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Design and Empirical Validation of a Bluetooth 5 Fog Computing Based Industrial CPS Architecture for Intelligent Industry 4.0 Shipyard Workshops

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ABSTRACT Navantia, one of largest European shipbuilders, is creating a fog computing based Industrial Cyber-Physical System (ICPS) for monitoring in real-time its pipe workshops in order to track pipes and keep their traceability. The deployment of the ICPS is a unique industrial challenge in terms of communications, since in a pipe workshop there is a significant number of metallic objects with heterogeneous typologies. There are multiple technologies that can be used to track pipes, but this article focuses on Bluetooth 5, which is a relatively new technology that represents a cost-effective solution to cope with harsh environments, since it has been significantly enhanced in terms of low power consumption, range, speed and broadcasting capacity. Thus, it is proposed a Bluetooth 5 fog computing based ICPS architecture that is designed to support physically-distributed and low-latency Industry 4.0 applications that off-load network traffic and computational resources from the cloud. In order to validate the proposed ICPS design, one of the Navantia's pipe workshops was modeled through an in-house developed 3D-ray launching radio planning simulator that allows for estimating the coverage provided by the deployed Bluetooth 5 fog computing nodes and Bluetooth 5 tags. The experiments described in this article show that the radio propagation results obtained by the simulation tool are really close to the ones obtained through empirical measurements. As a consequence, the simulation tool is able to reduce ICPS design and deployment time and provide guidelines to future developers when deploying Bluetooth 5 fog computing nodes and tags in complex industrial scenarios.

INDEX TERMS Industry 4.0, IIoT, cyber-physical system, ICPS, fog computing, edge computing, Shipyard 4.0, Bluetooth 5, LP-WAN, 3D ray launching.

I. INTRODUCTION

The application of the Industry 4.0 and Industrial IoT (IIoT) paradigms to traditional industrial facilities is changing dramatically the way factories and industries operate and communicate thanks to the use of some of the latest technologies for managing, monitoring and optimizing industrial processes [1]. Shipbuilding is one of the many industries that can benefit from Industry 4.0 and IIoT principles, since building large vessels is a really complex task that involves many processes that can be enhanced and optimized through technology to meet time and quality constraints.

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Navantia, a Spanish 300-year old company, is one of the shipbuilders that is pushing the application of Industry 4.0 technologies to improve its competitiveness. To do so, Navantia is leading the "Shipyard 4.0" project, which seeks to create a modern shipyard through the application of the Industry 4.0 principles to build the next generation of hi-tech military and civil vessels.

There are different research lines established within the Shipyard 4.0 project, but the so-called Auto-ID for Intelligent Products line is among the ones with the greatest impact on a shipyard, since its objective, which consists in identifying objects, products, facilities, tools or people automatically throughout their lifetime, has potential to affect almost every shipbuilding process.

A pipe workshop is one of the most important locations in a shipyard due to the number of pipes to be built for a vessel (usually between 15,000 and 40,000), their different features (e.g., dimensions, material, accessories) and the fact that each pipe requires to be processed through different stages depending on the desired features. Therefore, it is essential to track the pipes of a workshop in order to improve the efficiency and overall performance of the shipyard. Currently, pipe workshops usually make use of printed labels that are attached to pipes. Such labels include information on the identification of the pipe or on the processes that have to be carried out on each pipe. However, such an identification method implies certain limitations:

- The identification process is performed manually, thus requiring the intervention of the pipe workshop operators that devote a relevant amount of their working time using devices like barcode readers to collect information from tagged pipes.
- Human intervention during pipe identification is prone to errors. For instance, readings may be not performed or they may be performed at the wrong time instants.
- Printed label-based identification usually requires Line-of-Sight (LoS) between the reader and the read label due to the use of barcodes or QR codes. This is a problem in environments where obstacles prevent the existence of LoS.
- In the cases where the whole information is printed on a label, it is not possible to update it without replacing the label.
- In order to locate a pipe, shipyard operators need to look for it through the facility, since pipes are usually moved continuously through the different stages of the workshop (i.e., a pipe exact position is only known when its label is read, but its location is unknown between readings).

Therefore, ideally, pipe tracking should:

- Be automatic.
- Be as autonomous as possible, ideally requiring no intervention from shipyard operators.
- Be able to work where there is Non-Line-of-Sight (NLoS) between the tags attached to the pipes and a reader.
- Enable dynamic updates on the information associated with the labels. This can be achieved with the help of unique pipe identifiers and databases that can be accessed through a reading device.
- Allow for positioning the pipes automatically in real or near-real time. It is important to note that pipe location awareness enables automating multiple tasks, like the notification of the arrival of a pipe to a certain area of the workshop.

This article presents the design and empirical validation of an architecture of an Industrial Cyber-Physical System (ICPS) based on the use of Bluetooth 5 and fog computing that is aimed at tracking and monitoring in real time the pipes built in a shipyard workshop. The proposed system considers the practical problems that arise when deploying a pipe identification system in a shipbuilding scenario, where there are usually a lot of metallic objects (most of which are usually large) whose presence derives into signal blockage, numerous reflections and, as a consequence, into signal fading.

In addition, this article analyzes the feasibility of the use of Bluetooth 5 in a pipe workshop, validating it through simulated models and practical experiments. This validation has been performed by means of an in-house developed 3-Dimensional Ray Launching (3D RL) simulation tool. To the knowledge of the authors, this deterministic approach has not been used previously in similar industrial scenarios. Moreover, it is also the first time that the tool has been validated for Bluetooth 5 communications. Furthermore, no previous evaluation has been found in the literature on the use of Bluetooth 5 for similar scenarios. Therefore, this article includes the following four main contributions:

- A novel Bluetooth 5 based fog computing architecture for ICPSs is proposed.
- To the knowledge of the authors, this is the first article that analyzes the deployment of Bluetooth 5 based ICPS in an industrial environment like a shipyard.
- The article details how a radio-planning tool can be used to design the deployment of Bluetooth 5 infrastructure for such a unique scenario.
- Finally, the usefulness of the proposed tools and methodology is demonstrated by comparing real empirical measurements and simulations.

The rest of this article is organized as follows. Section II describes the wireless propagation characteristics of Navantia's pipe workshop and reviews the state of the art on ICPSs, fog computing and Bluetooth 5 developments for industrial scenarios. In addition, Section II also analyzes the most relevant communications architectures and identification/tracking technologies for shipbuilding applications. Section III details the proposed system architecture and the characteristics of the used Bluetooth 5 devices. Section IV validates the proposed system in a test scenario and then

