Evaluation of LoRaWAN for Sensor Data Collection in an IIoT–based Additive Manufacturing Project

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***Abstract*—The continuous evolution of additive manufacturing allows to produce innovative objects that are adopted in several diverse fields of applications. This trend can be further enhanced by the spreading of the Industrial Internet of Things (IIoT) paradigm which ensures effective interconnection among distributed, possibly heterogeneous, components and allows remote access by means of commercial devices such as PCs, tablets and smartphones. In this paper, we address a large additive manufacturing project which effectively exploits an IIoT architecture by embedding sensors (temperature, humidity, light, etc.) within the produced artifacts, so that they can make available diverse measurement data collected during both the production process (in real–time) and the subsequent lifetime of the artifacts, enabling further off–line analyses. This clearly represents an innovative and challenging feature that needs to be adequately investigated. To this regard, after describing the automation system of the project, we focus on the wireless system that implements the collection of measurements by the sensors within the artifacts. The design process led to the selection of a Low Power Wide Area Network, namely LoRaWAN, as a suitable communication solution. In this respect, we present here the tests performed to assess the actual feasibility and performance of such network in this specific application context. The obtained results are encouraging, since the sensors within the artifacts revealed able to exchange the required measurement data with the automation system in an effective way.**

***Index Terms*—Industrial Internet of Things (IIoT), Distributed Measurement systems, Low Power Wide Area Networks (LP-WAN), LoRa**

I. Introduction

Additive manufacturing is an emerging technology with great potentialities and expectations in several fields such as buildings, medicine, material sciences, environmental policies, etc [1]. Artifacts are produced by specific devices, namely 3D Printers, that may have different features depending on their application contexts. The automation system of a 3D Printer may be further interconnected with other equipment, systems and facilities hence exploiting the Industrial Internet of Things (IIoT) paradigm [2], [3].

In this manuscript we address a large additive manufacturing project, namely ADMIN–4D (ADditive Manufacturing & INdustry 4.0 as INnovation Driver) currently under way in Italy, in the framework of a regional project. At the core of the ADMIN–4D project, there is the implementation of a 3D Printer, based on a powder–bed waterjet technology, to produce mineral artifacts of large sizes [4]. One of the most innovative aspects of ADMIN–4D is represented by the introduction of sensors inside the artifacts during the production process.

Such embedded sensors are then exploited to measure variables like temperature, humidity and mechanical stress that are used for two different purposes. The first one, referred to as "real–time feedback", is based on the acquisition, by the automation system of the 3D Printer, of the measurements directly during the production phase. Such measurements are used to possibly adjust the behavior of the printer while production of the artifact is in progress. The second purpose is represented by the off–line analysis of the behavior of the artifacts. More precisely, measurements from the sensors inside the artifacts will be acquired over the time, after they are put into operation, and transmitted to a remote cloud. In this way, it will be possible to carry out analyses that allow, for example, predictive maintenance activities. Particularly, the outcomes of such analyses will be used to better tune future productions of artifacts.

Enabling the activities described above for the realization of an IIoT–based measurement system, requires the adoption of a communication infrastructure that implements the secure and reliable transmission of the measurements acquired by the sensors to both the automation system of the 3D Printer and the cloud. As it will be detailed in the following, Low Power Wide Area Networks (LP-WANs) [5], that recently become a significant opportunity for IIoT [6], represent an appealing

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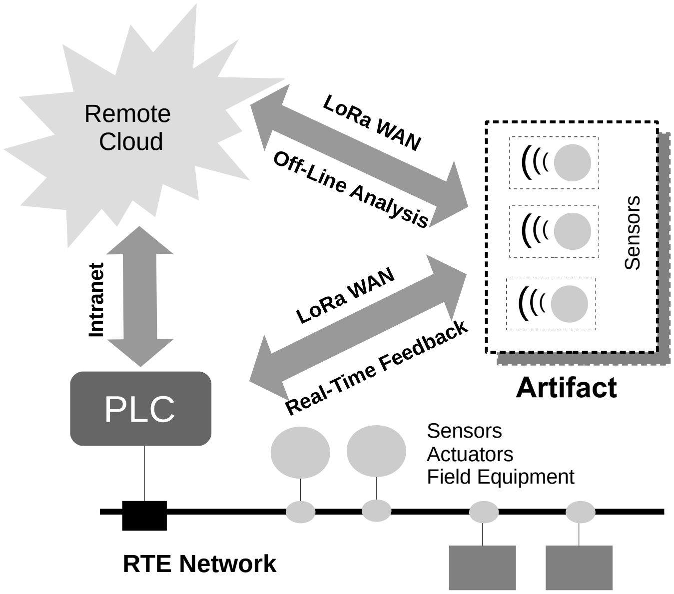

Fig. 1. Automation System of the 3D Printer

and effective solution for the ADMIN–4D project. Among such networks, we selected LoRaWAN [7] to implement the communication with the sensors inserted within the artifacts.

