# Hardware Design of Mobile Probe for Validating 5G-IoT Technologies

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***Abstract*—The evolution of 5G-IoT systems (5G - Internet of Things) has had a significant impact on how modern IoT devices are viewed and has opened numerous new use-cases for such technologies. As the new technologies become widely available, more IoT-technology-driven devices are being adopted in many branches of the industry and more of the bussiness subjects opt for the new IoT-enabled devices over the standard devices. For some businesses, choosing the correct technology may proove challenging as their knowledge in the particular topic may be limited.**

**In this paper we present the hardware design and initial test cases of a modular Mobile Probe for validating 5G-IoT technologies. The probe is intended to help bussinesses to make informed decisions for the particular use-case based on the autonomous measurements of various 5G-IoT technologies parameters. Due to it's simplicity the probe could also serve as an educational platform for students. After the description of the hardware design, initial testing results for NB-IoT and LTE Cat-M technologies are presented and discussed in terms of the probe capabilities and compatibility with given technologies.**

***Index Terms*—IoT, 5G, hardware design, LTE Cat-M, NB-IoT, ESP32**

## I. Introduction

As the market with IoT technologies grows, many new IoT-enabled devices and use-cases appear on the market constantly. This has steered the industry for faster adoption of the IoT revolution by incorporating such devices into their portfolio/inventory. While some businesses choose to adopt these devices on their own some are required to do so by legislation especially in the distribution industry.

In Czech Republic, a legislation that requires all new energy meters, installed from 2024, to be remotely accessible, was passed. This has left the distributors in a difficult position as some of the use-cases could not be covered by standard broadband technologies due to variety of the environment and coverage issues (metal electric distribution boxes, cellars, remote areas etc). With little to no expertise they often turned to third party evaluation to perform measurements and seek advice, effectively costing a lot of money and resources in the process for testing, as the distributor technicians have to be present on-site during the measurements.

To tackle this issue we created a modular, battery-powered testing probe for 5G-IoT technologies that helps the businesses evaluate the communication parameters for the given use-case and make an educated decision based on the measurement results. Furthermore the device saves the businesses significant amount of costs and human resources as the device can be left unattended by the technician while performing the measurement.

This paper focuses on description and validation of the hardware design of the test probe as well as validating the measurement capability by measuring the border parameters and throughput for two CIoT (Cellular IoT) technologies NB-IoT and LTE Cat-M.

The key outputs of our work can be summarized as follows:

- The testing probe is capable of succesful validation of a given CIoT technologies and is suitable for bussiness use as well as a education platform.
- The modularity of the platform ensures long usability for technologies to come (for example RedCap - Reduced Capability).

The rest of the paper is organised as follows. In Section II we give an overview of the design process of the probe. In Section III brief description of tested technologies NB-IoT and LTE Cat-M is given as well as result of the hardware testing. Finally, in Section IV, we conclude the paper.

## II. Design Process

At the start of the design several must-have requirements have been set based on our prior experience with such devices and intended technologies for testing.

**Sufficient computing power** - For this task the ESP32-S3 module from Espressif system was selected. It features a dual-core XTensa LX7 microcontroller with maximum clock rate of 240 MHz supplemented with high-speed octal SPI flash memory. Additionally, it includes integrated 2.4 GHz, 802.11 b/g/n Wi-Fi, and Bluetooth 5 (LE) for local connectivity. This module was chosen based on a sufficient number of GPIO pins, price, availability and connectivity options.

**Battery power** - To ensure the testing capability in enclosed environments the battery power was a necessity for such a tester. This task has been met by implementing a single Li+ battery with USB-C connector and appropriate charging and protection circuits.

**Local storage** - To store the results of a performed measurement or user configuration the device was equipped with a SD card interface.

**Modularity** - To allow the device to be used with various types of technologies, modular interface had to be included. The available options were Mini PCI Express (mPCIe) or M.2, formerly Next Generation Form Factor (NGFF). The first one mentioned has larger pin spacing including the dimensions of entire connector and a fixed structure of pulled out signals. In contrast, M.2 is a specification that is divided into several subgroups based on the position of the cutout, each with a different choice of buses that are pulled out and used on the connector. The connector surfaces have smaller dimensions, allowing more of the pins to fit on a connector. For this task the M.2 interface was selected.

