On the Performance of Narrow-band Internet of Things (NB-IoT) for Delay-tolerant Services

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***Abstract*—Narrowband IoT (NB-IoT) stands for a radio access technology standardized by the 3GPP organization in Release 13 to enable a large set of use-cases for massive Machine-type Communications (mMTCs). Compared to legacy human-oriented 4G (LTE) communication systems, NB-IoT has game-changing features in terms of extended coverage, enhanced power saving modes, and a reduced set of available functionality. At the end of the day, these features allow for connectivity of devices in challenging positions, enabling long battery life and reducing device complexity. This article addresses the development of the universal testing device for delay-tolerant services allowing for in-depth verification of NB-IoT communication parameters. The presented outputs build upon our long-term cooperation with the Vodafone Czech Republic a.s. company.**

***Keywords*—NB-IoT; IoT, mMTC; LPWAN; Network services**

I. INTRODUCTION

The Internet of Things, often referred to as IoT, encompasses the vision of ubiquitous connectivity across the globe. The deployment of IoT, consisting of various types of devices interconnected for communication, is expected to reach a massive scale in the near future. Furthermore, wireless connectivity through Low-power Wide-area (LPWAN) networks will be an important component of forthcoming communication scenarios [1]. The estimations from Cisco predicts 12 billion connected devices in 2021 [2]. The vision of Ericsson goes even further and advocates up to 18 billion communicating devices in 2022 [3]. Those predictions lead us to the question, *What are the devices that will become connected and are not yet online?* Based on the outputs from the available reports, the early-adopters will be in the first deployment phase represented by smart meters (gas, water, electricity) and monitoring devices (smoke sensors and fire alarms) [4]. Therefore, traditional use-cases such as connecting utility meters to support, e.g., distribution and billing, will most likely increase in numbers [5]. Thus, the Industrial IoT sector related to the smart metering opens the door for the delay-tolerant remote reading of the measured data [6], [7].

The predicted growth of connected devices transmitting Machine-to-Machine (M2M) data is supported, or perhaps even managed, by the recent work performed by the Third Generation Partnership Project (3GPP) development organization in the Release 13 [8]. Based on the requirements given by the IoT vision, the design of new Cellular IoT (CIoT) technologies has been rethought, and a new radio access technologies operating in licensed frequency spectrum have been developed and became available within a very short period of time [9]. The three new technologies targeted to provide communication for IoT in cellular infrastructure are known as: (i) Extended Coverage Global System for Mobile Communications Internet of Things (EC-GSM-IoT), (ii) Long-Term Evolution for Machine-Type Communications Category M1 (LTE Cat-M1), and (iii) Narrowband IoT (NB-IoT).

A. Narrowband IoT (NB-IoT)

As the situation evolved, the NB-IoT has became the preferred cellular communication technology for remote metering across the Europe[1]. NB-IoT is a radio access technology that reuses technical components from its predecessor in some aspects, i.e., Long Term Evolution (LTE) to facilitate operation within licensed LTE frequency spectrum. This technology also supports a stand-alone operation. As the name reveals, the entire system operates in a narrow spectrum, starting from only 200 kHz, providing unprecedented deployment flexibility because of the minimal frequency spectrum requirements in comparison with the legacy LTE. The bandwidth of 200 kHz is divided into channels with 3.75 kHz or 15 kHz spacing to support a combination of extreme coverage and high uplink capacity, considering the narrow spectrum deployment [10].

While LTE Cat-M1 solely utilizes existing LTE/LTE-A frequencies restricted to 1.4 MHz bandwidth, NB-IoT supports maximum flexibility of the deployment and prepares for re-farming scenarios [11]. Accordingly, NB-IoT is possible to deploy in three modes of operation: (i) stand-alone, (ii) in-band, and (iii) guard-band. Fig. 1 depicts all the possible NB-IoT deployments in frequency spectrum.

