Coverage Study of a Sustainable IoT System for Industrial Applications

Jesus Lopez-Ballester, Sandra Roger, Carmen Botella-Mascarell and Juan J. Perez-Solano
Computer Science Department
Universitat de València
Burjassot (Valencia), Spain
e-mails: {jesus.lopez-ballester, sandra.roger, carmen.botella, juan.j.perez}@uv.es

***Abstract*—Internet of Things (IoT) devices are very useful to monitor information in industrial scenarios even in areas which have difficult or impossible access through traditional wired connections. Reliable wireless communications can be challenging in industrial environments, where the communications signal is often blocked due to the presence of industrial machinery, with possible intermittent and/or unpredictable blockages. This paper evaluates the coverage characteristics of a low-cost sustainable IoT deployment to monitor an industrial facility dedicated to the design and assembly of automation systems for the food industry. For this purpose, a measurement campaign has been carried out at different points of the industrial site using the aforementioned IoT system. The results show that the system is able to provide enough coverage around the whole area, with a reduced number of outages. Substantial differences in terms of received power and outages are observed when comparing the measurements in a totally empty area and an area with machinery and workers. Finally, the received power measurements have been fitted to a simplified pathloss model, showing a pathloss exponent value consistent with previously reported values for industrial environments.**

***Index Terms*—IoT, wireless sensor networks, industry 4.0**

I. Introduction

The development of wireless communications standards revolutionized all segments of our society. The massive use of wireless devices with ubiquitous communication, sensorization, detection and computing capabilities is making possible to interconnect millions of physical objects to the Internet. This set of interconnected devices, known as the Internet of Things (IoT), constitutes an integral part of the Internet of the future and receives a lot of attention from both the academic world and the industry due to its great potential to offer new services to the society [1]. IoT technologies can be applied in a broad range of sectors, such as smart homes and buildings, intelligent transport systems, smart cities, health care, energy saving and industrial automation [1]. In particular, its application in the field of industrial automation gave rise to what some authors call the Fourth Industrial Revolution [2] or Industry 4.0. It is a new paradigm in which there is widespread connectivity between machines, objects and users, sensorization, actuation and control tools that allow a group of machines to manufacture products faster and with greater precision [3]. Undoubtedly, industrial wireless communications create new perspectives of reliable automation by monitoring areas with difficult or impossible access through traditional wired connections, and play a key role in providing information of various kinds in real time.

IoT technologies are part of the Information and Communication Technologies (ICT), and hence they are fundamental towards achieving the Sustainable Development Goals (SDGs) [4] established in 2015 by the United Nations 2030 Agenda. This Agenda is a framework for addressing major global challenges directly related to sustainable development. The Agenda consists of 17 main SDGs with cross-sectoral representation of ICTs in all of them and with a very notable impact on at least 7 of the SDGs, relating for example to fields such as e-health, innovative collaboration, biodiversity protection, climate monitoring, sustainable production or infrastructure innovation. Under the framework of the SDGs, the industrial community has focused its technological advances from a sustainable point of view. The purpose is to develop technologies with the lowest possible environmental impact in terms of both energy consumption and manufacturing resources and materials. In particular, industrial IoT deployments can make a big impact towards achieving SDG 9, which is focused on building resilient infrastructure, promoting sustainable industrialization and fostering innovation, but the developed systems should be compliant with the sustainability constraints.

The objective of this work is to evaluate the performance of a low-cost sustainable IoT-based wireless communication deployment in an industrial environment dedicated to the design and assembly of automation systems for the food industry that plans to implement Industry 4.0 technologies. Wireless technologies integrated in IoT devices are diverse. First versions of standards were based on short-range and low-consumption communications (LOWPAN) such as Wi-Fi (IEEE802.11), Zigbee (IEEE802.15.4), Bluetooth, Ultra Wide Band (UWB) or Radio Frequency Identification (RFID) [5], [6]. Later, they evolved towards low power wide area networks (LPWAN) such as LoRa and Sigfox [7]. In addition, there is a current trend to integrate these technologies within the umbrella of cellular communications based on 5G and its future 6G versions [8], for example with the 3GPP standards such as NB-IoT and LTE-M standards [7], [9], [10]. The most suitable

