NB-IoT Versus LoRaWAN: An Experimental Evaluation for Industrial Applications

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***Abstract*—Low power and long-range communications are crucial features of the Internet of Things (IoT) paradigm that is becoming essential even for industrial applications. Today, the most promising long-range communication technologies are LoRaWAN and Narrow Band IoT (NB-IoT), which are driving a large IoT ecosystem. In this article, we evaluate the performance of LoRaWAN and NB-IoT with accurate in-field measurements using the same application context for a fair comparison in terms of energy efficiency, lifetime, quality of service, and coverage. The NB-IoT energy transmission is scarcely dependent on the payload length. Thus applications that can tolerate buffering and caching techniques on the node are favored. On the other hand, LoRaWAN consumes 10 × lower energy compared to NB-IoT for occasional and latency-sensitive communications, for which it enables much end-device lifetime. Finally, this paper provides design guidelines for future industrial applications with stringent requirements of long-range and low power wireless connectivity.**

***Index Terms*—Energy efficiency, internet of things (IoT), industrial internet of things (IIoT), low power wireless area network (LPWAN), long-range communication, LoRa, LoRaWAN, NB-IoT, wireless sensor networks.**

I. Introduction

A MAJOR trend in the Industry 4.0 [1] revolution is the adoption of autonomous wireless devices, which pervasively connect machines and objects [1], creating a new domain called industrial Internet of Things (IIoT) [2]. Wireless systems will need to support more than tens of billions of connected devices [3]. Indeed, one of the key goals of the 5G transition is to enable an “all-connected” world for humans and objects [1]. Many IIoT deployments can be found in the industry today, with widely different requirements and constraints [4, 5]. Hence, in recent years many approaches have been proposed to improve crucial factors, such as low power consumption and communication range [6], [7].

Following the rapid IoT market expansion, LPWAN has become one of the faster-growing areas in IoT. Low Power Wireless Area Network (LPWAN) is the common term to identify the wireless technologies that enable wide-area communication at low cost and low power consumption. The LPWAN typical application scenario needs to transmit a few bytes with a long-range. Many LPWAN technologies are emerging in both licensed and unlicensed markets, such as LoRa, LTE-M, SigFox, and Narrow-Band Internet of Things (NB-IoT). Among them, LoRa and NB-IoT are the two leading technologies [6], [7].

On the cellular networks side, the 3rd Generation Partnership Project (3GPP) has developed the Narrow-Band Internet of Things concept as part of Release 13 [7]. To improve energy efficiency, NB-IoT combines the benefits of the 4 G mobile network, namely the global coverage and the long-range, with the energy efficiency typical of LPWANs. Moreover, NB-IoT is designed to provide better indoor coverage and support for a massive number of low-throughput devices [8]. It is conceived to serve the high-value IoT market that pays for very low latency and high quality of service [3], [9]. In contrast, LoRaWAN is targeted to lower-cost devices, with very long-range (high coverage), occasional communication needs, and very long battery lifetime requirements.

Today, both NB-IoT and LoRaWAN are offering long-range and low power consumption with the primary aim to be employed as a wireless solution for IoT [10]. However, to the best of our knowledge, there is no detailed comparison helping to select one of these two networking solutions given a specific application scenario. Although some characteristics of the considered technologies, such as the maximum range or the used bandwidth, are not directly comparable, there is a need for a thorough comparison in term of QoS, deployment cost and energy consumption.

Indeed, SHM allows evaluating the aforementioned challenges that are considered the primary obstacles for LPWAN

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deployments [3], [11]. The contribution of this paper can be summarized as follows: (i) we compare performance between NB-IoT and LoRaWAN, using experimental data from a real WSN application; (ii) we measure the energy consumption from the most recent radios, and we provide the corresponding battery lifetime estimate in 15 different configurations, varying payload size and radio signal strength; (iii) we provide deployment guidelines outlining the quality of service, cost and coverage differences between LoRaWAN and NB-IoT; (iv) Using in-field measurements for the first time, we discuss how the wireless sensors-equipped with NB-IoT could reach a target 10-year battery life, and we analyze the detrimental consequences of message delivery latency when many samples are accumulated in one single uplink. The rest of this article is organized as follows. Sections III-A and III-B describe the LoRaWAN and NB-IoT architectures, respectively describe the LoRaWAN and NB-IoT architectures, respectively. Section IV introduces the sensor equipped with both LoRaWAN and NB-IoT transceivers used in the experimentation. Sections V-A and V-B describe the sensor consumption patterns according to the different technologies presented, showing the results collected by varying the Received Signal Strength Indicator (RSSI) and payload. In Section VI-A, we evaluate the life expectancy of the battery for the two configurations. Section VI provides the guidelines to choose between the two technologies considering the constraints of the applications. Finally, Section VII concludes this article.

II. Related Works

Recent literature on energy efficient communication [12], local area network, and LPWAN has been very prolific, proposing novel communication protocols and radio technologies. In the long-range communication domain, the most popular protocols are Sigfox, LoRaWAN, and NB-IoT [3], [11]. Sigfox allows remote transfer between devices and an access point through ultra-narrow band modulation, with uplink and payload size constraints. Sigfox is very similar to LoRaWAN in terms of power consumption and range [13], however, is not included in this article as it is a proprietary protocol, it is less used in IIoT due to its limited payload size (12B) [3], and for the transmission restriction of 140 B/day and 4 B/day for uplink and downlink respectively [11]. The LoRaWAN open standard enables large scale deployments through LoRa, a chirp spread spectrum modulation, with a communication range up to 15 km at low power operation. Many scientific works describe and model the energy performance for LoRaWAN [14] and the related scalability issues [15]. Moreover, in [16] authors introduce LoRaWAN end-devices with a battery life up to 10 years in real deployments, a standard spec for industrial devices.

