Experimental Evaluation on NB-IoT and LoRaWAN for Industrial and IoT Applications

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***Abstract*—Low power and long-range communications are essential features of the Internet of Things (IoT) paradigm that is becoming widespread across a spectrum of industrial applications. In this paper, we present performance evaluation of the most promising long-range communication technologies, namely LoRaWAN and NB-IoT. We present accurate in-field measurements using a monitoring application as a testbench for a fair comparison in terms of energy efficiency and lifetime. Experimental results highlight that NB-IoT payload length does not impact on transmission energy. Thus, applications that implement buffering and caching techniques are favored. On the other hand, LoRaWAN consumes 10× less energy to transmit a payload equivalent to that of NB-IoT, thereby allowing longer end-device lifetime.**

***Index Terms*—LPWAN, Long-Range Communcation, NB-IoT, LoRA, LoRaWAN, IoT, IIoT, Energy Efficiency**

I. INTRODUCTION

Many Industrial Internet of Things (IIOT) application scenarios require long-range communication coupled with battery lifetime for wireless sensor nodes [1]. Low power consumption and communication range are some of the essential features for IIoT devices that are further exacerbated by extremely battery lifetime requirements. Today's most promising wireless protocols for IIOT are NB-IoT and LoRaWAN.

The LoRaWAN open standard permits large scale deployments through LoRa, a proprietary chirp spread spectrum modulation, and a communication range up to 15km at low power operation. Recent previous works focus on analyzing the performance and energy of LoRa and LoRaWAN [2] and the related scalability issues [3] with and without ALOHA MAC (Medium Access Control) protocol [4]. Battery life up to 10 years in real deployments is a standard spec for industrial LoRaWAN end-devices [5].

NB-IoT [6] is a variant of LTE (4G Long Term Evolution) developed to meet the IoT requirements in civil and industrial applications. The main features of NB-IoT are the coverage extension, long battery lifetime, backward compatibility, and user equipment cost reduction [7]. The energy efficiency of NB-IoT is affected by a multitude of parameters, related to the country's settings and network operator requirement, that can drastically change the end-device average power consumption.

Recent 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 tight constraints in term of battery life [8]. On the other hand, LoRaWAN cannot provide the same QoS of NB-IoT, because it uses a licensed spectrum and a time slotted synchronous protocol [9]. Even though these qualitative differences are well understood, to the best of our knowledge, there is no detailed comparison to help to make the right decision about the deployment of one of these two networking solutions given a specific application scenario. The main goal of this paper is to perform an experimental evaluation with quantitative measurements of NB-IoT vs. LoRaWAN for IIoT applications. Figures of merit used in the comparison are power consumption, energy per bit, and battery lifetime.

The rest of the paper is organized as follows. We describe the LoRaWAN and NB-IoT architectures in Section II. We introduce in Section III the sensor equipped with both LoRaWAN and NB-IoT transceivers used in the experimentation. We describe the sensor consumption patterns according to the different technologies presented in Section IV-A and IV-B, showing the results collected by varying the Received Signal Strength Indicator (RSSI) and payload. In Section IV-C, we evaluate the life expectancy of the battery for the two configurations. Section V concludes the paper.

II. LORAWAN AND NB IOT

A LoRaWAN network consists of a star-of-stars topology. Three fundamental elements are defined by the standard: the end-device, the gateway, and the central network server [10]. ISO/IEC ISM regulations impose to each node, working on ALOHA MAC protocol, a limitation about the maximum duty cycle, which cannot exceed 1% of the channel time. The predefined LoRaWAN radio channels are defined by the country rules. There are three classes of LoRaWAN devices, called A, B, and C. The main difference in the three operating modes is the downlink connection. Class A opens very short reception windows after sending a message, and then the device goes in a sleep state to save energy. The Class A operating mode needs 225× less energy than used by Class C