Thanks to Grant PID2020-113785RB-100 funded by MCIN/AEI/10.13039/501100011033, Grant RYC-2017-22101 and Grant BES-2017-082340 funded by MCIN/AEI/10.13039/501100011033 and “ESF investing in your future”. S. Roger thanks the Generalitat Valenciana for Grant AEST/2021/064.

technology will in practice depend on the environment where the network is deployed. For instance, in indoor environments with nodes separated by short distances, it would be preferable to use technologies such as Wi-Fi or Zigbee.

In order to fully exploit the potential offered by wireless communications for industrial mobile robotics, automation, control and monitoring applications, there is a growing need to provide novel wireless communication schemes and deployments that offer low latency as well as improved performance in terms of reliability, energy efficiency [11], [12] and sustainability in general. Furthermore, industrial settings are highly dynamic environments that require the ability to adapt to changes in operating conditions. This is a challenge in industrial environments where the communication signal is often blocked due to the presence of the industrial machinery itself, such as robots, storage tanks, cranes, trucks, etc., with intermittent and/or unpredictable blockages. Therefore, it is important to know how communication technologies behave in these environments and understand the factors that can reduce their performance or even interrupt the connectivity. Actually, modeling the normal activity of a factory may allow to reinforce connectivity through measures such as increasing access point density or identifying their optimal placement.

In the industrial site under study, the current infrastructure for data monitoring is fully wired, based on typical industrial sensors and actuators with binary inputs/outputs connected to programmable logic controllers (PLC). This infrastructure has limitations in terms of the number and nature of sensors and actuators, since their maximum number is limited by the connections of each PLC. Besides, classical industrial sensors only handle binary data, not being able to monitor continuous magnitudes through analog values. To fully achieve the capabilities of an Industry 4.0 based facility, wireless devices need to be deployed. These devices should be enabled to handle both digital and analog sensors and actuators, even on moving elements, which can be deployed without relying on PLCs. In this work, the wireless connectivity characteristics will be evaluated by deploying a low-cost IoT system using Wi-Fi connection. IoT nodes will collect received signal strength, which will allow to evaluate the coverage offered by the system, analyzing the impact of the construction characteristics and the activity carried out on the site. Note that by coverage, in this paper we are referring to the operational capacity of the nodes, taking into account their low cost and limited connection capabilities with the configuration used. Based on the current analysis, a definitive system could be designed tailored to the connectivity needs.

The remainder of the paper is structured as follows. Section II presents the scenario and the IoT system setup. Section III describes the procedure followed to obtain the measures, while section IV presents the evaluation results and characterization of the wireless connectivity. Finally, conclusions are drawn in section V.

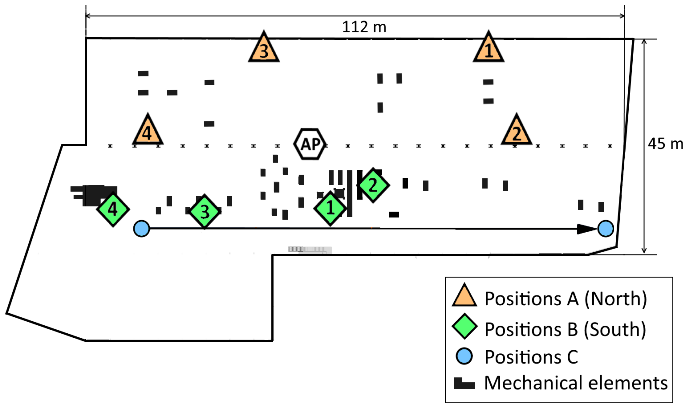


Fig. 1: Geometry of the analyzed industrial scenario. Positions of nodes and access point, and dimensions.

