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Assessment of LoRaWAN Transmission Systems under Temperature and Humidity, Gas and Vibration Ageing Effects within IIoT Contexts

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Abstract—Within the big picture of the Internet of Things (IoT), a brand new paradigm has risen since few years ago in the context of industrial scenarios: the Industrial Internet of Things (IIoT), whose aim is to transplant all of the features, characteristics and scopes of the IoT into industrial settings. The latter ones might be subject to a wide range of environmental conditions from the point of view of both temperature and relative humidity, along with harmful gases exposure and vibration due to, for instance, machineries. Therefore, whenever their monitoring is performed by means of devoted infrastructures, such extreme working conditions must be born in mind during the pertaining design phases. Mostly, industrial monitoring is put into effect by resorting to wireless sensor networks enabled by Low Power Wide Area Network (LPWAN) technologies. This set of facilities includes an ample heterogeneity of standards and techniques. However, the Long Range (LoRa) modulation and the LoRa Wide Area Network (LoRaWAN) protocol extensively proved to be reliable and robust alternatives. Thus, in this paper the variations of hardware performances of a LoRaWAN sensor node, in terms of transmission capabilities, due to the changes of temperature and relative humidity, vibration and gaseous atmospheres like CO, NO and NO₂, which are typical of industrial processes, are investigated. In so doing, an ageing process due to the aforementioned phenomena was induced. To this end, a measurement campaign within controlled environments (i.e., a climatic chamber, a fume extraction plant and an ad-hoc vibration test bench) was sorted out, whose results show a physiological performances drop that neither undermine the network reliability, nor damage the sensor node electronics.

Index Terms—IoT, IIoT, LoRa, LoRaWAN, Performance Assessment, Vibrations, Gas Exposure.

I. INTRODUCTION

LoRa Range (LoRa) technology, thanks to its robustness allowed both by a maximum link budget up to 157 dBm and by the exploitation of Forward Error Correction (FEC) techniques along with a high receiver sensitivity down to −137 dBm, has already demonstrated to be an excellent candidate for the realization of distributed monitoring systems to be deployed in critical contexts. Indeed, successful LoRa transmissions were achieved from underground [1], [2], from underwater [3], [4] and from the inner space of metallic housings [5]. At the same time, the effectiveness of LoRa has been also demonstrated in standard transmission settings (i.e., in open air and in urban or rural areas) and even by studying correlations with different meteorological and environmental conditions [6].

All these results make LoRa a suitable technology for the realization of distributed monitoring infrastructures in industrial contexts too [7]–[9], where extreme environmental conditions may be experienced. Indeed, in several industrial applications, parameters like temperature and humidity may span in a wide range: extremely low or tremendously high temperatures may occur while elevated humidity levels, up to 100%, may be present within working environments. Furthermore, severe environmental conditions can be characterised by a high vibration intensity (e.g., machineries, turbines and pipelines) and high concentration of various gases such as Nitric Oxide (NO), Nitrogen Dioxide (NO₂) and Carbon Monoxide (CO). For this reason, the characterization of the LoRa transmission channel in these operating conditions is crucial to validate the usability of this technology for remote data acquisition within the context of the Industrial Internet of Things (IIoT).

Therefore, this paper aims at studying the behavior of LoRaWAN transmitters whenever the relative electronics is exposed to a wide range of temperature and humidity values (i.e., from very low to the most extreme ones), as well as to machinery vibration and NO, NO₂ and CO gases. Tests were carried out by performing several transmissions putting the transmitter in different environmental conditions by employing a climatic chamber, an ad-hoc vibration test bench and a fume extraction test bench thus having full command on both temperature and humidity, vibration frequency and amplitude, and gases concentration, therefore obtaining a controlled environment. Such working conditions are typical of industrial contexts (e.g., oil and gas field), where wireless communication technologies are widely spread. Therefore, this paper sheds light on the assessment of transmission performance drops due to the aforementioned environmental conditions.

This paper extends [10], in which typical industrial values of temperature and humidity concentration were reproduced in a controlled environment; accordingly, preliminary results were reported. Herein, tests related to temperature and humidity were performed once again by following the same methodology of [10], and trials on vibrations and gaseous atmospheres...
were brand new.

