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Deployment and Evaluation of an Industry 4.0 Use Case over 5G

Winnie Nakimuli[1], Jaime Garcia-Reinoso[1], J. Enrique Sierra-Garcia[2], Pablo Serrano[1], and
Isaac Quintana Fernández[3]
[1] Departamento de Ingenieria Telematica, Universidad Carlos III de Madrid, Madrid 28911 Spain
[2] Department of Electromechanical Engineering, University of Burgos, and ASTI Mobile Robotics, Burgos, Spain
[3] Ericsson Spain, Retama 1, Madrid 28045, Spain

Abstract - The arrival of 5G paves the way for the deployment of the so-called Industry 4.0, which is a new paradigm devoted to the digital transformation of manufacturing and factory production. Because of the resources required to perform this transformation, the importance of field trials and experimentation cannot be overstated, both to support the design of novel methodologies and to validate these designs. In this paper, we leverage the 5G EVE end-to-end open platform to design and validate a novel operation approach for automated guided vehicles (AGVs). This use case consists of the placement of the intelligence that controls the AGV in a remote entity. This movement could improve and simplify the operation of industrial processes. The customizability of the 5G validation platform proves fundamental to evaluate the solution under different deployment architectures and to assess its performance under hazardous radio conditions. Our results demonstrate the ability of 5G to handle latency-constrained use cases with superior performance compared to the current state-of-the-art mobile technology.

Keywords: 5G, AGV, Industry 4.0, KPI

I. INTRODUCTION

5G aims to disrupt mobile networking, in contrast to previous generations that mostly focused on improving the data rate. On the one hand, 5G also considers applications with higher data rate demands (enhanced Mobile Broadband). On the other hand, a special interest is given to services where the limiting factor is the latency/reliability (Ultra-Reliable Low Latency Communications) or the number of connected devices (massive Machine Type Communications). Moreover, the goal of 5G is two-fold: to enhance the communication technologies used in current applications and support novel services that are unfeasible today.

However, to impel verticals to adopt 5G, it is crucial to provide them with easy-to-use 5G platforms to validate the service key performance indicators (KPIs). Instead of experimental software-based platforms for 5G prototyping [1], verticals demand real-life platforms to design and test their applications under realistic conditions. Thus, it is of paramount importance that these platforms support the formal definition and execution of experiments implementing different scenarios.

The European H2020 5G EVE project [2] offers an end-to-end 5G experimental platform that facilitates the definition, execution, and validation of vertical applications using 5G. One of the main objectives of the 5G EVE platform is to reduce the complexity when defining an experiment, allowing verticals to specify them using natural language commands. Furthermore, apart from the pass/fail KPI results, the platform also provides a very detailed report of the experiment execution, highlighting the specific components where the corresponding stakeholder (e.g., vertical, operator, vendor) could improve the performance of the overall system. Although the main objective of the project is to deliver an open platform to accommodate experiments of a plethora of use cases, the consortium includes several verticals that have provided an extensive set of requirements [3]. These use cases are classified as Smart Transport, Smart Tourism, Industry 4.0, Smart Energy, Smart Cities, and Media and Entertainment.

One of the use cases studied in the project, in the context of the Industry 4.0 paradigm, is novel deployment strategies for Automatic Guided Vehicles (AGVs) in factories. These use cases will significantly benefit from 5G [4]. AGVs allow important improvements in the temporal and spatial flexibility of the production lines by adjusting the distribution and the cadence of the production flows. Currently, to minimize latency, AGVs are embedded with internal controllers, which are used to command the actuators (i.e., motors and steering devices) by leveraging the AGV sensor information. However, this “local” placement of the controller has some drawbacks like, for example, scalability and the challenging coordination of multiple AGVs. Consequently, this has motivated removing the controllers from the AGVs, into either central application servers [5] or distributed clusters [6]. On the other hand, shifting the controller from local to remote locations imposes stringent requirements to the communication link connecting sensors/actuators and controllers. Moreover, as AGV functionalities evolve, it would be necessary to transmit other kinds of information in both directions, like pictures and video. In this context, 5G has emerged as a suitable candidate to fulfill those current and future demanding communication requirements [3].

