Pitfalls of LPWA Power Consumption: Hands-On Design of Current Probe

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***Abstract*—The unique opportunities introduced by the emerging Industrial Internet of Things (IIoT) applications have accelerated the momentum of the massive Machine-Type Communications (mMTC) worldwide. As the number of already deployed Low-Power Wide-Area (LPWA) applications growth exponentially over the last decade, new open challenges started to be discussed across the industry sector. The most critical parameter of the LWPA devices in question is energy efficiency and the overall power consumption of designed end-devices. Therefore, the need for precise measurement of power consumption has attracted engineers' attention as the unique communication parameters of the LPWA devices form the current consumption measurements challenging task. To facilitate accurate current measurements ranging between hundreds of nA and hundreds of μA, we propose a unique design of the current probe prototype. We then demonstrate the obtained results concerning the accuracy, measurement range switching, and sufficient sampling speed. All the measurements from the designed prototype are further compared with the industry-grade DC power analyzer Agilent N6705B.**

***Index Terms*—LPWA, Power consumption, Shunt method, Measurements, Current probe, Narrowband IoT**

I. INTRODUCTION

The tremendous growth of the Internet of Things (IoT) profoundly influences the way how the Machine-to-Machine (M2M) data is going to be transferred over heterogeneous communication networks [1]. As the communication technologies for IoT-driven scenarios have matured over the last decade, the newly deployed end-devices, i.e., sensors, actuators or actors stand for the entirely new group of devices. With green IoT, energy-efficient sensing, and communication capabilities, that are the parameters defining the usability in real-world scenarios, the demand for precise measurements of the power consumption is already rising [2], [3]. As energy-constrained IoT devices are periodically required to be plugged into the power socket for battery recharge as well as their built-in batteries replacement introduces high costs and could be even hazardous, the attention is given to the fine design of the IoT devices with respect to the optimized power consumption [4].

This paper discusses the current measurement challenges for Low-Power Wide-Area (LPWA) technologies that operate in different modes aiming to improve the lifetime of battery-powered IoT devices with a specific focus on Narrow Band Internet of Things (NB-IoT) technology [5], i.e., the licensed cellular IoT representative for massive Machine-Type Communication (mMTC) [6]. To this aim, we start by over-viewing the approaches on how to measure the current consumption. Then, we carry out an extensive description of the developed current probe prototype. Finally, we measure and verify the developed probe's accuracy for the selected wave-forms (square, sinus, and ramp) at predefined frequencies using the constructed current probe.

The key findings of the paper are:

- The gathered results have shown the prototype to perform the current sensing comparable with a well-proven design. Measurement of NB-IoT module (Quectel BC68) current flow and comparison with results from DC power analyzer Agilent N6705B have proven that the presented prototype is sufficient for the current sensing in LPWA technologies.
- Based on the conducted measurements, the presented design causes occasional instability of sensing circuitry. Therefore, better filtration circuits and techniques preventing OpAmp saturations must be implemented. Another more marginal limit of the presented device is range switching speed and overall processing speed.

The rest of the paper is organized as follows. We first provide an overview of the current measurement challenges for LPWA devices in the Section II. The constructed prototype of current probe is then described in Section III. In Section IV, the initial verification of the prototype is done using a variable load test circuit. Further, comparative results of the designed prototype and DC power analyzer Agilent N6705B are presented for the NB-IoT module Quectel BC68. Finally, the conclusions are drawn in the Section V.

II. LPWA CURRENT MEASUREMENT CHALLENGES

The noticeable differences in power consumption of LPWA technologies in disparate operational states make the measurement a challenging task. Most of the time, the LPWA devices spend in power-saving modes with power consumption in the order of units of μA. On the other hand, current consumption peaks can reach hundreds of mA during data transmission. These different phases, together with the fast transition between them (i.e., in case of NB-IoT), make accurate current sensing difficult [7], [8].

NB-IoT is an excellent example demonstrating all pitfalls of LPWA power consumption measurements. Its power consumption in Power Save Mode (PSM) reaches only $4\,\mu$A.