II. Scenario and IoT system

A. Scenario

The industrial scenario under study is represented in Fig. 1 and consists of a nearly rectangular-shaped area of dimensions 112 m $\times$ 45 m at ground level. It corresponds to an industrial warehouse located in the Mediterranean Coast of Spain. The area is divided in the direction of the X axis by a line of metal pillars with HEB profile, equally spaced every 5 meters that support a roof of height 8 m. This forms 2 different work zones: the northern zone, which at the time of the analysis did not present much activity, and the southern zone, where there were operators working on various mechanical elements typical of an industrial assembly line. Specifically, in the southern area, a robotic manipulator was found with a 3 m long arm, heavy and light roller tracks, connecting walkways and steel shelves, all of them with various integrated electro-mechanical elements such as servomotors, sensors and actuators, that can interfere with wireless communications and that are sketched in black in Fig. 1. Both areas were analyzed separately.

B. IoT system and protocol

The IoT system designed to perform the measurements can be seen in Fig. 2. It is made up of 4 IoT nodes and a control node, forming a system with a star-type network topology. The IoT nodes are of NodeMCU type based on the ESP8266 microcontroller, which is in charge of executing the program that governs the operation of the node. Sensors and actuators connected to the node give it the ability to interact with the physical world that surrounds it. Besides the microcontroller, the nodes integrate a wireless transmitter/receiver and a battery that allows their autonomous operation even with mobility. The control node is made up of a Raspberry Pi 3B which, in addition to controlling communications, implements the database function. To provide the Wi-Fi signal to be used by the wireless network, a basic range router (ZTE ZXHN H218N) has been located at the position of the control node.

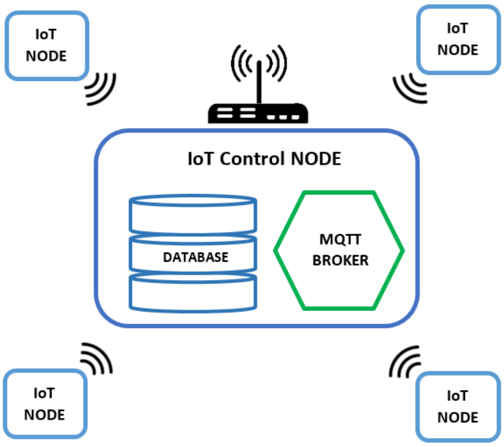


Fig. 2: Scheme of the considered IoT system.

The router is configured to operate in the 2.4 GHz band with automatic channel selection and 20 MHz bandwidth.

The total cost of the system is less than €200 with the average prices of the current market, so it represents a very low cost for an IoT system with the characteristics described in this article. These devices were chosen due to their excellent value for money, offering an easily, scalable and sustainable system with the necessary robustness. The only element that could be improved to enhance the system is the router, which has been deliberately chosen with very modest specifications. The specifications of the rest of the devices in the system can sufficiently satisfy the demands of the applications and are prepared for even more demanding measurements, for example, those requiring faster sampling, different types of sensors, or connection to real-time representation systems.

The Message Queue Telemetry Transport (MQTT) [13] protocol is used for communication, which was specifically created for machine-to-machine (M2M) communications. It is based on messaging between clients and a broker over the TCP/IP stack. Clients of the MQTT protocol can publish and subscribe to data published in a certain topic defined in the broker. The control node acts as a client that is subscribed to the same topic in order to collect the data published by the nodes and store it. The packets exchanged within the MQTT protocol [14] can be of different types according to their function: “Connect”, “Subscribe”, “Publish”, etc. In our case, once the connection with the broker is established, the packets sent with the collected data are of type “Publish”. The IoT system has been designed with 4 nodes, but it is easily scalable if more nodes are needed, by authenticating them in the broker and publishing in the same topic as the rest.