In this article, we present and validate a solution for the remote control of AGVs using a real 5G deployment, assessing its performance in terms of service KPIs (in correlation with 5G network KPIs) and identifying suitable operation scenarios. Additionally, we also provide evidence on the improved performance of 5G over 4G. These results constitute significant contributions as compared against previous works, which are typically either based on the use of experimental platforms (e.g., [1]) or limited to theoretical studies. For instance, in [7], authors discuss the various use cases, requirements, and challenges that 5G wireless communication will have to address in Industrial automation, concluding that 5G is well suited to handle these use cases. We confirm this good performance with the real-life 5G deployment of our use case. Along similar lines, authors in [8] present different deployment strategies to support Industry 4.0 use cases (i.e., from stand-alone to deployments sharing functions with public land mobile networks), along with the costs associated with each option (security, isolation, etc.). We add to this discussion by analyzing the impact of the delay between the AGV and the controller on performance, identifying the operational limits. Finally, in [9], authors examine the use of licensed and unlicensed bands for ultra-reliable low-latency communications (URLLC) factory automation (FA) use cases, discussing the limitations of the unlicensed band and the improvements brought by 5G. Apart from confirming the improved operation obtained with 5G, we contribute to this challenge by analyzing the impact of channel impairments on performance.

The rest of the paper is organized as follows. Section II gives a detailed description of the use case that will be analyzed in this work and the associated service KPIs. In Section III, we discuss the primary use case components, and the use case design, deployment, and validation leveraging the 5G EVE platform. Section IV presents the results of the use case service KPIs evaluation under different conditions, including a comparison between 4G and 5G and the emulation of different communication impairments to identify the feasible deployment scenarios. Finally, Section V summarizes the work done in this paper and provides future work directions regarding this use case.

II. USE CASE DESCRIPTION AND SERVICE KPIS

AGVs are unmanned transport vehicles used to substitute manned industrial trucks and conveyors. Each AGV is controlled by a programmable logic controller (PLC), a module in charge of governing the internal control loop, i.e., collecting the information of the guiding sensors and taking the appropriate control decisions. Because of the tight latency requirements, the PLC is typically co-located with the AGV, so all communications with the sensors and actuators are wired. This architecture is illustrated in Figure 1(a).

When tens or hundreds of AGVs are deployed in the same factory, the above “local control” architecture has severe limitations, e.g., the challenges of coordinating multiple AGVs, or their PLC update. One promising approach to overcome these issues is to delocalize the PLC, i.e., to migrate the intelligence to external servers outside of the AGV. More specifically, the approach consists of a separation of the PLC into (1) an onboard slave PLC (sPLC), which collects the information from the sensors and physical inputs, and is connected to the actuators, and (2) a virtual master PLC (mPLC) running in a server, in charge of processing all information. The mPLC is responsible for taking the appropriate control decisions and sending them back to the sPLC, which translates them to signals to command the actuators. Particularly, the sPLC acts only as a physical signals gateway, and all the control decisions are virtualized and carried out in the mPLC. The “remote control” architecture is illustrated in Figure 1(b). This approach supports the design of more sophisticated control algorithms and more flexible and reconfigurable factories, this being one of the critical advantages of the so-called Connected Industry 4.0. These advantages add to the inherent benefits of the virtualization of the mPLC, for example, redundancy, cost savings, scalability, reduced energy consumption, and hardware independence.