To be able to enable a long-term battery powered use-cases, 3GPP Releases 12 and 13 introduced such features as extended Discontinuous Reception (eDRX) and Power-Saving Mode (PSM) to support this type of operation aiming to optimize the power consumption. In most use cases, the device actually spends the majority of its lifetime in idle or power

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[1] See "Vodafone Brings NB-IoT to UK, Starts Trial With Scottish Power" by Light Reading, 2018: https://www.lightreading.com/iot/nb-iot/vodafone-brings-nb-iot-to-uk-starts-trial-with-scottish-power/d/d-id/746377

saving mode as most of the IoT applications only require infrequent transmission of relatively short packets. Traditionally, an idle device function is to monitor paging and perform mobility measurements, although, the energy consumption during idle mode is much lower in comparison with the connected mode. Further energy saving can be achieved by simply increasing the periodicity between paging occasions or not requiring the device to monitor paging at all in case of PSM.

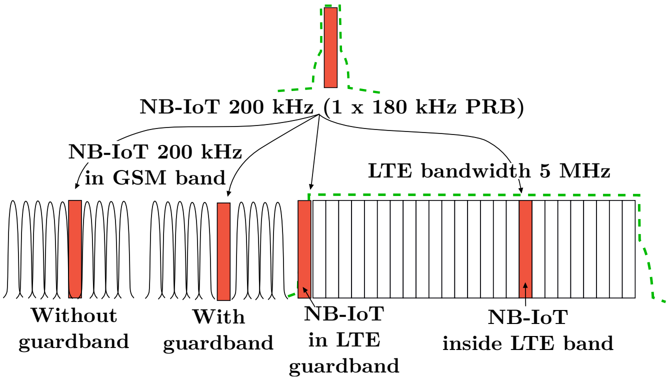

Fig. 1. The possible NB-IoT deployments: NB-IoT stand-alone deployment using refarmed GSM / LTE spectrum; inside an LTE carrier, either using one of the LTE PRBs (in-band deployment) or using the LTE guard-band (guard-band deployment).

In essence, a device can switch off its radio module and only keep a basic oscillator running for the sake of keeping a time reference to know when it should come out of the PSM or eDRX. The reachability during PSM is set by the Tracking Area Update (TAU) timer with the maximum settable value exceeding one year. Moreover, eDRX can be configured with a DRX cycle just below 3 hours [12], [13]. The overall summary diagram of end-device behavior in NB-IoT network is depicted in Fig. 2.

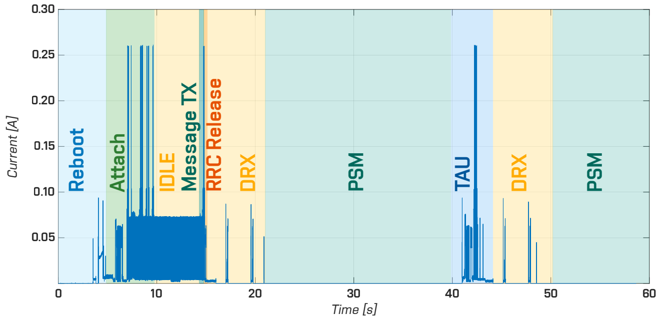

Fig. 2. Summary diagram of end-device behavior in NB-IoT with the utilization of release assistance to further decrease the power consumption.

B. Our Contribution

In this work, we report our unique cooperation with Vodafone Czech Republic a.s. telecommunications operator, with the goal to design the NB-IoT prototype for delay-tolerant services in Czech Republic. First, we discuss our design of the NB-IoT board focused on the ability to measure and evaluate the transmission parameters while sending data from end-device towards the remote server. On top of the basic scenario, we extend the transmission parameters to cover different communication use-cases.

The main contributions of our paper can be summarized as follows:

- Design of the NB-IoT board for in-depth measurements;
- Precise evaluation of the data transmission with respect to wide-variety of parameters;
- Evaluation of NB-IoT performance for delay-tolerant services in the IoT landscape.