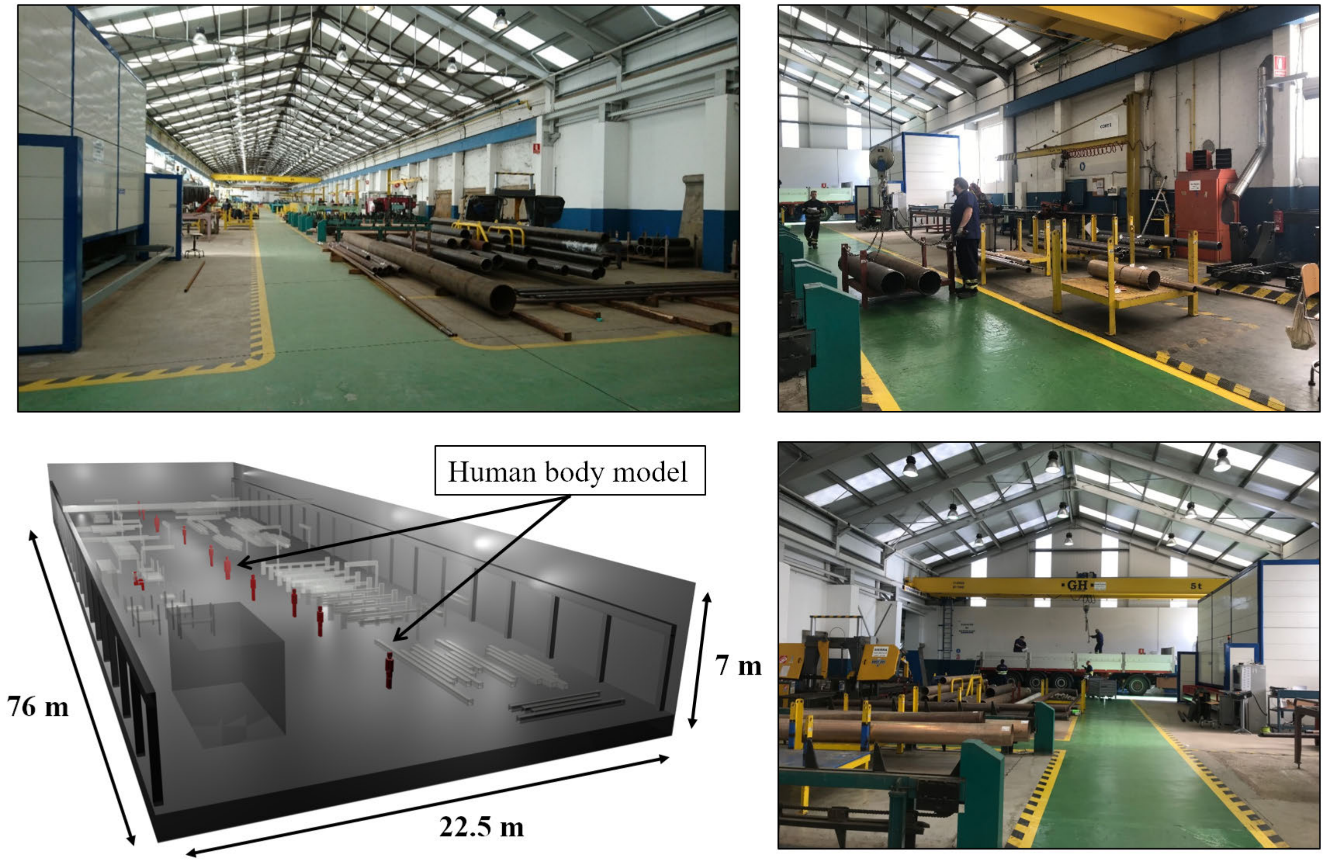


FIGURE 1. Pictures of the general view (top left) and different areas (top right, bottom right) of the pipe workshop together with the 3D model of one of the wings of the workshop (bottom left).

analyzes the radio propagation characteristics of the proposed Bluetooth 5 system in Navantia's pipe workshop by comparing the results obtained by the in-house simulation tool with empirical measurements. Finally, Section VI is devoted to the conclusions.

II. RELATED WORK

A. PROPAGATION IN NAVANTIA'S PIPE WORKSHOP

The specific pipe workshop where the experiments shown in this article took place is in an unobstructed two-wing building that is roughly 120 m long and 40 m wide. Part of the workshop is shown in Figure 1 together with the 3D model of one of the wings. Inside the building, pipes go through multiple areas depending on the manufacturing processes they are subjected to [2].

As it can be observed in the pictures in Figure 1, there are a relevant number of large metallic objects in the workshop. Such metallic objects create a highly reflective scenario with strong multipath components that usually derive into high levels of electromagnetic interference [3] that affect the system reliability [4], [5]. In fact, interference within industrial environments strongly degrades system performance because of the existence of impulse noise sources [6], which can be more relevant in the case of wireless sensor networks due to limitations in radio resource allocation and signal processing capabilities [7].

In the past, intensive measurement campaigns were carried out in similar industrial environments that showed the influence on wireless communications of multiple interference sources (e.g., power converters, welding systems, electrical engines) and certain industrial components [5]. Moreover, previous studies provided radio planning solutions based on regressive propagation loss models [5] or on the use of stochastic models for short-range wireless communications [8]. The methods proposed in such works provide an estimation on the initial coverage/capacity as a function of the required sensitivity, but provide little information in terms of time-domain characterization (e.g., power delay profiles or delay dispersion). In order to fully consider the impact of highly reflective objects (mainly metallic pipes) as well as their distribution, deterministic estimation of the wireless channel will be taken into account in this work. Specifically, this article details the use of an in-house 3D RL tool that includes specific code to construct complex metallic pipe distributions. Moreover, the tool is able to perform specific processing of the received power data and time-domain characterization in order to optimize code convergence and hence minimize computational cost. The tool considers the transmitted signals and the interference contributions, thus leading to a higher accuracy in coverage/capacity estimations, which can be employed for network analysis as well as for the network planning and design phases prior to deployment.

It must be also noted that current communications technologies used for IIoT scenarios have not yet been able to manage properly the requirements of long reading ranges and cost-efficiency, especially in scenarios that are hostile for electromagnetic propagation [4]. Nevertheless, recent solutions like Low-Power Wide-Area Networks (LPWANs) have emerged as a promising alternative that can be combined with the so-called short-range technologies. This is one of the reasons why in 2016 the Bluetooth Special Interest Group (SIG) presented Bluetooth 5 [9], whose primary aim is to enhance the previous versions of Bluetooth and thus provide significant enhancements with respect to the preceding specifications regarding range, speed, broadcasting capacity, reduced power consumption and coexistence with other cellular and LPWAN technologies.

B. INDUSTRIAL CYBER-PHYSICAL SYSTEMS

ICPSs are expected to empower the fourth industrial revolution by enabling the creation, operation and interconnection of intelligent heterogeneous systems [10], [11]. The latest academic literature is mainly focused on reviewing the state-of-the-art and on improving certain specific aspects of ICPSs. For instance, in [12] the authors review the state of the art of distributed filtering and control of ICPSs. As a result, they devise future research lines for practical ICPSs in order to face their limitations in communications links, communications bandwidth, computational burden, energy consumption, plug-and-play capabilities, scalability and special engineering requirements. Similarly, in [13] the authors indicate open research directions after analyzing the latest advances in scheduling and analytical techniques for achieving real-time performance. Considering the growing complexity and increased connectivity of ICPSs, other researchers focused on improving their cybersecurity. For example, in [14] the researchers propose to apply a runtime enforcement to prevent physical damage from a compromised control system.

Other authors tackled interoperability challenges. For instance, in [15] it is proposed an open-source implementation of an interoperability layer that maps data into an ISA95-based information model without requiring changes on legacy devices. The performance of the proposed approach is evaluated under several deployment configurations. Finally, it is worth mentioning that some authors focused on advanced service-oriented computing architectures to collect and handle industrial big data [16]. Despite the abundance of ICPS-related literature, to the knowledge of the authors of this article, apart from their previous work [2], [17], there are no other recent articles that present novel developments for ICPS for the shipbuilding industry.