**User accesible SIM card connector** - To allow users to swap the SIM card without dissassembling the device's enclosure a SIM card slot holder had to be mounted on the main board. This feature allows user to test the CIoT technologies with various connectivity providers.

**User Interface** - The user interface is a crucial part of the whole device design. As the device is meant for use without prior technology knowledge it has to be intuitive and user friendly.

### *A. Motherboard PCB*

This is the device's main printed circuit board. It contains an ESP32 microprocessor module, an external connector for a communication module adapter, a charging connector, integrated circuits that deliver suitable voltage levels with sufficient current capacity to the device, connectors for local, removable storage, a SIM card slot, and user interface connectors, including those for probe programming and debugging, as shown in Fig. 1.

*1) Power Section:* The device features a USB-C (Universal Serial Bus - C) connector supporting USB 2.0 data communication and power supply, including battery charging. The connector supplies USB standard signals such as VBUS, DP, DN, CC1, CC2, and GND to the board. The input supply voltage is applied to the autonomous charger MAX77751 IC (Integrated circuit) intended for 1-cell Li+ batteries. This IC has integrated USB Type-C CC detection and reverse boost compatibility. It also offers fast-charge current selection and top-off current threshold setting using externally connected resistors. The IC implements the Adaptive Input Current Limit (AICL) function to limit the maximum input current and regulate the input voltage to prevent the supply voltage from collapsing due to a possible soft source. The device features a Smart Power Selector and a battery true-disconnect FET (Field Effect Transistor) to regulate charging and discharging or isolate it in case of a failure [1].

To ensure data communication with the ESP32, a USB DPDT switch is included in the design. The ESP32 controls and switches the switch after the initial setting of the maximum possible charging currents that the adapter can deliver. The LiPol battery selected for the probe serves as the power source

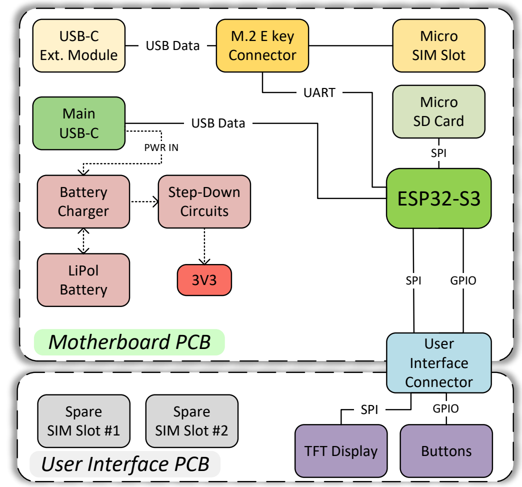


Fig. 1. Block diagram describing device composition.

in regular mobile operation. The step-down converter is used to reduce the voltage to the required supply level of 3.3 V. Two converters from Renesas, the ISL9120IR and ISL91107IR, are connected in parallel, and their connection to the circuit can be selectively changed using resistors with zero resistivity. Both chips require few external components and have a wide input voltage range of 1.8V to 5.5V and a conversion efficiency of at least 85%. The weaker IC can deliver a maximum output current of 0.8A, while the stronger IC can deliver up to 2A [2], [3]. This parallel connection serves for future current draw testing.

The resulting 3.3V voltage level powers all peripherals, including the Low Drop-Out (LDO) 1.8V voltage regulator MCP1802T, which can supply up to 300mA. The power rails are equipped with sufficient filter capacitors, including a TVS diode PESD3V3L1BA,115, and LED signaling of the present voltage [4].

*2) Expansion boards:* The M.2 connector is utilized for expansion boards of various communication module adapters. The connection of this connector partially adheres to the reference design presented in the congatec document. The E-key version is used, meaning pins numbered 24 to 31 are omitted. This text describes multiple deviations from the congatec reference specification. As a result, the connection falls under the category of proprietary applications of the M.2 E-key connector [5].

