Multi-RAT LPWAN in Smart Cities: Trial of LoRaWAN and NB-IoT Integration

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Abstract—**The landscape of the contemporary IoT radio access technologies (RATs) is excessively diverse, especially when it comes to such a complex environment as Smart City. On the one hand, this diversity offers operators sufficient flexibility to select the most appropriate RAT for their target application. On the other, it becomes a severe limiting factor, as it leads to high level of uncertainty for the IoT device vendors, who need to decide, which technology to support in their hardware. In this paper, we consider the provisioning of the low-power wide area network (LPWAN) devices with multiple RATs. First, we briefly discuss the parameters of several potential radio technologies, and analyze the pros and cons of combining them in a single device. Next, we prototype a real-life device capable of communicating via two perspective LPWAN technologies, namely, LoRaWAN and NB-IoT, and report the initial results of our performance evaluation. These results confirm the feasibility of instrumenting a dual-mode device as well as reveal several important aspects related to the development of multi-radio devices and their performance. In our view, due to their higher flexibility, reliability, and dependability, the devices such as the one developed can be beneficial for various Smart City applications, with smart energy grids and road traffic control being just two of many examples.**

I. INTRODUCTION

The landscape of the today's Internet of Things (IoT) grade wireless communication technologies is excessively diverse [1], [2]. The dozens, if not hundreds of various short, medium and long-range solutions intended for different applications, use cases and operating environments have been proposed through the recent decades. Almost each of these technologies has a niche and a killer application among the sheer diversity of the use cases within the Smart City paradigm [3], [4]. Nonetheless, given the huge geographical span of a city, the LPWAN technologies [5], [6], [7], aiming at providing connectivity for massive deployments of resource-limited machines, outstand from the mass and draw very serious attention as of today.

Over twenty of the different technologies, which can be attributed to Low-Power Wide-Area Networks (LPWANs), do exist today. Table I lists few of these technologies, along with their illustrative characteristics. Notably, aside of conventional LPWANs, the problem of increasing the communication range for Machine-to-Machine (M2M) communication has recently been addressed within the IEEE 802.11 working group (i.e., IEEE 802.11ah [8]) and by Bluetooth special interest group (i.e., coded BLE PHYs in Bluetooth 5.0 [9]).

Each of these technologies has particular unique features, combination of which within a single solution may enable the new functionalities, increase the flexibility or enable the new degree of dependability [10]. The latter is especially important for the critical infrastructure and machine applications: e.g., autonomous vehicles and robots in context of smart logistics and manufacturing, meters and invertors of the smart energy grids, wearables for smart healthcare and assisted living.

Notably, the trend for combining multiple radio access technologies (RAT) within one chipset is not novel. Already today several manufacturers of the short-range chipsets offer commercial chipsets [11], [12], which can be configured in the software (SW) to communicate over IEEE 802.15.4, BLE, or use a proprietary modulation coding scheme (MCS). The possibility for simultaneous use of multiple short-range communication technologies in a single IoT end device has also been demonstrated, e.g., in [13].

In this paper, we address the construction of a multi LPWAN RAT capable device. Namely, we instrument a real-life prototype sensor node, which can communicate – either simultaneously or by selecting one of the two technologies – over NB-IoT [14] and LoRaWAN [15]. The instrumented technology artifact was evaluated through a series of measurements and these preliminary results are reported in the paper. These results show that even though both RATs have much in common, there are scenarios where either technology appears to be more efficient than its counterpart. To the best of our knowledge, the combination and use of the two LPWAN RATs in a single device has not been contributed in the past. We believe that the presented results and the reported lessons learned, which offer useful guidance and highlight the important practical aspects, may be beneficial for the community. Some directions for further studies are pointed out as well.