The remainder of this paper is structured as follows. In Section II, we discuss the design of constructed NB-IoT prototype following the requirement to improve the lifetime of the battery-powered device. Going further, Section III provides the description of measurement scenarios together with the discussion on the obtained results. Finally, concluding remarks together with lessons learned are provided in Section IV.

II. DESIGN OF NB-IOT PROTOTYPE

On the contrary to widely-accepted requirements of 10 years battery life for NB-IoT devices, the target of our design work is to design a handheld device for short-term measurements. This is supported by the need of industrial companies that seek a universal communication tester for their employees who will do the intensive field evaluation in the restricted areas.

A. Key Parts of the Prototype

The prototype was designed as a two-sided printed circuit board (PCB), see Fig. 3, and the main components are: (i) NB-IoT communication module (SARA-N211) capable of working in either 800 MHz frequency band (band 20) or 900 MHz frequency band (band 8). In this work, band 20 (832 – 862 MHz for uplink and 791 – 821 MHz for downlink) was selected inasmuch as it is utilized by Vodafone Czech Republic a.s. (ii) SMD (Surface Mount Device) antenna, and (iii) charging circuit with rechargeable Li-Pol battery. The charging circuit consists of: (i) USB controller, (ii) battery charger, and (iii) buck-boost converter. We have selected 32-bit micro-controller STM32L152RDT6 as the main control unit. To control the communication tester, buttons and LCD (Liquid Crystal Display) are implemented as well. Further, the Global Navigation Satellite System (GNSS) module SAM-M8Q was added for precise coordinates of each measurement point.

B. Components Layout

The device has been designed as a hand-held, so the placement of all the components was adjusted to that factor – the overall size of the board was selected to be comfortable in hand and buttons are in reach of the thumb, as depicted in Fig. 3. Above buttons, there is an LCD placed on the box of the device, not at the board itself. The antenna is placed at the top of the device (close to the edge) to ensure as low interference from components and from the operator as possible. Subscriber identity module (SIM) and microSD cards can be plugged-in/out from the side of the device with no need of opening the box of the communication tester. On top of this, it was crucial to ensure impedance of antenna trace 50 Ω and of the

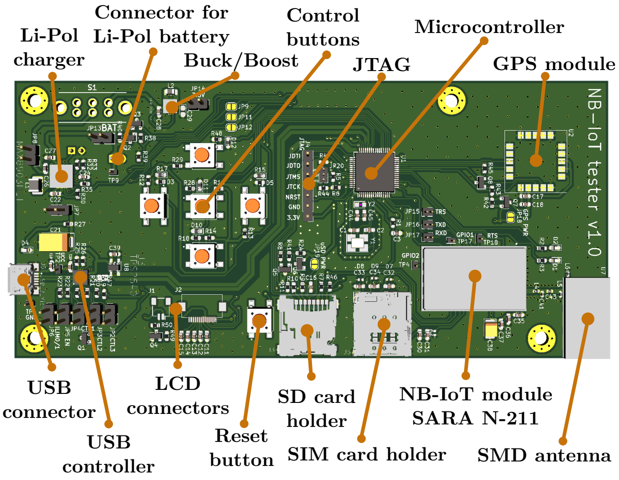

Fig. 3. Model of NB-IoT prototype.

```
while not registered to the network do
    if connected to the network == True then
        open socket;
        goto Message;
    end
    if timeout then
        Error Can not connect to the network;
        exit;
    end
    sleep for 1 s;
end

Message:
while $i < 5$ do
    before = get statistics;
    send message Flag: $0x200$, Len: $n$;
    while not delivered do
        wait for ACK;
        if timeout then
            Error Message was not delivered;
        end
    end
    after = get statistics;
    delay = time after - time before;
    overhead = (tx bytes after - tx bytes before) - $n$;
    sleep 30 s;
end
```

Algorithm 1: Measurement procedure.

USB differential pair 90 Ω. To ensure proper decoupling, the oscillators of the MCU are separated from the circuit via guard ring with a single grounding point.

C. Intended Operation Procedure

Expected functionality of the constructed NB-IoT prototype is summarized in following lines.