C. FOG COMPUTING FOR SHIPBUILDING

Although cloud computing and service-based solutions have been traditionally used by ICPSs [16], they may get in conflict with certain Industry 4.0 principles that seek to avoid single points of failure, that limit the dependency on external systems and that foster geographically distributed heterogeneous platforms, decentralized processing, autonomous decision-making, scalability and reliable real-time control of critical resources. Fog computing solutions were introduced to tackle such problems and provide storage and local processing together with low latencies and enhanced security by pushing the computation resources into the network edge [18]. There are few examples of ICPS for shipyards in the literature and, apart from the previous work of the authors [2], [17], none of such ICPSs deals with the use of fog computing on shipyards to fulfill service requirements. Specifically, in [2] the foundations of an ICPS for a shipyard pipe workshop are described, while in [17] a fog computing based communications architecture is validated through extensive experiments. In such a latter paper the results show that, under regular loads, fog computing gateways react between 5 and 481 times faster than a traditional cloud computing based approach.

D. BLUETOOTH 5 FOR INDUSTRIAL SCENARIOS

The IIoT paradigm can cover a wide array of use cases [19], [20], so there is not a single identification and tracking technology that can be applied to all of them. For instance, LPWAN technologies may fulfill the reading range and power consumption requirements of certain IIoT applications, but they are not suitable for applications that demand high throughput, low latency and scalability [21]. However, Bluetooth 5 holds the promise of meeting the demands of most IoT applications, so it can be considered a good candidate for IIoT implementations.

The application of Bluetooth 5 has been previously evaluated in different scenarios. For instance, in [22] the suitability of Bluetooth 5 was assessed in low-power home automation devices. The results presented in such a paper show that the evaluated devices reach four times the range of the previous version of Bluetooth (4.2), they transmit twice as fast and their broadcasting capacity is multiplied by eight. Yin *et al.* [23] confirm such results and show that Bluetooth 5 has a stronger robustness against interference.

There are not many references in the literature on the use of Bluetooth in shipyard applications and all of them are rather outdated. One of such examples is [24], where the authors propose a Bluetooth system for positioning workers that was able to achieve a 1.2 m accuracy in a cluttered environment inside a mockup shipyard workshop. A similar system is proposed in [25], where experiments for tracking workers' positions and movements were performed with 6 base stations within an initial area of $15 \times 20\,\mathrm{m}^2$ achieving a Root Mean Square (RMS) error of 3.4 m. Such an area was decreased to $7 \times 7\,\mathrm{m}^2$ reaching an RMS error of 1.3 m. These results were further compensated by adding a second mobile station attached on the wearer's back decreasing the error down to 2.3 m and 1.2 m, respectively.

In the case of general industrial scenarios, although there are some recent works that evaluate the feasibility of using Bluetooth Mesh networking for indoor localization within smart factories [26] or wearable operator monitoring [27], there are just a few of recent articles that use Bluetooth 5. For instance, a preliminary design of an asset tracking system is presented in [28].

E. IDENTIFICATION AND TRACKING SYSTEMS FOR SHIPBUILDING

The optimization of the tasks involved in smart factories processes has been thoroughly studied in the past years and certain Industry 4.0 technologies have already been analyzed thoroughly [1], [29]. Examples of such enabling technologies are wireless communications, additive manufacturing, big data and data analytics, industrial augmented and virtual reality, autonomous robots and vehicles, simulation software [30] and, recently, more disruptive technologies like blockchain [31], [32] or post-quantum IoT [33].

For instance, in the case of shipbuilding, the use of robots has been proposed for optimizing tasks like hull blasting [34] or welding [35]–[39]. Similarly, wireless sensor technologies have been recently used for monitoring shipbuilding tasks. Most of the examples are focused on toxic gases detection [40], or more specifically, the concentration of CO [41]. An example of a safety management monitoring system using sensors and Radio Frequency IDentification (RFID) is presented in [42]. The system, which was designed for a Korean shipyard, proposes a risk-free backward operation of forklift trucks, a driver safety management service, a Green Zone service, and an integrated monitoring service to prevent safety accidents during transportation of pipes for large vessels. A system with a similar purpose is introduced in [43], where the authors propose a LoRaWAN-based smart health, safety and environment system for shipbuilding and onshore plants. In such an article, the use of a LoRa relay is introduced to ensure a higher Signal-to-Noise Ratio (SNR) and improve the packet reception rate both for an underground scenario and confined spaces.

Finally, it is worth mentioning that, in the last years, Industrial Augmented Reality (IAR) solutions have been also presented to help in the manufacturing process and the visualization of the location of tools and products in the shipyard [44]. Moreover, recent solutions describe the so-called hyper-environments that combine sensor networks, RFID and Virtual Reality (VR) to improve supply tracking in construction and assembly industries [45].

F. POTENTIAL TECHNOLOGIES AND COMMUNICATIONS ARCHITECTURES

There are different wireless technologies that can be used for providing communications interfaces and identification to pipe tags. The most relevant of such technologies are compared in Table 1. These technologies are compared in terms of their operating frequency, maximum reading range, maximum theoretical data rate, key features and main applications.

Navantia's pipe workshop currently tracks pipes using barcodes, a set of parallel lines that store a limited amount of information. Barcodes can be either lineal or two-dimensional (e.g., QR codes) and in order to read them, the distance to the reader has to be up to tens of centimeters (several meters in some specific models) and with LoS.

Among the technologies compared in Table 1 there are several that seem promising, like Wi-Fi HaLow, RuBee or NBIoT, but, as of writing, there are only a few commercial devices that support them. DASH7 is a standard evolved from RFID that is designed for long range and low power applications that require low bandwidth (up to 200 kbits/s). It may operate between 315 MHz and 915 MHz. Some authors consider that DASH7 fills the gap between LoRaWAN and NB-IoT [46]. There are also not many well-documented academic developments based on DASH7, but a few researchers that suggested its use for tracking and monitoring applications. For instance, in [47] the authors analyzed the DASH7 Alliance Protocol v1.0 specification and implemented bird tracking and a greenhouse monitoring.

Other technologies like Low Frequency (LF) RFID or Near-Field Communications (NFC) are not appropriate for identifying pipes at a medium-to-long distance, since such a kind of tags can only be usually read at up to one meter. Moreover, there are technologies like WirelessHART, ZigBee or Wi-Fi that can be used for certain product tracking or IIoT applications [48], but they were initially not conceived for supporting them.

Furthermore, technologies like Ultra-Wide Band (UWB) may be used for indoor positioning [49], but they make use of very high frequencies whose propagation is difficult in scenarios with a lot of metallic objects. In contrast, SigFox, LoRa and LoRaWAN use transmission frequencies below 1 GHz to improve their wave propagation in unfavorable environments, but their architecture is optimized for covering long distances (e.g., some areas of a smart city [50]) providing low data rates (up to 50 kbit/s) [51], [52].

Regarding the rest of the technologies compared in Table 1, most of them have been previously evaluated for asset tracking applications in industrial scenarios. For instance, in [53] it is described an RFID system that tracks products and collects real-time production data for shop-floor management. In the case of Bluetooth and Bluetooth Low Energy (BLE), their beacons (i.e., devices that broadcast certain information periodically) have been previously used for tracking applications in industrial scenarios. For example, in [54] the authors propose a real-time simulator that makes use of BLE beacons to locate workers in a manufacturing line.

Bluetooth 5 is still being widely adopted by hardware manufacturers, but its low power consumption, long range and backward compatibility with other Bluetooth specifications (a comparison of most recent Bluetooth versions can be found in [55]) make it a good choice for the proposed pipe tracking industrial environment and, in general, for IoT/IIoT applications [9], [56], [57]. However, it is worth mentioning that, just after the adoption of Bluetooth 5 in 2017, the Bluetooth SIG released another new specification on network topology, Bluetooth Mesh [23].

TABLE 1. Main characteristics of the most relevant communication and identification technologies for pipe tags [2].