The manuscript continues as follows: Section II thoroughly depicts the papers related to the topic. Section III shows the importance of characterizing the environmental effects on the hardware, while Section IV is devoted at showing the testing setup, and the relative results are reported in Section V; eventually, Section VI highlights conclusions and remarks while suggesting future works.

II. RELATED WORKS

Wireless links performances suffer from temperature and humidity regardless of the exploited modulation. For instance, in [11] sensor nodes relying on IEEE 802.15.4 standard were adopted to study the aforesaid dependence: the authors found out that the Received Signal Strength Indicator (RSSI) linearly drops with temperature and humidity rising. Similarly, [12] performed a study on path loss variations with respect to changes of temperature and relative humidity values pointing out that bigger path losses occurred along with high temperatures and relative humidity. These results are furthermore validated by [13] where a linear inverse correlation amid RSSI and temperature arises. Such dependency is far from being unexpected, though, for a twofold reason: firstly, the higher the temperature, the more elevated the thermal noise; secondly, the higher the humidity, the larger the percentage of water vapor in air and the bigger its electric permittivity. Likewise, in [14], [15] environmental tests were carried out to validate the same relationship within the Ultra High Frequency (UHF) band (which includes the operating frequencies of LoRa). In particular, during tests in [14] constant values for humidity, atmospheric pressure and wind speed and direction were experienced, and the authors demonstrated that RSSI linearly decreases whenever temperature raises. On the other hand, in [15] tests at different frequencies within the UHF spectrum were carried out highlighting the same inverse proportionality between temperature and RSSI regardless of the frequency. Finally, [16] investigates relationship amid RSSI and relative humidity within UHF band discovering a linear inverse proportionality.

The literature also proposes similar studies which are focused on LoRa modulation and Long Range Wide Area Network (LoRaWAN) protocol. An in-depth work on the performances of LoRaWAN channel under different environmental condition is the one in [6] where a long length link was tested throughout a 70-day timespan experiencing sundry meteorological conditions. The key result is, once again, that relative humidity hinders the transmissions degrading both RSSI and Signal-to-Noise Ratio (SNR) still confirming LoRa robustness and reliability. Dependency on temperature of RSSI for LoRa links was investigated in [17] where tests were sorted out by employing different LoRa transceivers. Performances were evaluated over a range of 60°C determining an average decrease of RSSI of 1 dB/10°C. Moreover, the same authors extended the latter study in [18]; by making use of a temperature-controlled testbed, a correlation between performance diminishing and temperature rising was furthermore highlighted along with the fact that over a certain threshold (e.g., more than 55 °C) LoRa links are almost unfeasible. However, a careful tuning of transmission parameters may be helpful in expanding the probability of successful broadcasts thus becoming a pivotal method to lighten undesired phenomena caused by temperature. The importance of this kind of temperature validation is given by the fact that it was proven that both reliability and safety aspects are heavily affected by a superficial knowledge of the parameters variations over time [19], [20]. In particular, it is well-known that electronics notably suffers from both temperature stress and ageing leading to unacceptable performance losses.

Besides temperature and humidity, also vibration drastically affects the performances of electronic components. As a matter of fact, in [21] the authors presented a theoretical and experimental vibration analysis of electronic packages that are subject to vibration during their normal operation. Furthermore, [22] investigated the fatigue damage of electronic modules subject to random vibrations during the operational conditions. In [23]–[25] the authors proposed the use of Wireless Sensors Networks (WSN) for vibration condition monitoring and fault diagnosis in industrial applications such as industrial motors and rotating machineries. Similarly, [26] used a low power Zigbee transceiver to transmit vibration measurement of a single phase induction motor in order to prevent damage. Unfortunately, as far as the authors are concerned, radio performances, such as RSSI and SNR, under vibrating conditions have not been studied yet, but it is possible to find papers that analyse the transmission performances of WSN nodes applied to moving objects, especially in the automotive scenario. In fact, [27] studied the LoRaWAN protocol transmission performances (i.e., RSSI, SNR and packet loss) in a vehicular context at different speeds. Similarly, [28] studied the RSSI metrics of a WSN operating in the frequency band from 2400 MHz to 2483.5 MHz in a fast moving scenario. Both articles show a very small performance decay among all the speed values.

