Testbed and Empirical Current Consumption of 5G Reduced Capability Devices

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Abstract

With the rapid expansion of the 5G ecosystem, RedCap technology has emerged to address the growing need for energy-efficient, cost-effective connectivity solutions in industrial and consumer IoT applications. RedCap is designed to have a small form factor, low complexity, and low energy consumption. RedCap supports medium data rates, which are lower than legacy 5G New Radio but higher than Narrowband-IoT, making it ideal for use cases that demand reliable yet power-conscious performance. In this work, we present an empirical analysis of the current consumption of a commercial RedCap module, RG255CGL, operating over a 5G standalone time-division duplex network in a controlled laboratory setup. We systematically characterize the module's current consumption under diverse usage scenarios, starting from the RedCap device bootup, and including cell search, network attachment, and context release, as well as DL and DL traffic using both transmission control protocol and user datagram protocol, GNSS activity, and sleep mode. By examining the current consumption across these operational states, our study reflects realistic deployment conditions and offers valuable insights for optimizing energy consumption and extending battery life in 5G-enabled IoT devices.

CCS Concepts

• **Hardware → Power and thermal analysis**; **Wireless devices**; **Power estimation and optimization**.

Keywords

3GPP, 5G NR, energy consumption, IoT, RedCap, measurement

1 Introduction

Modern mobile networks support a wide range of applications—from high-bandwidth video streaming to occasional small data transfers from Internet of Things (IoT) sensors. To meet these diverse needs, 5G introduced several technologies. 5G New Radio (NR) handles Enhanced Mobile Broadband (eMBB) and Ultra-Reliable Low Latency Communication (uRLLC), while Narrowband IoT (NB-IoT) and Enhanced Machine Type Communication (eMTC) focus on Massive Machine Type Communication (mMTC). However, NB-IoT and eMTC are designed for low data rates [1]. This creates a gap for mid-range applications, such as video surveillance, wireless industrial sensors, and wearables, which do not require the full capabilities of high-end 5G NR but still need more than what NB-IoT and eMTC can offer. Third Generation Partnership Project (3GPP) Release 17 introduced a new device category, 5G Reduced Capability (RedCap) [2], to bridge this gap. RedCap reduces device complexity and cost, supports a smaller form factor, and incorporates energy-saving features such as Extended Discontinuous Reception (eDRX). Initially developed for NB-IoT and eMTC, eDRX enables longer sleep cycles between data receptions [3]. This makes RedCap a suitable choice for the next generation of mid-range IoT applications.

This work presents a comprehensive empirical analysis of the current consumption behavior of a commercial RedCap UE across different operational phases, ranging from boot-up, cell search, and network attachment to data transmission uplink/downlink over Transmission Control Protocol (TCP) and User Datagram Protocol (UDP), and context release. An open-source 5G test network is used to provide controlled radio conditions, and current is measured using a DC power analyzer. Throughout the experiments, we collect real-time User Equipment (UE) key performance indicatorss (KPIs), which offer valuable insight into how varying radio conditions and resource utilization impact the UE's current consumption. The key contributions of this study are: (i) a detailed phase-wise current profiling of a RedCap UE under realistic 5G procedures, highlighting how current consumption varies across operational states; (ii) a protocol-level analysis of current and throughput behavior under TCP/UDP and uplink/downlink configurations, enabling a practical understanding of energy-performance trade-offs; (iii) a correlation study between real-time RedCap UE KPIs and measured current consumption, providing insights into how network conditions influence device energy use; (iv) an evaluation of global navigation satellite system (GNSS) receiver activation and sleep modes on overall energy behavior, addressing peripheral and idle energy aspects often overlooked in earlier RedCap studies; and (v) a reproducible measurement methodology based on open 5G infrastructure and commercial RedCap hardware, supporting future benchmarking and validation efforts.

The structure of this work is as follows: Section 2 provides a brief overview of existing research on energy consumption in 5G networks. Section 3 highlights the key features of the RedCap technology. Section 4 describes the laboratory measurement setup used in this study. Section 5 presents the UE current consumption at various operational stages, and Section 6 concludes the findings.

2 Related Works

5G RedCap has been explored in several scientific publications as a newly introduced device category aimed at bridging the gap between high-end 5G NR and low-power IoT technologies. The authors of [4] provide a detailed overview of 5G RedCap requirements, features, and potential performance. For RedCap devices with minimum capabilities (e.g., a single downlink (DL) Multiple

Input Multiple Output (MIMO) layer) [4] states that peak physical data rates in 5G Time Division Duplexing (TDD) networks can reach 60 Mbit/s. In terms of battery life, The authors calculate that the battery life can be extended depending on the eDRX cycle length and Inter Arrival Time (IAT) of the data traffic. Particularly, eDRX cycles of ten minutes and 60 minutes IAT can extend battery life by a factor of 70 compared to scenarios without eDRX. In [5], the authors propose a comprehensive analytical model for estimating the energy consumption of 5G RedCap devices. Although the model accounts for various energy states in detail, its practical applicability is constrained by the absence of empirical power measurements specific to 5G RedCap hardware. The authors of [6] report experimental results for 5G RedCap devices, showing physical DL data rates reaching up to 141 Mbit/s when utilizing two receive branches. However, due to the lack of detailed information regarding the measurement setup, Device Under Test (DUT), and network configuration parameters such as the Modulation and Coding Scheme (MCS), the reproducibility of these results is limited. In [7], the author did a comprehensive empirical energy measurement of the RedCap. They considered Tapped Delay Line (TDL)-A model applicable for users in urban areas. For energy consumption under throughput analysis, they only considered UDP, without giving insights for the TCP protocol, which is an acknowledgment-based protocol and consumes more energy.