Technology	Operating Frequency	Maximum Range	Max. Data Rate	Main Characteristics	Main Applications
NFC	13.56 MHz	<20 cm	424 kbit/s	Low cost, tags require no batteries	Asset tracking, payments
LF RFID	30–300 KHz (125 KHz)	<10 cm	<640 kbit/s	Low cost readers and tags	Product tracking and security access controls
HF RFID	3–30 MHz (13.56 MHz)	<10 m	<640 kbit/s	Low cost readers and tags	Product tracking, payments
UHF RFID	30 MHz–3 GHz	<120 m	<640 kbit/s	Low cost	Asset tracking
UWB/IEEE 802.15.3a	3.1 to 10.6 GHz	< 10 m	>110 Mbit/s	Low power (batteries last from hours to days)	Real-Time Location Systems, short-distance streaming
WirelessHART	2.4 GHz	<10 m	250 kbit/s	Compatibility with HART protocol	Wireless sensor network applications
RuBee	131 KHz	30 m	8 kbit/s	Magnetic propagation	Applications with harsh electromagnetic propagation
IQRF	868 MHz	hundreds of meters	100 kbit/s	Low power and long range	IoT applications
DASH7/ISO 18000-7	315–915 MHz	<10 km	27.8 kbit/s	Low power (batteries can last months to years)	Product tracking and identification
Weightless-P	License-exempt sub-GHz	15 Km	100 kbit/s	Low power	IoT applications
ANT+	2.4 GHz	30 m	20 kbit/s (burst), 60 kbit/s (advanced burst)	Ultra-low power, up to 65,536 nodes	Health, sport monitoring
Thread (802.15.4-2006)	2.4 GHz band, with a roadmap to sub-GHz bands	Up to 200 m	250 kbit/s	Low power (coin-cell battery)	Home automation and IoT applications
ZigBee	868-915 MHz, 2.4 GHz	<100 m	20−250 kbit/s	Low power (batteries last months to years), up to 65,536 nodes	Smart Home and industrial applications
Wi-Fi (IEEE 802.11b/g/n/ac)	2.4–5 GHz	<150 m	up to 433 Mbit/s (one stream)	High power consumption (batteries usually last hours)	High-speed, ubiquity
Wi-Fi HaLow/IEEE 802.11ah	868-915 MHz	<1 km	100 Kbit/s per channel	Low power	IoT applications
NB-IoT	LTE in-band, guard-band	<35 km	<250 kbit/s	Low power and wide area coverage	IoT applications
LoRa, LoRaWAN	2.4 GHz	kilometers	0.25−50 kbit/s	Low power and wide range	IoT applications
SigFox	868-902 MHz	50 km	100 kbit/s	Global cellular network	IoT applications
Bluetooth 5	2.4 GHz	<250 m	up to 2 Mbit/s	Low power (batteries can last days to weeks)	Beacons, IoT applications

In the case of the experiments presented in this article, each tag implements Bluetooth 5 through an nRF52840 Preview Development Kit, which currently costs around €35 and is based on an nRF52840 System-on-Chip (SoC). The kit is not only able to be programmed to act as a Bluetooth 5 device, but also as an ANT, ANT+ or NFC device. As it can be observed in Figure 2 on the left, the Bluetooth 5 kit used as a tag contains different connectors for communications, for debugging and for powering the board, as well as multiple General-Purpose Input-Output (GPIO) pins.

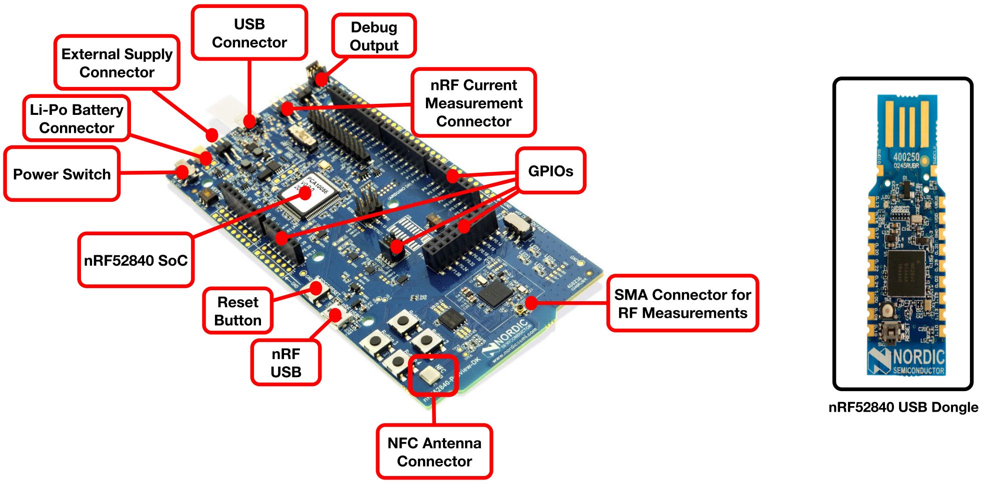
Regarding the Bluetooth 5 reader, which is actually a Bluetooth 5 sniffer, an nRF52840 dongle was selected (it is shown in Figure 2 on the right). Such a dongle is a small and low-cost (less than €5 as of writing) USB device whose firmware can be reprogrammed to support Bluetooth 5, Bluetooth mesh, Thread, ZigBee, 802.15.4, ANT and other 2.4 GHz proprietary protocols.

For the interested reader, further details on these technologies are described in [19].

G. BLUETOOTH 5 VERSUS RFID FOR ITEM TRACKING APPLICATIONS

In our previous work, an ICPS was proposed to track pipes in real time [2]. Such an ICPS made use of active RFID for locating and identifying pipes in highly-metallic shipyard environments. Nonetheless, the relatively high cost of the deployment (each of the selected RFID tags costs around €35, while RFID readers, around €2,000), prevents their use in certain applications and industries. In addition, due to the progressive growth in the number of monitored items (whose transactions may affect the remote cloud performance) and the need for location awareness and low-latency responses, a fog computing architecture was designed and tested in Navantia's pipe workshop [17].

The pipe identification system described in this article makes use of Bluetooth 5 devices since the latest core specification (Bluetooth 5.1) is still relatively recent (it was released on January 21st 2019 [58]), so, as of writing, there is barely any off-the-shelf Bluetooth 5.1 hardware available. Bluetooth



nRF52840 USB Dongle

FIGURE 2. Internal components of the Bluetooth 5 tag (left) and sniffer (right).

5 has been devised for being used in IoT applications, it is able to provide long reading ranges in harsh environments (in terms of communications propagation) and its cost is expected to decrease progressively (it is still in its earliest commercialization stages), as Bluetooth 5 devices become massively produced.

With respect to active RFID, Bluetooth 5 offers significantly cheaper deployments, specially considering that Bluetooth 5 tags costs around €5, while the reader is only around €40 (substantially less than an active RFID reader). Although active RFID and Bluetooth 5 may achieve a similar battery lifetime, Bluetooth 5 outperforms most active RFID solutions in terms of maximum data rate and maximum range (a wide-area coverage can be achieved by implementing a mesh topology). Nevertheless, as indicated in [9], it is still unexplored how Bluetooth 5 performs in terms of scalability, interoperability, data mining, secure access and ubiquity.