This paper moves from the above considerations and, in this direction, provides the outcomes of some design activities as well as the results of meaningful measurement campaigns. Specifically, after a description of the automation system, we will address the requirements of the communication systems and then we will provide the outcomes of an experimental campaign to access their performance. In detail, the paper is organized as follows. Section II describes the automation system of the 3D Printer, along with the requirements of the communication systems it adopts. Section III provides some basics about the LoRaWAN protocol, stressing the features of interest for the 3D Printer. Section IV reports the results of the experimental campaigns carried out to assess the performance of LoRaWAN in the context of the 3D Printer. Finally, Section V concludes the paper and provides some directions for future activities.

II. Automation System of the 3D Printer

The automation system of the 3D Printer is shown in Fig. 1. As can be seen, a Programmable Logic Controller (PLC) [8] is used to handle the whole production process. The PLC is connected to a Real–Time Ethernet (RTE) network, namely EtherCAT [9], that implements the timely data exchange with all the sensors/actuators of the printer. The PLC also communicates with the remote cloud via an Intranet. The communication with the sensors embedded within the artifacts has some specific requirements that, to some extents, resemble those of modern process control systems [10]. They can be summarized as follows.

- Cyclic data transmission with periods $\approx 10\,\mathrm{s}$ for the real–time feedback and $\approx 100\,\mathrm{s}$ for the off–line analysis
- Transmission of short payloads (a few bytes)
- Long battery lifetimes
- Large area coverage

In particular, the battery duration represents a very important issue because, once the sensors have been installed within the artifacts, they can not be replaced anymore, nor their batteries can be recharged. Clearly, the lifetime of such devices has to ensure the transmission of data for long periods of time, possibly years.

In the distributed measurement systems and IIoT scenarios several opportunities have been investigated within the research community to implement a reliable, secure and effective wireless connectivity [11]–[13]. Recently, Low Power Wide Area Networks (LP–WANs) are interesting emerging opportunities for the remote acquisition of sensor data [14]. These are networks that operate on both licensed and unlicensed bands, with long communication ranges. Moreover, the radio transceivers they use are characterized by very low power consumption, thanks also to the medium access techniques adopted. The most popular LP–WAN standards are NB-IoT, SigFox, Ingenu Weightless and LoRaWAN, to mention some [15]. LP–WANs are definitely able to cope with the requirements listed above and, consequently, they have been taken into consideration for the ADMIN–4D project. Among the available products, we selected LoRaWAN. This choice was mostly due to the availability of commercial products, and to the interest by the scientific community toward these systems also for measurement purposes [16]–[18], as well as to the expertise of some of the project partners that were already familiar with such a standard. Notably, a technique that resembles that proposed in this paper has been outlined in [19], where the authors consider an embedded wireless sensor network (WSN) for monitoring reinforced concrete structures. However, [19] has a different focus, in that it addresses a substantially different type of network which, additionally, requires re–charging of the nodes.

The two LoRaWAN networks shown in Fig. 1 implement the communication systems between the sensors inserted within the artifacts and, respectively, the PLC (for the real–time feedback) and the remote cloud (for the off-line analysis). For the sake of clarity, these two networks will never be contemporaneously present since, during the production phase of an artifact, only the communication with the PLC is necessary (in case some data need to be transmitted also to the cloud, they will be forwarded by the PLC). Conversely, after the artifacts are put into operation, only the communication with the remote cloud will be active.