1) Operator of the developed device should be able to set up measurement parameters during initiation of measurement procedure such as the message period, message size, operation mode, i.e., uplink/downlink measurements, utilization of release assistance and other optional parameters using the control buttons through the text user interface on the LCD screen.
2) After initiation step, the device determines its location using the GNSS module that is connected to the STM32 MCU via Inter-Integrated Circuit (I^2C). Following positioning phase, device starts attempt of connecting to the network via communication module SARA-N211[2]. NB-IoT module is controlled by MCU using AT commands delivered via Universal Asynchronous Receiver and Transmitter (UART). After successful registration to the network, device starts transmitting using setup defined in initial phase. The procedure scheme of performed measurement is shown in Algorithm 1. For the purpose of this paper, the algorithm does not include the positioning procedure as it was not a critical parameter for our measurements related to delay-tolerant services.
3) In case of successful transmission or in case of an error, the operator is informed about the current state via implemented LED and by the LCD screen. All statistics from the measurement along with error messages either from communication module of from other peripherals of the device are being stored on SD card. Data extraction could be done via micro USB due to fact that USB is configured as mass storage device.
4) Another functionality of the micro USB port is for charging of the battery. The device is capable of fast charging mode using USB 2.0 BC1.2 protocol by a dedicated USB controller. This feature ensures supplying current up to 1.5 A to the device via compatible USB port.
5) Charging circuit can simultaneously charge the battery and provides a power supply for the rest of the circuit. Further, 5 V from USB is regulated via the buck-boost converter to 3.3 V that is utilized by all remaining components.
6) Although it is not a target of the device performance to have battery life of several years, it is important to lower power consumption as much as possible. To do so, all the currently inactive components are shut down and MCU goes to power safe modes as frequently as possible. As display is concerned it has power off timer and its backlight can be dimmed.

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[2] See "SARA-N2 series: Power-optimized NB-IoT (LTE Cat NB1) modules" by u-blox, 2019: https://www.u-blox.com/en/product/sara-n2-series

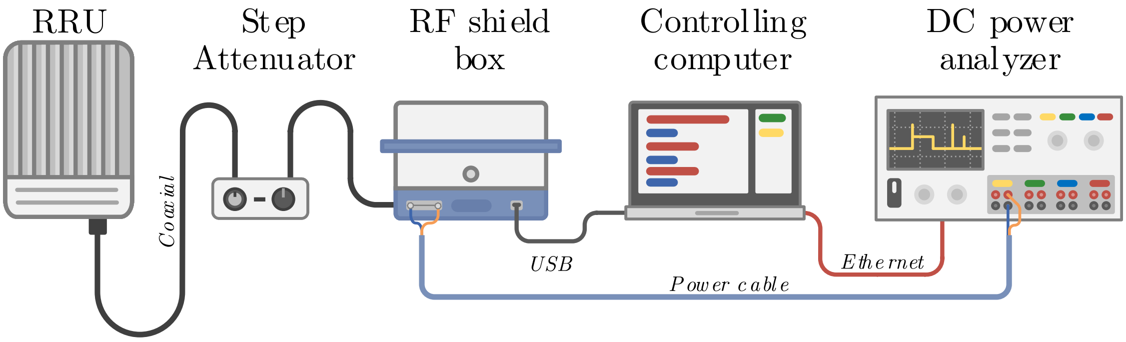

Fig. 4. Schematic of the realized laboratory test-bed.

III. MEASUREMENT METHODOLOGY

Conducted measurements comprise notably on transmission delay in an uplink direction together with signaling overheads of NB-IoT technology. Reflecting real-world application where the signal level varies significantly, five different Received Signal Strength Indicator (RSSI) values were evaluated in all Coverage Enhancement Levels (ECLs).

A. Behavior of NB-IoT Prototype

While performing the measurements, NB-IoT module can operate in following states: (i) Reboot, (ii) Attach – registration to the network, (iii) IDLE, (iv) MessageTX – transmission of message with defined length, (v) RRC Release, (vi) DRX, (vii) PSM, and (viii) TAU – tracking area update. All the states are depicted in Fig. 2.