The connector incorporates multiple interfaces, including I2C, SPI, UART, USIM, and USB, along with various generic signals. The USIM interface signals are safeguarded by TVS diodes against overvoltage conditions and connected to the push-push type housing for Micro SIM cards. In the initial version of the probe, the USB data are used for control and FW local update of used comm. module is connected to the secondary debug USB-C connector, which may not be included in future versions. The Texas Instrument's TXB0102DCUR chip is adopted as a level-shifting IC, fully satisfying the requirements for possible NB-IoT and Cat-M modules. Future prototypes may employ the TSX0108E IC, which can provide up to eight possible level-shifting signals for I2C, SPI, and UART in addition to the existing architecture.

*3) Local Storage:* The micro SD, figuring as local storage, card was connected using a Molex 47352-1001 connector with a PUSH-PUSH type mechanism, utilizing the SPI bus. All signals are equipped with 10k Ohm pull-up resistors and are safeguarded by a TVS diode array, specifically the SP0503BAHTG model, which incorporates three protective diodes in its body.

*4) Placement of components on the PCB:* A preview of the component layout on the probe's motherboard is shown in Figure 2. Here you can see two USB-C connectors, a USB switch, a circuit ensuring charging with voltage transmission from the battery to two step-down converters connected in parallel and a 1.8V voltage source. In addition, we can find a slot for a Micro SIM card with the necessary ESD protection, a Micro SD card, the necessary header connectors, an M.2 slot for expansion adapter boards and an ESP32 process module.

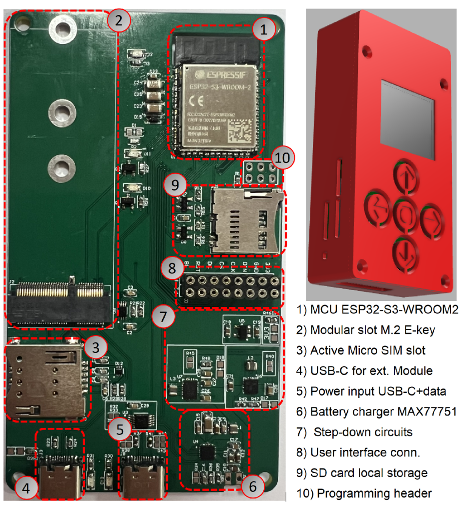


Fig. 2. Motherboard PCB in Altium with 3D render.

## B. User Interface PCB

The second board is used to complete the device. It contains a mechanically fixed color TFT (Thin Film Transistor) display, a group of control buttons, and a connector for connection to the lower baseboard. Additionally, there is space on the bottom of this board for soldering two other unconnected slots, which can be used for local storage of additional micro SIM cards for possible connection to the networks of other potential operators. The probe device has a total of three slots for SIM cards, allowing for testing of major domestic operators such as Vodafone, T-Mobile, and O2 in the Czech Republic. Each button connected to the connector in its closed state acts as a 100 k$\Omega$ to 10 k$\Omega$ voltage divider connection, i.e., a 10:1 conversion ratio. The signal itself is equipped with a TVS diode to protect against possible accidental transients that could, for example, cause faulty actuation.

# III. Measurement Capability Testing

To evaluate the devices testing capability for various technologies we have opted for the M2 key add-on board with LPWA (Low Power Wide Area) module Quectel BG77.

BG77 is a dual RAT (Radio Access Technology) modem enabling connectivity via two CIoT technologies LTE Cat-NB (Narrowband IoT) and LTE Cat-M. NB-IoT and LTE Cat-M are a part of the 5G-ecosystem technologies for IoT applications and their utilization has been on the rise in the Czech Republic due to the growing demand for IoT connectivity and legislative requirements especially in the smart metering field.