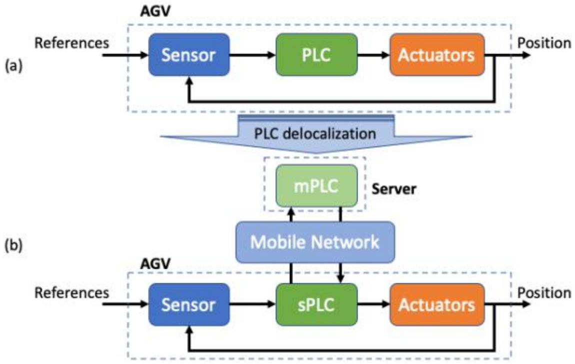

Figure 1. Local control (top) vs central control (bottom)

The “remote control” architecture imposes stringent delivery requirements on the link connecting the sPLC and the mPLC, e.g., short latencies and low packet losses. If the wireless technology cannot fulfill such requirements, it would result in a degradation of the system performance. For example, (i) path deviations of the AGV (and its inherent safety risks), (ii) higher energy consumption, and (iii) AGV service interruption (i.e., the AGV implements a “dead man” control switch that stops the vehicle when no control messages are received in due time) with the associated economic costs. Thus, it is crucial to define a set of service key performance indicators (KPIs) and their related thresholds to identify the regions where performance is adequate.

In this work, we focus on two service KPIs to assess the AGVs’ operation efficiency. As we will see, these KPIs provide a more sophisticated assessment than just the existence of reliable communication between the sPLC and mPLC [10]. These service KPIs are:

- Guide error: the deviation (in centimeters) of the AGV from the correct path, gathered by the sensor in the AGV and sent to the mPLC. Sometimes we are more interested in the variance of this guide error, which marks the correctness of the control.

- Current consumption: the instantaneous current (in Amperes) consumed by the AGV, also collected by the AGV and sent to the mPLC.

Naturally, these two service KPIs are related: large and frequent guide errors will trigger frequent variations in the control actions (i.e., fluctuations in the angular velocity) to correct them, resulting in more significant energy consumption. Furthermore, as will be illustrated in our experiments, these service KPIs are related to the network KPIs (i.e., the end-to-end delay and channel reliability between the sPLC and the mPLC). In particular, large delay or packet loss rates result in bigger guide errors, which in turn, result in large actuator corrections by the controller, subsequently increasing the AGV current consumption. Consequently, if the delay or packet loss rates keep increasing, this will cause the AGV system to be unstable and lose its trajectory. All these relationships are analyzed in detail in Section IV.

Given the substantial costs associated with the deployment of this novel central control architecture for AGV operation, it is paramount to validate its operation under real-life conditions and assess its tolerance to communication impairments. In what follows, we will first present the software and hardware elements used to specify and run these validation experiments and then provide the performance evaluation results.

III. USE CASE DEPLOYMENT AND VALIDATION

We next present all the steps required to design a set of 5G experiments for any use case, using the tools provided by the 5G EVE platform: we first introduce the information models available to describe a service and its associated experiments; then, we describe the operation workflow to specify and run experiments, as well as the 5G EVE platform, with emphasis on the key components for this use case; and finally, we particularize the methodology for the use case.

A. 5G EVE Information Model

The 5G EVE platform [2] is an end-to-end 5G facility currently used by vertical industries to run and validate their use cases via the appropriate KPI measurements. The platform comprises three main layers: the access portal, the inter-working layer, and site-specific modules. All three layers work together to facilitate the different phases of an experiment: design, onboarding, instantiation, execution, monitoring and validation.

For the design of the experiments, the project has defined an information model of high-level templates, called blueprints. To fully define an experiment, users start from the service blueprint, which serves to identify the service components or applications, the connectivity among them, and application-specific parameters and metrics. If verticals need to test their service under different network conditions, they rely on context blueprints to define, e.g., different communication conditions (delay, bandwidth, packet loss). All actions performed during a given experiment are defined in the so-called test case blueprints. After these blueprints are defined, verticals can integrate them in the experiment blueprint, which combines one vertical service blueprint, one or many context blueprints, one or many test cases blueprints, the infrastructure metrics, and vertical service KPIs. Besides, the assessment (i.e., pass/fail test) of the target service KPIs is defined in this blueprint.

Once these high-level templates are defined, a user has to specify the low-level deployment templates used to describe the implementation details (resources and connectivity) of the functions composing the service. Specifically, using the physical network function descriptors (PNFDs) and virtual network function descriptors (VNFDs). These templates are combined in the so-called network service descriptors (NSD), which are low-level deployment templates to identify the constituent VNFDs, PNFDs, and their interconnections. Each blueprint, apart from the test case blueprint, is accompanied by the corresponding NSD.