III. Basics of LoRaWAN

LoRaWAN is a Standard, in the context of LP–WANs, built on top of a physical layer, called LoRa, developed by a private firm, namely Semtech Corporation. The LoRaWAN protocol is mainly concerned with the Medium Access Control (MAC) strategies in that it defines the way in which a station can access the physical medium as well as the format of the used frames. The LoRaWAN protocol specifies three different

Fig. 2. Insertion of a LoRaWAN End Device within an artifact

devices, namely, End Devices, Gateways and Network Server. End Devices are used at the field level, as they are basically sensors/actuators, instruments and other field equipment in general. End Devices communicate with the Gateway, which is connected to the Network Server. A LoRaWAN network may comprise more than a Gateway, but only one Network Server, that represents the device which schedules all the network traffic. It is important to observe that, while the communication between End Devices and Gateways takes place via wireless connections, that between Gateways and Network Server may rely either on a wired connection or a wireless one (typically a cellular network link). At the physical layer, the wireless LoRa communication makes use of a chirp spread spectrum modulation that relies on two fundamental parameters, namely Bandwidth (B) and Spreading Factor (SF), which is comprised between 7 and 12, so that the duration of symbols is comprised in the range: $(\frac{1}{B} \times 2^7) \div (\frac{1}{B} \times 2^{12})$. Roughly speaking, the higher the SF, the more robust the transmission. However, high SF values imply longer symbol duration and, hence, limited data rates. Indeed, for LoRaWAN, the maximum data rate is 5.47 Kbps, which is reached for $SF = 7$. The operation of LoRa networks takes place in the Industrial Scientific and Medical (ISM) bands. The band selected in Europe is 863-870 MHz, where a rigid power limitation is fixed to 14 dBm per device. This is accomplished by LoRa introducing very long sleeping periods in the devices that are allowed to transmit with very low duty cycles (the highest one being 10%), with the consequent beneficial impact on the battery lifetime.

An End Device that has a message to transmit can access the physical medium with a simple random technique based on the well known ALOHA scheme, then it can open two receive windows in order to get the (possible) answer from the Network Server. For all the other time, the End Node remains in sleep mode. The features of LoRaWAN, briefly described above, make it a good candidate for the ADMIN–4D project. As an example, the LoRaWAN network which connects sensors within the artifact and the remote cloud (used for the off–line analysis) has been implemented with the architecture described in Fig. 3.

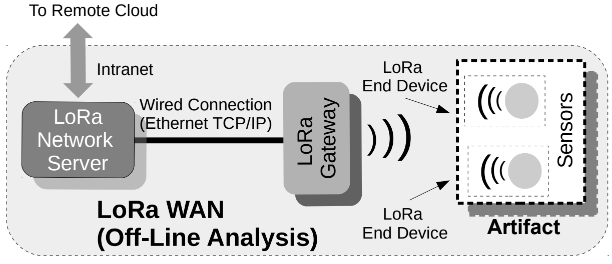

Fig. 3. LoRaWAN network that connects sensors within the artifact and the remote cloud

TABLE I

MAIN PARAMETERS OF THE OF THE LORAWAN NETWORK

Parameter	Value
CRC	Enabled
Bandwidth	125 kHz
Code rate	4/5
Transmitting power	14 dBms

IV. MEASUREMENT CAMPAIGN

The outcomes reported in this Section are mostly concerned with the behavior of the sensors inserted within the artifacts and equipped with a LoRaWAN interface. This is an innovative application for LoRaWAN devices since, to the best of the authors' knowledge, it represents the first example of this type of application.

The experimental campaign can be split in two different parts. In the first one, the actual feasibility of the insertion of a LoRa End Device within an artifact during the production phase has been assessed, with the aim of investigating possible mechanical as well as electrical issues. Secondly, a set of communication tests has been carried out to check the capability of the LoRaWAN network in this specific experimental context. In all the tests, we employed commercially available devices. In particular, we used an Evaluation Suite by Microchip Technology (Product code: DV164140) which comprises 2 LoRa End Nodes equipped with temperature and light sensors and a LoRa Gateway with Ethernet TCP/IP connectivity. The LoRa Network Server was implemented by an application running on a Personal Computer.

The main parameters of the of the LoRaWAN network used during the measurement campaign are reported in Table I.

A. Insertion within the artifacts

In this experiment, a LoRaWAN End Device has been inserted within an artifact during the production phase. The device was put in a common plastic box (protection degree IP 67), typically used in electric domestic plants, as briefly sketched by the photos reported in Fig. 2.

The main characteristics of the production process are reported in Table II. The produced artifact was dismantled after 48 hours, as described in Fig. 5. No damages were detected on both the plastic box and the LoRa End Device that revealed correctly working.

