Multi-RAT IoT – What's to Gain? An Energy-Monitoring Platform

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Abstract—Multiple LPWANs have been rolled out to support the variety of IoT applications that are crucial to the ongoing digital transformation. These networks vary largely in terms of qualityof-service, throughput and energy-efficiency. To cover all LPWAN use-cases most optimally, multiple networks can be combined into a multiple radio access technology (multi-RAT) solution. In particular environmental monitoring in both smart city and remote landscapes. We present and share such a multi-RAT platform. To derive an accurate profile of the multi-RAT opportunities in various scenarios, in the-field network parameter are monitored. The platform collects per-packet energy-consumption, packet delivery ratio (PDR) and other parameters of LoRaWAN, NB-IoT and Sigfox. Our preliminary measurements demonstrate the validity of using a multi-RAT solution. For example, we illustrate the potential energy savings when adopting multi-RAT in various scenarios.

Index Terms—IoT, Multi-RAT, LoRaWAN, Sigfox, NB-IoT, Energy Efficiency

I. INTRODUCTION

Internet of things (IoT) networks are being deployed for a great diversity of use cases. Many of them feature environmental monitoring applications. Monitoring air pollution in smart city landscapes [1] is a prime example. Another application is the monitoring of tree growth and soil moisture levels in remote rural areas [2]. Herein, a vast wireless sensor network (WSN) is deployed: connecting IoT sensor nodes to the Internet. These devices require long-range and low-power connectivity, limiting the wireless interface to low power wide area network (LPWAN) technologies.

IoT devices are typically battery-powered, so extra design efforts are needed to optimize the energy usage of IoT nodes [4]. In this paper, we consider LoRaWAN, Sigfox and NB-IoT. These technologies feature long-range connectivity whilst remaining relatively low power [5]. They vary, however, largely in terms of data bandwidth, quality of service (QoS) and energy-efficiency [5, 6]. For example, while NB-IoT provides more data bandwidth and QoS, its energy efficiency is considerably worse than Sigfox and LoRaWAN, especially when transmitting smaller payloads [7]. Due to these inherently different characteristics between LPWAN solutions, it is challenging to optimize any single technology for energyefficiency for a more complex and varying use case. It is clear that these differences can be exploited by combining multiple wireless connectivity solutions in one IoT node.

By combining multiple wireless technologies into one multi-RAT IoT node [7], several crucial benefits can be obtained:



Fig. 1: Picture of the presented, custom and open-source multi-RAT platform [3] to perform per-packet energy measurements of IoT communication in narrowband IoT (NB-IoT), LoRaWAN, and Sigfox networks.

(1) energy-efficient operation for variable payload sizes, (2) timely delivery for latency-critical messages, (3) improved service area, and (4) improved QoS. The energy consumption of the IoT node is determined by various parameters, both network and environment related. Literature focuses mainly on theoretical energy models or models obtained in lab conditions [8], omitting the non-negligible impact caused by vendor and operator-specific configurations or various coverage conditions. One publication by Michelinakis et al., published in-thefield observations of large differences in energy consumption between various network providers of NB-IoT. This highlights the need for platforms to obtain an accurate comparison and energy model of LPWAN IoT technologies, where both network and environment parameters are closely monitored.

Contributions– In this work, we present a platform for diverse, in-the-field parameter monitoring for LPWAN IoT networks. It includes for instance the power consumption on a per-packet basis. The platform consists of a custom-made hardware measuring module, as well as a cloud-based interface with an easy to interpret dashboard. Through this platform, we demonstrate the shortcomings of using a single technology and study the potential of multi-RAT in typical IoT settings and



Fig. 2: Schematic overview of the proposed system.

use-cases. Moreover, the cloud platform is publicly accessible¹ and both the software and hardware are open-source [3].

This paper is organized as follows. Firstly, we elaborate on the available wireless IoT technologies, focusing on various advantages of a multi-RAT solution. Secondly, we present our custom-designed multi-RAT measurement platform. Thirdly, the viability of such measurement platform is demonstrated. Finally, we summarize our main findings and suggest some further platform improvements e.g., remotely updating the monitoring algorithm to specific use cases.

II. WIRELESS TECHNOLOGIES AND MULTI-RAT OPPORTUNITIES

The considered LPWAN technologies (i.e., LoRaWAN, Sigfox and NB-IoT) are tailored to provide wide area coverage to energy-constrained devices. However, they differ largely in the design of both the physical layer and medium access control layer [4]. These differences result in a diverse set of corresponding applications and use cases.