B. 5G EVE workflow

Once the blueprints have been defined, the next step is to onboard them using the 5G EVE portal. When the experiment is ready, the user can trigger the instantiation of the experiment in the portal, which results in the deployment and interconnection of the network functions and applications. Consequently, users can select one of the test case blueprints previously defined in the experiment blueprint, which, as already mentioned, include the network conditions used to assess one or many service KPIs. The 5G EVE platform also allows experimenters to define their service using natural language commands, e.g., "Experiment with AGV in Spain on 22/03/2021 and time 14:00 with #5G #1 AGV #10% packet loss #50ms delay #30s duration and validate a guide error KPI below 1cm". Once the test is finished and based on the collected metrics and the service thresholds defined in the blueprints, the 5G EVE platform generates a validation report.

C. 5G EVE platform and Use Case components

We illustrate in Figure 2 a simplified version of the 5G EVE platform and its components, representing some of the main resources available at the Spanish site, hosted in the 5TONIC laboratory [11]. On the one hand, the two main components used in all use cases in the project are:

- The network function virtualization (NFV) platform comprises a management and orchestration (MANO) block and several compute nodes. This component is used to instantiate the corresponding virtual network functions and links, as defined in the network service descriptors of an experiment.
- A complete 5G non-standalone (NSA) mobile network provided by Ericsson Spain, which includes two radio nodes, the 5G New Radio

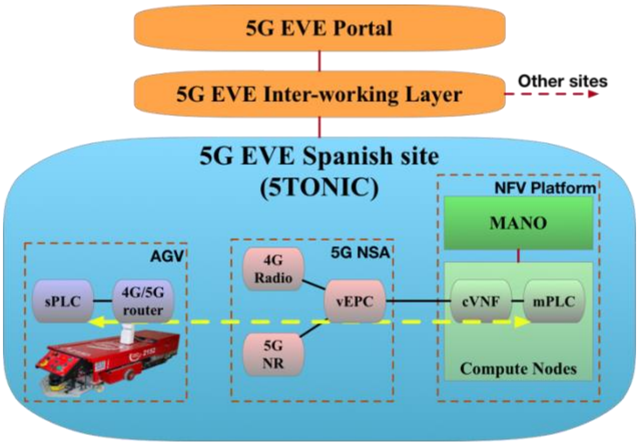

Figure 2. Use case components

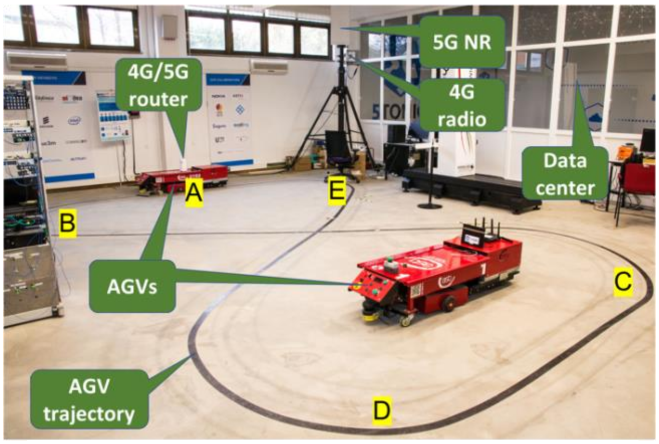

Figure 3. Picture with the main components of the use case

(NR) and the 4G radio, together with a virtualized Evolved Packet Core (vEPC) supporting NSA. The 5G new radio operates in the n78 band and provides a bandwidth of 50MHz with a time division duplex (TDD) pattern of 4:1. Whereas, for the LTE-only tests, we use the band b7 with a bandwidth of 20MHz.