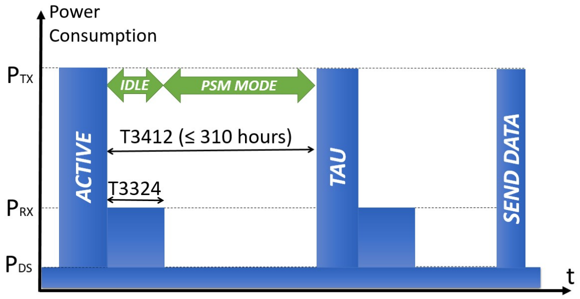

Fig. 1. Power Saving Mode: the device retains the network registration. At the expiry of the timer T3324, the device switches in PSM; the timer T3412 enables the periodic Tracking Area Update (TAU) procedure.

with static Spreading Factor (SF) and output power [11], and this mode is the most interesting for comparison with NB-IoT.

NB-IoT, also known as LTE Cat-NB1, is a novel protocol standardized by 3GPP [6] and conceived for Low Power Wide Area Networks (LPWANs) to work virtually anywhere when the supporting infrastructure is present. Each message can reach 1600 bytes of payload. The maximum data transmission rate is limited to 20kbps for uplink and 200kbps for downlink. As presented in [12], this protocol is designed for long-life devices and targets autonomy of more than ten years when transmitting 200 bytes per day. To achieve this performance, NB-IoT uses the LTE energy-saving mechanisms, extending the inactivity periods to minimize energy consumption. Figure 1 shows the Power Saving Mode (PSM) in the deep sleep operation state. It allows reduction of the current consumption maximizing the amount of time that a device can remain in the extremely low power mode during periods of inactivity. In this state, any communication is disabled, but since the unit is already registered on the network, no other action is needed when it is re-activated for transmitting. The timers T3324 and T3412, set by the device following the network policies, are responsible for managing the PSM mode.

III. SENSOR NODE

We use a low power wireless sensor developed to measure the cracks in reinforced concrete structures, such as bridges, dams, or skyscrapers [5]. The sensor node embeds an STM32F373 microcontroller (MCU), an analog front end, and two radio modules: LoRa and NB-IoT operated in a mutually exclusive manner. A smart power supply circuit uses a Li-MnO$_2$ lithium battery (3V - 1000mAh). We select the HopeRF's RFM96 that controls the LoRa physical layer and packet buffering. This module achieves a sensitivity of -148dBm with output power up to 20dBm, enabling a 168dB maximum link budget. The NB-IoT transceiver is the SARA-N211 from U-Blox and features data communication over an extended operating temperature with low power consumption, 3μA in deep-sleep and 220mA in transmission at 23dBm. The sensitivity of the receiver is -135dBm, and the radio achieves 158dBm of link budget. In active mode, the sensor node draws an average of 23mA (@3V) per second, used to sample, filter and encrypt the data acquired; the corresponding energy is 70mJ. For each sample, the MCU generates 12 bytes of data, which can be accumulated in one buffer or sent immediately to the application server.

IV. EXPERIMENTAL RESULTS

This section presents the comparison of the RFM96 and SARA-N211 modules in the above mentioned experimental setup. We focus on energy efficiency 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 multiple acquisitions queued in one packet or a single sample.

A. *LoRaWAN End-Device Analysis*

To realistically define an energy characterization of our sensor node, we develop a model based on measurements from a real LoRaWAN system and previous works [5], [13] assuming a fixed time interval between every transmission. Each Datarate (DR) used in this experimental 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 5469bps; moreover, the transmission time of air ranges between 225ms to 4s with 100bytes of payload.