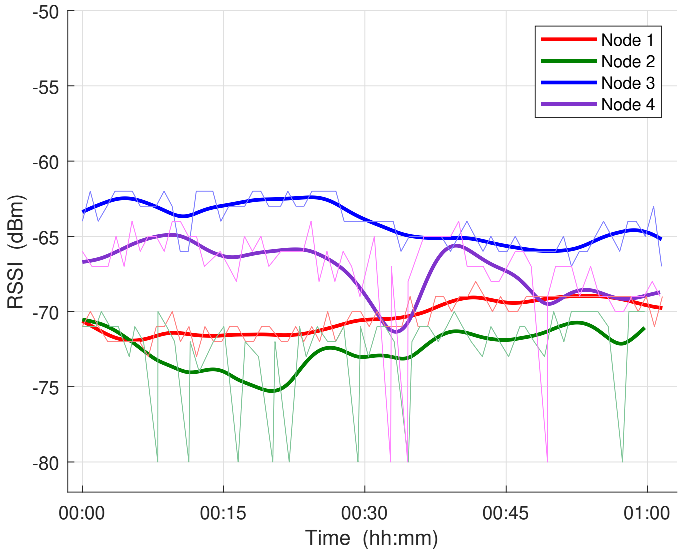
III. Measurement setup

The analysis performed is based on monitoring the Received Signal Strength Indicator (RSSI) parameter, which, on a reference scale of 1 mW, provides the power level received by a device. By studying the variation of the RSSI in different positions of the industrial site, it is possible to detect the most critical areas where the sensors could experience a poor connection or even an outage, and react accordingly. Since the RSSI measurements provide received power values, these can be directly used to adjust the propagation model equation by estimating, for instance, the pathloss exponent [15].

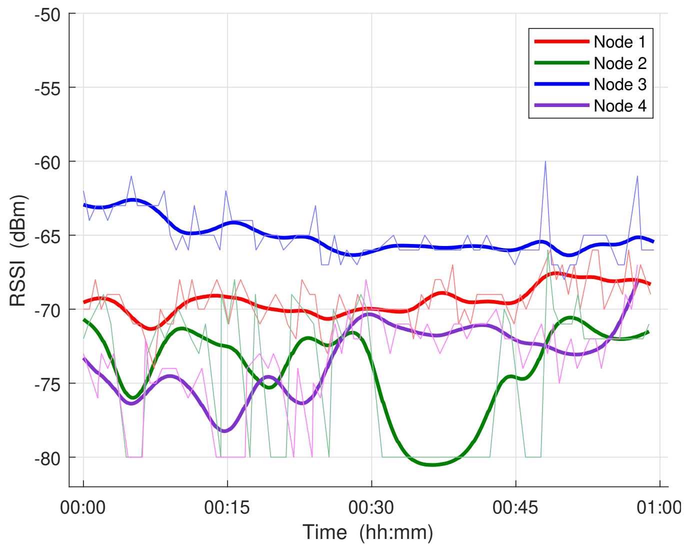
In the considered setup, the mobile nodes are configured to publish their measured RSSI values every 30 seconds. With sustainability in mind, to increase battery life and reduce energy consumption of the nodes, they are placed in a standby state with ultra-low power consumption during the time when they are not performing monitoring or data sending tasks. Thus, a message with the RSSI value is published every 30 seconds in a MQTT broker topic by means of a “Publish” type packet. The size of the packet used is 34 bytes, divided into a fixed header with information about the protocol and type of message (2 bytes), a variable header with additional control and security information (23 bytes), and a payload with the data to be sent (9 bytes). Of the 3 quality of service (QoS) levels allowed by MQTT (0, 1 and 2), we have used level 2, which guarantees that the message is received only once whenever there is active communication with the broker, without loss or duplication. Security has been implemented by means of user and password authentication, but without using encryption on the data sent by the nodes, due to the nature of the data. Although the aim of this setup is to collect RSSI information from each node, other metrics such as temperature, humidity, distance, pressure, etc. could be collected by installing different types of sensors.