However, when the Radio Resource Control (RRC) connection is active, the current increases up to 50 mA. In the case of active communication with eNodeB, the current peaks may reach hundreds of mA (the consumption among different NB-IoT modules slightly varies). The transition period between these modes is in order of units of ms. Therefore, measuring equipment must be capable of sensing such current levels and simultaneously providing quick range switching, sufficient sampling speed, and built-in/remote data storage [7], [8].

A. Measurement Methods

In general, there are numerous ways how to measure current depending on various factors such as the amount of flowing current, demands for precision, a requirement for the measuring device galvanic isolation, etc. The current sensing mechanisms can be divided into two groups (i) the indirect method and (ii) direct method [9]–[11].

The indirect method utilizes galvanic isolation from the measured circuit. This approach's usability is mainly suitable for large alternating current (AC) [9]–[11]. Therefore, this method is not suitable for LPWA power consumption measurement [7], [8].

The direct method is usable even for low current values in the order of μA, which is present during the sleep mode of LPWA devices. This method can be used for both AC and direct current (DC) measurement and provides a higher precision than the indirect method. Commonly utilized direct methods are with the shunt resistor and current to voltage conversion [9]–[11].

The shunt method utilizes a precise resistor with small value in series with a load connected either close to the voltage supply (high-side) or behind load close to the ground (low-side) [12]. According to Ohm's law, the current derived from the voltage drop measured on the shunt resistor is directly proportional to the passing current. The voltage drop is usually in the range of mV. Therefore, to convert it to a digital value for subsequent processing, the voltage must be amplified via a low noise amplifier. Shunts with different values need to be used for various current ranges; thus, shunt switching circuitry is necessary for automatic range selection. The main benefit of this method is relatively easy implementation [9]–[11].

The current to voltage conversion method has significantly lower noise compared to the shunt resistor. One way of implementation is with a resistor connected in the negative feedback loop of an operational amplifier (OpAmp). The input current goes through the feedback resistor. As the OpAmp input impedance is significantly higher, the quiescent current on an input pin does not influence the resulting current. Quiescent current is, in an ideal case, directly proportional to the input current. The feedback resistor controls precision, amplification, and sensitivity with high-value accuracy and low-temperature coefficient requirements. This approach benefits from a low voltage drop (almost none) compared to the shunt method and provides fast stabilization time. The downside is its dependency on the quiescent current of OpAmp input pins and their (a)symmetry [9]–[11].

III. PROTOTYPE OF LPWA POWER CONSUMPTION MEASUREMENT DEVICE

The developed prototype, depicted in Fig. 1, was designed to meet the requirements for the current measurement of LPWA devices described above, i.e., wide measuring range, sufficient sampling period. The prototype allows us to measure electric current ranging between hundreds of nA up to hundreds of mA for voltages up to 5 V. The range switching, sampling speed, and utilized storage provides sufficient performance to collect data implementation 100 μs. The measurement circuits use the current sensing method with a shunt resistor. The voltage drop across the shunt resistor is then amplified and converted to digital form for successive processing.

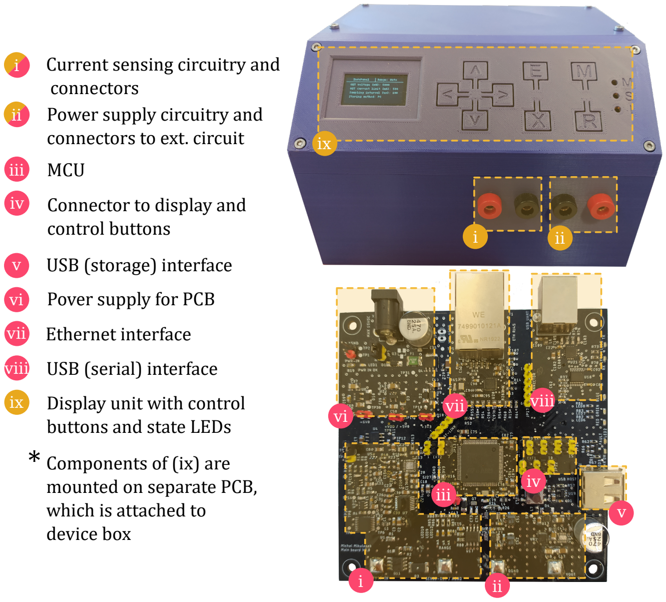

Fig. 1: Designed current probe prototype with description of main device parts.