The rest of the paper is structured as follows. In Section II, we discuss the pros and cons of combining multiple LPWAN RATs for a single LPWAN device. Going further, in Section III, we detail our implementation and the test set up. Section IV discusses the obtained results. Finally, Section V

TABLE I: Selected LPWAN technologies and their parameters (for EU bands)

Parameter	**LPWAN technology**			
	SigFox	**LoRaWAN**	**LTE-M**	**NB-IoT**
Architecture	Star-of-stars	Star-of-stars	Star-of-stars	Star-of-stars
Frequency band	ISM	ISM	Licensed	Licensed
Maximum range	Dozens of km	Dozens of km	Units km	Units km
Max. uplink PHY rate [kbps]	0.1	50	1000	250
Max. uplink bandwidth [kHz]	0.1	250	1400	180
Max. downlin PHY rate [kbps]	0.5	50	1000	226.7
Max. downlink bandwidth [kHz]	0.6	250	1400	180
MCS options option	1	7	multiple	multiple
TX power options option	1	5	multiple	multiple
Max. terminal TX power [dBm]	14	14	20	23
Internet Protocol (IP) support	From gateway	From gateway	From device	From device
Potential operators	SigFox & partners	Anyone	Telecom operators	Telecom operators
Devices in a cell (typically)	Dozens, thousands	Dozens, thousands	Dozens, thousands	Dozens, thousands
Illustrative subscription fee, USD/device/year	1-12[1], limited messages	0[2]-20[3], limited traffic	18-24[4]	n/a

concludes the paper and summarizes the lessons learned.

II. MULTI-RAT LPWAN DEVICES

A. Pros and Cons of Multi-RAT LPWAN Devices

If the technical feasibility of instrumenting a multi RAT LPWAN device may hardly cause a doubt, the expediency of such solution is arguable. Among the major drawbacks for supporting multiple RATs within a single IoT device can be listed the following:

- increased monetary cost of application development and production of each device due to higher complexity,
- increased operational expenditures per device due to need of paying subscription fees for multiple operators and/or supporting multi-RAT infrastructure,
- increased linear dimensions and weight of a device hosting multiple RATs,
- increased resource requirements (memory, processing power, etc.) and energy consumption to support communication (and even the potential of communication) over different RAT.

Among the other not trivial obstacles not listed above, one should note that the price of a multi-RAT enabled radio chipset or device increases not just due to the increase of the integrated circuit complexity, but also due to the royalty payments for all the critical intellectual properties for each RAT supported. Another obstacle, which affects the economic feasibility of the multi-RAT enabled devices, are the subscription conditions of the telecommunication operators. To give an example, as can be seen from Table I the current LPWAN operators, do not charge by traffic volume but offer a subscription with flat per-month rate. Under this condition a second communication technology requiring another subscription may be inexpedient. Finally, energy wise, addition of a new electronic component increases the total device energy consumption, even if this component is not powered up.

Among the major benefits of having multiple RAT communication capability are:

- higher reliability of the communication, since the data can be delivered by a more reliable technology or sent over all the technologies supported,
- higher flexibility, enabling covering the weaknesses of one technology with the strengths of another one.

Importantly, the aforenoted flexibility can be utilized in various ways. To give an example, the RAT to be used at each particular moment can be selected to minimize the energy consumption, the latency, maximize the delivery probability, reduce the costs of data delivery, etc.

B. LoRaWAN and NB-IoT Use-case

As illustrated in Table I, even though various LPWAN technologies address the same problem, their approaches differ somewhat. In what follows we consider the case of the two technologies, namely LoRaWAN [16] and NB-IoT [17], [18], [19].

The former one operates in the license-free industrial, scientific and medical (ISM) band using primarily an ALOHA like channel access model. Since the LoRaWAN gateways and the network server solutions are freely commercially available, basically anyone can deploy an own LPWAN for his devices or to act as an operator. Given these two specifics and subject to the high number of LoRaWAN devices and networks operating in a region, which is likely to be the case for a smart city, the delivery ratio and the latencies may get compromised. Another potential bottleneck of a LoRaWAN network is the need of obeying the duty cycle limitations imposed by the frequency regulations in particular regions of the world (e.g., the EU). As analytically shown in [20], this may substantially restrict the downlink traffic, and introduces a minimum delay between the sequential packets sent by a device and limits the peak throughput.