A. License-exempt technologies.

To comply with limitations imposed on the industrial, scientific and medical (ISM) band, duty cycle limits are put in place [9, 10]. This intereference mitigation measure results in a nonnegligible minimum delay between packets and limited peak throughput.

LoRaWAN makes use of the, on chirp spread spectrum (CSS) based, long range (LoRa) modulation technique. This technology operates in the ISM band and does not employ any multiple-access technique, i.e., ALOHA is used. LoRaWAN coverage can be freely extended with private gateways.

Sigfox uses ultra-narrow band (UNB) modulation with differential binary phase-shift keying (DBPSK) in the same license free ISM band as LoRaWAN [11]. Sigfox is a proprietary technology, and its network is deployed privately. To maximize PDR, Sigfox will send each data packet three times, each at another random carrier frequency. This diversity technique increases the probability of receiving at least one packet successfully. This, however, results in a larger time on air (ToA), thereby further reducing the throughput due to the duty cycle regulations [10].

B. Cellular Technology.

NB-IoT, as a derivative of LTE, typically operates in the licensed band spectrum. Radio resources are allocated by the network to IoT nodes, based on time-frequency slots. By simplifying some main LTE principles, a licensed LPWAN technology is created [12]. Special attention was paid to, among other things, lowering hardware complexity, coverage enhancement, and lowering energy consumption. By introducing extended discontinuous reception mode (eDRX) and longer power saving mode (PSM) delays, active radio time is reduced, thereby lowering the overall energy consumption of the IoT node [13].

C. Multi-RAT opportunities.

It is clear that, no matter how widely applicable any of the aforementioned technologies may be, there is no onefits-all technology. Equipping a node with multiple wireless technologies, will facilitate switching between message transmissions to obtain a higher energy-efficiency or to address new application requirements or context-switches.

When deploying energy-constricted IoT nodes requiring large payloads, for example, NB-IoT is the prime candidate. Yet, the energy cost of sending periodical 'alive' messages is rather high, in comparison to LoRaWAN or Sigfox. Therefore, a typical smart city setup, with both NB-IoT and LoRaWAN, can reduce the energy consumption by a factor of 4 [7] or more. Furthermore, NB-IoT power consumption is highly dependent on the operating conditions, such as network coverage and configuration [8]. Including alternative wireless radios can increase the energy-efficiency when detecting high energy costs in one network. These trade-offs and energy gains can be measured by the presented multi-RAT platform.

III. MULTI-RAT PLATFORM

In order to quantitatively assess the potential of a multi-RAT solution, and investigate possible practical energy efficiency optimization approaches, we created a prototype that is able to map the characterizations of IoT wireless networks. The realized prototype includes LoRaWAN, Sigfox and NB-IoT and is able to measure energy consumption on-device on a per-packet-basis. These measurements are wirelessly transmitted and evaluated in the back-end. This prototype enables IoT developers to adapt application requirements and restrictions based on measured, on-site energy consumption data. The prototype is depicted in Fig. 1.

A. On-Board Wireless Technologies

A schematic overview of the prototype testing platform is depicted in Fig. 2. The core of the device features the CMWX1ZZABZ-091 module by Murata. The module is powered by an ultra-low-power Arm Coretx-M0+ microcontroller (STM32L072CZ) and wireless transceiver (SX1276) [14] (LoRaWAN and Sigfox). The interface to program the microcontroller is user accessible, contradictory to other wireless modules. Thus, eliminating the need for an extra microcontroller [4]. The embedded wireless transceiver can be used to connect to either the LoRaWAN or Sigfox network. In this work, the controller firmware was customized in such a way, that dynamic switching between both networks is possible. The CMWX1ZZABZ-091 module hardware is extended with NB-IoT hardware: a custom designed extension board featuring a Quectel BG96.

B. Power/energy measuring

Power distribution of the platform is illustrated in Fig. 2. To accurately measure energy consumption on a per-packedbasis, high accuracy coulomb counting is used. To do so, two coulomb counting modules are used, measuring the power usage on each power rail. The coulomb counting algorithm is performed by the LTC2941 battery gas gauge. The accuracy of the calculated energy consumption is compared to a dedicated energy meter instrument, i.e., an Otii Arc². To eliminate an energy offset, the platform is calibrated based on the energy usage reported by both the coulomb counter and Otti Arc for 120 packets for each IoT technology. The utilized coulomb counter employs a sense resistor, measuring the voltage over the resistor to determine the current. The difference between the advertised resistance and the real value is determined based on the above-mentioned procedure. By scaling all measurements of the coulomb counter, this error is removed.