The NB-IoT [7] is a variant of LTE (4 G Long Term Evolution) developed to fulfill the IoT requirements in civil and industrial applications: coverage extension, long battery lifetime, backward compatibility, and user equipment cost reduction are common objectives [17]. The energy performance of NB-IoT is dependent on a multitude of parameters, related to the country's settings and network operator requirement, that can drastically change the end-device average power consumption. [18] shows the NB-IoT independence between the transport block size and power consumption. They vary the payload size between 50 and 100 b, and the measured power consumption is 716 mW on average. The energy used to join the network is 11.1 J with a connection time of 36 s. In our experiments, we have confirmed the same independence, which is also compared with the LoRaWAN protocol. Low power and lifetime are crucial for wireless end-devices and sensor nodes in IIoT and other applications as presented on many previous works [3], [9]. In [3] a LoRaWAN comparison analyzing several factors, such as QoS, latency, network coverage, cost, and scalability, based on the data declared by the developers, but without an actual practical test. They compare both protocols in various use cases, to ensure that LPWAN technologies can provide efficient connectivity solutions across critical and massive IoT deployment, determining their feasibility for specific applications. This article extends and complements this comparison, also providing in-field experimental measurements of the two protocols.

Industrial and consumer scenarios such as manufacturing automation [3], smart city [20], transportation [21], logistics [22], healthcare [21], agriculture and smart farming [21] are the typical use cases for NB-IoT and LoRaWAN. In the IIoT domain, there is a significant interest in evaluating LPWANs for future applications and services [3]. The two technologies have been evaluated in different scenarios: [20] affirms that NB-IoT is more robust in terms of Packet Error Rate (PER) than LoRaWAN. On the other hand, in [22] LoRaWAN has been selected over NB-IoT for environmental monitoring of assets and the interconnection of industrial facilities. The IIoT requests that LPWANs must satisfy are very challenging. In real-time monitoring scenarios, for example, manufacturing automation or assembly lines, there are stringent requirements for very low latency with a maximum of 1 ms and high-reliability of data delivery [23]. In logistics transportation and supply chain, the goods tracking system must be able to track at least 100000 devices per square kilometer in global coverage [23]. [21] discusses the limitations of existing LPWANs, underlining the most important weakness and limitations in each application scenario, which are the object of our experimental analysis (battery lifetime, QoS, and coverage).

These studies show that both protocols can coexist in the IoT market: LoRaWAN will serve as the low-cost and very long-range deployments, with infrequent transmissions and heavy constraints in term of battery life. In contrast, applications requiring low latency and high quality of service, in addition to an international coverage [24], will make use of NB-IoT. The results, about NB-IoT, in [18] and [3] show 13 years of operability with one transmission (TX) per day and 250 days if a packet is sent every hour in power save mode. These numbers decrease drastically, to 126 and 88 days, respectively, if the extended discontinuous reception is enabled (see Section III-B). Finally, [3] concludes that, despite the cellular companies' tests, the NB-IoT power profile currently leaves open questions on the battery life in real deployments.

This article presents accurate in-field experimental measurements of LoRaWAN and NB-IoT at the same conditions, allowing a direct in-field comparison. Moreover, the paper gives insights on the motivations behind the main similarities and differences, rooted in the architecture of the underlying communication protocols, and it details the key aspects. The article quantifies for the first time the benefits of LoRaWAN in terms of energy consumption in applications where accumulated measurements are not allowed. On the other hand, NB-IoT is competitive in energy efficiency for applications where messages can be buffered, because the energy for each transmission is independent of the payload size. Another novel contribution of the article is to provide guidelines on setting optimal configurations of the two protocols in a real deployment, using a model for quantifying the cost of implementation.

III. Technology Overview

We present the main features of LoRaWAN and NB-IoT, highlighting the differences, to provide an accurate in-field evaluation.

A. LoRaWAN and LoRa

A LoRaWAN network consists of a star-of-stars topology composed of three fundamental elements: end-devices, gateways, and a central network server [6]. National standards regulate predefined channels. Our testbed is deployed in Switzerland, Europe, where the ISM (Industrial Scientific Medical) band is at 863–870 MHz. LoRaWAN specifications [6] establish ten different channels; the first nine have a bandwidth of 125 KHz and support data rates between 0.3–5 kbps. ISO/IEC ISM regulations impose to each end-devices, working on ALOHA MAC (Medium Access Control) protocol, a limitation about the maximum duty cycle, which cannot exceed 1% of the channel time. However, as long as the restrictions for each band are respected, end-devices can transmit on different channels to increase their overall throughput [15]. They communicate with the network server through one or more gateways, which are also used to send downlink messages. The end-device uses the LoRa physical layer to exchange packets with the gateway, which communicates with the network server via an IP-based protocol stack. There are three classes of LoRaWAN devices, called A, B, and C. Class A and Class B devices are usually battery-powered, while class C devices need to be supplied by the main due to the high energy consumption. The main difference in the three operating modes is the downlink connection, which can be asynchronous (Class C) and synchronous after the uplink (Class A and B). Class A opens very short reception windows after sending a message, and then the device goes in a sleep state to save energy. In addition to Class A, Class B devices open further receive windows at scheduled intervals. Finally, Class C devices keep the radio in the continuous reception mode, allowing instant transmission of data. The different operating methods influence the power consumption and consequently, the battery life of this device. For example, in [25], authors show that Class C needs 225 $\times$ the energy used by Class A with static spreading factor (SF) and output power; for this reason, our sensor node uses the Class A operating mode.