The current sensing circuit was inspired by verified solution μCurrent GOLD[1]. Therefore the shunt method was selected out of the methods described in Section II for the first revision of the constructed prototype due to its simple implementation and optimization. To meet the requirements for the current range, three shunts (three ranges) were selected: nA (10 kΩ resistor), μA (10 Ω resistor), and mA(10 mΩ resistor). Resistors were selected in accordance with the need for precise value and low-temperature coefficient (max 10 ppm/°C).

As it was already mentioned, the ranges must have the ability of fast autonomous switching. For this application, switching with relays is not possible. Therefore, N-channel Metal Oxide Semiconductor Field Effect Transistors (MOSFETs) with low impedance, low leakage currents, and ability to be switched by 3.3 V or 5 V logic were selected to fulfill the speed requirement. Only the nA range shunt is connected permanently. This approach brings several benefits. If the

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[1] See information about μCurrent GOLD here: https://www.eevblog.com/projects/ucurrent/.

device is powered off, sensing connectors are still attached, and transistors do not influence the nA range accuracy. The nA shunt affects other ranges but within tolerable range (nA shunt behaves as a relatively high impedance connection).

Nevertheless, the impedance of a mA range transistor is not within tolerable limits. The selected transistor adds 9 mΩ of impedance, which almost doubles the overall impedance of the mA range. Due to this fact, the chosen mA range shunt is housed in a package designed for current sensing providing the lowest measurement error possible. The shunt resistors' signal traces continue to the 4-input analog switch, which connects the appropriate inputs to the amplifier. This component possesses only minimal leakage current and extremely low impedance. Three inputs of the switch are connected to the shunt resistors, and the forth is routed to the ground. The grounded pin can be utilized for offset calibration purposes.

The maximum allowed voltage drop on each shunt is 50 mA. When this value is reached, the system selects the higher current range. To utilize the full voltage range of the subsequent analog to digital converter (ADC), the OpAmp amplifies the voltage drop on the shunt resistor. The designed prototype contains two OpAmps in series with an amplification factor (gain) of 10. The OpAmps are low noise chopper types with very low voltage drifts and almost zero DC offset. Both OpAmps were selected due to their excellent DC characteristics and short saturation recovery times (less than $10\,\mu$s), preventing circuit instability.

Selected ADC is an 18-bit successive approximation (SAR) converter with the sampling rate of up to 1 MSps. The voltage reference is ensured by an external integrated circuit (IC), and both ADC inputs are protected by low-pass filters to prevent any undesirable noise. The ARM Cortex-M7 STM class F7 microcontroller (MCU) serves as the central computation unit. This MCU family provides sufficient computational power as well as various communication buses, including USB, Ethernet, and SD card interface.

The designed prototype is equipped with a USB interface allowing communication speed of up to 3 MBauds. This data rate is sufficient for both device control and real-time export of measured values. The USB is protected by galvanic separation IC to prevent any external interference, which can harm the device. The device also supports control and data export via a Fast Ethernet interface and enables data storage to external USB FLASH drive or SD card.

The device can also be controlled manually through the buttons on the prototype body. All the information to the user is delivered via built-in display or status LEDs.

The prototype features the option of output power supply for external circuits where it meets expectations for LPWA devices, which are voltage range between 2.5 V and 5 V, and current up to 500 mA. As a low noise option, the prototype is equipped with linear low-dropout regulators (LDOs), ensuring external power supply for connected devices. The output current and voltage are set via electrically configurable potentiometers.