In contrast, our study focuses on procedure-level current consumption behavior of a commercial 5G RedCap UE in a realistic 5G standalone (SA) deployment. Using an OAIBOX 40 MAX, a 5G core and gNodeB emulator, we conducted high-resolution current measurements across several distinct UE states: bootup, cell search, network attachment, release, complete uplink (UL) and DL data transfers over both TCP and UDP, GNSS activity, and baseline sleep mode. This fine-grained breakdown provides a deeper understanding of energy dynamics during specific operational procedure, which is not covered in previous work. Additionally, while previous studies typically focus on radio-specific behavior, we also characterize the energy of the GNSS subsystem, which is crucial for RedCap use cases involving location or time synchronization. Although our network setup did not support eDRX, we include sleep state consumption as a baseline reference and clearly explain the limitation. These contributions provide a complementary perspective to existing work by offering per-state energy profiling, protocol-specific data impact, and GNSS subsystem insights — all under realistic, reproducible 5G SA conditions using off-the-shelf hardware.

3 5G RedCap: Technical Background

3GPP Rel-17 introduces RedCap technology aimed at mid-range IoT devices by reducing cost and complexity compared to standard 5G NR. Rel-17 focuses on simplifying architecture, improving power efficiency, and minimizing performance loss [8]. It reduces FR1 bandwidth from 100 MHz to 20 MHz. In 3GPP Release 18, RedCap bandwidth is further reduced to 5 MHz, cutting data rates to 25% of Rel-17 levels. According to TR 38.865, peak data rates are approximately 10 Mbps [9]. RedCap reduces UE complexity compared to standard 5G NR by implementing several key strategies: (i) fewer receive (RX) branches, (ii) reduced bandwidth, (iii) half-duplex Frequency Division Duplex (FDD), (iv) simplified processing, (v) fewer MIMO layers, and (vi) lower modulation order.

Legacy 5G NR UEs use 100 MHz Frequency Range (FR1) and 200 MHz FR2 bandwidths as a reference. In contrast, RedCap UEs reduce the antenna count and bandwidth, leading to lower costs and power consumption, but also reduced performance.

- **RX Antenna Reduction:** Fewer receive branches reduce the number of DL MIMO layers, leading to lower peak data rates and reduced coverage. However, this also simplifies the radio frequency (RF) chain and baseband processing, lowering power consumption.
- **Bandwidth Reduction:** A smaller bandwidth significantly reduces complexity and cost. While peak data rates are lower, bandwidth options of 20 MHz (FR1) and up to 100 MHz (FR2) in Rel-17 are adequate for standard industrial, enterprise, and consumer use cases.

4 EXPERIMENTAL TESTBED

To enable current consumption measurements under controlled and repeatable channel conditions, we designed and implemented an experimental testbed tailored for real-time current consumption analysis. This section presents the structure, capabilities, and methodology of the developed test environment, with a focus on its application to RedCap UE power profiling. The overall testbed structure is presented in Fig. 1.

4.1 5G OAI BOX and Support for RedCap

OAIBOX, built on the OpenAirInterface (OAI) open-source platform, enables research and development in 5G technologies. Distributed under the OAI Public License V1.1, it simplifies testbed setup and ensures interoperability with major 5G modem vendors through seamless integration with the 5G core and radio access network (RAN). Its user-friendly Graphical User Interface (GUI) supports network management and 3GPP compliance. Being open-source, OAIBOX allows customization, including Commercial Off-The-Shelf (COTS) UE support via the oaibox.yaml file, which defines gNodeB parameters. To support RedCap UEs, we enabled Rel-17-specific features—such as 1Rx/2Rx access and disabled intra-frequency reselection—within this file. RedCap capabilities are signaled during the Radio Resource Control (RRC) procedure, prompting the gNodeB to activate relevant features. Additional configuration parameters are listed in Table 1.