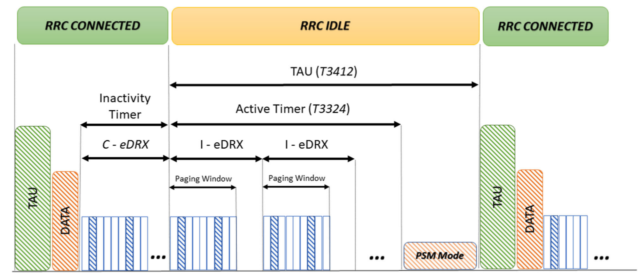

Fig. 1. Extended discontinuous reception: the periodicity value of the reception windows can reach 10.24 s in connected and 2.91 h in Idle state, respectively. Power saving mode: device remains registered with the network, and it is not necessary to reattach or reestablish the connection. The maximum duration of the PSM mode is 310 h.

B. NB IoT

NB-IoT is a novel protocol standardized by 3GPP [7]. It is also known as LTE Cat-NB1(NB2) and belongs to low power wide area (LPWA) technologies that could work virtually anywhere when infrastructure is present. It can operate in three different modes: stand-alone as a dedicated carrier, in-band inside the occupied bandwidth of a wideband LTE, and within the guard-band of an existing carrier [17]. In the first deployment, NB-IoT can occupy one GSM channel (200 kHz) while for in-band and guard-band deployment, it will use one Physical Resource Block of LTE (180 kHz). NB-IoT uses the orthogonal FDMA in the downlink and single-carrier FDMA (frequency division multiple access) in the uplink and applies the QPSK (quadrature phase-shift keying modulation) [17]. Each message can reach 1600 B of payload. The maximum data transmission rate is limited to 20 kbps for uplink and 200 kbps for downlink. As discussed in [26], NB-IoT is designed for long-life devices and targets a battery life of more than 10 years when transmitting 200 B per day. To achieve these performance, NB-IoT uses the LTE energy-saving mechanisms, extending the timers period to minimize energy consumption. There are two energy-saving features: extended discontinuous reception (eDRX) and power saving mode (PSM). For devices with rarely uplink data transmission, and need to receive messages, power consumption can be reduced significantly by the eDRX feature, shown in Fig. 1. There are two ways for using this feature, Connected-eDRX or Idle-eDRX according to the state of the devices. When a device is connected, and there is no traffic, it alternates active listening and sleep periods. This behavior is maintained for the duration of the Inactivity Timer (see Fig. 1). Otherwise, when a device is idle, new transmissions cannot be requested from the network, but the downlink channel is tracked at paging window (PW) events, to keep network synchronization and to discover if downlink data is pending. The time between two PW is the duration of an Idle-eDRX cycle (see Fig. 1).

The PSM feature, shown in Fig. 1 and defined in 3GPP Rel.12, is the deep sleep operation state. It allows reduction of the current consumption maximizing the amount of time that a device can remain in an extremely low power mode during periods of inactivity. After a wake-up, where data transmission generally takes place, it moves to the idle state, where reception windows are opened to allow downlink communication from the base station. The reception phase lasts according to the network policies agreed during registration. At the expiry of the timer T3324, the device switches in PSM. In this state, any receiving communication is disabled, but the device remains registered on the network, and re-joining is not necessary when it switches back to transmit. The timer T3412, set by the device following the network policies, is responsible for managing the PSM mode, enabling the periodic tracking area update (TAU) procedure. The device can disable the PSM at any time if it needs to send a message.

IV. Experimental Setup

In this paper, we use a low power wireless sensor developed to measure the cracks in reinforced concrete structures, such as bridges, dams, or skyscrapers [16]. This sensor has been designed to guarantee a high sensitivity, up to 1 μm, combined with an extended battery lifetime, which must be at least ten years measuring and sending data ten times per day. The critical aspects of a wireless sensor node are the radio budget link, power management, and analog front-end. The sensor node embeds an STM32F373 microcontroller (MCU), an analog front end, and two radio modules: LoRa and NB-IoT are operated in a mutually exclusive fashion. The MCU handles the analog and digital parts through the integrated Sigma-Delta ADC converter and the serial peripheral interface. A smart power supply circuit manages a Li-MnO$_2$ lithium battery (4.2 V -1000 mAh) with 80% of efficiency. We select the SX1276 from Semtech that controls the Lora Physical layer and packet buffering. This component achieves a sensitivity of -148 dBm with output power up to 20 dBm, enabling a 168 dB maximum link budget. The NB-IoT transceiver is the SARA-N211 from U-Blox. It is provided in the small LGA form factor (16.0 $\times$ 26.0 mm, 96-pin). The module offers data communication over an extended operating temperature with low power consumption, 3 μA in deep-sleep and 220 mA in transmission at 23 dBm. With a receive sensitivity of -135 dBm, it offers a 158 dBm of link budget. Finally, the M41T82 from ST microelectronics, an ultra-low-power real-time clock, wakes up the sensor node only at the scheduled time, and it consumes only 365 nA@3 V.

In the active mode, the sensor node draws an average of 23 mA@3 V/s, used to sample, filter and encrypt the data acquired; the corresponding energy is 70 mJ (E_{sensor}). Afterward, the MCU decides which radio protocol must be used depending on application and user's request. Reducing the wireless communication energy can be very valuable, since the radio transceiver is one of the components with the highest power consumption, as shown in [27]. For each sample, the MCU generates 12 B of data, which can be stacked in one buffer or sent immediately to the application server.

V. Experimental Results

This section presents the experimental evaluation of the SX1276 and SARA-N211 modules in the above mentioned experimental setup. In particular, we focus on the energy performance of the SHM sensor node with multiple payload sizes and coverage conditions to determine the battery lifetime. The sensor node periodically transmits an uplink message, which can include a single sample or multiple acquisitions queued in one packet.