As it was already introduced, the last aspect covered in this paper is the transmission performances of a LoRaWAN node operating in gaseous atmospheres that are frequently adopted in industrial environments, in particular CO, NO and NO₂. This theme is covered in many articles related to air pollution. In fact, due to the rapid industrialization, air pollution monitoring has become a hot topic. For this reason, [29] presented a literature review on WSN-based air pollution monitoring systems gathering information from air polluted environments, thus periodically monitoring pollutant gases in stationary and dynamic air flows. Furthermore, many articles report the employment of IoT-WSN for monitoring both outdoor and indoor air pollution [30]–[32]. These studies adopted a LoRa transceiver but did not analyse the radio performances in correlation to gases concentrations. Notwithstanding, many articles report the atmospheric corrosion effect on electronics produced by high concentration of various gases. This impact leads to pores and cracks of copper pads and traces, and it is commonly called “creeping corrosion” [33]. Industrial tests are usually performed by resorting to the Mixed Flowing Gas (MFG) test procedures, which simulate contaminated industrial environments to evaluate resistance to
corrosion [34]. Furthermore, in [35] the authors studied the effectiveness of an innovative corrosion test method called iNEMI FoS compared to other tests. In particular, they focused the analysis on recent hardware applications (e.g., IoT, Edge Computing, Artificial Intelligence, etc.). Eventually, just as it was formerly said for the vibrations context, the literature does not propose studies which are centered on transceivers radio performances placed in a high gas concentration controlled environment.

III. ENVIRONMENTAL CHARACTERIZATION IMPORTANCE

A. Temperature and Humidity

Temperature is important due to the effects on semiconductor diffusion and threshold changes in integrated amplifiers, impurity diffusion, material mismatch and electronic noise generation. On the other hand, humidity plays an important role too considering that at specific points where water vapour becomes liquid (i.e., dew points) such amount of water may induce, on the long run, rusting on contacts and local shorts. Therefore, it leads to uncontrolled and undesired system behaviours, up to premature and unpredictable failures which may result in a catastrophic system outcome. These considerations also apply to specific wireless transmission systems operating into open environments which are subject to environmental excursions and sudden seasonal variations. Nevertheless, such effects may affect even systems deployed into enclosed systems (e.g., IP67, or higher rating, boxes) due to the fact that the water content trapped inside the housing during maintenance activities may change status several times affecting different circuit parts due to temperature cycling.

Usually, measurement systems express either relative or absolute humidity which may lead to some confusion if temperature is not well known. Actually, absolute humidity and temperature are linked together by the following relationship:

\[
H(RH, T_M) = 216.7 \left[ \frac{RH \cdot P \cdot e^m}{273.15 + T_M} \right]
\]

where \( H \) is the absolute humidity expressed in \( \text{g/m}^3 \), \( RH \) is the relative humidity that can be measured in the operating environment, \( T = 243.12 \, ^\circ\text{C} \), \( P \) is the environmental pressure expressed in \( \text{g/m}^3 \), which can be assumed as \( 11 \, \text{g/m}^3 \), and \( m \) is a constant equal to 17.02. Finally, \( T_M \) is the actual temperature in \( ^\circ\text{C} \) which can be measured.

B. Gas

The standard DIN EN 60721.3.3 [36] is mainly used to specify corrosive environments by manufacturers that create products that are commonly used in these environments. Nevertheless, this standard does not address the way tests should be conducted. Therefore, the lack in quantitative evaluation criteria and missing thresholds may lead to inconsistent testing plans within products development planning. As a result, testing using mixed gases based on specific company experience is utilized in industry to demonstrate compliance with the specified requirements. Under this assumption, several works tried to deal with gas usage and effects on materials due to practical environmental exposure with the aim of understanding long term effects on both materials and components [38], [39]. Similarly, in these papers the authors tried to focus on a limited number of gases to explore short term effects on communication devices.

C. Vibration

Vibrations were extensively studied and used by companies to verify compliance with actual usage conditions. Moreover, such tests were proposed to prove the possibility to create aging models and enhance failure mechanisms connected to single components or electronic assemblies [39]–[42]. In light of this, in such papers the authors tried to investigate a very limited set of frequencies of interest in industrial applications to verify whether electronics transmission capabilities of wireless devices are affected on short term exposure.