The power to the developed prototype can be delivered in two ways. The first option is an external power adapter connected via a barrel jack with the output voltage ranging between 7.5 and 12 V, and the current limit of at least 1 A. The next option is to use mains voltage (80 – 264 VAC) connected to the power supply integrated inside the developed prototype. The power is distributed across the prototype by multiple 3.3 V and 5 V power rails. The device contains several LDOs to reduce the ambient noise transferred to the analog parts of the prototype.

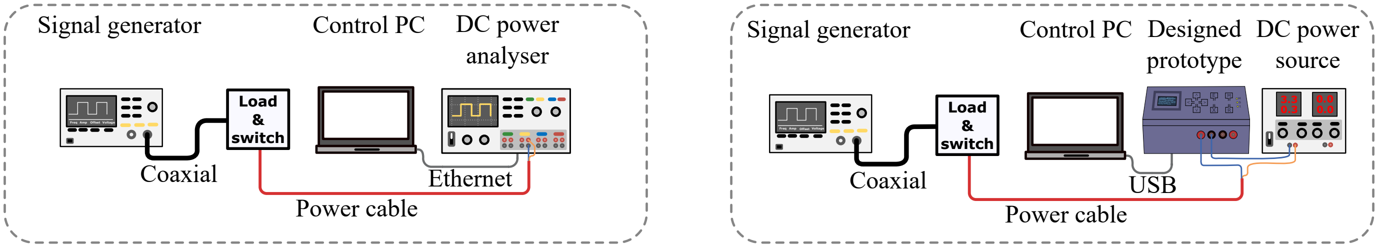
TABLE I: Comparable parameters of reference DC power analyzer and prototype current probe.

Parameter	DC analyzer Agilent N6705B	Current probe prototype
Input voltage [V]	0 – 20	0 – 5
Max. sensing current [A]	8	0.5
Sampling rate up to [us]	10.24	100
Control interfaces	USB 2.0, Ethernet	USB 2.0 (serial), Ethernet
Storage options	USB FLASH drive, int. storage	SD card, USB flash drive

To be able to verify prototypes functionality, the well-proven Agilent N6705B DC Power Analyzer was chosen as a reference for later comparison. As for the functionalities of both devices' concerns (summarized in Table I), it is evident that N6705B has a better performance. However, N6705B is a multifunctional device providing additional features like graphical representation of results, the ability to add extra modules, the ability to use arbitrary waveforms modulating outputs, etc. However, named features are not necessary and theoretical performance is more than enough for LPWA power consumption analysis for the intended use-case. On the other side, what is more important, the price of N6705B is ranging around 6000 € while the-open source prototype could be priced up to 10× lower with possible do it yourself (DIY) HW and SW improvements.