## A. NB-IoT and LTE Cat-M

Both technologies, described as a part of 3GPP Release 13, are derived from the existing LTE standard which ensures the interoperability with the existing public mobile network infrastructure and easy deployment for the mobile network operators. To better suit the IoT applications and to enable massive deployment, on the scale of millions, while keeping the cost-per-modem low, both technologies significantly reduce the hardware complexity (up to 80%), feature capability (such as MIMO) and also system bandwidth to achieve better coverage, enabling the connectivity for broader spectrum of devices. The LTE Cat-M1 technology reduces the system bandwidth to 1.4 MHz[1] and 5 MHz[2] respectively, while the NB-IoT reduces it even further down to 200 kHz (180+20 kHz). This results in a significant reduction of throughput for both technologies as the maximum theoretical throughput for LTE Cat-M1 is up to 1 Mbps and up to 3 Mbps for the Release 14 LTE Cat-M2, while the Release 13 NB-IoT achieves up to 62.5 kbps and up to 159 kbps in Release 14 respectively [6].

As both technologies are focused on IoT battery powered devices with goal of achieving 10+ years of battery life, they both implement standard power saving features such as PSM (Power Saving Mode) and eDRX (extended Discontinuous Reception) which, in addition with the reduced hardware complexity and reduced capability, help to reduce the power consumption of the technology-enabled devices [6].

To achieve better coverage both technologies implement Coverage Enhancement (CE) which modifies the radio parameters such as used modulation, number of repetitions or TX power to achieve more robust transmission in harsh radio conditions. The Coverage Enhancement level is assigned to the device by the operator's network and is based on well defined thresholds, based on the measured values of RSRP (Reference Signal Received Power) and SINR (Signal to Interference Ratio). The set threshold can vary from operator to operator as the operator is able to set these thresholds as required to ensure the best network performance. The NB-IoT features three Coverage Enhancement levels also known as ECL (Enhanced Coverage Level) classes 0,1 and 2 while the LTE Cat-M features Coverage Enhancement Modes A and B [6].

[1] 3GPP Release 13
[2] 3GPP Release 14

TABLE I
COMPARISON OF THE CIOT TECHNOLOGIES DEFINED IN 3GPP RELEASES 13 AND 14

| Technology | NB-IoT (NB1) | NB-IoT (NB2) | LTE Cat M1 | LTE Cat M2 |
|---|---|---|---|---|
| **3GPP** | Release 13 | Release 14 | Release 13 | Release 14 |
| **Frequency** | 700-2100 MHz | | | |
| **Bandwidth** | 200 kHz | | 1.4 MHz | 5 MHz |
| **Link budget** | 164 dB | | 155.7 dB | |
| **Max. EIRP** | 23 dBm | | | |
| **Max. payload** | 1600 B | | 8188 B | |
| **UL data rate** | 0.3-62.5 Kbps | 0.3-159 Kbps | HD: 375 Kbps; FD: 1 Mbps | HD: 2.625 Kbps; FD: 7 Mbps |
| **DL data rate** | 0.5-27.2 Kbps | 0.5-127 Kbps | HD: 300 Kbps; FD: 0.8 Mbps | HD: 2.35 Mbps; FD: 4 Mbps |
| **Consumption** | Tx: 240 mA Rx: 12 mA PSM: $<$1uA | Tx: 240 mA Rx: 46 mA PSM: $<$3uA | Tx: 360 mA Rx: 46 mA PSM: $<$3uA | Tx: 360 mA Rx: 70 mA PSM: $<$8uA |
| **Security** | LTE security | | | |

## B. Testing Scenarios

The tester was placed in a RF shield box R&S CMW-Z10 and connected through a step attenuator directly to the local commercial RRU (Remote Radio Head) via coaxial cable (Figure 3). This setup enabled us to directly control the RSRP (Reference Symbol Received Power) and SINR (Signal-to-Interference-plus-Noise Ratio) values read by the module. The local RRU is a production RRU of the Vodafone Czech Republic operator therefore any results measured on our testbed should directly match the results and parameters of a public network.

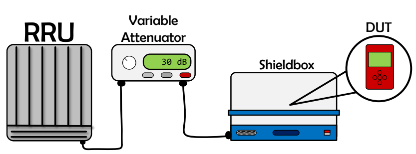


Fig. 3. Measurement testbed.