The control node and the router were located on the shelf that provided the most centered position inside the facility. Their position (labelled as AP) is shown in Fig. 1, which remained static throughout the analysis. Three different measurement campaigns were carried out, each of them considering a different set of positions:

- **Positions A**: This set of static positions covers an area with low activity and few mechanical obstacles, located in the northern zone of the industrial warehouse. The specific positions of the measurement sensor nodes are highlighted in Fig. 1 with orange background triangles including the node number. Device locations were selected based on the availability of shelves at the usual work sites to be studied in the zone.
- **Positions B**: This is a set of static positions covering the southern area of the industrial warehouse, which in this case contains more machinery in operation and industrial workers’ activity. The node positions are marked in Fig. 1 as green background diamonds with the node number inside. Note that nodes 1 and 2 have been located in conflict areas with high industrial activity and nodes 3 and 4 in distant areas with machinery located in line of sight from the router to the sensors in all cases.
- **Positions C**: In this case, a single node has been used, which has been moved through 41 different positions. They were selected by sampling every 2.5 meters a straight line between the two points marked with the arrow between blue background circles in Fig. 1. This



(a) Values in positions A



(b) Values in positions B

Fig. 3: RSSI results in positions A (North) and B (South).

measurement path was chosen to be quite close to the machinery while avoiding to interfere the workers' usual activity.

Throughout the measurement process, temperature and humidity levels were monitored to ensure that they did not present significant variations that could affect the communications signal. These were maintained at an average temperature of 24 ºC and 35% relative humidity, with a variation of less than 6% in both cases.

IV. Performance Analysis

Using the system described in section III, two time series of measurements were first taken with the 4 nodes in fixed positions A and B. Then, a series of measurements with the nodes in positions C was performed. In each of the latter 41 positions, 20 measurements were taken to average and compensate the effect of small-scale fading.

Recall that, in all cases, the control node and the router remained in the same position marked as AP in Fig. 1. In a first step, RSSI values were analyzed in order to extract meaningful information regarding the coverage in the warehouse. In a second step, parameters directly influencing the wireless communication model in the facility were derived, such as the values of the pathloss exponent and standard deviation of the shadowing.

A. RSSI results

Fig. 3 shows the RSSI measurements in the four nodes in positions A and B, superimposed with the results after averaging, the latter represented in a thicker line. Fig. 3a presents the results for the first series of measurements, obtained during approximately one hour with the nodes located at positions A. It can be seen that, for the four nodes, the RSSI level remains quite steady over time. This result is consistent with what was expected, given that the northern area of the warehouse is nearly diaphanous and without activity by operators that could hinder the received signal. Fig. 3b shows the temporal evolution of RSSI values for the second series of measurements in the southern area of the warehouse (nodes located at positions B). It can be seen that the RSSI values exhibit more variability over time and more often low RSSI values (down to -80 dBm), bringing up the impact of the reflections on the machinery and operators.

To further characterize the coverage in the warehouse, the mean values and standard deviations (σ) of the RSSI measurements were calculated. In addition, an experimental outage probability (p_{out}) was derived using the measurements in the sets of positions under study. By definition, p_{out} is the probability that the received power value falls below a certain threshold related to the minimum signal to noise ratio (SNR) required for a desired transmission rate [15]:

$$p_{out} = \text{Prob}(P_r < P_{min}). \tag{1}$$

Since the connectivity drops were observed for RSSI values below or equal to -80dBm, this value was chosen as threshold in this work ($P_{min} = -80$dBm).

Table I collects the coverage results for each of the nodes in positions A and B, where the distance from each node to the AP has also been indicated. It can be seen from the standard deviation values, that the measurements at position B show greater variability, with those at node 2 having a standard deviation reaching 4.4. These variations are justified by the presence of moving machinery and personnel in the signal path from the router, causing shadowing. Regarding the experimental p_{out} values, only the nodes 2 and 4 in both sets show a certain p_{out}. In particular, the p_{out} in node 2 of positions B is quite large due to its position surrounded by mechanical elements shadowing the signal (see Fig. 1).