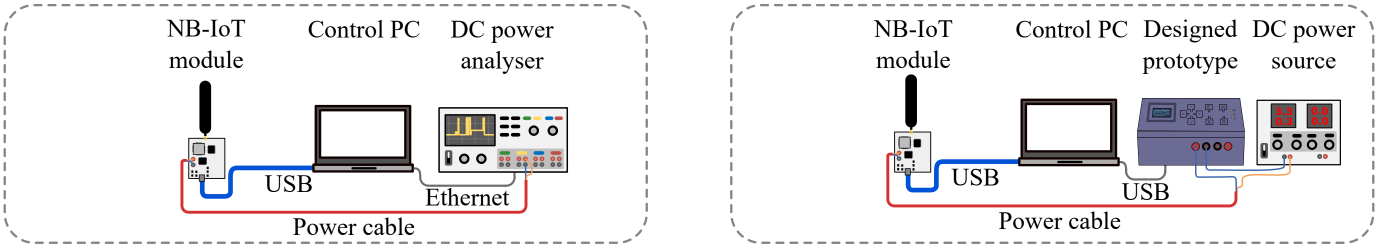
IV. MEASUREMENT SCENARIOS

The prototype's functionality was initially verified on a variable load test circuit consisting of a resistor and N-channel MOSFET in series. With the fully opened transistor, the resistor limits the current to 200 mA. The transistor was controlled by the external function generator, as depicted in Figs. 2a and 2b. The developed prototype was tested with three different waveforms (i) square, (ii) sinus, and (iii) ramp at frequencies: 10 Hz, 50 Hz, and 100 Hz. Chosen waveforms should verify whether the developed prototype provides sufficient accuracy and range switching. The 100 Hz frequency is set as the upper boundary of the system since it outmatches the transitions periods observed at NB-IoT current flow waveforms [7], [8]. As a reference value, we first conducted the measurements with a well-proven DC analyzer Agilent N6705B (see Fig. 2a) and subsequently with a designed prototype so the prototype's results can be verified with of the shelf solution. Comparative results from both devices are shown in Figs. 3 – 5. It is important to mention



(a) Verification measurement with reference DC power analyzer.

(b) Verification measurement with prototype current probe.



(c) NB-IoT power consumption measurement with reference DC power analyzer.

(d) NB-IoT power consumption measurement with prototype current probe.

Fig. 2: Schematics of the implemented laboratory test-bed.

that the resulting current curves correspond to the non-linear characteristic of N-channel MOSFET.

Closer analysis of the measurement results reveals the occasional overshoots during the range switch from μA to mA when the current consumption sharply rises. The overshoots are more apparent in cases of sinus and ramp waveforms. Moreover, even if the overshoot was not present, the developed prototype indicates more unwanted noise compared to Agilent N6705B. This behavior suggests that the prototype's switching, sampling, and processing speed has its limits, which are not-negligible (see compared results for sinus and ramp waveforms in Table II) but acceptable for intended use-cases of current measurement of LPWA devices. However, more severe overshoots occurred to a greater extent in the case of squared waveforms in the curve's plateau. Such behavior indicates that the circuit started to resonate due to higher harmonic signals in the square waveform. This oscillation further saturates the OpAmps, which leads to distorted results in the affected area. Also, the oscillation lingering can be seen from the results. These fluctuations are present for all measured frequencies.

Comparative results of the designed prototype and Agilent N6705B directly in numbers are described in Table II containing the mean absolute error (MAE) and root mean squared error (RMSE) of obtained results. The most significant deviation of results is present at the squared waveform case due to the number of overshoots described above. Besides that, the pattern applies for all waveforms and shows that with higher frequencies, the deviation increases but is still in acceptable limits. Thus the designed prototype is suitable for intended use-cases of current sensing but has its limitations that need to be considered.

After initial verification with predefined waveforms, the prototype was tested with a real LPWA communication module.

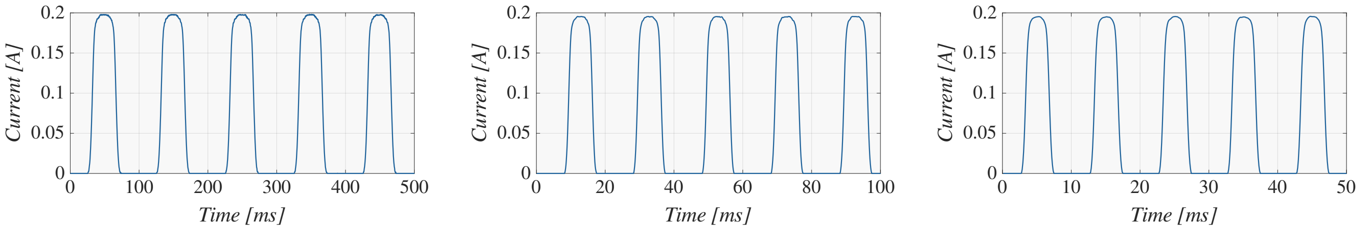
TABLE II: Accuracy of measured values.