B. Coverage Enhancements

NB-IoT is targeted to support end devices located in deep indoor environments that operate in remote areas. To fulfill these requirements, Release 13 contains a set of techniques to enable extended communication coverage[3].

Based on the signal strength received from the end device and the signal strength indicated by the end device, the Evolved Node B (eNodeB) evaluates the communication link and establishes a category for the end device. This is called ECL and stands, in a nutshell, for the number of repetitions in uplink channel.

There may be up to three levels, ranging from ECL 0 for normal operation to ECL 2 for the worst case. It is up to the network how CE levels are defined. In case of our work, scenario ECLs are defined as follows:

- ECL 0 – normal coverage with maximum coupling loss (MCL) up to 144 dB,
- ECL 1 – robust coverage with MCL up to 154 dB,
- ECL 2 – extreme coverage with MCL up to 164 dB.

C. Measurement Test-bed

Block diagram of measurement laboratory environment is shown in Fig. 4. Radio Remote Unit (RRU) enabled connection to the mobile network and was also connected to the RF shielded box. Designed prototype, described in Section II, was placed inside the shield box and was directly connected to the output of RRU via the coaxial cable. This approach was used to reduce ambient interference and to assure that testing device will be connected exclusively to the RRU in laboratory. The established scenario simulated connection and data transmission of the NB-IoT device to the network under specified and controlled coverage conditions in range of all ECLs described in Section III-B. Power to the device was provided from DC power analyzer capable of measuring consumption in time and storing data logs. Controlling of the NB-IoT device placed inside shield box via USB cable as well as controlling DC analyzer provided the computer the option to get all the data from measurements.

Demanded measured signal levels were set with step attenuator. RRU provided transmission signal power of 27 dBm and attenuator is possible to set up to achieve demanded received signal power up to signal level in range of ECL2 -125 dBm (equals to MCL 152 dB). Offset of -4 dB occurred during the measurement. That was caused by attenuation of cable and connection points.

Algorithm 1 describes the measurements methodology. During the attach phase, band 20 is set before tuning RF part on. Afterward, Access Point Name (APN) and the operator was set, and socket opened. Then it is followed by attempts of network registration. After successful registration, five messages of demanded length with flag 0x200 were sent out to the remote server.

D. Measurement Scenarios

In the first scenario, duration of network attach procedure was measured followed by measurements of message transmission delay in the uplink direction together with signaling overheads. Message size varied from 2 to 500 B and it was set in the following steps: (i) 2 B, (ii) 12 B, (iii) 100 B, (iv) 222 B, (v) 384 B and (vi) 500 B. Besides the message size, signal levels were configured for each of them as follows: -90 dBm

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[3] The improvement is estimated as $+20$ dB gain when compared to General Packet Radio Service (GPRS), corresponding to a Maximum Coupling Loss (MCL) of 164 dB.

and $-100\,\text{dBm}$ (ECL 0), $-115\,\text{dBm}$ (ECL 1), and $-125\,\text{dBm}$ (ECL 2).

All the measurements were repeated five times and then averaged as it is depicted in Table I for attach procedure, respectively in Table II for uplink transmission.

The primary purpose of measurements of the different signal level was to clarify differences in transmission delay in different ECL classes which differ in numbers of repetition and coding schemes. It is important to highlight that in each scenario, every first transmitted message has lower delay and overhead due to the fact that TAU is not present during transmission of the first message.

During the attach delay, measurements revealed that changing from ECL 0 (-70 and $-100\,\text{dBm}$) to ECL 1 ($-115\,\text{dBm}$) doubled the time needed for successful registration to the network in comparison to ELC 0. As for ELC 2 ($-125\,\text{dBm}$), there was increase of 2 s in comparison with ECL 1 as it is shown in Fig. 5 and Table I. Even though the higher ECL classes decrease the battery life drastically, on the other hand, a higher number of repetitions and robust coding scheme allow for utilization of NB-IoT in severe radio conditions without the reliability decrease.