A. LoRaWAN End-Device Analysis

To realistically define an energy profile of our sensor node, we develop a model based on measurements from a real LoRaWAN testbed and previous works [19], [28]. We assume a periodic behavior for each transmission, with a fixed time interval. Therefore we studied the power consumption during one period, which includes the packet generation, the cryptography, the uplink transmission, the RX1 Delay and, finally, the downlink window used to receive the acknowledge (ACK). each datarate (DR) used in this evaluation, from 0 to 5, generates several configurations that impact the LoRa modulation. For example, the equivalent bit rates (EBR) of DR0 and DR5 are respectively 292 and 5469 bps (1); moreover, the transmission time of air can vary between 225 ms to 4 s with 100 B of payload (2). Such variability impacts the communication range and the power consumption; therefore, smart management of these parameters is crucial to keep the node powered as long as possible. The transmission time takes into account 13 B of overhead, LoRaWAN needs to transmit the node's MAC to identify the packet on the server-side correctly. The coding rate (CR) and the preamble (N_{pre}) symbols are 4/5, and 8, respectively, and the CRC (cyclic redundancy check) is disabled. Finally, the bandwidth is 125 kHz. Under ISO/IEC ISM European regulations, LoRaWAN limits the packet size with a maximum of 51 B for DR0 and DR1, and up to 242 for DR5; moreover, since there is a 13 B protocol overhead, the payload size is limited to 38 and 229 B, respectively.

In [28], a study on LoRa SFs assignment is presented. Overestimating the SF may increase the packet error rate (PER) due to low SNR (signal-to-noise ratio), and an overestimate can also significantly decrease the battery lifetime because of the high packet time of flight.

Applying a PER strategy, where each sensor node assigns the lowest SF for which the PER falls below a fixed threshold, with a 0.01 PER lower limit [28], the SFs are allocated about 43% SF12, 20% SF11, 12% SF10, 8% SF9, 6% SF8, and 11% SF7. Since most of the sensor nodes are in high SF zone, in our work we consider the maximum packet size of 51 B for all the configurations; this allows to pack three samples, corresponding to three crack measurements, in one single packet. In [14], the authors show the correlation between network traffic and packet loss: they indicate a 10% packet loss for architectures with 1000 nodes, 36% for 5000, 59% for 10 000. Following, [28] shows the effect of saturating the available airtime with one gateway and a large number of nodes. They simulate an upstream scenario with a data period of 6000 s and 21B of payload. With the proposed SF assignment, the PER increases significantly when the number of devices exceeds 5000. Concerning the environments, a recent study [29] evaluates the packet loss under challenging environments, such as a data center facility and indoor industrial establishments. In these conditions, the packets received with

TABLE I
LoRaWAN EPB and EPP

DR	SF	EBR [bps]	EPB 1 [mJ]	EBP 2 [mJ]	EPB 3 [mJ]	Packet 1 [mJ]	Packet 2 [mJ]	Packet 3 [mJ]
DR0	12	293	6.69	5.31	4.00	641.28	1017.60	1152.01
DR2	10	977	1.68	1.30	1.01	161.28	249.59	290.88
DR5	7	5469	0.30	0.23	0.16	28.32	43.2	46.08

TABLE II
NB-IoT Energy Characterization

ID	C	N bytes	$T_{act.}$ [s]	I_{max} [mA]	E_{mean} [mJ]	E_{max} [mJ]	E_{min} [mJ]	RSSI [dBm]
a	G	10	11.9	138	2063	3007	517	-83
b	G	50	11.9	146	1858	3111	486	-81
c	G	100	12.0	135	1856	3240	499	-75
d	G	400	12.2	138	2067	3232	550	-75
e	M	10	13.7	245	2677	4549	1847	-112
f	M	50	12.8	232	2453	4078	1890	-109
g	M	100	12.6	219	2379	4150	1903	-110
h	M	400	12.8	225	2386	3786	1972	-107
i	B	10	46.6	151	9047	17072	5453	-130
l	B	50	41.1	175	7641	16298	5579	-136
m	B	100	37.2	169	6818	13264	5200	-135
n	B	400	40.5	185	7552	17845	5745	-134

the wrong CRC vary between 0.5% and 6%. Hence in our SHM testbed, the PER is not negligible and must be taken into account to estimate the average energy consumption. The SX1276, with the power amplifier enabled, generates a current consumption of 87 mA@17 dBm in TX and 11.5 mA in RX at 3 V; moreover, the overall energy per packet is highly correlated with the packet time of air. Table I presents the measured payload Energy Per Bit (EPB) with different DRs and sizes, considering the power used in TX, in RX and the energy used by the MCU to encrypt and decrypt the data: EPB1 refers to 1 sample (12B), EPB2 contains 2 (24B) and EPB3 3 (36B). In the last three columns, it presents the overall energy per packet (EPP) for a LoRaWAN transmission with different DRs and queue lengths: Packet 1 includes only one crack measurement (12 B of payload), whereas Packet 3 is composed of three. Moreover, Table I shows that the DR0 uses 22 $\times$ more energy in comparison with DR5. As expected, the EPB does not scale linearly with the payload due to the high ratio between preamble and payload size. For example, with 12 B and DR5, the preamble length is the 35% of the overall time of air, and with 36 B, it is only the 24%. This result clearly confirms that buffering the samples in one placket increases the transmission energy efficiency. To carefully model the sensor node behaviour, we measured the energy consumption for the first connection and authentication with the LoRaWAN server; this procedure exchanges the cryptography keys and establishes a secure connection between devices. The values measured for DR0,2 and 5 are, respectively, 581.29, 172.25, and 62.03 mJ. EPP values in Table I, and the equivalent T_{Packet} in (2), take into account the uplink packet [(T_{tx} - (3)] formed by the payload (PL), preamble and 13 B of LoRaWAN overhead, the waiting period (T_{rx1}) between the uplink and downlink windows and lastly, the receive period used to detect the ACK ((T_{rxw}).