Waveform	**Frequency [Hz]**	**MAE**	**RMSE**
Sinus	10	0.0135	0.0329
	50	0.0651	0.1218
	100	0.0995	0.1835
Square	10	0.0155	0.0585
	50	0.0773	0.4699
	100	0.1415	0.7099
Ramp	10	0.0135	0.0582
	50	0.0629	0.1307
	100	0.0781	0.1612

We selected NB-IoT technology for this purpose as it poses all the pitfalls of LPWA current consumption measurement. For this purpose, the switched load was replaced with an NB-IoT device fitted with module Quectel BC68 offering the communication over LTE Cat-NB1 as depicted in Fig. 2c and 2d. The same measurements were also conducted with Agilent N6705B providing the reference results.

As shown in Fig. 6, the measured results from both devices are almost identical. The small differences are caused by NB-IoT power consumption's dynamic characteristic caused by radio signal fluctuations, network synchronization, and random channel access procedure. During measurement, the radio conditions allowed the module to operate in extended coverage level (ELC) 0, which suggests excellent radio conditions [13]. These conditions are ideal for prototype testing because, in such good radio conditions, the less robust modulation and coding schemes are utilized, which leads to shorter current peaks that are harder to detect.

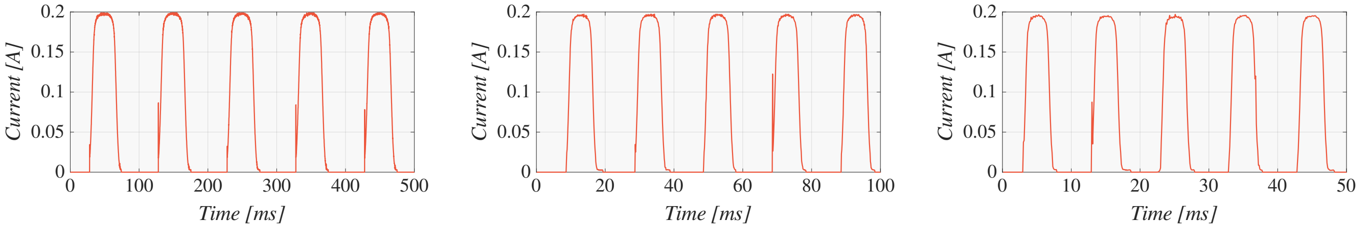
During the performed measurement, the device was firstly rebooted. When the machine started, the communication parameters were set, and the module registered to the network.