The residual error after calibration is shown in Fig. 3. Good overall accuracy is achieved with this low-complexity design. However, the fast transient currents of the IoT communication result in larger error margins. These need to be taken into account when determining the energy consumption of each technology.

²More information on Otii Arc: qoitech.com/otii/



Fig. 3: Recorded error margin on energy measurements using the proposed system, after calibration. The errors correspond to the energy difference measured by the platform and the Otti Arc power analyzer.

C. Parameter Monitoring

The energy consumption is determined by the configuration parameters of each technology and the context (e.g., network coverage). In order to map the measured energy expenditure to these parameters, a detailed list of all actual applicable parameters is retrieved and transmitted to the back-end for further analysis.

Common parameters for LoRaWAN, Sigfox and NB-IoT are:

- number of received messages at the gateway/back-end,
- number of transmitted messages,
- payload size,
- time of reception,
- location of the receiving gateway(s)/base station(s),
- received signal strength indicator (RSSI),
- signal-to-noise ratio (SNR),
- transmit power,
- global navigation satelite system (GNSS) position,
- motion speed.

Aside from more general information, a large number of IoT technology specific data is obtained from the on-board parameters and the available information at the back-end.

For a LoRaWAN transmission, the current spreading factor (SF) is recorded. The evolution of both the transmit power and the SF indicate the available LoRaWAN coverage when adaptive data rate (ADR) is enabled. For Sigfox transmissions, the estimated region where the device is located, reported in the back-end, is collected. For all NB-IoT transmissions, the used coverage enhancement (CE) level is stored, summarizing the network coverage. Other transmission specific data is also stored: reference signals received power (RSRP), signal-to-interference-plus-noise ratio (SINR), and reference signal received quality (RSRQ). eDRX and PSM settings are recorded, to estimate the current power profile.

D. Monitoring Algorithm

The aforementioned on-board parameters and energy consumption per technology are acquired according to the approach depicted in Fig. 4. The measurement cycle consists of two parts, where first we transmit one packet per IoT technology, followed by a message containing the captured results. In the first phase, both the payload size and transmit power are varied per measurement cycle. The used transmit power depends on ADR in LoRaWAN and the network in NB-IoT. For Sigfox, the transmit power is fixed to 14 dBm. In every measurement cycle, a random payload size is selected per technology. The maximum payload size is different for each technology, i.e., 12, 256 and 1547 B for Sigfox, LoRaWAN and NB-IoT, respectively.

Power consumption is monitored from the very start until the very end of the wireless transmission. In NB-IoT especially, this includes eDRX or delayed radio resource connection (RRC) releases. Each of these packets get sent to our custom cloud platform, either directly (NB-IoT) or through network operated cloud platforms (LoRaWAN and Sigfox). Power consumption and various other previously discussed transmission parameters are recorded and sent to the custom cloud platform using an extra NB-IoT packet. This transmission is not



Fig. 4: Monitoring algorithm overview.

included in the energy consumption metrics and is only used to communicate the stored measurements and configurations.

E. Dashboard

To ease the evaluation of the experimental data, a web interface for accessing real-time results was developed. Any relation between the discussed parameters (including consumed energy) can be analyzed by dynamically generating various graphs (e.g., scatter plots or maps). By applying multiple filters, one can easily focus on a particular use case. Hereby allowing IoT developers and researches to draw fast and easy conclusions regarding the influence of certain parameters on the energy consumption.

IV. EVALUATION

The proposed platform is experimentally validated by mapping the characteristics of several IoT networks in various circumstances (location, moving speed, indoor/outdoor and urban/rural). These circumstances correspond to a large number of use cases: performing sensor ratings in smart cities at a fixed location, tracking the movement of (rental) bikes in cities or monitoring environmental tracking of sensitive assets during transport.

In this validation, we focus on two parameters: PDR and energy consumption per (payload) byte. The PDR and energy consumption are measured for every individual IoT technology. In the experiments, any confirmation of reception is disabled on all IoT technologies. Downlink parameters are enabled, though, only to enable energy optimizing strategies such as ADR in LoRaWAN.