$$\text{EBR} = \text{SF} \cdot \frac{\left[\frac{4}{4+\text{CR}}\right]}{\frac{2^{\text{SF}}}{\text{BW}}} \tag{1}$$

$$T_{\text{Packet}} = T_{\text{tx}} + T_{\text{rx1}} + T_{\text{rxw}} \tag{2}$$

$$T_{tx} = \frac{2^{SF}}{\text{BW}} \cdot (N_{\text{pre}} + 4.25 + N_{\text{PHY}}) \tag{3}$$

$$N_{\text{PHY}} = 8 + \max\left[\text{ceil}\left[\frac{28 + 8 \cdot \text{PL} - 4 \cdot \text{SF}}{4 \cdot \text{SF}}\right] \cdot (\text{CR}+4), 0\right] \tag{4}$$

T_{tx} expresses the time in seconds required to transmit both the preamble and the payload; the latter is composed of the number of symbols calculated in (4).

B. NB-IoT End-Device Analysis

This section focuses on the NB-IoT energy performance of the sensor node in the same deployment conditions as the previous subsection. As it is not trivial to estimate the energy consumption of the transmission due to the multitude of NB-IoT parameters, such as the eDRX and PSM timers, the transmission power and the number of repetitions requested by the network, we combine a model based on measurements from a real NB-IoT testbed, and previous works [3], [18] to precisely derive the NB-IoT energy profile. We tested the SHM sensor node, varying the payload and the RSSI that influences the power consumption of the module. Precisely, we define the -80 dBm average RSSI as Good (G), -110 dBm average RSSI as Medium (M) and finally, -130 dBm average RSSI as Bad (B). Table II shows the measurements of energy per packet and T_{active} with 10, 50, 100 and 400 B of payload, depending on the three defined coverage levels. For each configuration, we performed $k = 50$ measurements. In Table II, each row is the average of k successive measurements, with the same RSSI condition, since it is the most relevant element to estimate the battery lifetime. The presented values consider the SARA-N211 energy consumption, with nominal voltage (V_N) of 3.6 V, measured using a 10 mΩ shunt resistor and the Tektronix MDO3014. For each test, we post processed the time series data point to estimate I_{max} and T_{active}. Moreover, integrating the power consumption, we calculated E_{mean} (5), E_{max} (6) and E_{min} (7).

$$E_{\text{mean}} = \frac{1}{50}\sum_{k=0}^{49}\left[\sum_t V_N I_t^{\text{SARA}-N211} t_t\right]_k \tag{5}$$

$$E_{\text{max}} = \max\left[\sum_t V_N I_t^{\text{SARA}-N211} t_t\right]_{k=[0,49]} \tag{6}$$

$$E_{\text{min}} = \min\left[\sum_t V_N I_t^{\text{SARA}-N211} t_t\right]_{k=[0,49]}. \tag{7}$$

Dividing the values in Table II for coverage conditions, the absence of correlations between energy and payload size (Table II—N bytes) can be appreciated. Indeed, between *(a)* and *(d)* the T_{active} and E_{mean} differences are respectively 2% and 10% sending 40 $\times$ more B. Similar behaviour can be detected in B coverage, between tests *(i)* and *(n)*, where the T_{active} ranges between 37.2 s in *(m)* and 46.6 s in (i); the E_{mean} is included in a 25% of variability. These measurements have been carried out with Swisscom network provider, which releases the default 3 min period for T3324, whereas the T3412 can be set up to 310 h, avoiding TAU signaling between successive uplinks. The T3324 energy consumption must be added for

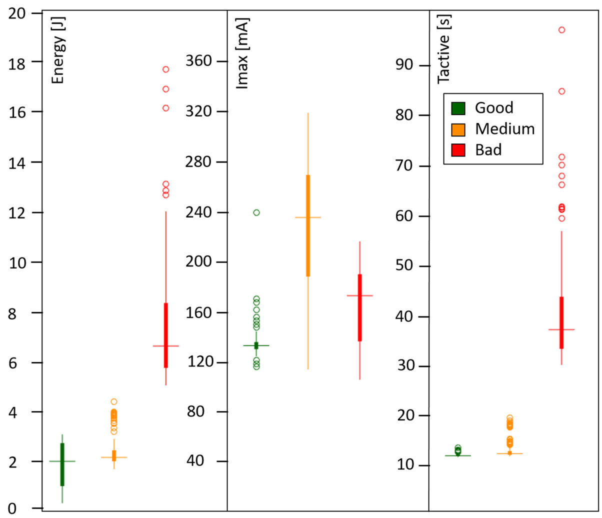

Fig. 2. NB-IoT characterization with median, 25th and 75th percentiles. Good (G) in green with an average RSSI of −80 dBm, Medium (M) in orange with an average RSSI of −110 dBm and, Red (R) with an average RSSI of −130 dBm.