TABLE I
LoRaWAN PACKET TIME ON AIR

DR	**SF**	**BW [kHz]**	**EBR [bps]**	**T$_{rx}$ [ms]**	**T$_{tx10}$ [ms]**	**T$_{tx50}$ [ms]**	**T$_{tx100}$ [ms]**
0	12	125	293	598.02	1318.91	2629.63	4268.03
2	10	125	977	149.50	370.69	780.29	1312.77
5	7	125	5469	18.69	66.82	148.74	251.14

The last three columns in Table I (T$_{tx10}$, T$_{tx50}$ and T$_{tx100}$) indicate the LoRaWAN packets time on air as a function of payload size (10-50-100 bytes). The Coding Rate (CR) and the preamble symbols are 1/4, and 8 respectively, and the CRC is disabled. Under ISO/IEC ISM European regulations, LoRaWAN limits the packet dimension with a maximum of 51 bytes for DR0 and DR1, and up to 242 for DR5; moreover, since there is a 13 bytes protocol overhead, the payload size is limited to 38 and 229 bytes. Considering most of the sensor nodes are in high SF zone, we establish the maximum packet size of 51 bytes for all the configurations; this permits a queue of three samples, corresponding to three crack samples in one single packet. Based on paper [14], that shows the correlation between network traffic and packet loss; we consider a scenario with 5000 units and an equivalent of packet delivery ratio of 64%.

The SX1276, with the power amplifier enabled, generates a current consumption of 87mA in TX and 11.5mA in RX at 3V; moreover, the overall energy per packet is highly correlated with the packet time of air. The transceiver output power is 14dBm, which is an accepted value in most countries. In Table II, we present the measured payload 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). This plot shows that DR0 uses 32× energy in comparison with DR5.

TABLE II
LoRaWAN EPB

DR	EPB 1 [mJ]	EBP 2 [mJ]	EPB 3 [mJ]
DR0	6.69	5.31	4.00
DR2	1.68	1.30	1.01
DR5	0.30	0.23	0.16

Because of the high ratio between preamble and payload size, the EPB does not scale linearly with the payload. For example, with 12 bytes and DR5, the preamble length is the 35% of the overall time of air, and with 100 bytes, it is only the 6%. This result implies that buffering the samples in one packet increases the transmission energy efficiency. Moreover, to accurately characterize the power consumption of the sensor node, we measured the energy consumption for the first connection and authentication with the LoRaWAN server. The values measured for DR0,2 and 5 are respectively 581.29mJ, 172.25mJ, and 62.03mJ.

B. NB-IoT End-Device Analysis

This section focuses on NB-IoT energy consumption under the same conditions of the previous subsection. U-Blox makes available only uplink, downlink and sleep power details, which are respectively 220mA (averaged current over 2 seconds @23dBm), 46mA and 6μA. NB-IoT standard has several parameters, such as the PSM timers, the transmission power and the number of repetitions requested by the network, which complicate the estimation of the energy used by the transceiver during the entire sensor node life. It is not trivial to estimate the EPB from power consumption model without measurements in real deployment [15]. Thus, we combine a model based on analyses from a real NB-IoT testbed, and previous work [16] to precisely derive the NB-IoT energy profile.

We tested the SHM sensor node, modifying the payload and the RSSI that influences the power consumption of the module. Precisely, we define the -80dBm average RSSI as Good, -110dBm average RSSI as Medium and finally, -130 dBm average RSSI as Bad. Table III presents the measurements of energy per packet and T$_{active}$ with 10, 50, 100, and 400 bytes of payload, depending on the three established coverage levels. Column E$_{mean}$ is a result of 50 consecutive measurements with the same RSSI condition to model the average energy for each one of the presented 12 tests. These measurements have been carried out with Swisscom network provider, which releases the default 3 minutes period for T3324, whereas the T3412 can be set up to 310 hours. The T3324 energy consumption must be combined for each transmission because the SARA-N211 module is awake in listening mode. The overall value for 3 minutes timer is 844mJ, equal for each coverage condition.

TABLE III
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 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)*. The good coverage group, in green, has an average RSSI of -80dBm; this generates a mean T$_{active}$ of 12s; with these parameters, the average energy for each packet is 1982mJ. In the M group, the T$_{active}$ insignificantly increases, with a mean of 13s, but the resulting energy 2474mJ grows of about 25% in comparison with good coverage; indeed, the maximum current is 100mA higher.