III. DESIGN OF THE SYSTEM

After reviewing the different aspects of the state-of-the-art, it is possible to point out a number of important shortcomings that motivated the design of the system. First of all, the lack of an automatic and autonomous pipe tracking solution that works under NLoS conditions and provides real or near real-time positioning of pipes. Second, the cost associated with the deployment (i.e., operation and maintenance) of current active RFID-based ICPSs is really high, and the larger the number of pipes that make up the system, the more expensive it becomes. Third, when deploying a system in a shipyard or in a harsh industrial scenario, it is desirable to use a radio-planning tool to design the deployment, since it may involve cumbersome tasks for installing infrastructure that, in some cases, might be very difficult or even impossible to deploy and such scenario involves a number of different areas with particular characteristics. Finally, the fourth shortcoming is related to the fact that, an industrial solution requires an enhanced resilience to bottlenecks and cyber-attacks that should be included in its computing architecture by design. Therefore, the system described in the next sections has been devised to take the previous shortcomings into consideration, and provides advantages in terms of functionality, cost, efficiency of the deployment and robustness.

A. COMMUNICATIONS ARCHITECTURE

Fig. 3 shows the proposed communications architecture, which is divided into three layers. The bottom layer is composed by Bluetooth 5 tags that are attached to pipes but that can also be used to track and identify industrial tools or shipyard workers.

Like in other Bluetooth and BLE applications [59], the used tags act as beacons, whose signal strength is collected by fog gateways that are connected to Bluetooth 5 sniffers. Every fog gateway is essentially a Single-Board Computer (SBC) (e.g., Raspberry Pi [60], Beagle Bone [61] or Orange Pi PC [62]) that runs the positioning service, which is responsible for processing the collected signal strength values and provide fast responses to the operators. Such operators can make use of mobile devices like tablets, smart phones or augmented reality glasses [63] to connect wirelessly to the fog gateways or to the ICPS to receive the positions of the monitored objects.

The inner workings of the fog positioning service are detailed in our previous work [17], where the performance of such an architecture was evaluated under regular (up to 1,000 pipes were monitored) and abnormal high loads (more than 10,000 pipes sent information concurrently).

It is important to note that, to provide local ad-hoc services, fog gateways are physically scattered throughout the shipyard in specific locations close to the working areas. Nonetheless, the proposed communications architecture allows physically distributed fog gateways to communicate with each other in order to collaborate when providing services. In addition, fog gateways can communicate with Navantia's cloud (in the

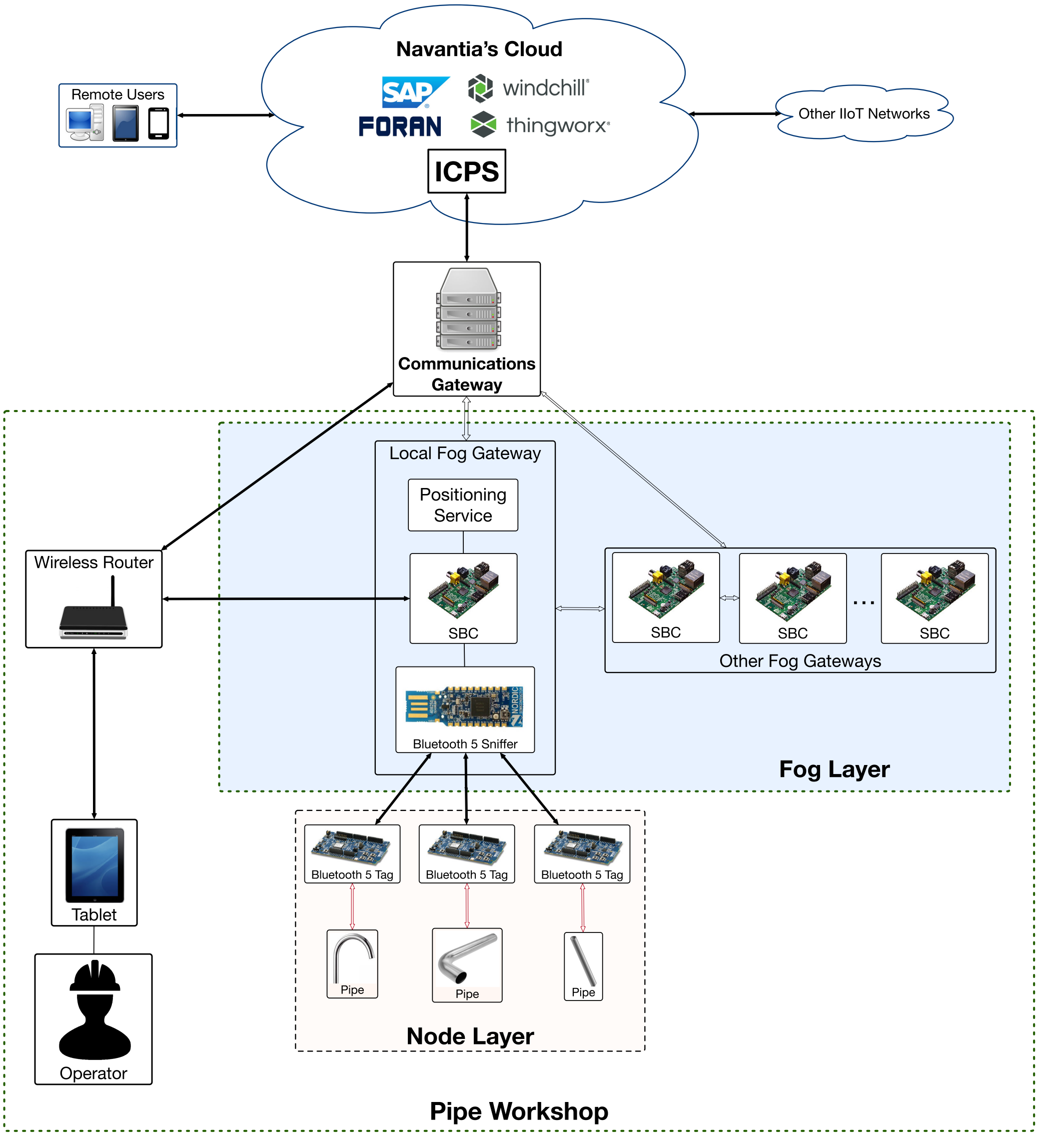


FIGURE 3. Proposed communications architecture.

layer at the top of the architecture), which is where the most compute-intensive tasks are executed. Such tasks are essentially performed by either proprietary developments (e.g., the developed ICPS) or third-party software (for instance, in the case of Navantia, SAP [64] is used as Enterprise Resource Planning (ERP), FORAN [65] is used for ship design, Windchill [66] works as Product Lifecycle Management (PLM) and ThingWorx [67] is currently being tested as IIoT platform). Thus, the cloud servers provide access to remote users (including other IIoT networks) to the mentioned software and to the data collected by the proposed Bluetooth 5 location system.

Figure 4 shows a map of the whole pipe workshop where it is represented the estimated initial location of the Bluetooth 5 readers and tags to be deployed. In the case of the tags, instead of the actual tags, it is represented the pipe density of each working area: the more Bluetooth 5 tag symbols in an area, the higher the pipe density in such a working area. Despite this first estimation, the area to be covered is so large and there are so many specific characteristics in every area, that the radio planning tool and the procedure described in the next section are essential in order to optimize the location of the Bluetooth 5 readers and thus guarantee full coverage of the tags deployed in the pipe workshop.