IV. TESTING SETUP

A. Transmitter-Receiver Architecture

Tests were performed employing the following devices. The transmitter node was composed of an ATtiny84A-SSU Micro Controller Unit (MCU) produced by Microchip, an RFM95 LoRa transceiver manufactured by HopeRF and a 2 dBd gain omnidirectional antenna. The MCU features an 8 kB flash program memory and an industrial functioning temperature in the range \(-40\) to \(85\) °C. The LoRa transceiver provides long range spread spectrum communication with high interference immunity and low power consumption, therefore it is highly recommended for IIoT devices operating in a deploy-and-forget fashion. Finally, the node was powered using a 3400 mAh NCR18650B Li-ion battery produced by Panasonic. In order to reduce the number of the involved variables within the experiments, all the electronics forming the transmitter were embedded within a printed circuit board (PCB). To this end, many PCBs were realised in order to make replicas of the same device so as to employ different clones for each of the testing setup. The receiver part was characterized by an LG308 Dragino LoRaWAN gateway for the tests related to temperature and humidity effect, while for the tests on vibration and gas impact on transmissions a RAK2245 LoRaWAN gateway was used. Both the receivers share the same electronics, and they were provided with the same antenna, therefore they ensure the same performances. In particular, they feature a sensitivity down to \(-137\) dBm.

B. General Methodology

Tests aiming at assessing the effect of temperature and humidity were carefully carried out within a climatic chamber (i.e., the ACS Angelantoni HYGROS 250 environmental test chamber) which permitted to precisely control temperature and humidity values. Similarly, tests concerning the impact of gas exposure on transmission performances were accomplished within a fume extraction plant for safety reasons and for ensuring a controlled environment as well. Likewise, the dependence of transmission performances on vibrations was evaluated by resorting to an ad-hoc vibration test bench that...
allows to precisely set vibration frequency and amplitude which are strictly related to acceleration.

Experimental tests were sorted out according to the following methodology. Tests on temperature and humidity, on gas exposure and on the effect of vibrations were comprised of many measurement sets, each consisting of three batches during which the sensor node sent 1000 LoRaWAN packets, and at the same time, RSSIs were sampled. This decision was adopted so to average measurements from the three batches of a single set in order to even out undesired disruptive phenomena which are not related to temperature or humidity, gases or vibration influence (e.g., fast fading effects).

While the tests on temperature and humidity and the ones on gas exposure were accomplished by making use of a single Spreading Factor (SF) for the transmission of the LoRaWAN packets (i.e., SF=12), all the SFs were tested during trials on vibrations. Such a choice was selected in order to find out probable correlations between the SFs and the movement resulting from vibrations. The remaining transmission parameters were shared between all of the tests within the whole measurement campaign. In particular, a bandwidth of 125 kHz, a coding rate of 4/5, a packet payload of 10 B, and eight different channels within the 863 to 870 MHz band (so to establish a frequency diversity scheme) were used. For what concerns the transmitter power output $P_{TX}$, three different values were selected (i.e., $-80 \text{ dBm}$, $0 \text{ dBm}$ and $14 \text{ dBm}$). In so doing, not only was the effect of the aforementioned agents investigated, but also the reception capability of the system at different levels of received power was assessed. Eventually, considering that the performances of the battery powering the transmitter falls outside the scope of the paper, it was not included within the experimental sites, and the node was activated by passing power cables through cable glands.

With the purpose of avoiding external environmental attenuation sources, the climatic chamber, the fume extraction plant and the vibration test bench were placed in a restricted area.