On the other hand, the specific components for this use case are the AGV and mPLC (portrayed in Figure 2) provided by ASTI Mobile Robotics [12]. This AGV is a mobile industrial platform equipped with: (i) sensors to measure critical variables such as the guide error, current consumption, battery status, and wheel velocity, to be reported to the master PLC (mPLC), (ii) a slave PLC (sPLC) connected to one of the ethernet ports of a 4G/5G router, responsible for transmitting this sensor information to the mPLC; and (iii) actuators, which comprise the motors and the wheels, to perform the guided movement following the received instructions from the master PLC (mPLC). A picture of the actual components and the real scenario is provided in Figure 3, where the MANO and compute nodes are located in the 5TONIC data center. This picture also shows the path trajectory, delimited by a magnetic band with a lemniscate-shaped (figure-eight) path with a perimeter of 27 meters. The AGV is placed on top of this path, and the main objective of this use case is that the AGV efficiently follows the path with minimal deviation (i.e., guide error) and energy consumption.

During the experiment execution, the sPLC sends the mPLC, via the mobile network, 10 UDP frames every 10ms with the sensor information. Among those 10 frames, 2 of them provide critical information for the guidance: one includes the speed of the AGV, and another transports the guide error. The mPLC implements a proportional-integral-derivative (PID) controller and, depending on the guide error sent by the sPLC, the mPLC generates the proper control signals for the AGV actuators; these signals are sent back to the sPLC and consequently trigger the actuators. The mPLC commands are transported using four different packets, where one of them includes the target linear and angular velocities of the AGV.

D. 5G AGV Use Case Design

Here we describe how to use the above resources to design the use case experiments. The first step is to define the service blueprint and its corresponding NSD, which includes the mPLC VNFD identifier, the related virtual links, and the two metrics to collect during the experiment execution: the guide error and the current consumption. The context blueprint and its associated NSD only include the context VNF (cVNF) with the corresponding VNFD identifier and two virtual links connected to the mPLC and the sPLC. This cVNF is a Linux virtual machine equipped with (i) the *tc* application from the Linux network emulation tools [13] is used to add network impairments (we confirmed the accuracy of the impairments introduced by *tc* in extensive offline tests), (ii) *Filebeat* from the Elastic project [14], a data shipper used to publish the application-specific metrics to the corresponding elements of the 5G EVE platform, (iii) *tcpdump* [15] to capture packets used to extract metrics, and (iv) a custom metric-processing script, which receives as input the captured network packets and computes the guide error and current consumption over time.

The test case Blueprint is composed of three scripts: configuration, execution, and reset configuration. The configuration script sets up all the necessary configurations before the tests start. The execution script varies per experiment and, in general, is configured to (i) add network impairments (e.g., delay and packet loss) to the cVNF using the Linux *tc* command, and (ii) start capturing packets on one of the interfaces of the cVNF, which in turn are processed in real-time by the custom metric-processing script. Finally, the reset configuration script performs three actions: (i) to stop the packet capture on the cVNF, (ii) to stop the mPLC, and (iii) to delete the introduced network impairments.

Finally, the experiment blueprint (and its NSD) combines the above blueprints into a single blueprint ready for deployment. Moreover, the service KPIs for this use case, i.e., current consumption and guide error, are defined in this blueprint.

All these blueprints and NSD files are published in the GitHub of the project, in the following URL: https://github.com/5GEVE/blueprint-yaml/tree/master/UC_3.1_Industry4.0_ASTI

IV. PERFORMANCE EVALUATION

In this section, following the methodology described in section III, we evaluate the performance of the remote-controlled AGV obtained under various scenarios. For each considered scenario, an experiment starts with the AGV in its charging station (position A in Figure 3) and finishes once the AGV returns to this position.

In section IV.A, we compare the performance of the remote-controlled AGV using 4G and 5G. Then, in sections IV.B, and IV.C, we analyze the relationship between the guide error, which is one of the service KPI defined by the vertical, and the main 5G network KPIs, i.e., delay and packet loss.