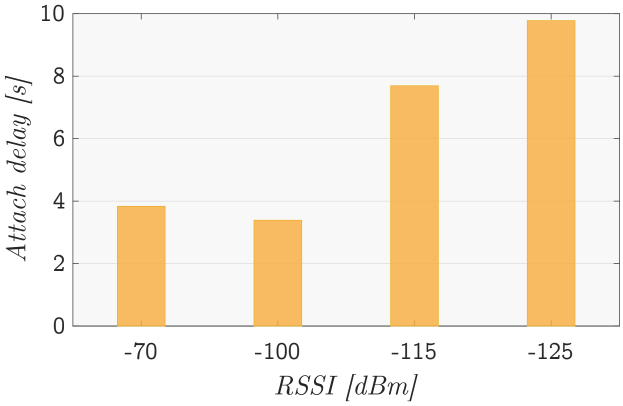

Fig. 5. Average attach procedure delay with respect to the RSSI.

TABLE I. ATTACH DELAY WITH RESPECT TO THE SIGNAL LEVEL.

Signal level [dBm]	Delay [s]
-70	3.835
-100	3.389
-115	7.694
-125	9.781

Measurements of the uplink transmission delay shown similar results for ELC 0 and ELC 1 with delay below 2 s for all message sizes and verified increase of transmission time with ELC 2 by 2 - 3 times in comparison with other ECLs as depicted in Fig. 6 and Table II. Results indicate that the delay is strongly dependent on the signal level. However, message size plays only a marginal role for signal levels in ECL 0 and ELC 1. Influence of message size started to be noticeable only in ECL 2 $-125\,\text{dBm}$, where transmission delay became dependent on payload size. First of all, it is caused by the increased number of retransmissions together with a robust modulation scheme of ECL 2 – in comparison to ELC 0 and ELC 1 as in the case of the attach procedure. Consequently, signal levels below $-120\,\text{dBm}$ resulted in increased overhead, see Fig. 7 and Table III. Dependency of the increased number of necessary retransmissions which results in increased transmission delay is shown in Fig. 6 and Table II. Results confirm that in severe radio conditions of ECL 2 (below signal level $-120\,\text{dBm}$), NB-IoT became less appropriate for delay-critical applications. On the other hand, reliable data transmission is still possible which proofs usability of NB-IoT for so-called deep indoor scenarios as well as for measurement points located at the edge of the cell.

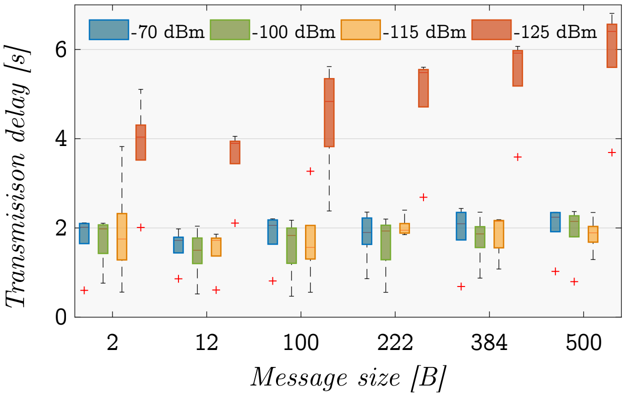

Fig. 6. Data transmission delay with respect to the RSSI level and message size.

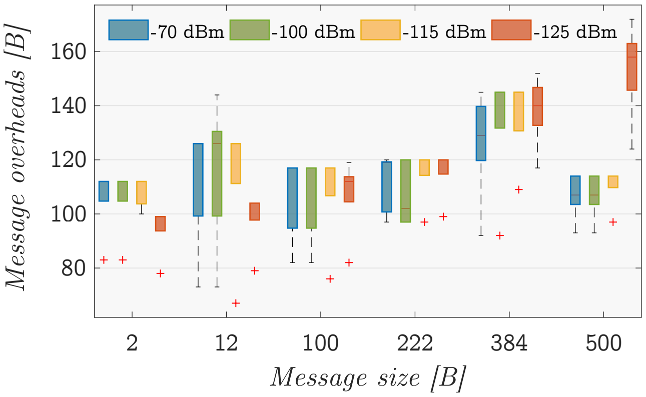

Fig. 7. Data transmission overheads with respect to the RSSI level and message size.