First of all, the NB-IoT node must register with the network: to precisely model the energy consumption we checked the energy used for the first connection and authentication with the cell; the values measured for G, M, and B are respectively 15843, 17182, and 19124mJ with an average connection time of 80s. NB-IoT enables a packet length up to 1600 bytes, 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 bytes. In Table IV, we present payload EPB with different coverages and sizes: EPB_1: 12 bytes of payload (1 sensor samples); EPB_2: 24 bytes 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).

TABLE IV
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

The EPB in Table IV considers the uplink energy used in T$_{active}$ and T3324 periods: it is evident that the equivalent EPB decreases increasing queue size, as presented in the recent literature [15].

Moreover, the T$_{active}$ does not depend from payload length but is strictly associated 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 [15]. We measured that the energy consumption between packets in static working conditions varies respect to network parameters: the output power, the number of retransmissions and the T$_{active}$ are not under the direct control of the U-Blox module and can be

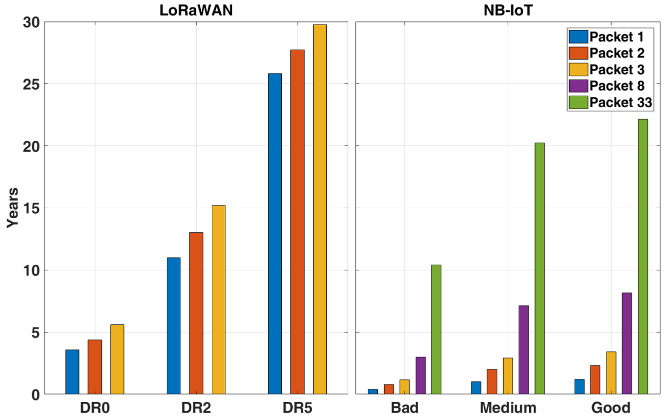

Fig. 2. Expected battery lifetime with LoRaWAN and NB-IoT. End-device coverage is divided into: DR0/Bad with an average RSSI of -130 dBm, DR2/Medium with an average RSSI of -110dBm and, DR5/Good with an average RSSI of -80dBm.

modified between successive uplinks by the network operator.

C. Battery life and comparisons

The estimation of the battery life in the SHM application scenario based on the presented power measurements is the goal of this subsection. One of the most challenging features of SHM applications is to achieve a lifetime of 10 years. In our evaluation, we consider each node equipped with a 1000mAh lithium battery @3V, which is a widely used type of battery for SHM nodes [5]. 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 calculated in previous sections to build the plots in Figure 2. In particular, based on paper [14], the average number of radio transmissions for each packet is 1.36 due to non-negligible packet collision probability of ALOHA MAC protocol. We consider this term for energy estimation in our LoraWAN case study and the results presented in Figure 2.

The resulting lifetime is less than ten years with Packets 1-8 for both protocols, due to the high EPB in DR0/Bad coverage, but it is interesting to notice that with Packets 1-3 LoRaWAN meets the constraint in DR2 and DR5. NB-IoT allows this duration only with Packet 33, in all coverage conditions, while LoRaWAN reaches the target from DR2 without queuing. The worst cases, when the application requires a transmission for each sample, are 4.5 months and 3.5 years expected lifetime for NB-IoT and LoRaWAN, respectively (e.g., in case of latency bounds on sample transmission).

V. CONCLUSION

We presented a comparison of LoRaWAN and NB-IoT as wireless communication technologies for industrial and monitoring applications. The comparison is based on experimental results obtained in-field using a sensor node. We evaluate both technologies with experimental results in several coverage conditions, with the purpose to estimate the energy consumption, the expected battery lifetime, and the packet loss. LoRaWAN protocol can increase the battery life up to 10× concerning NB-IoT, in applications where accumulated measurements and delayed transmissions are not allowed. NB-IoT is competitive with LoRaWAN when the energy constraint is not an issue because it offers the highest QoS and guarantees message delivery compared to 64% LoRaWAN packet delivery ratio.