These experimental results were collected at various locations across the Belgian region of Flanders, covering an area of $3000 \,\mathrm{km^2}$. Mobile measurements are collected by means of commuting between two cities using bike and train. In total, 4597 data points are gathered. The networks used are the

Proximus NB-IoT and LoRaWAN network. CityMesh is the official Sigfox Operator in this region. All of these operators claim full coverage across the region.

The results of the conducted experimental campaign are summarized in Table I and provide insight in both the PDR and energy consumption in various scenarios and various payload sizes. Based on this data, we derive three multi-RAT conclusions or opportunities.

- 1) Payload dependent multi-RAT switching for efficient energy consumption. IoT use cases with varying payload sizes will benefit greatly in terms of energy consumption from implementing a multi-RAT scheme. By only employing NB-IoT for sending larger messages (51 B 1547 B), and using LoRaWAN for smaller messages (1 B 51 B), energy is saved. As seen in Table I, energy consumption per byte (E_b) for smaller messages (1 B 51 B), improves slightly when comparing Sigfox to NB-IoT but at least quadruples when comparing LoRaWAN to NB-IoT. With the inclusion of NB-IoT, large packets can still be sent without the need for splitting payloads across different LoRaWAN or Sigfox packets (and thus otherwise increasing latency).
- 2) Mobility management IoT communication on mobile nodes can suffer from low PDR when moving at high speed. By comparing static to mobile measurements, it is clear that the PDR of Sigfox dramatically diminishes for mobile nodes. This can also be seen when plotting the PDR versus speed in the measurement platform dashboard (Fig. 5). For Sigfox, PDR drops with increasing speed, while the PDR of both NB-IoT and LoRaWAN largely remains constant. These results are consistent with measurements gathered by Wang et al. [15], in which packets are transmitted from IoT nodes moving at high speed.
- 3) Energy efficient multi-RAT switching for mission-critical IoT. Guaranteeing delivery in IoT requires a downlink channel for confirmation packets to be sent. Traditionally, one would opt for a high PDR IoT technology such as NB-IoT. However, the energy cost of sending a NB-IoT packet is relatively high when compared to LoRaWAN and Sigfox. First, attempting to send critical data via LoRaWAN or Sigfox (with a confirmation downlink channel) can improve energy consumption drastically.



Fig. 5: Comparison of packet delivery ratio (PDR) of NB-IoT, LoRaWAN and Sigfox in function of speed of the IoT node for packet payloads of 1 B-12 B.

TABLE I: Comparison between NB-IoT, LoRaWAN and Sigfox as experimental validation of the presented multi-RAT platform. packet delivery ratio (PDR) and the average energy per byte E_b serve as comparison metrics.

Payload Size (B)		Static						Mobile		
		Indoor			Outdoor			Outdoor		
		NB-IoT	LoRaWAN	Sigfox	NB-IoT	LoRaWAN	Sigfox	NB-IoT	LoRaWAN	Sigfox
1-12	PDR (%)	93.10	61.58	89.86	94.54	52.89	73.49	88.89	62.09	42.98
	$E_b ~(\mu W h/B)$	60.52	8.03	45.58	44.36	11.65	47.03	74.80	10.2	50.79
12-51	PDR (%)	98.53	71.90	-	92.85	53.95	-	81.98	58.46	-
	$E_b ~(\mu W h/B)$	12.61	3.69	-	18.65	6.56	-	32.85	0.53	-
51-255	PDR (%)	97.17	72.00	-	92.89	/	-	84.78	/	-
	E_b ($\mu W h/B$)	5.98	0.33	-	3.95	/	-	10.12	/	-
255-1547	PDR (%)	99.08	-	-	90.63	-	-	82.86	-	-
	$E_b \; (\mu W h/B)$	1.03	-	-	0.81	-	-	0.89	-	-

V. CONCLUSION

In this work, we presented a multi-RAT platform for in the field analysis of multiple IoT networks, with a particular focus on energy consumption in real life scenarios such as remote monitoring of environmental parameters. A diverse set of parameters is monitored (such as RSSI or location) to be able to match energy consumption with various environmental circumstances. All data relations can be studied via an easy-touse web interface. When developing IoT solutions for highly specific use cases, the proposed platform can be used to determine multi-RAT insights and optimization before largescale adoption. As experimental evaluation of the proposed platform, we studied the PDR and energy consumption per byte E_b and posed three multi-RAT conclusions for common use cases. This platform opens many opportunities for further research. For example, an analysis on the impact of confirmed communication of IoT nodes is required, most notably the usage of TCP instead of the current, unconfirmed UDP scheme, in NB-IoT. The proposed platform can be extended by providing the possibility to adapt the monitoring algorithm remotely.