The NB-IoT technology in its turn implies use of the licensed bands, where the available radio resources are designated to the devices by the network. This allows to minimize the collisions on one hand and handle decently good both uplink and downlink traffic on the other. At the same time the NB-IoT networks are likely to be deployed primarily by the traditional telecom operators, e.g. by updating their current infrastructure. Therefore, to use this technology one needs to ensure that the area of operation is covered by an NB-IoT operator and make a contract with him. Another downside of this approach is the need for a device to synchronize with the

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[1] https://radiocrafts.com/kb/much-cost-use-sigfox/

[2] Infrastructure owned by the user.

[3] https://www.telecomasia.net/content/sk-telecom-launches-nationwide-lorawan

[4] http://www.fiercewireless.com/wireless/at-t-launches-nationwide-lte-m-network-for-iot

network, which results in energy consumption and takes decent time. The latter can become a bottleneck in case of energy-harvesting powered devices with limited energy buffers.

From the discussion above one can clearly see that in the case if an IoT device needs to be sure that their data are delivered (e.g., a notification about the detected error), requires getting a lot of data in downlink or needs IP the NB-IoT technology may be more advantageous. Meanwhile in case if a user wants to own the infrastructure and the traffic is primarily uplink and loss-tolerant, use of LoRaWAN may be more advantageous. In the case if both these use cases are combined in the target application a dual radio can become the solution of choice. To list a few practical use cases which can benefit of dual-RAT approach:

- a security or malfunction detection system with heartbeat status messages over LoRaWAN and emergency alarm traffic over NB-IoT or both technologies,
- an assisted living wearable with low priority traffic over LoRaWAN and emergency traffic over NB-IoT,
- actuators with heartbeats or status reports over LoRaWAN and direct control loop traffic over NB-IoT,
- a shipment tracking system using NB-IoT whenever available and private LoRaWAN in remote areas (in warehouses, on ships in the sea, etc.).

Notably, the LoRaWAN architecture is much simpler than that of the NB-IoT and can be implemented in a decentralized manner (e.g., by running a network server right on the gateway). This makes LoRaWAN a good candidate for a back-up communication solution in the case if the infrastructure goes down (e.g., due to blackout).

III. INTEGRATED LORAWAN AND NB-IOT DEVICE AND SYTEM ARCHITECTURE

In order to assess the feasibility, and investigate the specifics of design, and performance of a dual-RAT LPWAN device we prototyped a solution based on the CWC's modular WSAN/IoT device platform [21]. The photo of the designed prototype device along with its structural diagram are depicted in Fig. 1.

The core of the node is composed of the STM32F217 32-bit microcontroller and a power regulator circuitry. Below the core module three extension modules are attached: the sensor module featuring multiple environmental sensors, the LoRaWAN communication module (built around RN2483 transceiver from Microchip) and, optionally, the battery power supply module. Above the core module the adapter board and an NB-IoT shield hosting the Cat NB1 Ublox N211 chipset are connected. All the boards except the NB-IoT shield were designed in the University of Oulu.

The firmware of the node has been instrumented based on the FreeRTOS embedded operating system and was structured as shown in Fig. 2. The three threads are initialized and operate in parallel: the two communication threads controlling the NB-IoT and a LoRaWAN communication and the main thread, reading the data from sensors and forwarding them to the communication threads. In the first test case the main thread first forwards a 12-byte packet of sensor data to the first communication thread (i.e., LoRaWAN) and then, once the acknowledgement of transmission is received from the transceiver, to the second one (i.e., NB-IoT).

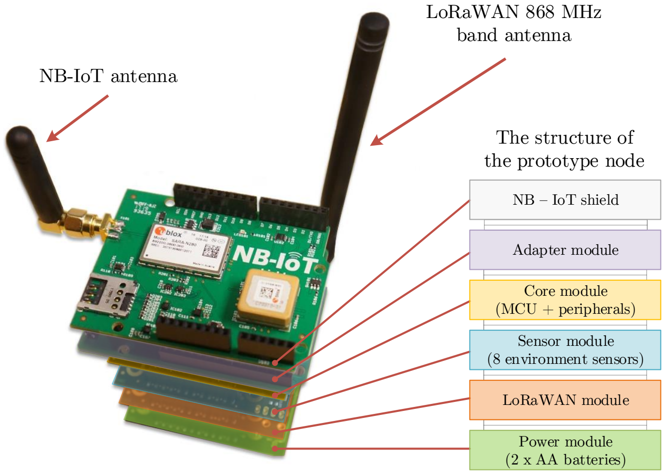

Fig. 1: Photo and the structural diagram of a designed double-RAT LPWAN device prototype used in experiments.