ACKNOWLEDGMENT

The research contribution presented in this paper has been partially funded by a research grant of MediCon Ingegneria.

REFERENCES

[1] S. Maksuti, A. Bicaku, M. Tauber, S. Palkovits-Rauter, S. Haas, and J. Delsing, "Towards flexible and secure end-to-end communication in industry 4.0," in *2017 IEEE 15th International Conference on Industrial Informatics (INDIN)*. IEEE, 2017, pp. 883–888.
[2] A. Augustin, J. Yi, T. Clausen, and W. M. Townsley, "A study of lora: Long range & low power networks for the internet of things," *Sensors*, vol. 16, no. 9, p. 1466, 2016.
[3] T. Polonelli, D. Brunelli, A. Marzocchi, and L. Benini, "Slotted aloha on lorawan-design, analysis, and deployment," *Sensors*, vol. 19, no. 4, p. 838, 2019.
[4] L. Tessaro, C. Raffaldi, M. Rossi, and D. Brunelli, "Lightweight synchronization algorithm with self-calibration for industrial lora sensor networks," in *2018 Workshop on Metrology for Industry 4.0 and IoT*, April 2018, pp. 259–263.
[5] T. Polonelli, D. Brunelli, M. Guermandi, and L. Benini, "An accurate low-cost crackmeter with lorawan communication and energy harvesting capability," in *2018 IEEE 23rd International Conference on Emerging Technologies and Factory Automation (ETFA)*, vol. 1. IEEE, 2018, pp. 671–676.
[6] Qualcomm, "Qualcomm, incorporated, narrowband iot (nb-iot), rp-151621, 3gpp tsg ran meeting #69, sept. 2015. [online]." 2015.
[7] Y.-P. E. Wang, X. Lin, A. Adhikary, A. Grovlen, Y. Sui, Y. Blankenship, J. Bergman, and H. S. Razaghi, "A primer on 3gpp narrowband internet of things," *IEEE Communications Magazine*, vol. 55, no. 3, pp. 117–123, 2017.
[8] O. Elijah, T. A. Rahman, I. Orikumhi, C. Y. Leow, and M. N. Hindia, "An overview of internet of things (iot) and data analytics in agriculture: Benefits and challenges," *IEEE Internet of Things Journal*, vol. 5, no. 5, pp. 3758–3773, 2018.
[9] R. S. Sinha, Y. Wei, and S.-H. Hwang, "A survey on lpwa technology: Lora and nb-iot," *Ict Express*, vol. 3, no. 1, pp. 14–21, 2017.
[10] N. Sornin, M. Luis, T. Eirich, T. Kramp, and O. Hersent, "Lorawan specification," *LoRa alliance*, 2015.
[11] P. San Cheong, J. Bergs, C. Hawinkel, and J. Famaey, "Comparison of lorawan classes and their power consumption," in *Communications and Vehicular Technology (SCVT), 2017 IEEE Symposium on*. IEEE, 2017, pp. 1–6.
[12] A. Adhikary, X. Lin, and Y.-P. E. Wang, "Performance evaluation of nb-iot coverage," in *Vehicular Technology Conference (VTC-Fall), 2016 IEEE 84th*. IEEE, 2016, pp. 1–5.
[13] T. Polonelli, D. Brunelli, A. Bartolini, and L. Benini, "A lorawan wireless sensor network for data center temperature monitoring," *arXiv preprint arXiv:1902.09400*, 2019.
[14] T. Polonelli, D. Brunelli, and L. Benini, "Slotted aloha overlay on lorawan-a distributed synchronization approach," in *2018 IEEE 16th International Conference on Embedded and Ubiquitous Computing (EUC)*. IEEE, 2018, pp. 129–132.
[15] M. Lauridsen, R. Krigslund, M. Rohr, and G. Madueno, "An empirical nb-iot power consumption model for battery lifetime estimation," in *Ieee Vts... Vehicular Technology Conference*, 2018.
[16] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A comparative study of lpwan technologies for large-scale iot deployment," *ICT Express*, 2018.