IV. RADIO PROPAGATION IN THE PIPE WORKSHOP

The particular characteristics and complexity of the radio propagation in the pipe workshop make it really useful to use a deterministic Ray Launching (RL) simulation tool. This is due to the fact that deterministic-based techniques provide higher levels of accuracy in comparison to statistics-based approaches, which are usually employed in interference analysis in indoor/industrial scenarios. In fact, although statistics-based and empirical methods provide results very fast (obtained by a formula), the accuracy of their estimations is much lower due to the fact that such methods

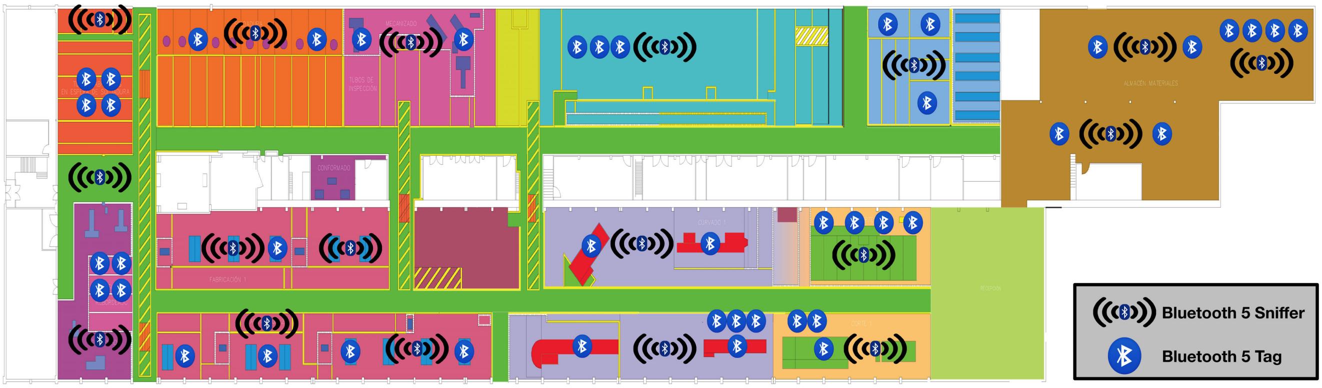


FIGURE 4. Initial locations of the Bluetooth 5 readers and tags.

are not site-specific. That is: they do not consider the real morphology of the scenario under analysis or the specific elements/obstacles within it, which are key when complex indoor scenarios (i.e., with a dense multipath propagation) are analyzed. Therefore, deterministic methods seem to be a proper solution for the presented pipe workshop scenario.

Moreover, the use of such deterministic techniques allows for obtaining, for instance, the time-domain characterization, which provides relevant information related to the multipath component characteristics or to the NLOS links.

Specifically, for the experiments performed for this article, an in-house developed 3D-RL algorithm based on Geometrical Optics (GO) and the Uniform Theory of Diffraction (UTD) was used [68], since such a GO/UTD technique combination was previously validated in the literature to predict wireless propagation within complex 3D environments [69], [70]. Basically, the selected RL technique is a precise approximation of the full wave methods, which are based on Maxwell's equations. The RL methodology is based on a principle that indicates that the wave front of a radiated electromagnetic wave can be approximated with a set of rays (launched by a transmitter antenna) that propagate along the full volume of the scenario, following a combination of optics and electromagnetic assumptions. In order to reduce computational cost and to enable the analysis of large scenarios, the radio propagation simulation tool can make use of hybrid techniques based on neural network interpolators [71], on the application of the electromagnetic diffusion equation [72] and on collaborative filtering data mining [73].

The procedure to be followed when making use of the simulation tool first requires creating a complete 3D scenario that considers all the obstacles of the environment under evaluation. As the considered industrial scenario is a complex environment in terms of radio wave propagation (mainly due to the rich multipath components created by the large number of metallic obstacles within it), a precise simulation environment is needed in order to obtain accurate estimations. For the experiments performed in this article, the different areas of Navantia's pipe workshop were recreated in the simulation tool. Such areas included elements like cranes, metal cabinets, stacking areas (where metallic pipes of different lengths are stored), a pallet area for loading and unloading raw materials and a random distribution of shipyard operators that were placed both in the corridors and in different working areas.

In the simulation tool, the material properties of all the objects within the scenario are indicated by defining their dielectric constant and permittivity. In addition, other parameters are considered for the simulation, like the operation frequency, the maximum number of permitted reflections (i.e., the number of interactions between a propagated ray and the existing obstacles), the angular and spatial resolution (i.e., the angle between the launched rays and the simulation mesh size, respectively), or the transceiver setup (i.e., antenna type, transmission power level, radiation pattern). Furthermore, it is important to note that the construction of the selected scenario requires the definition of a large set of metallic pipes that differ in their geometry and location, which involved implementing a specific pipe construction modeler in the 3D-RL tool.

During the simulation process, the 3D scenario is structured as a matrix of fixed-size cuboids (defined by the spatial resolution parameter). When a ray goes through a specific cuboid, its propagation parameters are stored in the corresponding position of the matrix. After simulating ray propagation, all the data collected by each cuboid can be retrieved for their analysis. Each cuboid obtains the received power, which is calculated as the sum of the incident electric vector fields (in terms of magnitude and phase) during a time interval Δt that is defined by the user and that depends on the transmission data rate of the evaluated wireless communications technology.

V. EXPERIMENTS

In order to ease the deployment of Bluetooth 5 fog computing nodes and to determine the reading range of the tested Bluetooth 5 tags, several experiments were performed. First, the tags and the simulator were tested in a preliminary scenario located at the University of A Coruña. Once the hardware and the simulation tool were validated in such a

FIGURE 5. Picture of the real test scenario.

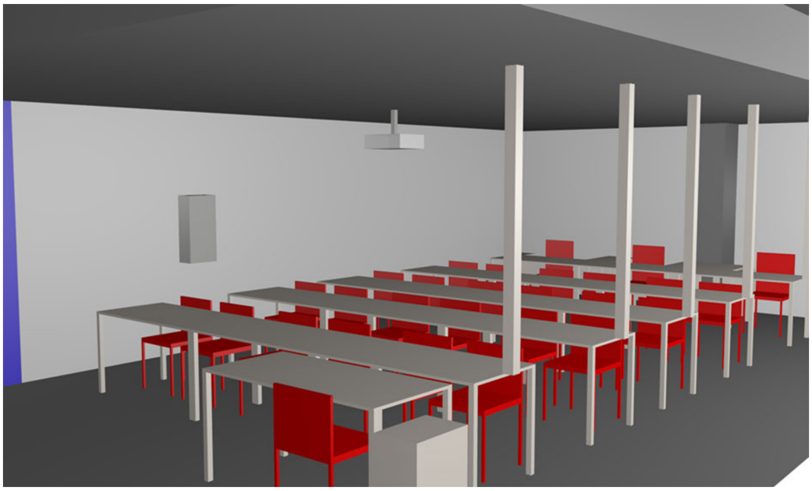


FIGURE 6. Virtual scenario created for the 3D-RL tool.

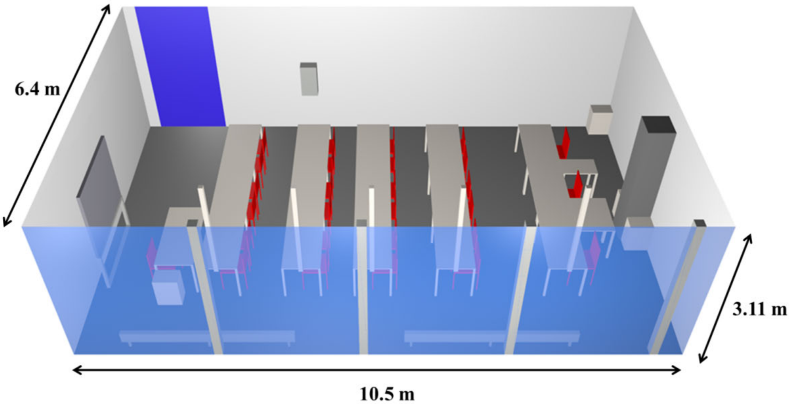


FIGURE 7. General view and dimensions of the scenario created for the 3D-RL tool.