(a) DC analyzer, $f = 10\,Hz$

(b) DC analyzer, $f = 50\,Hz$

(c) DC analyzer, $f = 100\,Hz$

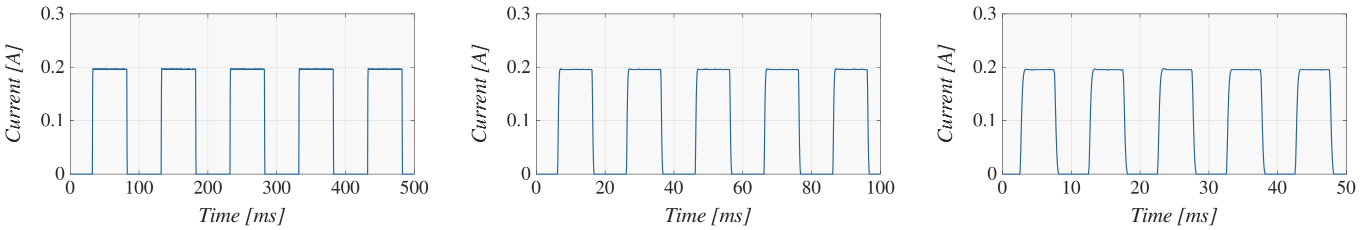


(d) Prototype, $f = 10\,Hz$

(e) Prototype, $f = 50\,Hz$

(f) Prototype, $f = 100\,Hz$

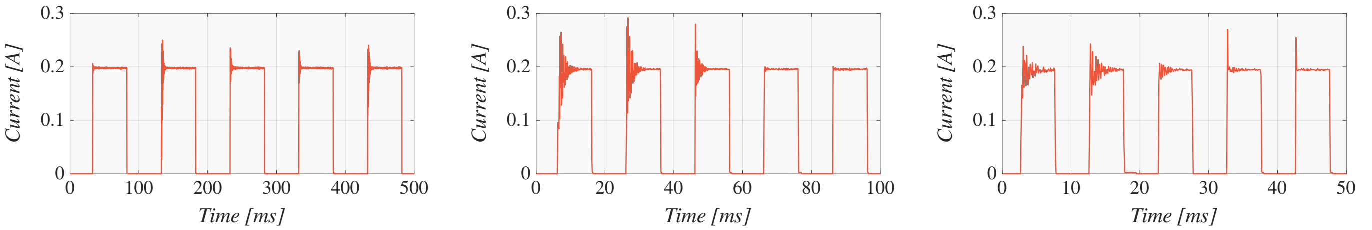
Fig. 3: Measured sinus waveforms.



(a) DC analyzer, $f = 10\,Hz$

(b) DC analyzer, $f = 50\,Hz$

(c) DC analyzer, $f = 100\,Hz$



(d) Prototype, $f = 10\,Hz$

(e) Prototype, $f = 50\,Hz$

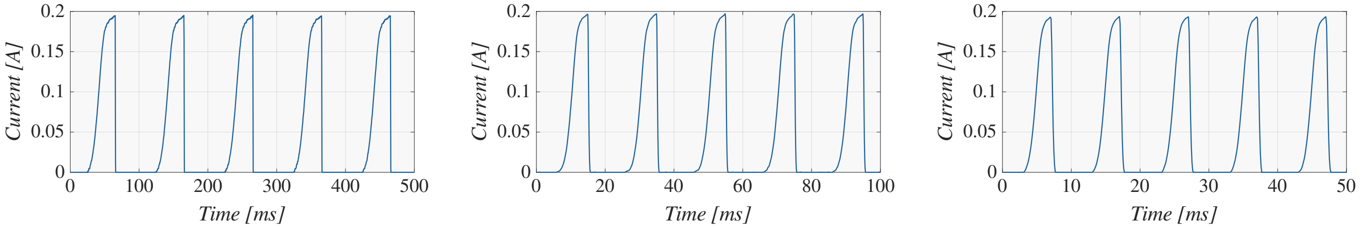
(f) Prototype, $f = 100\,Hz$

Fig. 4: Measured square waveforms.

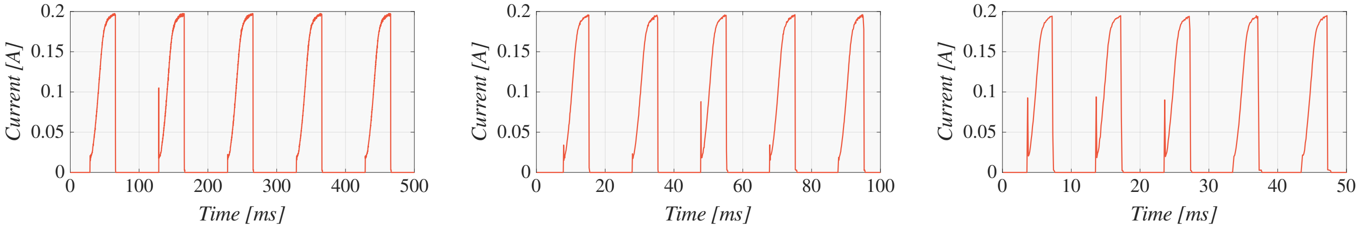
At this point, there are apparent frequent rises of current from units to hundreds of mA. This increase is caused by active radio communication.The same growth is noticeable after successful registration to the mobile network where a 500 B message utilizing user datagram protocol (UDP) was transmitted. The UDP was selected as sufficient for current measurement purposes. Other protocols with acknowledgments (i.e. transmission control protocol (TCP), message queuing telemetry transport (MQTT)) would bring current peaks with even less deterministic distribution than UDP, and the performance comparison of the developed prototype and Agilent N6705B would be more difficult. After successful message transmission, 20 s idle state (active RRC connection) occurred, followed by RRC release at the end. The designed prototype successfully and precisely sense all the current changes and performed almost identically as Agilent N6705B. Thus the measurements proved the prototype as a suitable solution for current consumption measurements of LPWA devices.

