will operate over LTE. Fig. 7 provides an overview of the designed solution using Raspberry Pi-based LTE gateways (GW) to interface the production line and the wireless LTE channel. This solution is easily adjustable to WiFi by simply replacing the LTE modems with WiFi dongles and making a few adjustments

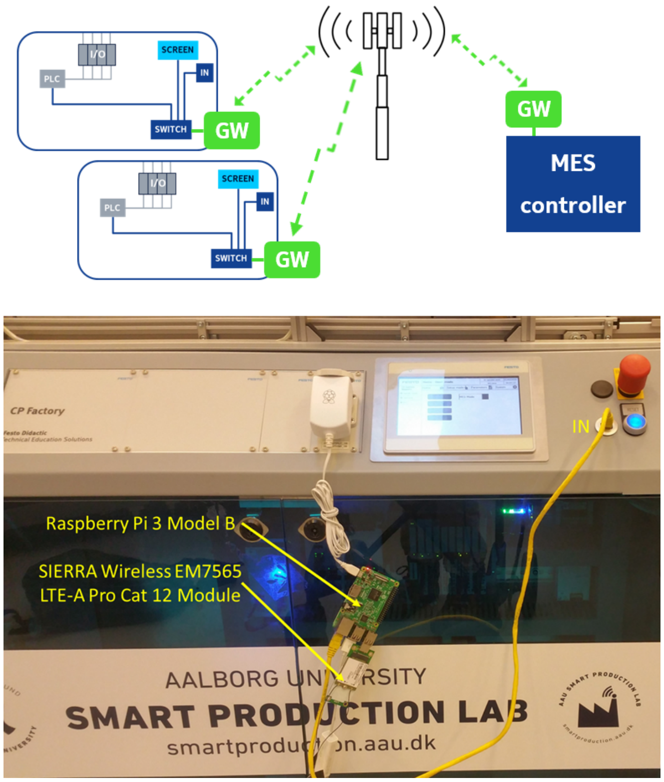

Fig. 7. Simplified overview of LTE GW-based wireless MES solution considering the central MES controller and 2 stations (above) and a picture of one of the implemented GW devices (below) interfaced to the production line for the initial testing.

to the gateway software, and it will be also considered and implemented soon. Since the control communication at MES level is delay-tolerant, we can interchange the them freely. However, a poorer performance is expected in the case of WiFi. While scheduling in LTE will ensure bounded access delays, in the case of WiFi, the contention-based medium access will make the access delays to increase with the number of connected stations, resulting a degraded performance.

The current LTE gateways work by tunneling layer 2 packets on the Ethernet port (production line side) of the Raspberry Pi over LTE. In details, the current solution encapsulates the layer 2 packets in LTE IP UDP packets (other protocols could be considered as well) and sends them via a dedicated access point name (APN) through the core network of the mobile operator to another gateway that will then de-encapsulate it and forward it to its Ethernet interface as a regular layer 2 packet. By using this technique, the gateways act a wireless "cable" between the two end points, that are completely oblivious to the fact that the packets are sent via LTE. This implementation ensures that network functionalities such as dynamic host configuration protocol (DHCP), ARP, broadcast and multicast work without any restriction or the need for extra configuration.

Some initial quick tests performed with the LTE-based solution, considering two gateways (one connected to the central MES controller and one connected to one of the stations), operating over the public LTE1800 network of one of the Danish operators, exhibited a reliable performance with an average end-to-end latency of approximately 90 ms with a variance of 8.8 ms (these includes over-the-air and mobile network core latencies and also tunneling processing delays at the gateways). As expected from current wireless LTE access, where packets need to travel through the radio access and core networks of the mobile operator to be routed [12], these latency values are higher than those provided by the original wired Ethernet-based system. However, as the MES control operations are delay-tolerant, the overall impact on the production system performance is foreseen to be small.

IV. Future Considerations

The first full live trials over the production line of the AAU Smart Production Lab, with all stations operating over wireless LTE, will be soon executed. As mentioned in the previous section, there are plans of making a WiFi version of the system; and the performance over the different technologies will be measured and compared. The scalability of the solution will be also analyzed and tested. However, based on the current MES communication requirements, the system is expected to operate in larger scenarios with a higher number of manufacturing stations than the selected production line.

In cooperation with a Danish mobile operator, the system will be moved from operating over the commercial LTE network to a dedicated industrial private LTE network. Further, virtualized core functions will be considered. It is expected that following these sequential steps will result in a progressive improvement of the end-to-end latency of the system [13].

As a future step, new technologies will be investigated and integrated in the setup to address the wireless provisioning of the time-critical communication at sensor and actuator level [14]. This new level of capabilities, together with the inherent mobility of the wireless systems will soon allow to explore the possibility of overcoming the sequential paradigm of the assembly line by, for example, enabling mobile robots moving items over different work stations according to customized production needs. The envisioned wireless setup will support indeed both the centralized and decentralized control of robots, being the latter enabled by virtual device-to-device communication at IP level. Advanced multi-connectivity protocols such as multipath TCP (MTCP) [15] and multipath quick UDP internet connection (MPQUIC) [16] may be utilized for increasing the transmission redundancy and providing uninterrupted wireless connectivity to the robots while moving across the factory.