REFERENCES

- [1] A. Candia, S. N. Represa, D. Giuliani, M. Á. Luengo, A. A. Porta, and L. A. Marrone, "Solutions for SmartCities: proposal of a monitoring system of air quality based on a LoRaWAN network with low-cost sensors," in 2018 Congreso Argentino de Ciencias de la Informática y Desarrollos de Investigación (CACIDI). IEEE, 2018, pp. 1–6.
- [2] V. Matasov, L. Belelli Marchesini, A. Yaroslavtsev, G. Sala, O. Fareeva, I. Seregin, S. Castaldi, V. Vasenev, and R. Valentini, "IoT Monitoring of Urban Tree Ecosystem Services: Possibilities and Challenges," *Forests*, vol. 11, no. 7, p. 775, 2020.
- [3] G. Leenders, "Energy Profiling Platform for Multi-RAT." [Online]. Available: http://dx.doi.org/10.5281/zenodo.6579821
- [4] G. Callebaut, G. Leenders, J. Van Mulders, G. Ottoy, L. De Strycker, and L. Van der Perre, "The Art of Designing Remote IoT Devices—Technologies and Strategies for a Long Battery Life," *Sensors*, vol. 21, no. 3, 2021.
- [5] K. Mekki, E. Bajic, F. Chaxel, and F. Meyer, "A Comparative Study of LPWAN Technologies for Large-Scale IoT Deployment," *ICT express*, 2019.
- [6] Y. Li, X. Cheng, Y. Cao, D. Wang, and L. Yang, "Smart choice for the smart grid: Narrowband Internet of Things (NB-IoT)," *IEEE Internet of Things Journal*, vol. 5, no. 3, pp. 1505–1515, 2017.
- [7] G. Leenders, G. Callebaut, G. Ottoy, L. Van der Perre, and L. De Strycker, "Multi-RAT for IoT: The Potential in Combining LoRaWAN and NB-IoT," *IEEE Communications Magazine*, vol. 59, no. 12, pp. 98–104, 2021.

- [8] F. Michelinakis, A. S. Al-Selwi, M. Capuzzo, A. Zanella, K. Mahmood, and A. Elmokashfi, "Dissecting Energy Consumption of NB-IoT Devices Empirically," *IEEE Internet of Things Journal*, vol. 8, no. 2, pp. 1224– 1242, 2020.
- [9] N. Sornin, M. Luis, T. Eirich, T. Kramp, and O. Hersent, "LoRaWAN Specification," *LoRa Alliance*, 2015.
- [10] M. Aernouts, R. Berkvens, K. Van Vlaenderen, and M. Weyn, "Sigfox and LoRaWAN datasets for fingerprint localization in large urban and rural areas," *Data*, vol. 3, no. 2, p. 13, 2018.
- [11] C. Gomez, J. C. Veras, R. Vidal, L. Casals, and J. Paradells, "A Sigfox Energy Consumption Model," *Sensors*, vol. 19, no. 3, p. 681, 2019.
- [12] R. Ratasuk, N. Mangalvedhe, Y. Zhang, M. Robert, and J.-P. Koskinen, "Overview of Narrowband IoT in LTE Rel-13," in 2016 IEEE conference on standards for communications and networking (CSCN).
- [13] O. Liberg, M. Sundberg, E. Wang, J. Bergman, and J. Sachs, *Cellular Internet of Things: Technologies, Standards, and Performance.* Academic Press, 2017.
- [14] "Discovery kit for LoRaWAN, Sigfox, and LPWAN protocols with STM32L0." [Online]. Available: st.com/resource/en/data_brief/ b-1072z-lrwan1.pdf [Accessed on: November 19, 2021].
- [15] S.-Y. Wang, J.-E. Chang, H. Fan, and Y.-H. Sun, "Performance Comparisons of NB-IoT, LTE Cat-M1, Sigfox, and LoRa Moving at High Speeds in the Air," in 2020 IEEE Symposium on Computers and Communications (ISCC). IEEE, 2020, pp. 1–6.

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