C. Temperature and Humidity Test Setup

Regarding the tests within the climatic chamber, transmitter and receiver were respectively put inside and outside it (see Fig. 2): taking into account the chamber door, the former 10 cm-distant, while the latter 40 cm-distant. The climatic chamber is thought to precisely set temperature and humidity values in order to perform environmental tests, however it is important to point out that for each temperature value the humidity concentration range is limited to certain values defined by psychrometric principles. For instance, for negative temperatures it is not possible to set a desired relative humidity. Similarly, relative humidity higher than 90% cannot be reached for positive temperatures. On the other hand, minimum relative humidity ranges from 60% at 10 °C, down to 20% at 30 °C and finally down to the minimum of 10% for temperatures from 50 °C and over. Such shortcomings entailed that not all of the relative humidity values may be freely spanned. Thus, tests were sorted out throughout twelve environmental sets each of which is characterized by its own temperature and humidity pair: $-25 ^\circ \text{C}$ and $-10 ^\circ \text{C}$ for negative temperatures while $10 ^\circ \text{C}$, $30 ^\circ \text{C}$, $50 ^\circ \text{C}$, $70 ^\circ \text{C}$ and $90 ^\circ \text{C}$ for the positive ones. Concerning the latter ones, relative humidity was only tested for the minimum and maximum achievable value for each of the temperatures. Tests were compliant with IEC 60068-2-1, IEC 60068-2-2 and IEC 60068-2-78 for cold, dry heat and damp heat environmental testing standards respectively. These standards describe approaches which are directly related to specimen characteristics and temperature changes over time. According to them, the specimen under test (i.e., the transmitter) can be considered as non-heat dissipating. As a matter of fact, the hottest point on its surface is always $5 ^\circ \text{C}$ below the ambient temperature of the environment after temperature stabilization. In this measurement campaign, the non-heat dissipating specimen was exposed to a gradual change of temperature. Consequently, the test methods that correspond to each of the aforementioned IEC standards are:

- Test Ab for cold environment;
- Test Bb for dry heat environment;
- Test Cab for damp heat environment.

Fig. 1 depicts the temperature profiles for cold and hot tests, which were deduced by the aforementioned IEC standards. More specifically, the tests follow the subsequent approach. The specimen was introduced into the climatic chamber when both of them were at laboratory temperature. The chamber was turned on and the temperature was gradually augmented to reach the desired value with a rate of $1 ^\circ \text{C}$ per minute. No sooner had the system reached the target temperature, than the transmitter was turned on and the data acquisition started. Once the test set at hand was over, the temperature was gradually settled to the laboratory one with a rate of $1 ^\circ \text{C}$ per minute. The specimen remained in this condition for at least 1 hour so as to allow the whole thermodynamic system to get to the steady state. During the measurement period, the chamber provided a stable temperature and relative humidity with $\pm 2 ^\circ \text{C}$ and $\pm 3\%$ relative humidity in turn. The proposed tests complied with typical and severe operating conditions for offshore applications. Nevertheless, their aim was to assess the transmission capabilities and discover potential issues for a transmitter that could be used, for instance, in the oil and gas market. Throughout these tests, the transmitter was not coated at all in order to expose the hardware to the harshest possible conditions so as to assess whether the transmission performances suffered from such a testing condition or not.

D. Gas Test Setup

Tests on gas effect were accomplished so to expose the transmitter to an atmosphere composed of a fixed concentration of a target gas diluted in a carrier gas consisting of $N_2$. The test was repeated for three target gases: $CO$ (with a concentration of 200 ppm in $N_2$), $NO$ (with a concentration of 50 ppm in $N_2$) and $NO_2$ (with a concentration of 50 ppm in $N_2$). The transmitter was put in a containment box in which a constant flow (i.e., 100 mL/min) of the gas mixture was fluxed. The box had an inlet pipe, supplied with the gas mixture flow, and an outlet pipe to let out the mixture. The gas mixture flow was obtained by mixing a sample gas mixture, from reference gas tanks, with $N_2$ by means of two mass flow meters: for
both, the full-scale flow was 200 mL/min. The used mass flow meters were the Bronkhorst F201C. One flow meter was used to set a flux of \( N_2 \) and the other one was used to dose a mixture of the target gas. The two gas flows were mixed obtaining a constant total flux of 100 mL/min at the required concentration. The mass flow meters controller was connected to a PC hosting a LabVIEW program allowing an automatic control of the test. Once that the transmitter was housed within the containment box, the gas mixture was fluxed within the latter for two hours so to let it act on the electronics. Such box was placed within the fume extraction plant 10 cm-distant from the plant door, while the gateway was placed outside the plant 40 cm-distant from the door (see Fig. 3). Then, the three batches were sequentially accomplished. The experiments on gas exposure were compared with two control tests. Both of them were sorted out by placing the transmitter and the receiver one in front of the other at a distance of 50 cm, and in the same position (i.e., the node within the fume extraction plant and the gateway outside the latter). The former was carried out before proceeding with the current fume exposure in order to collect a reference. On the other hand, the latter, which can be named as post experimental set, was executed 24 hours after the fume exposure so to assess whether the gases detrimental effect is permanent or not.