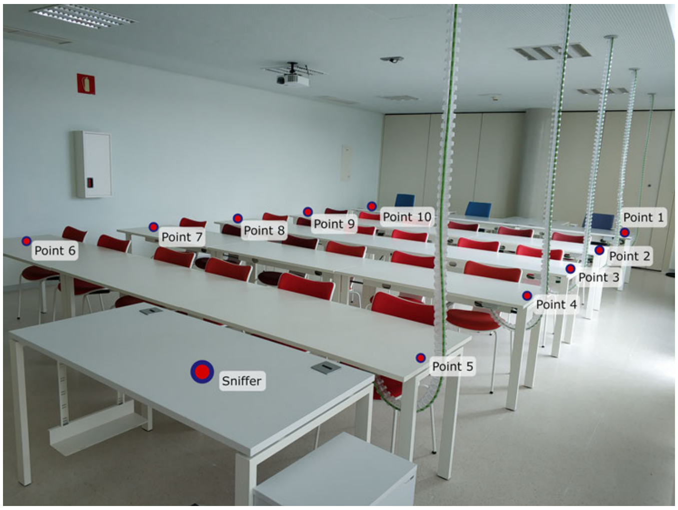


FIGURE 8. Location of the measurement points in the test scenario.

test environment, a measurement campaign in a much more complex pipe workshop was carried out. The empirical results obtained during the campaign were then compared with the ones obtained by the simulation tool.

After describing the configuration of the employed 3D-RL simulator, the next subsections detail the performed simulation-based estimations and empirical results (i.e., RF power distribution and delay-spread), which were obtained when positioning a Bluetooth 5 fog computing node in different locations of the considered preliminary non-industrial scenario and in Navantia's pipe workshop in Ferrol.

A. 3D-RL SIMULATOR SETUP

For the simulations presented in this article, the 3D-RL tool parameters were configured according to previous convergence analyses [74]–[76] and were based on the real characteristics of the selected Bluetooth 5 devices:

- Operation frequency: 2.44 GHz.
- Antenna type: monopole.
- Transmitted power level: 0 dBm.
- Maximum permitted reflections: 6.
- Horizontal/vertical angular resolution of the launched rays: $\pi/180$ rad.
- Cuboid size: 0.5 m × 0.5 m × 0.5 m.

With such configuration parameters, RF power distribution and different time-domain results were obtained for both the test scenario and the pipe workshop. Since the presence of human operators within the pipe workshop is common, a computational human body model was included in the simulations (a complete description of the developed human body model can be consulted in [77]).

B. TEST SCENARIO VALIDATION

A classroom of the University of A Coruña (Spain) was selected as a first test scenario to validate the proposed system. Figure 5 shows a picture of the real scenario, while Figures 6 and 7 show the virtual scenario created for 3D-RL simulations, as well as its dimensions.

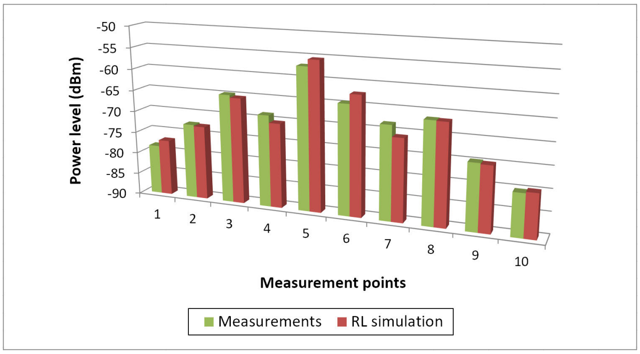


FIGURE 9. Comparison between measurements and simulation results.

For the measurements, the Bluetooth 5 nodes were deployed in a point-to-point static configuration. Figure 8 shows the location of the Bluetooth 5 sniffer (i.e. the receiver) and the 10 different positions where the Bluetooth 5 tag (i.e., the transmitter) was placed during the validation measurements. Figure 9 shows a comparison of the average empirical Received Signal Strength Indicator (RSSI) values (from 180 received frames) and the RF power level estimations obtained by the 3D-RL simulator. As it can be observed in the Figure, the RF power level estimations are really close to the experimental results, obtaining a mean error of 0.01 dB and a standard deviation of 1.41 dB. As a consequence, these preliminary results validate the proposed methodology in order to be employed within the much more complex pipe workshop environment.

C. PIPE WORKSHOP EXPERIMENTS

The next sections describe the experiments carried out in the pipe workshop previously illustrated in Figure 1. Specifically, Section V-C.1 analyzes the RF power distribution in the pipe workshop, while Section V-C.2 studies the obtained

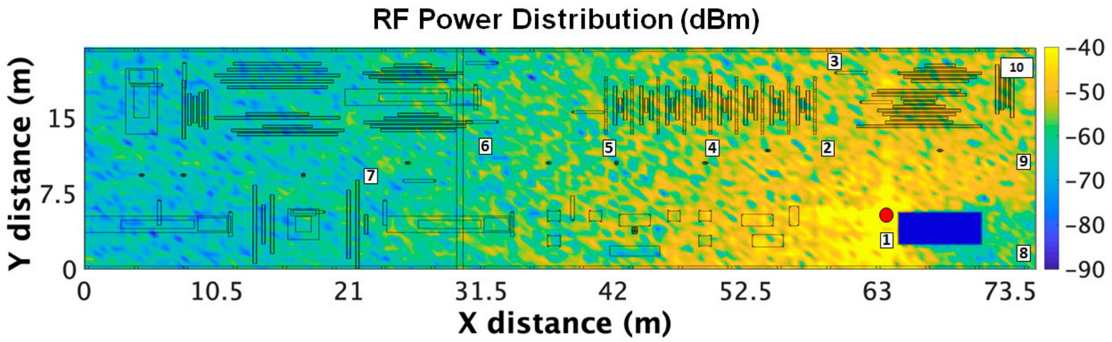


FIGURE 10. Bi-dimensional RF power distribution results obtained by the 3D-RL at a height of 1.5 m.

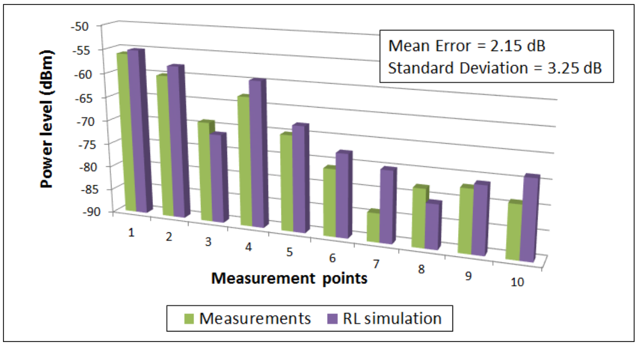


FIGURE 11. Comparison between measurements and simulation results.

time-domain response. The obtained results are later analyzed in Section V-C.3.

1) RF POWER DISTRIBUTION

Figure 10 shows the bi-dimensional RF power distribution at a height of 1.5 m. In such a Figure, the location of the Bluetooth 5 tag, which acted as a beacon (at a height of 1.62 m), is represented by a red dot. The empirical measurement points, which were obtained at different heights that range between 0.1 m and 0.9 m, are depicted as white rectangles that are numbered from 1 to 10. As it can be observed in this example, the RF power distribution presents the typical rapid variations related to the multipath propagation phenomenon. In addition, the presence of large metallic structures and metallic pipes contribute significantly to this rich multipath environment and affects significantly the RF power distribution in their surroundings (e.g., shadowing effect), making it a complex environment when carrying out radio planning tasks.