IV. Lessons Learned and Conclusions

In this paper, we have evaluated the performance bounds of the Narrowband IoT technology from the transmission delay perspective, which thus has allowed us to consider the possible delay-tolerant application scenarios for this communication technology adoption. Such an approach aims for facilitation to the early-adopters represented by smart meters as the key

TABLE II. DATA TRANSMISSION DELAY WITH RESPECT TO THE SIGNAL LEVEL AND MESSAGE SIZE.

	Size message [B]					
	2	12	100	222	384	500
Signal level [dBm]	Delay [s]					
-70	1.765	1.585	1.832	1.837	1.923	2.035
-100	1.711	1.436	1.574	1.647	1.761	1.938
-115	1.897	1.512	1.720	2.019	1.858	1.854
-125	3.844	3.844	4.478	4.938	5.446	5.925

TABLE III. DATA TRANSMISSION OVERHEADS WITH RESPECT TO THE SIGNAL LEVEL AND MESSAGE SIZE.

	Size message [B]					
	2	12	100	222	384	500
Signal level [dBm]	Overhead [B]					
-70	106	112	106	111	127	107
-100	106	115	106	107	134	107
-115	108	114	109	115	136	111
-125	95	99	107	116	138	153

communication parameter in case of Smart Grids is represented by the success rate followed by no packet loss.

To be able to evaluate the suitability of the NB-IoT technology for delay-tolerant services e.g., remote metering in Smart Grids, we have designed universal hand-held measuring device capable of measurements of the NB-IoT technology performance. An example where the designed prototype could find its placement is for short-term initial verification of communication capabilities in locations where the radio conditions do not allow to deploy the legacy communication technologies as they do not deliver the expected performance.

We performed measurements of the transmission delay and have shown that there is a significant increase of time required for the device to register to the network with a signal level below $-115\,\text{dBm}$, as shown in Fig. 5. What is more, a change of coding schemes and modulations for signal level lower than $-120\,\text{dBm}$ caused an increase in message transmission delay. Therefore, delay became more dependent on the message size for signal levels above $-120\,\text{dBm}$, see Fig. 6. Increased time was also supported by increased overheads as shown in Fig. 7. This situation was caused by necessary retransmissions in case of signal levels within ECL 2, i.e., for signal level $-115\,\text{dBm}$ and lower. What is important to highlight is the fact that even though the vast majority of tests was below the signal level of $-115\,\text{dBm}$, the data transmissions were successfully finished in all cases.

Following the aforementioned, the NB-IoT has proven to be competitive in terms of reliability and delay tolerance:

- Reliability – as the NB-IoT network guarantees the delivery, this turned out to be the game-changing aspect, since guaranteed delivery may indicate a significant energy cost for other LPWA technologies, e.g., LoRaWAN or Sigfox. As reliability is important for use-cases related to the smart metering area, no doubt this is a decisive fact.
- Delay tolerance – based on the information related to the reliability of NB-IoT, the price to pay for low power consumption is increased variability in case of the transmission delay. On the other hand, the obtained results, see Section III, reveal that NB-IoT still operates in scenarios with signal level significantly below $-100\,\text{dBm}$. As depicted in Fig. 6, the transmission delay in those cases increases and almost reaches the delay of 7 seconds. No doubt, this can be one of the main stoppers of NB-IoT in case of delay-intolerant applications. On the contrary, the target applications for NB-IoT cellular technology are the scenarios where the smart meters send out data several times per day or even less frequently and, therefore, the delay is not critical – the allowed delay in case of remote metering devices is in units of seconds.

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