A. AGV Baseline performance with 5G in comparison with 4G

We start our performance assessment by first deploying the use case under the best possible conditions, i.e., with the mPLC closest to the AGV (i.e., zero additional delays) and non-impaired channel conditions, and then validating the correct operation of the service. Thanks to the 5G EVE platform functionality, which collects service-specific metrics published by the vertical application, we can access the target angular velocity (TAV) sent by the mPLC to the sPLC. The TAV is computed by the mPLC based on the guide error received from the sPLC and feeds the actuators of the AGV, which in turn control the orientation and velocity of the AGV. We represent this TAV for one execution of the experiment in Figure 4 (bottom) for its whole duration, which lasts for approximately 2 minutes: as the figure illustrates, at around 15s, the AGV turns left in two steps (position B in Figure 3); then at 50s, it turns right (position C); at 70s, it turns right again (position D) and finally, at approximately 100s turns left (position E) before reaching the charging station (position A). Note that we repeated the experiment several times and obtained a very similar performance, with minor differences.

To assess the quality of the AGV movement using the 5G network, we leverage the guide error reported by the magnetic antenna sensor to the mPLC, which is also stored in the monitoring component of the 5G EVE platform. More specifically, we first compute the differences between two consecutive samples of the guide error, and then calculate the absolute value of the result. This absolute variation of the guide error (AVGE) is represented using a moving mean (MM) of 300 samples (for ease of visualization) in the top graph of Figure 4 (blue line). According to the results, this error variance oscillates between 0 and 0.08cm, with an average value of 0.031cm. To put these results in context, we repeat the experiment using a 4G deployment and represent the corresponding absolute variation guide error (orange line): in this case, the performance is much more erratic, with peaks close to 0.1cm and an average value of 0.048cm. These results illustrate the improved performance caused by the lower latency of the 5G NR compared to 4G radio [7], as the former reduces the guide error by approximately 34.5% compared to the latter.

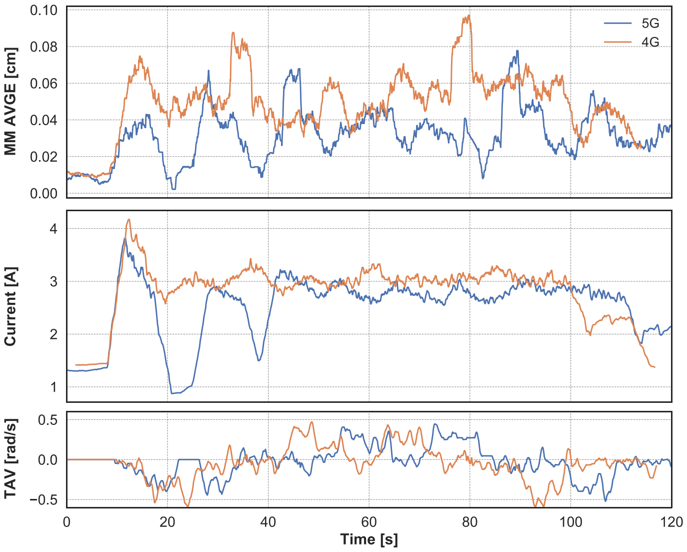

Figure 4. Comparison between 4G and 5G

A smaller guide error not only extends the scenarios in which this use case can be deployed, as a “stringent” operation can be achieved, but also results in a more efficient operation. To illustrate this, we also collect the current consumed by the AGVs (i.e., the second considered service KPI). Accordingly, we compute the moving mean of 300 samples for the same scenarios as shown in Figure 4 (middle subplot). Here, although the differences are smaller, the average current consumption is reduced from 2.78A to 2.47A, i.e., the consumption is reduced by approximately 11%, resulting in a notable improvement of the lifetime of the device (until its batteries must be recharged). For instance, for the 150Ah battery used by the AGV, the use of 5G results in a lifetime extension of 5 hours.

B. Impact of the vPLC placement

In the design of a 5G AGV use case, it is essential to determine the exact placement of the remote mPLC. This decision affects the communication delay between the sPLC and the mPLC, which, in turn, has a direct effect on the AVGE and the energy consumption of the AGV. Thus, in this work, we define several experiments to emulate different mPLC placements, introducing an extra delay in the communication between the sPLC and the mPLC. As already presented, the 5G EVE platform easily supports the addition of these types of impairments.