For the evaluation, several tests were performed for both technologies available (NB-IoT and LTE Cat-M) to test the probe's capability of testing the technologies to their full extent. As the design is targeted for the technology evaluation, validation and user testing, the test scenarios were selected to fit the scheme. The selected tests include:

- Border communication parameters measurement.
- Throughput measurement.

## C. Border communication parameters measurement

This test was designed to evaluate the HW testing capabilities in terms of the border radio parameters for a given technology.

*1) Measurement Scenario:* For this measurement we utilized the variable attenuator to lower the value of RSRP read by the device. In each iteration, we attempted a registration to the network and evaluated whether the registration was succesful. For each iteration we also performed a basic data exchange utilizing the *ping* feature and monitored the CE level for each step. During the tests, all modem$<->$MCU communication was logged and saved onto the SD card and later evaluated.

*2) Measurement Results:* From the measurement the NB-IoT technology was able to perform a succesful registration to the network at the threshold of **-129 dBm RSRP**. After the -129 dBm threshold, we were not able to succesfuly register to the network. However, after already being registered to the network the device was able to successfuly exchange data for down to *-132 dBm RSRP*. For the CE Level, we have reached the **ECL 0** at **-111 dBm RSRP** and **ECL 2** at **-127 dBm RSRP** due to the SINR exceeding the threshold value of -3 dB.

For LTE Cat-M, here the technology was able to succesfuly register to the network for down to **-127 dBm RSRP** with the last data exchange being measured at **-129 dBm RSRP**.

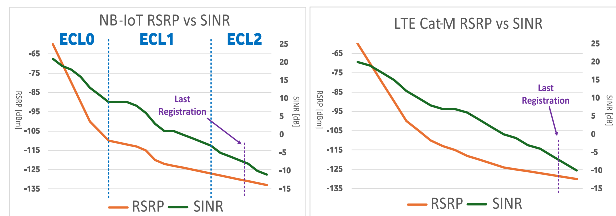


Fig. 4. NB-IoT and LTE Cat-M1 measured sensitivity.

## D. Throughput measurement

The goal of this measurement was to evaluate the design of the communication lines, in other words, whether the device is capable of saturating the communication interface and fully exploit the limits of the given technology. This measurement also allowed us to verify the technology's limits as seen in table I.

*1) Measurement Scenario:* For testing throughput, PPPoS (Point to Point over Serial) connection was estabilished to the BG77 module. We utilized the *iperf* application, in UDP mode and uplink direction, which is available for the ESP32 via the its development framework. We started our measurement at -60 dBm RSRP and using the variable attenuator we lowered the RSRP value in granular steps based on the current RSRP measured by the module. In each iteration we ran the *iperf* and saved the results on a SD card.

*2) Throughput measurement results:* After the measurements we removed the SD card from the device and evaluated the results saved on the SD card.

For the LTE Cat-M technology the throughput of maximum of **1003 kbps** was achieved. This is the maximum throughput the LTE Cat-M technology can achieve as seen in table I. From this result we can conclude that the communication interface is designed correctly as it is able to saturate the technology communication channel. The LTE Cat-M maintains stable maximum throughput up to -104 dBm RSRP where the sudden decline can be seen in figure 5. The decline appears to be linear with the average decline of 52 kbps per dB of RSRP. In comparison to the Border limits measurement we were not

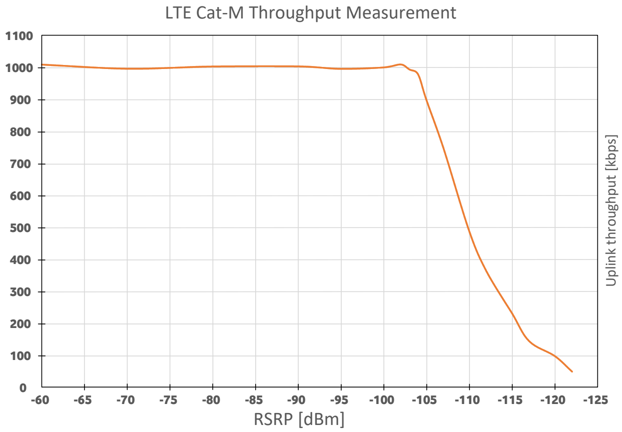


Fig. 5. LTE Cat-M1 measured throughput.

able to achieve any data throughput beyond the -122 dBm of RSRP which is probably due to the *iperf* application not being able to estabilish a connection due to harsh conditions and heavy packet loss.