### E. Vibration Test Setup

In order to evaluate the performances of the transmitter in presence of external vibrations, a vibration test bench (see Figure 4) was sorted out, where the vibration source is a modified loudspeaker actuated by a power amplifier [43]. The loudspeaker was modified by mounting a rigid aluminum disk on the diameter of the voice coil which is used as a support for the node and a reference accelerometer. The voice coil has a diameter of 65 mm, such as the one of the aluminum disk. The payload given by the disk, the transmitting node and the accelerometer can be easily driven by the 700 W coil of the speaker and the 1 kW power amplifier. The reference accelerometer is needed to measure the acceleration of the vibration exerted by the loudspeaker itself. The adopted accelerometer is a triaxial piezoelectric B&K 4326A coupled with a three channel piezo amplifier [44]. The tests were performed by vibrating the transmitter with sinusoidal vibrations at known accelerations and specific frequencies. In particular, the tested frequencies spanned from 25 Hz to 285 Hz with variable amplitudes providing acceleration from 3.14 m/s\(^2\) to 17.90 m/s\(^2\). In particular, all of the frequency-acceleration pairs will be listed in Section V. Moreover, for frequencies lower or equal to 125 Hz the vibration amplitude was set so that a speed of 0.02 m/s was ensured, while for higher frequencies the amplitude was set in order to produce a speed of 0.01 m/s. In addition, a set of transmissions was performed when the system was still (i.e., vibration frequency equal to 0 Hz) in order to collect a reference sample. The selected speed amplitudes and corresponding frequency ranges were chosen because these are the ones that are requested by all the electronic devices mounted on offshore applications in oil and gas context. Additionally, the proposed speed levels result in a higher severity with respect to IEC 60068-2-6 standard for sinusoidal testing. For this purpose, a signal generator was used to feed the loudspeaker power amplifier. To adjust the output level of the signal generator, the output of the accelerometer charge amplifier was monitored. In particular, the charge amplifier was set to provide 1 V/g, and the vibration level supplied to the node was adjusted by controlling the amplitude of the signal coming from the charge amplifier itself. Since such tests were conducted at low frequencies, the transmitter was fixed onto the aluminum disk support by making use of hot glue, and it was placed 50 cm apart from the LoRaWAN gateway. Similarly as before, the transmitter was a brand new PCB so to reduce the number of experimental

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**Fig. 1:** Adopted temperature profiles for the temperature and humidity tests according to the IEC standards (see Section IV-C): (a) Cold Tests and (b) Dry Heat Tests.

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variables.

V. TESTS RESULTS

This Section is devoted at showing tests results for each of the tests setup. As it was previously mentioned, this paper aims at assessing performance variations of the transmitting node, therefore battery discharge was not monitored during the tests. However, due to the well-known low power consumption of LoRa modulation, and due to the fact the battery was replaced with a fully charged one for each of the testing sets belonging to each of the measurement batches, tests results may be considered as reliable. However, because of the strong robustness of LoRa modulation, if the battery would reach low values, then it is reasonable to deem that no intense disruptive effects on results would have been experienced. As it is reported below, test results remarked the well-known robustness of LoRa technology that enables receivers to successfully demodulate signals far below the noise floor power level. Therefore, LoRaWAN protocol, and LoRa modulation in particular, suitability as enabling technologies for data gathering within critical contexts, like the industrial ones, was
underlined thus fostering the effectiveness and the feasibility of IIoT infrastructures.