More specifically, we vary the one-way extra delay from 0 to 250ms in steps of 50ms. For each considered value, we conduct five different tests, each one corresponding to an additional lap. For each

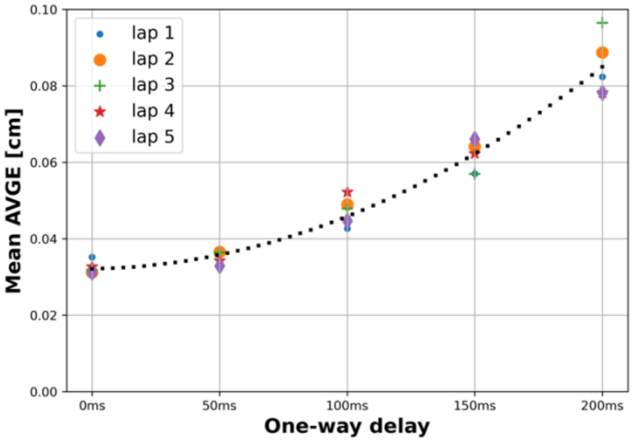

Figure 5. AGV mean guide error for different placements of the mPLC

lap, we proceed as in the previous section to compute the AVGE (i.e., there are five AVGE values per delay considered). Figure 5 presents the statistical mean of the AVGE for each lap and for all given extra delays defined in the experiment (note that there are no results for 250ms since the AGV never completed the lap). For example, the result in Figure 5 corresponding to a 0ms extra delay and lap 5 is the mean value of all AVGE samples presented in section IV.A for the 5G experiment.

According to the results, there seems to be little impact on performance when adding 50ms of extra delay. However, from this threshold, the AVGE noticeably increases with the delay, with an average rate of approximately 4mm/s. Nonetheless, the relationship between this service KPI and delay is far from linear but can be well approximated with a second-order polynomial (depicted as a dotted line in Figure 5). A more detailed analysis of this relationship is part of our future work.

From the results, we conclude that although a maximum delay of 200ms could be tolerated, the rapid increase of the mean AVGE with the delay (and the associated energy consumption increase, shown earlier) suggests sticking to relatively lower values.

C. *Impact of radio conditions*

Factories are challenging environments for wireless technologies [7]. Thus, it is crucial to analyze the behavior of the use case under radio channel impairments, to understand the sensitivity of the AGV operations to these effects. Subsequently, we define a set of experiments where the percentage of packet losses varies from 5% to 40%, in steps of 5%. The same packet loss rate is applied in both directions, so both actuator commands and sensor information packets are affected (the rest of the parameters are left unchanged). The results from these experiments are depicted in Figure 6.

Similarly to Section IV.B, only the mean AVGE is presented for each of the five laps in every packet loss percentage defined in the conducted experiments. Furthermore, we illustrate in Figure 6, using a dotted line, a second-order polynomial adjustment of the mean AVGE to the packet loss values. Note that we include the results when the packet loss is 0% for the sake of completeness, as these correspond to the case with no extra delay described in the previous section. Notice that the results for 40% are not shown, as the AGV does not complete any single lap under such conditions.

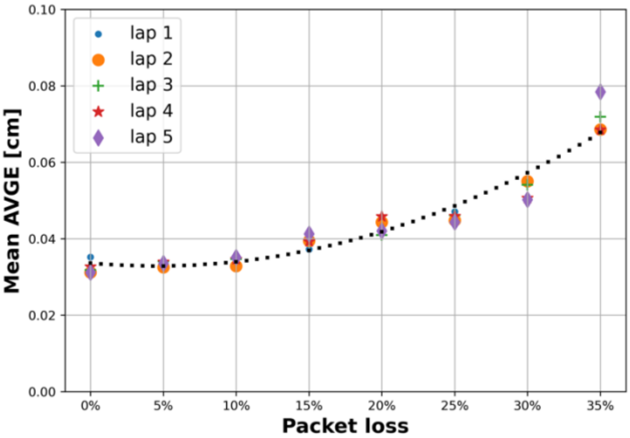

Figure 6. AGV mean guide error for different radio conditions

These results illustrate the tolerance of the system to packet losses. For 10% of packet loss or less, the AGV stirs over the path smoothly. The increase from 10% to 30% has a severe impact on the correctness of the guide, and errors above 30% result in unacceptable performance.