The complete structural diagram of our implemented system is depicted in Fig. 3. Operation of the designed device has been tested at Brno University of Technology, Czech Republic, in commercial NB-IoT (Band 20) and proprietary LoRaWAN network, and in Oulu, Finland, in a proprietary LoRaWAN network. First, it was confirmed that the instrumented dual RAT device connects to NB-IoT and LoRaWAN networks and communicates in them. Next, a series of experiments were conducted. In our initial experiments we primarily focused on the energy consumption aspect of the developed solutions, albeit few other performance metrics were also assessed.

IV. EXPERIMENTAL RESULS AND THEIR DISCUSSION

The illustrative radio power consumption profiles of the instrumented device operating in the two networks are illustrated in Fig. 4 and in Fig 5. The current consumption profiles, measured by Keysight N6705B power analyzer under stable 3.3V supply, were recorded and post-processed. First, the constant consumption of the microcontroller, sensors and other peripheral components were filtered out, leaving only the consumption of the two radio interfaces. Further the data were analyzed (e.g., the auto-correlation function was calculated to assess the periodicity).

The different phases of operation of the engineered dual-RAT enabled device are shown in Fig. 4 and in Fig 5. Note that the consumption profiles depicted in these figures were obtained under different data rates (DRs) and transmit power settings for LoRaWAN transceiver.

As one can see from the presented figures, the consumption profile of a LoRaWAN transceiver is quite straightforward and is composed of:

- a transmit phase, duration of which and consumption during which depend on the used DR and transmit power index, respectively,

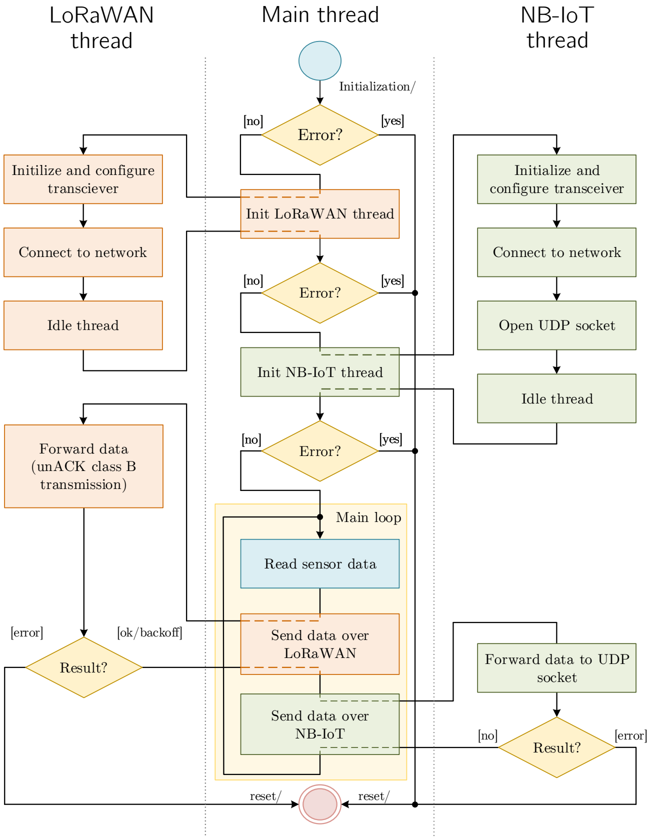

Fig. 2: High-level algorithm of the firmware operation.

- and the two receive windows (RW1 and RW2) opened 1 and 2 seconds after transmission, respectively.

The duration of the RW1 is proportional to the duration of a transmit symbol and thus also depends on the DR. The duration of RW2 is constant, since RW2 implies use of DR0. In between these phases the LoRaWAN radio core stays in idle mode with constant consumption of about 10 mW.