TABLE I: Coverage analysis in positions A and B.

Positions	Node ID	d_i (m)	$RSSI_{av}$ (dBm)	σ	p_{out}
A (North)	1	40.46	-70.87	1.13	0
	2	40.77	-72.47	3.04	0.12
	3	22.66	-63.68	1.42	0
	4	37.47	-67.23	2.85	0.04
B (South)	1	11.28	-69.27	1.46	0
	2	11.69	-73.41	4.40	0.42
	3	31.09	-65.02	1.63	0
	4	50.18	-73.14	2.83	0.09

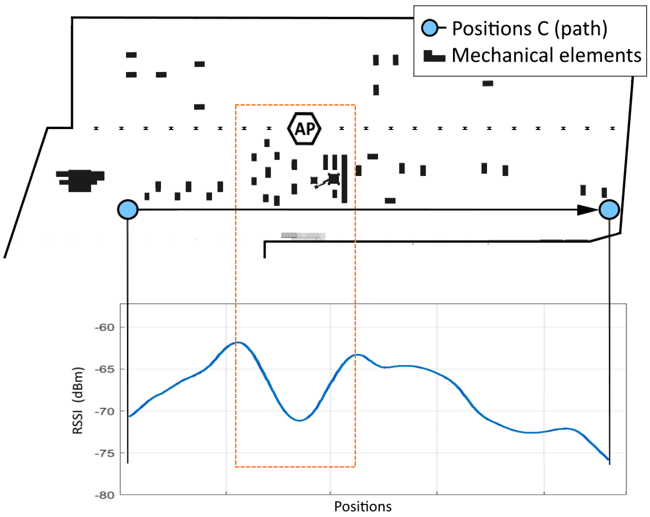


Fig. 4: RSSI results in positions C.

Regarding node 4, since it is located farther away from the AP than the other three nodes, its RSSI values were already lower due to the distance and more susceptible to falling below -80 dBm with shadowing. In practice, a second AP or some multi-hop communication mechanism should be used to reinforce the connectivity in the southern area in order to avoid the observed outages.

B. Wireless communication properties

In this subsection, the aim is to characterize the properties of the wireless communication in the facility using the last series of measurements (in positions C). Fig. 4 shows the averaged RSSI results in positions C, including their correspondence with the real positions in the industrial warehouse. The RSSI level increases as the node moves towards increasing values on the x-axis, that is, as it gets closer to the AP, until it reaches the part where machinery and personnel hinder the signal. A drop in the average RSSI level of around 8 dBm can be observed in such area. Once the node has traversed the central part of the warehouse, the RSSI level begins to increase again and then begins the expected decrease with distance as it moves away from the AP.

Next, the main parameters of the propagation channel model have been extracted. For the sake of simplicity, we use the simplified pathloss model given by [15]:

$$\frac{P_r}{P_t}(dB) = K_{dB} - 10\gamma \log_{10}\left(\frac{d_i}{d_0}\right), \tag{2}$$

where P_t is the transmitted power (dBm), K_{dB} is the constant path-gain factor in dB units at a reference distance d_0, γ is the pathloss exponent, and d_i is the distance between the transmitter and receiver. The shadowing is assumed to follow a zero-mean log-normal distribution with σ^2 variance. This assumption is consistent with the scenario, since the number of possible obstacles and blockages is random and large, which allows for the application of the central limit theorem. The received power model is then obtained by adding the pathloss and shadowing contribution.