each transmission because the SARA-N211 module is awake in listening mode. The overall value for 3 min timer is 844 mJ, equal for each coverage condition. The maximum energy measured in G condition [test *(a)*] is 6 × higher compared to minimum, and the *(n)* test maximum energy is 37 × the test *(b)*. Analyzing Table II and Fig. 2, we detect a significant increase of the variance in B than M and G coverage. These results reveal the high power consumption variability of the NB-IoT, which is not under the direct control of user. Indeed, each network provider manages differently the network parameters, such as the number of repetitions, the transmission power, TAU, and eDRX timers. For future designs, Table II—I_{max} is a useful tool for power management calculations. The good coverage group, in green, has an average RSSI of −80 dBm; this generates a mean T_{active} of 12 s; with these parameters, the average energy for each packet is 1982 mJ. In the M group, the T_{active} slightly increases, with a mean of 13 s, but the resulting energy 2474 mJ grows of about 25% in comparison with good coverage; indeed, the maximum current is 100 mA higher. This behavior means that the NB-IoT cell increases the output power before raising the number of retransmissions. In analogy with LoRa, the NB-IoT's T_{active} is highly correlated with the communication latency that for the latter reaches up to 46 s in worst cases (see Table II). Tests (*i*), (*l*), (*m*), (*n*) are close to the maximum sensitivity of the module, the resulting energy, and T_{active} grow heavily: the average time is 41 s with a maximum of 17845 mJ and, a medium of 7765 mJ. Fig. 2 presents the statistical analysis of the Energy, I_{max} and T_{active} features showing the median, 25th, and 75th percentiles of all the data acquired (600 samples). The energy grows with respect to the received RSSI decrease, which is the result of the T_{active} and I_{max} combination depending on the coverage strength and the network request. Indeed, the NB-IoT protocol raises the output power in TX before increasing the number of retransmissions, and the correlated T_{active}. The packet time difference between G and M is negligible, but B's T_{active} is at least 3 × compared to G. Furthermore, in M the output power correlated with the I_{max} is 2 × and 1.3 × compared with G and B, respectively, but the T_{active} is still comparable with B. The I_{max} difference between G and B is 1.2, which is lower than G and M. Indeed, the SARA-N211 increases the EPB, and the SNR at the receiver side, rising the number of repetitions rather than the transmission power. To carefully model the sensor node behaviour, we checked the energy used for the first connection and authentication with the NB-IoT cell; this procedure subscribes the sensor node on the network. The values measured for G, M, and B are respectively 15843, 17182, and 19124 mJ with an average connection time of 80 s. NB-IoT enables a packet length up to 1600 B [30], but the used module (with firmware version: 0.6.57, A07) is limited. Consequently, the queue is restricted to 33 samples, each consisting of 12 B. In Table III, we present payload EPB with different coverages and sizes: EPB 1: 12 B of payload (1 sensor samples); EPB 2: 24 B of payload (2 sensor samples); EPB 3: 36 bytes of payload (3 sensor samples); EPB 8: 96 bytes of payload (8 sensor samples); EPB 33: 396 bytes of payload (33 sensor samples). The EPB in Table III takes into account the uplink energy used in T_{active} and T3324 periods: it is clear that the equivalent EPB decreases as the queue size increases, due to the tremendous impact of the protocol overhead, as presented in the recent literature [18]. Compared to LoRaWAN, sending one sample per packet with NB-IoT reduces the battery life drastically as we will present in the following subsection. Moreover, the T_{active} does not depend from payload length but is strictly correlated with the coverage condition, i.e., the average RSSI; in fact, the NB-IoT protocol increases the number of retransmissions from 32 to 2048 when the RSSI is low. As expected, power consumption is independent of the uplink and downlink data rate [18]. We measured that the energy consumption between packets in static working conditions varies respect to network parameters requested by the operator: the output power, the number of retransmissions and the T_{active} can be modified between successive uplinks, and are not under the direct control of the U-Blox module. To prove the NB-IoT higher EPB for sporadic and tiny transfers, we performed the measures presented in Fig. 3. Taking as reference the Test (*d*) with 400 B of payload and a G coverage, we evaluate the T_{active} and the E_{mean} sending one (Pkt1) to ten (Pkt10) multiple packets with 400 B of payload in G coverage. For each packet stream we consider one single connection composed by first transmission request, which needs 12.2 s (see Table II-*d*) to re-synchronise the sensor with the cell, and $(N_{pkt}-1)$ successive transmission requests with no appreciable delay between one and the next. In contrast to LoRaWAN, the energy does not grow linearly with the number of uplinks in a single connection (see Fig. 1—DATA)

TABLE III
NB-IoT EPB

C	EPB 1 [mJ]	EPB 2 [mJ]	EPB 3 [mJ]	EPB 8 [mJ]	EPB 33 [mJ]
G	29.4	14.8	9.8	3.6	0.9
M	34.5	17.2	11.5	4.2	1.0
B	89.6	44.9	29.9	11.2	2.7

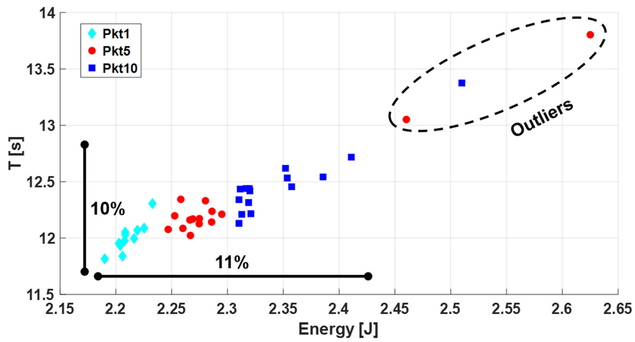

Fig. 3. Differences between single and multiple packet transmissions in a single connection. The outliers values are due to the NB-IoT network that changes parameters asynchronously.

but it only increases of 11% sending 10 times more bytes. In Pkt10 condition, the EPB is about 0.1 mJ, 9 X less than the EPB 33 presented in Table III. However, a buffer of 330 samples could generate an excessive latency for many application; hence in this article, we will compare the EPB considering only one transfer for each connection, as well as commonly used in a deployment where sporadic transmissions are required. As mentioned before, the control parameters of the NB-IoT are not fully accessible to the final user. Indeed, the number of repetitions and the radio output power can be varied under infrastructure network control. In Fig. 3, we highlight three outliers due to the different network conditions autonomously managed by infrastructure control.

$$E^{*}_{\text{mean}}(C) = E_{\text{mean}}(C) \cdot (1 + N_{\text{pkt}} \cdot 0.01) \tag{8}$$

Finally, the expected E^{*}_{mean} generated in a single connection where multiple packets are transferred, is presented in (8). The C variable points at the coverage condition energy in Table II—E_{mean} and N_{pkt} is the number of packets transmitted together.