Meanwhile, the consumption profile of the NB-IoT transceiver is much more complex. Since not so much information is available about the internal logic of the used commercial chipset, we attempted to reconstruct it from the results of our measurements. First, as depicted in Fig. 4 (zoomed chart at bottom right corner), there is a background consumption. Based on the analysis of the autocorrelation function we have determined that this consumption has periodic nature with a period of 80 ms. The latter corresponds to the duration of a single NB-IoT sub-block, which makes us assume that this consumption is due to listening to Narrowband Physical Broadcast Channel (NPBCH) for upkeeping the synchronization with the network. The multiple peaks of constant consumption exceeding the background consumption level can be attributed to the transmission. For example, as discussed in [17], a transmission of a single NB-IoT report using radio resource control connection resume request involves minimum nine transmission events (namely: NB-IoT Physical Random Access Channel (NPRACH), connection resume request, resume complete and release messages, four Hybrid Automatic Repeat Request (HARQ) acknowledgments, and the uplink report). Interestingly, these peaks have two different levels. This can be explained by the operation of power control of NB-IoT, which implies open loop power control only if the number of repetitions does not exceed two and uses maximum transmit power otherwise [17]. In future we plan to extend our measurements to evaluate this and study this problem more specifically.

Interestingly, the presented results show that even though the firmware for the main controller of our device was designed to use the two RATs sequentially (i.e., the data were forwarded to NB-IoT transceiver only once the LoRaWAN transceiver has acknowledged transmission of the data and vice versa) in practice the transceivers of the two RATs were often operating in parallel. For example, as one can see from Fig. 4, the NB-IoT communication often happened during transmission of the packed over LoRaWAN. The reason for this is that many radio operations are executed by the transceivers in the background (e.g., upkeep of the network synchronization for NB-IoT or opening RW1/RW2 for LoRaWAN) and cannot be controlled by the central processor.

If to compare the consumption of the two used technologies, one can see that NB-IoT transceiver has rather high background consumption on one hand, and high peak consumptions in transmit and receive. If the former is hardly surprising since the maximum transmit power for NB-IoT of 23 dBm, the latter may be a result of more complex (and thus energy-hungry) receive procedures on the NB-IoT chipset. The time of a packets transmission over NB-IoT was typically lower than that of LoRaWAN, especially accounting for the need for opening the receive windows after an uplink transmission. Another critical difference between the two technologies can be observed by comparing the two consumption profiles shown in Fig. 5. While using the low data rates (i.e., DR0 and DR1) the LoRaWAN transceiver reached the maximum duty cycle and had to back-off the transmission for about 8 seconds following the frequency use regulations. During this period of time NB-IoT was the only technology used for uplink communication. Note, that the LoRaWAN network used in our experiments included the three obligatory uplink channels (with cumulative duty cycle of 1%) as well as one uplink channel in 869.5 MHz band with a duty cycle of 10%.

In respect to the communication performance, the packets transmitted over either of the radio technologies have shown delivery ratio of well over 95%. This result is hardly surprising, given that the test networks were sparsely populated and the interferences were minimal. As one can easily calculate, using simultaneously the two RATs with 95% packet delivery rate each and assuming that radio channels and infrastructure malfunctions for RATs are uncorrelated, we end up having a packet delivery ratio of 99.75%. Such a high delivery ratio may enable use of a multi-RAT enabled devices for new applications imposing more strict reliability constraints, like, e.g., the smart energy grids. When this comes to the communication ranges both RATs have demonstrated the