The ratio P_r/P_t in dB has been represented as a function of distance in Fig. 5, where measurements made at positions to the left of the AP (labelled as southwest) have been plotted separately to those made to the right of the AP (southeast), since both sides have different types and amounts of machinery affecting the propagation. The power ratio has been computed from the difference $P_r(\text{dBm}) - P_t(\text{dBm})$, considering $P_r(\text{dBm}) = \text{RSSI}(\text{dBm})$ and $P_t = 1$ mW (0 dBm). To facilitate the fitting correspondence with Eq.(2), the x-axis displays the normalized distance $\log_{10}\left(\frac{d_i}{d_0}\right)$ with $d_0 = 16.48$ m. Using the Matlab Curve Fitting Toolbox, the values have been fitted to a linear polynomial $y = ax + b$, with $a = -25.53$ and $b = -62.37$ (see Fig. 5). According to Eq. (2), the a term provides -10γ, whereas the b term provides directly the value of K_{dB}, which leads to $\gamma = 2.55$ and $K_{dB} = -62.37$ dB. Note that the obtained pathloss exponent is consistent with previous works where, for industrial environments, reported γ values are usually between 2 and 3, for instance, in the obstructed in factories model [16] and the results of the analysis in [17].

The standard deviation of the measurements was also obtained, resulting in $\sigma = 4.23$ dBm. This value provides the shadowing standard deviation, which is usually added to the pathloss in the simplified channel model [15]. The experimental probability of outage is $p_{out} = 0.12$. It can be observed that these σ and p_{out} values are higher than those measured in positions A and B. However, power variations have still allowed to carry out most of the measurements throughout the warehouse with few outages, demonstrating the viability of the proposed low-cost system even without line-of-sight communication.

V. Conclusion

In real-world industrial environments, both the mechanical elements and the activity carried out by operators often alter the wireless communications signal due to intermittent and unpredictable blockages. To guarantee reliable communications able to support Industry 4.0 applications, it is crucial to carry out proper coverage studies customized to the facilities, considering regular activity periods and analyzing different working areas. This allows to prevent possible communication problems.

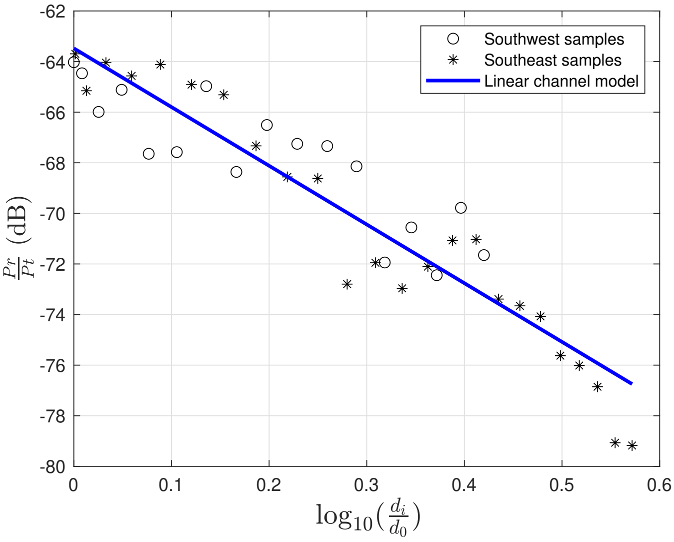


Fig. 5: Available samples and channel model fitting with measurements at positions C.

This paper has described the coverage study carried out with a low-cost sustainable IoT system with Wi-Fi connectivity in two different areas of an industrial warehouse located in the Mediterranean region in Spain. In particular, the received power in different points of the two areas has been measured through the Received Signal Strength Indicator (RSSI) parameter provided by the IoT nodes. The measurement campaign allowed first to estimate experimental outage probability values, average RSSI values and standard deviations of measurements, which highlighted some positions where wireless communication should be reinforced, for instance, including more wireless access points. A set of measurements in the area with more working activity was also used to fit a simplified pathloss model, where a pathloss exponent value consistent with previously reported values in industrial environments was obtained. As a result, the considered low-cost IoT system has demonstrated an excellent trade-off between cost/energy efficiency and performance to characterize and provide wireless communications for industry 4.0 applications. As future work, it would be interesting to assess the cost and energy efficiency versus performance of an equivalent IoT system based on 3GPP machine-to-machine (M2M) communication standards.