V. Conclusion

In this paper, we have presented our vision for a wirelessly-controlled production line, which aims at cost reduction and enhanced production flexibility with respect to a traditional wired setups. In order to identify the communication needs, an analysis of the architecture and the control data traffic over the different entities of a fully-automated assembly line was carried out. Such analysis highlighted that the traffic requirements are more stringent in the communication between programmable logic controllers (PLCs) and sensors/actuators than in the two-way communication between the PLCs and the central manufacturing execution system (MES) entity.

In view of the rather relaxed requirements both in terms of UDP/TCP traffic and latency, we have proposed a wireless MES solution where the Ethernet infrastructure is replaced by cellular connectivity via a commercial or dedicated Long Term Evolution (LTE) network. Future considerations on a private wireless network setup able to support robot swarms scenarios with uninterrupted mobility were also presented.

Acknowledgment

This work is partly supported by the Manufacturing Academy of Denmark (MADE). The authors would like to express their gratitude to Casper Schou and Kelvin K. Nygaard from the AAU Smart Production Lab for their support throughout the different activities. The authors would also like to thank Mads Lauridsen, Guillermo Pocovi and Troels E. Kolding from Nokia Bell Labs for the fruitful discussions.

References

[1] B. Chen, J. Wan, L. Shu, P. Li, M. Mukherjee, and B. Yin, “Smart Factory of Industry 4.0: Key Technologies, Application Case, and Challenges,” *IEEE Access*, vol. 6, pp. 6505-6519, 2017.

[2] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S.A. Ashraf, J. Huschke, I. Aktas, and J. Ansari, “Wireless Communication for Factory Automation: An Opportunity for LTE and 5G Systems,” *IEEE Communications Magazine*, vol. 54, no. 6, pp. 36-43, 2016.

[3] O. Madsen, and C. Møller, “The AAU Smart Production Laboratory for Teaching and Research in Emerging Digital Manufacturing Technologies.” *Procedia Manufacturing*, vol. 9, pp. 106-112, 2017.

[4] FESTO, Industry 4.0 - Qualification for the factory of the future [Online] Available: https://www.festo-didactic.com/int-en/highlights/qualification-for-industry-4.0/cyber-physical-factory/ [Accessed Feb. 2019].

[5] M. Nardello, O. Madsen, and C. Møller, “The smart production laboratory: A learning factory for industry 4.0 concepts,” in *Proc. CEUR Workshop*, 2017.

[6] B.Galloway, and G.P. Hancke, “Introduction to Industrial Control Networks,” *IEEE Communications Surveys & Tutorials*, vol. 15, no. 2, pp. 860-880, 2013.

[7] M. McClellan, *Applying Manufacturing Execution Systems*, CRC Press, 1997.

[8] ANSI/ISA-95.00 (IEC 62264), Enterprise-Control System Integration, Parts 1-5, 2010-2013.

[9] M. Wollschlaeger, T. Sauter, and J. Jasperneite, “The Future of Industrial Communication: Automation Networks in the Era of the Internet of Things and Industry 4.0,” *IEEE Industrial Electronics Magazine*, vol. 11, no. 1, pp. 17-27, 2017.

[10] Tcpdump & Libpcap [Online] Available: https://www.tcpdump.org/ [Accessed Feb. 2019].

[11] ETF RCF-5905, Network Time Protocol Version 4: Protocol and Algorithms Specification, 2010.

[12] G. Pocovi, T. Kolding, M. Lauridsen, R. Mogensen, C. Markmøller, and R. Jess-Williams, “Measurement Framework for Assessing Reliable Real-Time Capabilities of Wireless Networks,” *IEEE Communications Magazine*, vol. 56, no. 12 pp. 156-163, 2018.

[13] V. G. Nguyen, T. X. Do, and Y. Kim, “SDN and Virtualization-Based LTE Mobile Network Architectures: A Comprehensive Survey,” *Wireless Personal Communications*, vol. 86, pp. 1401–1438, 2016.

[14] G. Berardinelli, N.H. Mahmood, I. Rodriguez, and P. Mogensen, “Beyond 5G Wireless IRT for Industry 4.0: Design Principles and Spectrum Aspects,” in *Proc. IEEE Globecom, URLLC Workshop*, 2018.

[15] C. Paasch and O. Bonaventure, “Multipath TCP,” *Queue*, vol. 12, no. 2, pp. 40-51, Feb. 2014.

[16] IETF, QUIC: A UDP-Based Multiplexed and Secure Transport, draft-ietf-quic-transport-14, Aug. 2018.