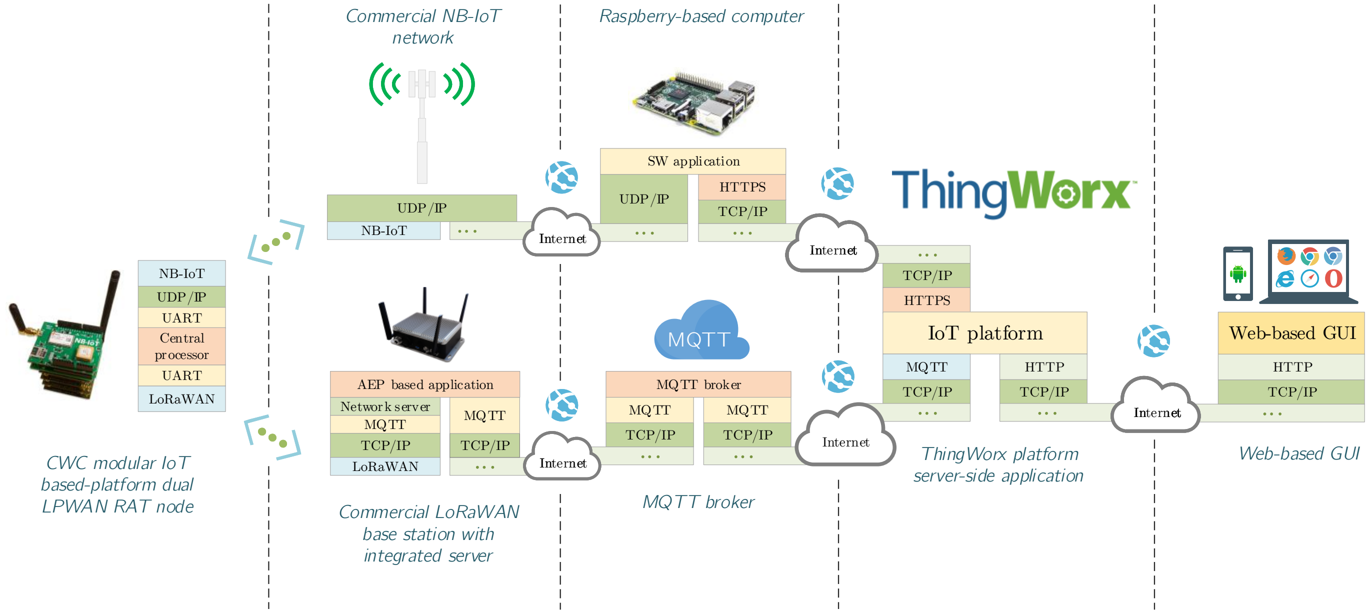

Fig. 3: High-level diagram of the complete implemented system.

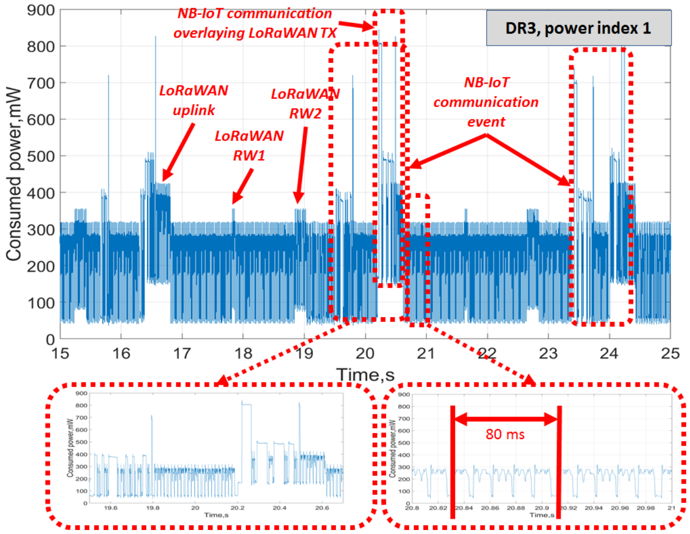

Fig. 4: Power consumption of a dual-mode LPWAN RAT (LoRaWAN: DR3, transmit power 14 dBm).

possibility of delivering the data over multiple kilometers distances.

V. CONCLUSIONS AND LESSONS LEARNED

In the current paper we advocated the design of multi LPWAN RAT enabled devices. First, we briefly sketched the landscape of the LPWAN technologies and speculated on the pros and cons of having a multiple LPWAN RAT enabled within a single device. Among the former ones we identified the higher flexibility, which can transform into increased communication reliability, more effective use of available resources, or enable novel functionalities. Among the major