REFERENCES

[1] A. Al-Fuqaha, M. Guizani, M. Mohammadi, M. Aledhari, and M. Ayyash, "Internet of Things: A survey on enabling technologies, protocols, and applications," *IEEE Communications Surveys and Tutorials*, vol. 17, no. 4, pp. 2347–2376, 2015.

[2] P. Ross and K. Maynard, "Towards a 4th industrial revolution," *Intelligent Buildings International*, vol. 13, no. 3, pp. 159–161, 2021.

[3] D. Preuveneers and E. Ilie-Zudor, "The intelligent industry of the future: A survey on emerging trends, research challenges and opportunities in industry 4.0," *Journal of Ambient Intelligence and Smart Environments*, vol. 9, no. 3, pp. 287–298, 2017.

[4] "United nations, sustainable development goals," https://www.un.org/sustainabledevelopment/, accessed: 2022-07-05.

[5] D.-L. Yang, F. Liu, and Y.-D. Liang, "A survey of the Internet of Things," in *Proceedings of the 1st International Conference on E-Business Intelligence (ICEBI 2010)*. Atlantis Press, 2010/12, pp. 524–532.

[6] P. Lopez, D. Fernandez, A. J. Jara, and A. Skarmeta, "Survey of Internet of Things technologies for clinical environments," in *2013 27th International Conference on Advanced Information Networking and Applications Workshops*, 03 2013, pp. 1349–1354.

[7] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of LPWAN technologies for large-scale IoT deployment," *ICT Express*, vol. 5, no. 1, pp. 1–7, 2019. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2405959517302953

[8] D. C. Nguyen, M. Ding, P. N. Pathirana, A. Seneviratne, J. Li, D. Niyato, O. Dobre, and H. V. Poor, "6G Internet of Things: A comprehensive survey," *IEEE Internet of Things Journal*, 2021.

[9] 3GPP TSG RAN, "Cellular system support for ultra-low complexity and low throughput Internet of Things (CIoT)," 3GPP, TR 45.820 V13.1.0, 12 2015.

[10] A. F. Khalifeh, K. Aldahdouh, K. A. Darabkh, and W. T. Al-Sit, "A survey of 5G emerging wireless technologies featuring LoRaWAN, Sigfox, NB-IoT and LTE-M," *2019 International Conference on Wireless Communications Signal Processing and Networking (WiSPNET)*, pp. 561–566, 2019.

[11] A. Ahmadi, M. Moradi, C. Cherifi, V. Cheutet, and Y. Ouzrout, "Wireless connectivity of CPS for smart manufacturing: A survey," in *2018 12th International Conference on Software, Knowledge, Information Management & Applications (SKIMA)*. IEEE, 2018, pp. 1–8.

[12] R. Kunst, L. Avila, A. Binotto, E. Pignaton, S. Bampi, and J. Rochol, "Improving devices communication in industry 4.0 wireless networks," *Engineering Applications of Artificial Intelligence*, vol. 83, pp. 1–12, 2019.

[13] U. Hunkeler, H. L. Truong, and A. Stanford-Clark, "MQTT-S—A publish/subscribe protocol for wireless sensor networks," in *2008 3rd International Conference on Communication Systems Software and Middleware and Workshops (COMSWARE'08)*. IEEE, 2008, pp. 791–798.

[14] A. Stanford-Clark and H. L. Truong, "MQTT for sensor networks (MQTT-SN) protocol specification," *International business machines (IBM) Corporation version*, vol. 1, no. 2, pp. 1–28, 2013.

[15] A. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[16] T. S. Rappaport, "Wireless communications: principles and practice," in *Upper Saddle River*. Prentice Hall, 2002.

[17] J. Miranda, R. Abrishambaf, T. Gomes, P. Gonçalves, J. Cabral, A. Tavares, and J. Monteiro, "Path loss exponent analysis in wireless sensor networks: Experimental evaluation," in *2013 11th IEEE International Conference on Industrial Informatics (INDIN)*, 2013, pp. 54–58.