VI. Deployment Overview

This section, aims to provide readers with a fair and realistic comparison of the two standards in terms of battery life, QoS, cost, and coverage in a real-life deployment scenario.

A. Battery Life and Comparisons

This subsection focuses on the estimation of the battery life in the SHM application scenario based on the above-presented power measurements. One of the most challenging features of SHM applications is to achieve a lifetime of 10 years. In our evaluation, we assume each node equipped with a 1000 mAh lithium battery @3 V. which is a widely used type of battery for SHM nodes [16]. Thus, the energy consumption for each sensor's sampling is constrained, and its usage is regulated by the energy per packet and the queue length. For our estimation, we consider the energy used for the initial connections ($E_{\text{connection}}$) calculated in previous sections with ten samples per day (N_{tx}) to fulfill the plots in Fig. 4. In particular, based on previous considerations, the average packet loss changes considerably depending on every single deployment, varying between 0% to

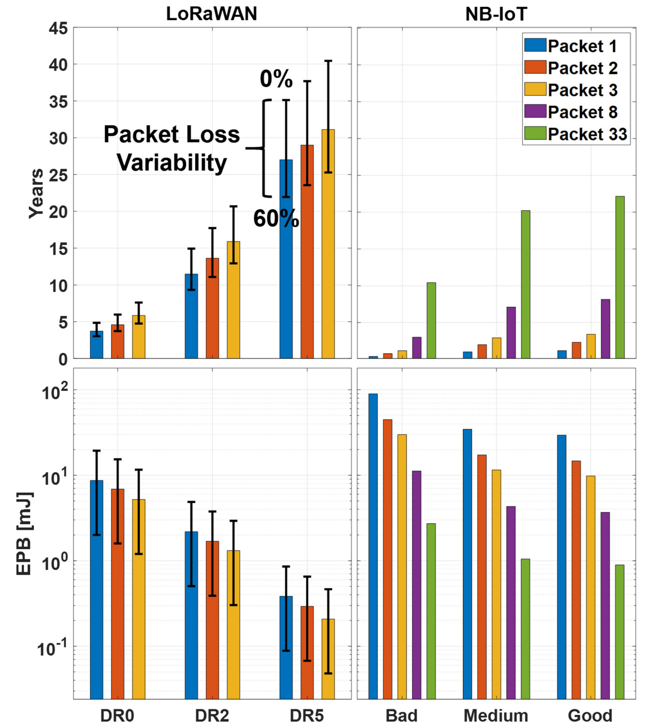

Fig. 4. Expected battery lifetime and EPB with LoRaWAN and NB-IoT. End-device coverage is divided into: DR0/Bad with an average RSSI of −130 dBm, DR2/Medium with an average RSSI of −110 dBm and, DR5/Good with an average RSSI of −80 dBm.

60% due to crowded radio channels or electromagnetic noisy environments. Hence it is misleading to provide a single result for each configuration. We consider the packet loss probability for energy estimation in our LoraWAN case study and, the Fig. 4 takes into consideration the effective communication variability, providing a lower and upper bound between 0–60% (P_{PktLoss}). For a conservative parameter, it is important to consider the integer bar to estimate the average sensor life-time span depending on the queue and DR configurations. Equations (9) and (10) show the formulas used to calculate the data in Fig. 4 for LoRaWAN and NB-IoT respectively. T_{LoRa} and $T_{\text{NB-IoT}}$ provide the times in days, E_{SLEEP} is the sleep energy calculated with a 365 nA current. Lastly, C and Q select the coverage and queue configurations from Tables I and III.

$$\begin{cases} T_{\text{LoRa}} = \frac{(\text{DCDC}_{\text{eff}} \cdot E_{\text{batt}}) - E_{\text{connection}}(C)}{[E_{\text{LoRa}} + E_{\text{sensor}}] \cdot \frac{N_{tx}}{Q} + E_{\text{SLEEP}}} \cdot 86400s \\ E_{\text{LoRa}} = \left(12 \cdot Q \cdot 8 \cdot \text{EPB}(C, Q) \cdot \frac{1}{1 - P_{\text{PktLoss}}}\right) \end{cases} \tag{9}$$

$$T_{\text{NB-IoT}} = \frac{(\text{DCDC}_{\text{eff}} \cdot E_{\text{batt}}) - E_{\text{connection}}(C)}{[E^{*}_{\text{mean}}(C) + E_{\text{sensor}}] \cdot \frac{N_{tx}}{Q} + E_{\text{SLEEP}}} \cdot 86400s \tag{10}$$

The resulting lifetime is less than 10 years with Packets 1–8 for both protocols in DR0/Bad coverage (see Fig. 4), but it is interesting to notice that with Packets 1–3 LoRaWAN reaches this threshold in DR2 and DR5. NB-IoT allows this duration only with Packet 33, in all coverage conditions; on the other side, LoRaWAN reaches the target from DR2 without queuing. If the application requires a transmission for each sample, the expected lifetime is respectively 4.5 months and 3.5 years for NB-IoT and LoRaWAN in the worst case. As shown in Fig. 4, with equal coverage, NB-IoT EPB is one order of magnitude higher than that measured with LoRaWAN. The LoRaWAN EPB decreases more if coverage improves compared to the use of buffering techniques, as opposed to NB-IoT, where the decrease is similar. Finally, the only cases where EPB is advantageous for NB-IoT is when the coverage is at least DR2/M and the message sent contains 33 samples (Packet 33).