V. CONCLUSIONS

This paper discussed the difficulties of the LPWA devices' current sensing as well as provided the prototype design of a current consumption meter. As the current flow of LPWA communication technologies is diverse, the prototype has to have the ability of an accurate current measurement ranging between hundreds of nA and hundreds of mA and simultaneously provide fast measurement range switching, sufficient sampling speed, and data storage functionality.

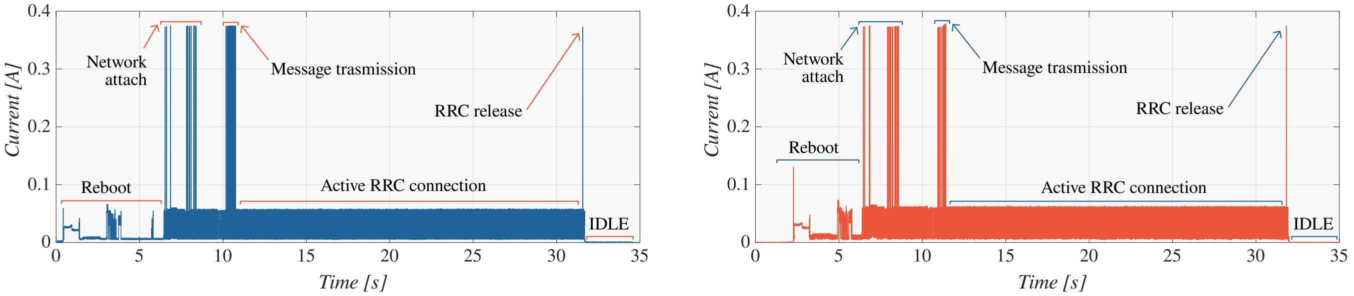


(a) DC analyzer, $f = 10\,Hz$ (b) DC analyzer, $f = 50\,Hz$ (c) DC analyzer, $f = 100\,Hz$



(d) Prototype, $f = 10\,Hz$ (e) Prototype, $f = 50\,Hz$ (f) Prototype, $f = 100\,Hz$

Fig. 5: Measured ramp waveforms.



(a) DC analyzer (b) Prototype

Fig. 6: NB-IoT power consumption for 500 B message.

The implemented design was initially verified by predefined signal waveforms and compared with the same measurement results obtained from well-known industrial DC power analyzer Agilent N6705B see Figs. 3 – 5 and comparison of parameters given in Table I. The gathered results have shown the prototype to be able to perform the current sensing comparable with commercially available devices, although with certain not-negligible limitations. It has been demonstrated that the sensing circuit is still vulnerable to undesirable oscillation with the signals containing higher harmonics. The design thus must implement better filtration circuits and techniques preventing OpAmp saturations and occasional instability of sensing circuitry.

Another more marginal limit of the presented device is the range switching speed and overall processing speed. Follow-up work could solve this by implementing a Field Programmable Gate Array (FPGA) for input signal processing. A combination of FPGA and better performing ADC with higher resolution could fasten the overall processing time and bring more accurate results. Later revisions of a prototype could also be improved in the implementation of other current sensing methods, more precisely current-to-voltage conversion utilizing the operational amplifier instead of a shunt resistor method.

Nevertheless, subsequent measurements of NB-IoT module current flow and comparison with results from DC power analyzer Agilent N6705B (see Fig. 6) have proven that the prototype is sufficient for electrical current sensing of LPWA technologies and detailed power analysis with above-described limitations. The carried-out device is a price-friendly open design current probe capable of power consumption analysis for diverse technologies as LPWA is.

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