A. Temperature and Humidity Test Results

Fig. 5 shows the RSSI values during the twelve measurement sets, for each of the $P_{TX}$, related to the tests within the climatic chamber that are distinguished by their own temperature and humidity values, that are reported on the abscissa of the chart in Fig. 5. Results from the literature were partially met: while there is a performance drop as temperature increases, it seems that such a tendency is not exactly confirmed for humidity rises. Indeed, at constant temperature values, RSSIs do not particularly suffer from humidity increments. Despite results for relative humidity go against what can be retrieved in the literature, they might be considered as well trustworthy since tests were sorted out within a controlled environment (i.e., the climatic chamber).

Conversely, temperature results are in agreement with the ones of related works albeit no linear behaviors were found. Indeed, within Fig. 6 experienced RSSI values for any tested temperature were averaged and plotted in function of temperature so to check the aforementioned linear correlation: it is evident that dependence amid RSSI and temperature may be underlined thus fostering the effectiveness and the feasibility of IIoT infrastructures.

$$P_{TX} = 0 \text{ dBm, } P_{TX} = 5 \text{ dBm, } P_{TX} = 14 \text{ dBm}$$

Fig. 6: Mean RSSI trend in function of temperature.

$$N_T = 10 \log_{10} \left[ \frac{K_B \cdot T \cdot BW}{0.001} \right] \tag{2}$$

where $N_T$ is thermal noise expressed in $dBm$, $K_B$ is Boltzmann constant, $T$ is the temperature expressed in $K$ and $BW$ is the bandwidth in $Hz$. Under these assumptions it is evident that temperature variations, and thermal cycling in particular, have an influence on the induced noise by analog and digital electronic components. The increase in the electron junction ionization activity with temperature justifies the reason why the aforesaid parameters negatively affects transmission performances. Concerning the humidity contribution, it is possible to notice that an increase of the water content in air enhances capabilities communication. This may be justified by the increased thermal capacity of water vapor with respect to dry air, and with a local lowering of the junction temperature of the single involved components.

B. Gas Test Results

Fig. 8 shows the RSSI mean values of the gas exposure test sets in comparison with both the control ones. First of all, no packet loss arose during each of the testing setup. Moreover, and as it can be drawn from the plot, no significant disruptive effects occurred, both immediately after the exposure and several hours later. Indeed, at a given $P_{TX}$, only slight difference amid mean RSSIs throughout the three test sets (i.e., the control, the experimental and the post experimental ones) were measured. In particular, when $P_{TX} = -80 \text{ dBm}$ such discrepancies were respectively of 4.23 dB, 4.50 dB and 0.98 dB in turn for $CO$, $NO$ and $NO_2$. Similarly, when $P_{TX} = 0 \text{ dBm}$ such differences were respectively of 4.92 dB, 1.27 dB and 3.63 dB in turn for $CO$, $NO$ and $NO_2$. Finally, when $P_{TX} = 14 \text{ dBm}$ such variations were respectively of 4.71 dB, 1.68 dB and 3.40 dB in turn for...
entails movement, and movement entails acceleration (at least when an object starts moving from a still state): both of them were ascribed to be detrimental factors for wireless communication technologies performances (see Section II). These tests highlighted an interesting result concerning the effect of the detrimental agents (i.e., vibration and acceleration) on transmission performances by varying the SF, which are in line with a previous work entailing LoRaWAN transmissions from moving vehicles [27]. In particular, RSSIs at a given frequency or acceleration, and at a given transmitter power output, are very close to each other regardless of the SF. Indeed, discrepancies are always no bigger than 6 dB. On the contrary, what is strongly varying is the number of received packets. While no loss occurred whenever $P_{TX} = 0$ dBm and $P_{TX} = 14$ dBm, no matter what SF was exploited, no data was barely received for $P_{TX} = −80$ dBm whenever SF=8 and SF=7 were selected. In particular, at SF=7 data was only received at the vibration frequencies of 135 Hz and 145 Hz the 21% and the 6% of the times in turn. Similarly, at SF=8 no data was received at the vibration frequencies spanning from 165 Hz to 275 Hz, while it was correctly received from the 1% to the 94% of the times for the other tested frequencies. Such results may be considered as spurious because they seem to be the consequence of external effects rather than systematic outcomes. This hits at the fact that higher SFs are by far preferable whenever the transceiver is subject to vibrations and a low transmitter power output is used in order to limit consumption, and this is due to the fact that the receiver sensitivity proportionally augments along with SF. All in all, apart from the just mentioned cases, it can be drawn that no significant correlation between RSSI degradation and vibration or acceleration can be found, and that successful data transmission is ensured even when exiguous transmitter power output values are used. However, another result is that vibrations do affect RSSI on the whole. Indeed, independently on the SF, an average drop of 3 dB can be experienced between measurements at 0 Hz and at 25 Hz when $P_{TX} = −80$ dBm. Similarly, such drop averagely becomes bigger as $P_{TX}$ augments: 10 dB if $P_{TX} = 0$ dBm, and 12 dB if $P_{TX} = 14$ dBm. Nevertheless, such degradation does not undermine the system reception capabilities thus underlying the robustness of LoRa modulation and LoRaWAN protocol.