B. Communication tests

In this measurement session, experiments have been carried out at the Department of Information Engineering of the

Fig. 4. LoRa End Device inserted in the modular cube for communication tests

Fig. 5. Dismantling of the artifact

University of Padova, which represents one of the places in which some prototype artifacts will be located. We tested the reliability of the connection between LoRa End Devices and Gateway in a configuration typical of the considered application. More precisely, an End Device with two sensors (temperature and light) was inserted within an artifact, as sketched in Fig. 4, located in a laboratory. The artifact, in this case, was slightly different from that of the previous experiment, since it was a cube of similar dimensions but with modular and removable sides, so that different thicknesses of the cube side could be tested (namely, 5, 10, 15 and 20 cm).

The Gateway was moved over five different positions, identified as $P_1, P_2, \ldots P_5$, located in various parts of the Department, characterized by the presence of fixed obstacles (walls, equipment, etc.) as well as by the flow of people. In particular, position P_1 coincides with the laboratory. A draft indication of the positions is provided in Figure 6, that reports the aerial view of the area in which the experiments were performed. Additional information about the experimental positions is

TABLE II
MAIN CHARACTERISTICS OF THE PRODUCTION PROCESS

Item	Value/Meaning
Shape of the artifact	Cube of 50 cm side
Side Cube Thickness	20 cm
Weight	≈ 150 kg
Material	Sands and binder
Binder	Water and Minerals
Duration of Production Process	≈ 45 min
Temperature inside Cube	≈ 75°C

Fig. 6. Aerial view of the experimental area

TABLE III
POSITIONS OF THE GATEWAY

Position	Internal/External	Distance [m]	LOS
P_1	Internal	2	Yes
P_2	Internal	45	No
P_3	External	110	No
P_4	External	150	No
P_5	External	250	Yes

given in Table III, where the column "Internal/External" indicates whether the Gateway is located inside a building or not, whereas "Distance" specifies the distance from the End Device as the crow flies. The environment in which the experiments have been carried out was characterized by the presence of other wireless communication systems, such as WLANs and WPANs, but no other LoRa networs were deployed.

For each position, a total of N=300 packets, with a 30 Byte payload, were sent from the End Device to the Gateway. We first measured the number of lost packets, N_{PL}. Then, among the received packets, we measured the correct ones N_{CR}. All the experiments were performed for three different values of Spreading Factor SF, namely, 7, 9 and 12. It is worth noticing that, as a first outcome, the thickness of the artifact has not impacted in any way on the performance of the communication system. Hence, such a parameter has not been considered in the subsequent analysis.

The obtained results about lost and correctly received packets are presented in Fig. 7 and Fig. 8, respectively. As can be seen, both positions P_3 and P_4 are critical for the communication. For $SF = 7$ we have obtained a 100% packet loss in both positions, whereas for $SF = 9$ we have obtained a slightly better figure with a packet loss of about 82% in P_4. However, looking at Fig. 8, in P_4 less than 40% of packets were then received correctly, confirming the criticality of those locations. Indeed, both the positions are located outside the building, non in line–of–sight, with several obstacles between End Device and Gateway.

Conversely, position P_5, although being at a greater distance from the End Device, is in line–of–sight, so that the quality of the communication is good. More importantly, the beneficial effect of increasing the Spreading Factor is evident. Indeed, with $SF = 12$, the performance of the communication are acceptable, even for the most critical positions. This is confirmed by the number of lost packets (Fig. 7) for all the positions, and subsequently by the number of correctly received packets reported in Fig. 8.

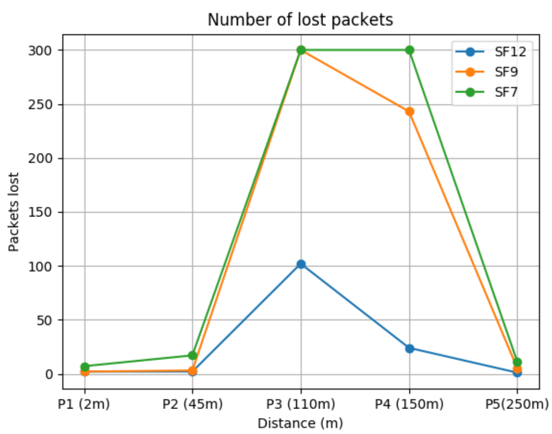

Fig. 7. Number of Lost Packets N_{PL}

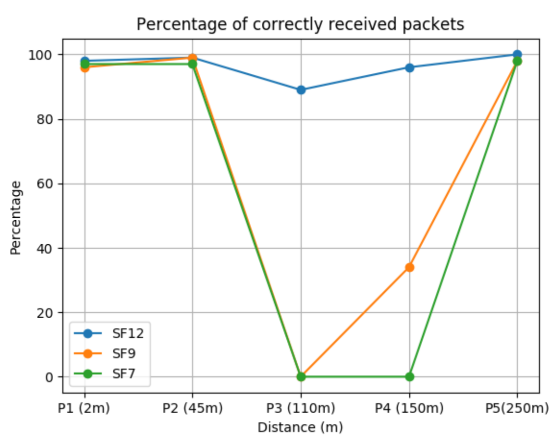

Fig. 8. Number of Correctly Received Packets N_{CR} [%]