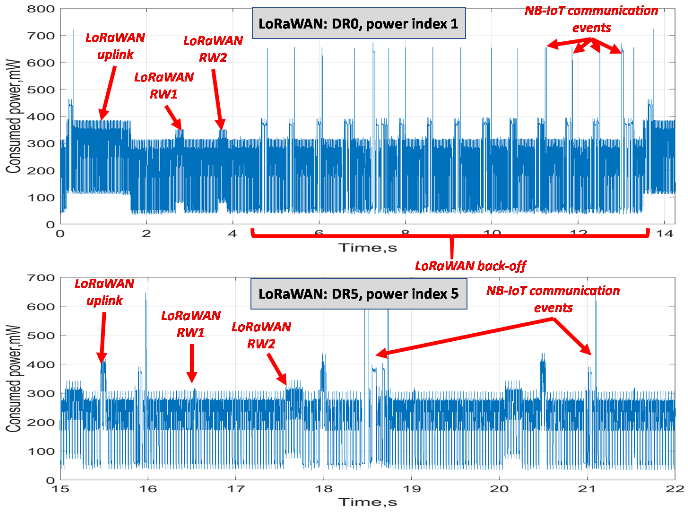

Fig. 5: Power consumption of a dual-mode LPWAN RAT (LoRaWAN: DR0, transmit power 14 dBm, and DR5, transmit power 2 dBm).

drawbacks are the additional production and operational costs, and potentially higher resource needs of multi-RAT radios.

Next, we instrumented a prototype device, which can communicate and report its data over LoRaWAN and NB-IoT. First, we have tested the basic functionalities of the device by connecting it to a commercial NB-IoT and proprietary LoRaWAN network and confirmed that the data are delivered to the application platform over either of the radio interfaces. Then we conducted a set of measurements, which shed some light onto the energy consumption of the instrumented device and the logic of operation of its radio interfaces.

Our measurements show that the used NB-IoT chipset consumes over 200 mW in average for upkeeping network synchronization and has rather high (350 - 700 mW), albeit decently short, periods of peak power consumption during transmit. Due to the lower maximum transmit power of only 14 dBm in EU bands, the peak consumption of LoRaWAN transceiver in transmitting appeared to be below 60 mW, albeit the duration of transmission was often quite long. Even though the LoRaWAN transceiver did not consume any energy for synchronizing to the network, the need for enabling the receiver for the two receive windows resulted in extra energy being consumed. Also these windows negatively affect the throughput and the latency of the communication, especially at high data rates (DR5-DR7). Another substantial difference between the two technologies, which we observed during our measurements, is the need for LoRaWAN transceiver to back-off frequent transmissions, especially at low data rates (DR0 and DR1) due to the duty cycle restrictions imposed by the frequency regulations.

When this comes to the design of a multi LPWAN RAT device, there are few things we can point based on our experience. First, this is a need for a power supply circuitry capable of supporting simultaneous operation of the protocols (e.g., 0.3 - 0.4 A current in our case). As was shown in this study, since many operations are handled by the radio transceivers in the background, the central processor can hardly control them. The second specifics of the two used radio transceivers is the need of using the UART interface and ASCII based commands (AT commands for NB-IoT chipset and proprietary command interface for LoRaWAN chipset). Given the limited data rate (57600 bps for RN2483 and 9600 for current version of N211) supported and the overall low efficiency of the interface, this can become a bottleneck.

Finally, we would like to note that the used in our studies NB-IoT chipset had one of the very early firmware releases, which may have limited their functionality and could have affected the results of the measurements. Also the LoRaWAN and NB-IoT base stations in our measurements situated in the different locations. Given this, the presented results are not intended and should by no means be used to directly compare the two addressed LPWAN technologies with each other.

In the current paper we have shown in practice the technical feasibility and identified few important practical aspects of enabling a multi LPWAN RAT enabled devices. In the future, the reported implementation will be used as a testbed for further measurements and experiments. Within these experiments we plan to address the reliability, energy consumption and coverage aspects of the two technologies and their combination.

Meanwhile, the practical enablement of a multi-RAT enabled device introduces few novel research questions. The first one is the optimal selection (both from the device and/or network perspective) of the RAT(s) to be used for a particular scenario on a multi LPWAN RAT enabled device. The other one is the analysis of the feasibility and identification of the application area requiring and benefitting from the multi-RAT enabled LPWAN. In our opinion, many of these use cases come from Smart City domain, including the applications of smart utilities, smart traffic, smart home and many others.

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