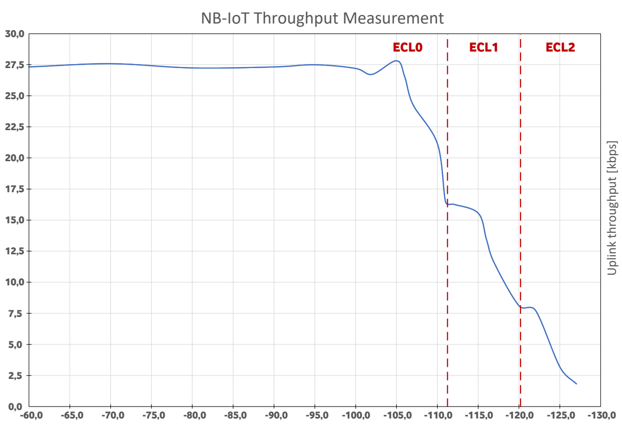


Fig. 6. NB-IoT measured throughput.

For the NB-IoT case, the throughput was stable for up to **-107 dBm** RSRP until the data throughput decline can be seen as in comparison with the LTE Cat-M. The maximum achieved throughput was measured as **28 kbps** which does not match the comparison in table I, however we believe the value to be correct for the given setup and to be the result of network limitations as the tester was able to saturate the LTE Cat-M technology at 1 Mbps without further issues. These results also **correlate with our previous measurements** of the NB-IoT technology.

For the NB-IoT data rate decline, two ”step-like” deviations from the linear decline pattern can be seen in Fig. 6 as the throughput declines. These deviations are due to changes of the ECL class from 0 to 1 and from 1 to 2 respectively, which significantly improved the channel realiability for the given RSRP value.

Here, as well as with the LTE Cat-M we were not able to get any throughput beyond -128 dBm due to *iperf* issues.

## IV. Conclusion

With the growing demand for IoT technologies in Czech Republic in mind, especially in the smart metering field, the target was set to create a battery-powered probe that can be used directly by the distributor or other subjects, without third-party contractor involvement, to evaluate the technology for the specific use-case, effectively saving costs and human resources required for such validation.

In this paper, the Hardware design of the Mobile Probe for validating 5G-IoT Technologies was presented as well as tests performed to validate the correct functionality of the device.

The probe was designed as a modular device platform, enabling the user to test and validate different technologies or module manufacturers which is achieved via the M.2 E-key interface where the external add-ons can be mounted.

For the hardware evaluation the BG77 M.2 E-Key add-on board was selected. During the evaluation, various aspects of the hardware design were tested (such as USB and UART speed, SIM card slot, sufficient SD card interface speed for logging) as well as the basic comparison for two uprising CIoT technologies NB-IoT and LTE Cat-M was presented.

While the LTE Cat-M technology is capable of reaching speeds up to 1003 kbps the NB-IoT is able to provide more coverage especially in environments with bad radio conditions (RSRP $<$ -125 dBm).

From the initial testing, we conclude that the probe design is sufficient for testing 5G-IoT technologies as the capabilities and limits of both technologies could be achieved with the design. This leads to the conclusion that the **device's capabilities are suitable for use by companies as a verification device** or as an education tool for students.

### A. Future Work

In the future work we will focus on developing the software for validating different aspects of both technologies and higher layer protocols to further demonstrate the technology limits and features to the user of the probe.

The future development includes:

- Software for autonomous testing of various technology aspects and features (throughput, PSM, eDRX, Packet loss and more).
- Sufficient User Interface for the tester.
- Layer 4 and Layer 7 protocols testing features. (TCP, UDP, MQTT, CoAP and more).

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