C. Communication with the remote Cloud

In a further session of tests, we addressed the ability of the system to support the communication of measurement data

sensor	datetime	type	value
104	2019-10-24 15:06:33	LIGHT	452
105	2019-10-24 15:06:33	TEMP	22
104	2019-10-24 15:01:23	LIGHT	277
105	2019-10-24 15:01:23	TEMP	22
104	2019-10-24 14:56:13	LIGHT	335
105	2019-10-24 14:56:13	TEMP	22
104	2019-10-24 14:51:03	LIGHT	301
105	2019-10-24 14:51:03	TEMP	22
104	2019-10-24 14:45:53	LIGHT	327

Fig. 9. Graphical Interface provided by the Services of the Remote Cloud

with the remote cloud. In this case, the LoRa Gateway was located in position P_1, and we implemented the connection scheme depicted in Fig. 3. In the remote cloud, temperature and light sensor measurements were stored in a MySQL database, where they can be displayed and analyzed. An example of the graphical interface provided by the remote cloud services is reported in Fig. 9. As can be seen, sensor measurements are collected with a period of 5 minutes and 10 seconds. This "unusual" period was due to a specific requirement of the cloud communication system. The measurements units are °C for the temperature sensor and Lux for the light one, respectively. For the sake of completeness, it has to be mentioned that in this experiment, the top side of the cube was removed, since otherwise the measurement of the light sensor would have been always zero.

D. Discussion

As pointed out in Subsection IV.B, in some positions (particularly P3 and P4) the communication quality was rather poor. However, the measurement campaign was conceived to understand, as much as possible, the propagation mechanisms in the operational scenario, in order to define the locations of LoRa Gateway and artifacts when these latter ones are finally positioned. In this respect, it is expected that in practical deployments the actual distance between artifacts and Gateway will be some tens of meters, typically in LOS. This allows to conclude that the performance figures are adequate for the envisaged applications, even if they will need to be further validated in real application contexts. Moreover, as discussed in Section II, the transmission periods of the sensor data are in the order of some tens of seconds or more. Consequently, high Spreading Factors (typically, $SF = 12$, to ensure low packet error rates) can be safely adopted, since the correspondent lower transmission rates do not impact on the timing requirements. Also, although the tests have been carried out over some days, with different climatic conditions, the performance of the communication systems has not shown any noticeable discrepancy. This is due, on our opinion, to two different aspects. The first one is related to the robustness of the LoRa protocol. The second aspect is concerned with the care adopted to insert the LoRa sensor modules within the artifacts. Indeed, as can be seen in Fig. 5, an IP 67 plastic box has been used to ensure a very high protection of the modules. Finally, the communication experiments did not include tests during the production phase, since this phase has not started yet. We are aware, however, that the experimental conditions in such scenario might be different with respect to those of the measurements reported in this paper. Consequently, communication tests while an artifact is actually being produced represent a meaningful benchmark which is left for future activities.

V. Conclusion and Future Works

In this paper we presented an additive manufacturing project based on the IIoT paradigm. Among the innovative aspects of the project, we focused on the possibility of embedding sensors within the artifacts, a feature that allows the transmission of measurement data (typically temperature, mechanical stress and humidity) to both the PLC that handles the 3D Printer and the remote cloud that implements off–line data analysis. The communication system deployed for the transmission of sensor data has been implemented using LoRaWAN, a popular wireless LP–WAN network that is able to satisfy the specific requirements of the application. The tests carried out have demonstrated the feasibility of this feature, since the collection of measurement data from the deployed sensors within the artifacts worked effectively.

The project is still in progress and some future activities will be addressed in the next months. Particularly, a throughout assessment needs to be undertaken about power consumption of the sensors. Indeed, since they are fed-up by batteries that can not be changed, it is of paramount importance to keep the power consumption as low as possible to prolong their lifetime. Also, the first prototype artifacts are going to be printed and put into operation. This will allow to check the complete behavior of the project and, in particular, the performance of the communication systems for the real–time feedback and the off–line analysis.

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