In order to validate the obtained simulation results, a measurement campaign was carried out. For such a purpose, the Bluetooth 5 tag shown in Figure 2 was placed at the position marked by a red dot in Figure 10. Then, the received power level at the measurement points were obtained through the Bluetooth 5 sniffer, which was placed in the positions numbered from 2 to 10 in Figure 10. Figure 11 shows a comparison between the obtained simulation results and the empirical measurements. Such results show the expected fast signal variations due to the constructive and destructive effects of the multipath propagation components. The mean error between the empirical measurements and the estimations provided by the simulator was 2.15 dB with a standard deviation of 3.25 dB, which is certainly a low error providing that the performed simulations assumed a static scenario, while the empirical measurements were collected in a dynamic scenario where operators, machinery and even vehicles were moving through it [78], [79]. Therefore, the obtained simulation results can be considered a good approximation and allow for stating that the simulation tool is useful for RF planning in complex industrial scenarios like the pipe workshop.

2) TIME-DOMAIN RESPONSE

Figure 12 shows the obtained time-domain radio propagation results, which illustrate the complexity of the evaluated industrial environment in terms of multipath propagation. The delay spread results obtained for the plane at a 1.5 m height are shown on the left of Figure 12. These results, presented in nanoseconds, indicate the time interval between the first and the last received multipath component at each point of the scenario (in this case, the points of the bi-dimensional plane at a 1.5 m height). Besides the values observed near the location where the Bluetooth 5 tag was placed, large values also arise at points far from it, indicating that the scenario under analysis is very rich in terms of multipath propagation (i.e., there is a large number of multipath components that propagate within it).

The abundance of multipath components on the pipe workshop can also be observed in Figure 12 on the right, which depicts a Power Delay Profile (PDP) for a point next to the measurement point labeled as '1' in Figure 10. The PDP shows all the multipath components (represented by yellow dots) that reached this specific single point within the simulated scenario, showing again the complexity that presents the scenario under study.

It has to be noted that the validity of the presented time-domain estimations is based on the previously validated RF power level results: since the RF power level is calculated using the received rays at each point shown in the Power Delay Profiles (using the magnitude and the phase of each ray), the time-domain results are also considered validated.

3) DISCUSSION

After analyzing the obtained results, it can be concluded that all of them show the great complexity of the evaluated

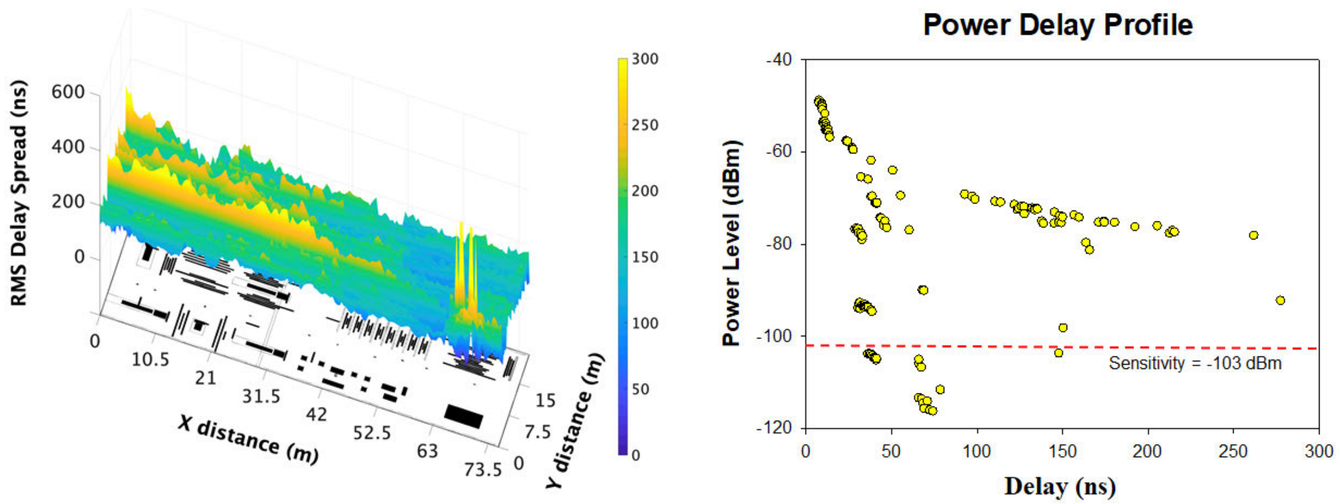


FIGURE 12. Delay Spread results for a plane at 1.5 m height obtained by 3D-RL simulations (left) and Power Delay Profile (right) for a point next to measurement point 1.

industrial scenario. Such results (the RF power level distribution estimations, as well as the time domain results) agree with the results and conclusions of the NIST Technical Note 1951 [5], which emphasizes the need for using accurate tools when carrying out optimized radio planning tasks in industrial environments. Moreover, wireless communications in industrial environments are subject to specific effects, such as the strong multipath components that arise because of the existing highly reflective surroundings and high levels of electromagnetic interference [3], which can impact system reliability [5]. In order to provide radio planning solutions, the authors of [5] present regressive propagation loss models based on intensive measurement campaigns, while in [8] stochastic models for short range wireless communications are proposed. Channel modeling approaches have also been suggested, in which interference contributions are modelled as the superposition of additive white Gaussian noise and impulse noise, while following a two-state Markov process model [6]. However, such methods provide an assessment of the initial coverage/capacity estimations as a function of the required sensitivity, but provide little information in terms of time-domain characterization, like power delay profiles and delay dispersion. Thus, deterministic propagation modeling techniques such as ray tracing and ray launching techniques can provide time-domain information, as well as precise characteristics of other aspects like spatial distribution models for interference sources, which are relevant to physical layer determination [7]. In this way, it can be stated that the presented deterministic 3D Ray Launching algorithm has been proved to be an adequate and accurate tool to perform the required radio planning tasks in this particular environment.

VI. CONCLUSIONS

Pipe traceability is a unique industrial challenge in shipbuilding. To tackle such an issue, this article presented the design and validation of a Bluetooth 5 fog computing based ICPS architecture for a real pipe workshop. The proposed architecture enables novel Industry 4.0 applications and guarantees quick responses to critical events while forwarding complex and computing-intensive tasks to the cloud. To implement the architecture, the latest and enhanced version of Bluetooth, Bluetooth 5, was considered as the best cost-effective technology in order to develop the proposed ICPS. A radio propagation assessment was performed by using an in-house 3D Ray Launching simulation tool that considered the harsh electromagnetic propagation conditions that exist in a pipe workshop. After validating the proposed tool and measurement methodology in a non-industrial scenario, a 3D real pipe workshop scenario was modeled considering the presence of pipes, specific machinery and the daily workforce in the main working areas. The results obtained with the simulation tool show a good overall accuracy when compared with the obtained empirical measurements, thus validating the use of the tool for such a complex environment. As a consequence, it can be stated that the simulation tool is able to provide useful guidelines during the network planning phases for the future deployment of Bluetooth 5 based systems in intelligent Industry 4.0 shipyard workshops.

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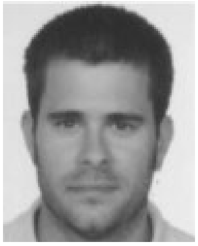

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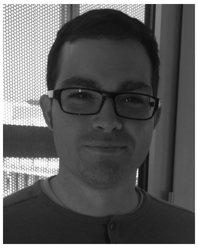

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