B. Quality of Service, Cost, and Coverage

Wireless communication energy consumption is the principal issue in IIoT applications. Nevertheless, many factors should be considered, including the QoS, the cost, and the coverage. This article highlights that LoRaWAN works on unlicensed ISM channels with an asynchronous protocol and, in crowded channels and industrial environments, the packet loss cannot be considered as a negligible factor given that it can decrease the expected battery lifetime up to 37%. On the other hand, NB-IoT offers an optimal QoS, with guaranteed data delivery, working on licensed spectrum and an LTE-based synchronous protocol. However, its communication latency is not optimal. Indeed, the maximum LoRaWAN packet time, which corresponds to the transfer delay, is 2630 ms with DR0. It is $17\times$ lower than the NB-IoT's T_{active} in B coverage (see Table II—*i*). Different parameters must be examined for the implementation costs. A generic NB-IoT module can exceed 20€ compared to 3–5€ of a LoRa transceiver [3]. Moreover, it is important to consider the cost related to traffic generated by each device (500 MB of traffic are priced today at 10€. This amount of data are more than enough for the entire sensor life in a typical monitoring application. On the other hand, a LoRaWAN network must have at least one access point (300€/gateway) and the server (1000€/base station). In the considered SHM application, the system generates 120 B daily allowing more than 100 years of hypothetical operation with a single subscription. In summary, (11) quantifies the deployment cost of the two technologies.

$$\begin{cases} \text{Cost}_{\text{NB-IoT}} = (\text{Cost}_{\text{module}} + \text{Cost}_{\text{SIM}}) \cdot N \\ \text{Cost}_{\text{LoRa}} = \text{Cost}_{\text{module}} \cdot N + \text{Cost}_{\text{Gateway}} + \text{Cost}_{\text{Server}} \end{cases} \quad (11)$$

Whenever the number (N) of sensor nodes is a few tens, the NB-IoT is more affordable due to the high installation cost of LoRaWAN gateway and server, as shown by (11), enabling quicker time to market (TTM) in regions where the LoRaWAN is not deployed yet. On the other hand, LoRaWAN is today more affordable for large-scaled deployments, due to the larger cost of NB-IoT modules. When the TTM is a concern, NB-IoT has an advantage because of the plug-and-play service offered by network operators. Moreover for national scale coverage applications, for example in the monitoring of transportable goods to determine the pallet locations on highways or railroads, the use NB-IoT is the only solution due to the infrastructure already provided by the network operators. To cover limited areas, or remote areas where networks operators do not offer good coverage, LoRaWAN devices with dedicated support can instead be more efficient.

TABLE IV
STANDARDS COMPARISON

	NB-IoT	LoRaWAN
Battery life	Highly sensitive to the amount of buffering allowed by the application (energy per byte improves with large packets, the link is not energy-proportional).	Battery life up to 10× against NB-IoT for small packets (the link is energy proportional: energy per bit does not change much from small to large packets).
Quality of Service	QoS Data delivery guaranteed.	PER depends on network density and average nodes throughput.
Module Cost	20€	3-5€
Infrastructure Cost	Network operators support the infrastructure. The service cost is approximately 10€/500 MB.	300€/gateway and maintenance needed.
Coverage	National scale (areas with infrastructure).	The coverage depends on the investment for the number and location of gateways.
Time To Market	Plug and Play service offered by network operators.	Deployment infrastructure time needed.

TABLE V
IIOT APPLICATIONS

	NB-IoT	LoRaWAN
Manufacturing Automation	The remote control of the machines requires real-time monitoring of the operating procedures of the various automatic stations. At present, the current standards cannot satisfy the latency times required for these applications (less than a millisecond).	
Supply Chain Management (SCM)	NB-IoT extends SCM at the global scale: movement and storage of raw materials, work-in-process inventory, and finished goods from the point of origin to the point of consumption.	SCM within the production site, or in any case on a limited geographical scale. LoRaWAN can be more convenient for power-consumption and cost aspects.
Monitoring and Maintenance	NB-IoT is more efficient for significant amount of data transmitted (e.g., thermograph images or continuous data collecting for machine learning).	LoRaWAN class A supports uplinks of few KBs per day, allowing a reliable operation with low data rate sensors.

C. Summary and IIoT Applications

The main factors analyzed in this chapter were listed in Table IV. Finally, we select three industrial applications reported in chapter II, detailing the main differences between LoRaWAN and NB-IoT in Table V. Future work will focus on finding ways of enabling real-time communication and a high data rate in LPWAN to support manufacturing automation in an efficient way.

VII. CONCLUSION

This article evaluates LoRaWAN and NB-IoT as wireless communication technologies for industrial application scenarios that require to transfer a few bytes per day. The evaluation is based on experimental results obtained in-field expecting a sensor node for crack measurements in civil structures. We test both technologies with experimental results in different coverage conditions, intending to assess the energy consumption, the estimated battery lifetime, and the packet loss. Our assessment shows that LoRaWAN outperforms NB-IoT in terms of energy consumption. In an application where buffering is not allowed, the LoRaWAN protocol increases the battery life up to 10 $\times$ against NB-IoT: for Packet 3 scenario (36 B payload), DR2/M Coverage, NB-IoT EPB is 10 $\times$ higher compared to LoRaWAN. However, NB-IoT is adequate for applications where information can be buffered on the node because the energy for each transmission is almost independent of the payload size. For example, in Packet 33 scenario (396 B payload), DR2/M Coverage, if high delivery latency is tolerable, NB-IoT EPB is 11 $\times$ lower compared to LoRaWAN, due to the larger number of messages sent by LoRaWAN. Moreover, we verify that T_{active} in the NB-IoT is heavily dependent on network coverage, as it grows up to 3 $\times$ times passing from a "Good" (average RSSI of -80 dBm) coverage to a "Bad" one (average RSSI of -130 dBm). On the other hand, NB-IoT offers the highest QoS, which guarantees data delivery. This feature makes it a potential replacement to LoRaWAN in all the applications where the energy constraint is not an issue or when communication reliability is a crucial factor and good NB-IoT coverage is available.

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