VI. Conclusions

The scope of this paper was to investigate hardware behavior of a LoRaWAN transmitter when it is integrated in a data acquisition system designed to operate in harsh environmental conditions (e.g., in industrial application scenarios like the oil and gas one). Indeed, in such context, sensor nodes may be subject to severe meteorological conditions as well as to mechanical stresses or corrosive action deriving from the presence gaseous substances of different types. Detrimental phenomena include extreme temperatures and relative humidity (which are very common in outdoor installations), vibrations (that may occur due to wireless sensing systems positioned on machineries), and gaseous atmospheres principally made of CO, NO and NO$_2$ (which are usually present in several
industrial processes to be monitored). To this end, transmission tests were sorted out by placing a LoRaWAN transmitter within controlled environments. In particular, temperature and humidity tests were sorted out within a climatic chamber; experiments related to gas effect were accomplished in a fume extraction plant by making use of flow meters so to control the gas mixtures to which the transmitter was exposed to; and vibration tests were executed by exploiting an ad-hoc test bench so to finely control both amplitude and frequency of vibrations. In so doing, the whole measurement campaign took place by following a controlled fashion whose outcome was to induce an ageing process due to the aforementioned phenomena. The aforesaid operational effectiveness changes were assessed for different radio settings in terms of transmitter power output, by evaluating how transmission performances, in term of RSSIs, accordingly varied.

Following the first set of tests, it was found out that temperature directly hinders performances: such outcome was partially in agreement with the literature since it is not regulated by a linear trend as related works pointed out. On the other hand, at any tested temperature, relative humidity proportionally improved performances thus reaching a complete countertrend phenomenon with respect to comparable researches. In any case, it should be underlined that the difference in terms of RSSI among the best and the worst case is always in the order of few dBs, thus suggesting the feasibility of LoRaWAN networks for the implementation of IoT architectures regardless of the specific environmental conditions for what concerns the actual data transmission capabilities.

The second result of this study was that gas exposure has a very limited impact on the overall performances of the transmission module. Indeed, for the three tested output powers, and with all the gases used in the tests, the maximum RSSI decrease was lower than 5 dB: such impact may be crucial only for extremely low RSSI values that may occur at very large distances among the transmitter and the receiver. Such negative configuration is very rare in industrial applications where an accurate positioning of the gateway can be set up, thus avoiding the system to operate very close to the actual receiver sensitivity level.

Finally, tests related to vibrations showed an overall degradation of the performances with respect to the stationary case. Indeed, when moving, the RSSI measures had a drop that ranges from 3 dB when $P_{TX} = -80$ dBm to 12 dB when $P_{TX} = 14$ dBm. This fact should be taken into account for all those applications when a LoRaWAN sensor node is expected to be deployed on a vibrating asset. Moreover, when choosing the lowest power output, also the SF should be taken into account since at low SFs high packet losses are experienced: however, this aspect is not directly related to the experimental
setup because losses also occur when the node was still, but it is mainly due to the different receiver sensitivity values in conjunction with the extremely short transmission ranges reachable with such a low transmitter power output. In general, choosing such a low power output does not allow to exploit one of the most significant characteristics of LoRaWAN technology (i.e., its long range coverage).

However, despite LoRa modulation and LoRaWAN protocol proved an overall performance decrease throughout all of the aforementioned tests, such facilities gave evidence of robustness and reliability within critical contexts highlighting their practicability in IoT scenarios.

REFERENCES