V. CONCLUSIONS AND FUTURE WORK

To promote the adoption of 5G mobile networks among verticals, it is crucial to validate the fulfillment of their service key performance indicators in real-life conditions. Thus, 5G evaluation platforms are considered fundamental to achieve this goal. It is also vital to facilitate the definition and execution of such experiments intuitively, and, in this respect, the H2020 5G EVE platform offers this kind of service. In this work, we have performed several experiments using this platform to investigate all feasible scenarios to deploy a remote-controlled AGV use case using 5G. Our results show that it is feasible to use 5G as the mobile technology to interconnect the AGV with the virtualized controller, placed on the edge or in the cloud, close to the edge. Furthermore, the system presents good performance even with a large percentage of packet loss, which is the effect of hazardous radio conditions typical in a factory.

As future work, we plan to extend our tests using new generation AGV equipped with more sensors and cameras, imposing more stringent requirements on the mobile network. These new tests will be carried out using a 5G stand-alone network.

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BIOGRAPHIES

Winnie Nakimuli received the Bachelor's Telecommunications Engineering from Makerere University in Kampala, Uganda in 2011, and the Master in Telecommunications Engineering from the University of Trento, Italy in 2014. She is currently a PhD candidate at the Univ. Carlos III de Madrid, Spain. She is involved in the European Union's H2020 5G-EVE research project. Her research interests include 5G Network Slicing, Network Functions Virtualization (NFV), Software Defined Networking (SDN) and Machine Learning.

Jaime Garcia-Reinoso received the Telecommunications Engineering degree in 2000 from the Univ. de Vigo, Spain and the PhD in Telecommunications in 2003 from Univ. Carlos III de Madrid, Spain, where he is a visiting professor. He has published over 50 papers in the field of computer networks in magazines and conferences. He has been involved in several international and national projects related with next generation networks, signaling protocols, information-centric networking and 5G networks like the EU IST MUSE, 5G-Crosshaul, 5G-Transformer and 5G EVE.

J. Enrique Sierra-García received his M.Sc. degrees in Electronics and Telecommunications from the University of Valladolid (UVA) in 2007 and 2015 respectively, his M.Sc degree in Control Engineering from the National University for Distance Education (UNED) in 2014, and his Ph.D in Computer Science in 2019. Since 2012 he has been with the University of Burgos, where he is currently a Lecturer in System Engineering and Automatic Control in the Department of Electromechanical Engineering. He is the founder of the Joint Research Unit ASTI-UBU on Autonomous Vehicles, Mobile Robotics and AGVs. He has been principal researcher in 15 research projects related with mobile robotics.

Pablo Serrano got his Telecommunication Engineering degree and his PhD from Univ. Carlos III de Madrid (UC3M) in 2002 and 2006, respectively. He has been with the Telematics Department of UC3M since 2002, where he currently holds the position of Associate Professor. He has held visiting positions at Univ. Massachusetts Amherst, Univ. of Edinburgh, Trinity College Dublin and Telefónica R+D Barcelona. His research interests lie in the analysis of wireless networks and the design of network protocols and systems. He has over 80 scientific papers in peer-reviewed international journals and conferences and has served on the TPC of many conferences. He is a Senior Member of the IEEE.

Isaac Quintana Fernández got his Telecommunication Engineering degree in 2008. He worked as research assistant in Montana State University for 8 months, 1 year in British Telecom and almost 4 years for Nokia. For the last 9 years, he is 5G, IoT & LTE RAN (Radio Access Network) Solution Architect at Ericsson, with extensive experience in product and solutions for 5G, Internet of things, LTE and 3G build up in the main telecommunication operators in Spain as Telefónica, Vodafone, Orange and abroad such as Vodafone Portugal, Ireland and Germany or Deutsche Telekom in Germany.