4.2 RedCap RG255C-GL module

The RG255C-GL is a compact M.2 LGA 5G modem based on 3GPP Rel-17 RedCap, designed for sub-6 GHz standalone (SA) networks. It also supports Long Term Evolution (LTE) Cat 4 (Rel-15/16) for backward compatibility. RedCap devices operate exclusively on 5G SA networks. Key features include 5G Local Area Network (LAN), URLLC, and network slicing, making it suitable for industrial IoT and latency-sensitive applications. The modem supports global 5G NR bands (n1–n78), operating at Power Class 3 (23 dBm ±2 dB) and Class 2 High Power User Equipment (HPUE) (26 dBm ±3 dB) for

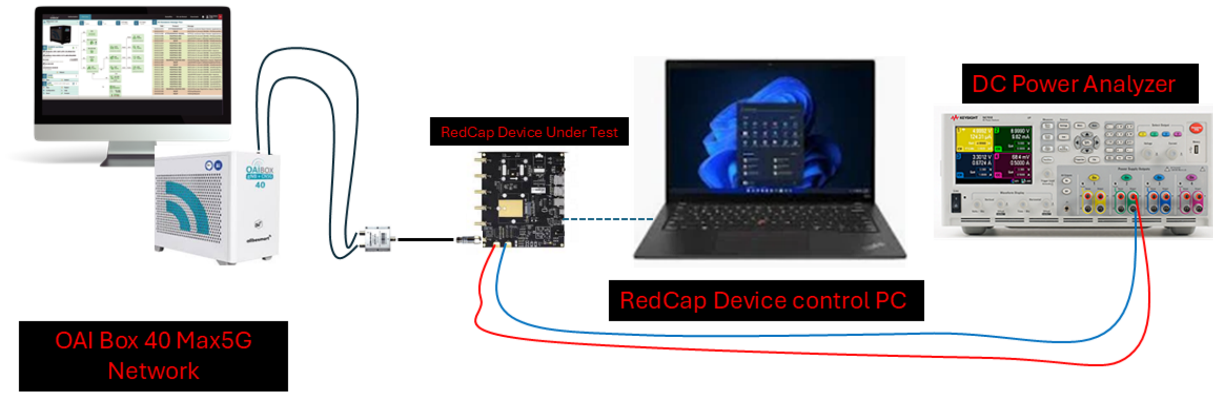

Figure 1: Experimental test setup for RedCap current consumption measurement.

Table 1: Key Network Parameters to support RedCap UE

Parameter	Value
SCS	30 kHz
Bandwidth (UL/DL)	51 RBs
MIMO Layers	1
DL Antenna Ports	1
UL Antenna Ports	1
TDD Pattern	3DL / 1UL
Band	n77
TDD ULDL Periodicity	5 ms
Max MCS	28
p_{Max}	23 dBm

enhanced coverage in selected bands. It supports MCS from Quadrature Phase Shift Keying (QPSK) to 256-Quadrature Amplitude Modulation (QAM), with 15 kHz subcarrier spacing in FDD and 30 kHz in TDD. It includes interfaces for a primary antenna (ANT_MAIN), Rx diversity (ANT_DRX), and GNSS (ANT_GNSS) [10].

The 5G-M2 EVB (evaluation board) supports multiple 5G modules and provides test points to measure current consumption with slight modification. Once modified and powered via an external connector, power is supplied directly to the module. Communication with the modem is done using Quectel's QCOM software.

4.3 Communication Channel

For our experiments, we set up a control laboratory setup with stable attenuation for each measurement. We made sure that the channel is repeatable and there is no interference from surrounding devices. The 5G box has one transmitting antenna (TX) and one receiving antenna (RX). To connect with UE, we used a mini circuit splitter/combiner [11]. The two cables from the OAIBOX are connected to the combiner, and the output wire is connected to RedCap UE. The channel was repeatable and we maintained the Received Signal Strength Indicator (RSSI) of −89 dBm and Reference Signal Received Power (RSRP) of −63 dBm with little to none ±1 dBm variation.

4.4 DC Power Analyzer N6705B

A DC power analyzer was used to source and measure the DC voltage and current into the device under test. The power supply has a built-in datalogger that can be used to record the current data over time. It can log data in continuous mode at 20 μs sampling period. The logged data can be exported in CSV file format [12].

4.5 iperf3 as a Traffic Generation Tool

iPerf3 is a widely used, cross-platform tool for testing and tuning network performance. Operating in client-server mode, it generates traffic between two endpoints and measures throughput in one or both directions using standardized metrics.

5 CURRENT CONSUMPTION ANALYSIS

Using the laboratory setup described in Section 4, we measured the current consumption of RedCap UE. For TCP and UDP (DL and DL), multiple 2-minute experiments with 1 ms sampling were performed. The data was analyzed using Student's t-distribution to estimate the mean and standard deviation, capturing variability across experiments. Single-trial measurements were used for baseline, GNSS-enabled, and sleep modes without statistical analysis.

5.1 Current Consumption Profiling During UE Network Attachment and Release

This experiment profiles the current consumption of a RedCap module during its operation, starting from boot up, and including cell search, network registration in the stable RRC-connected phase, and finally, during the release state. The module was powered by a DC supply rated at 3.8 V and 2.5 A, using the external connector. The UE performs cell search using the set frequency band (n77), registers itself with the network, performs link adaptation, and then enters a stable RRC-connected phase. Fig. 2 shows the illustrative current consumption profile. The gNodeB logs menu provide logs of the UE initial registration and data connection.

To provide further context, the UE KPIs logged once UE appears on the network dashboard across these operational phases are visualized in Fig. 3, which clearly distinguishes the resource

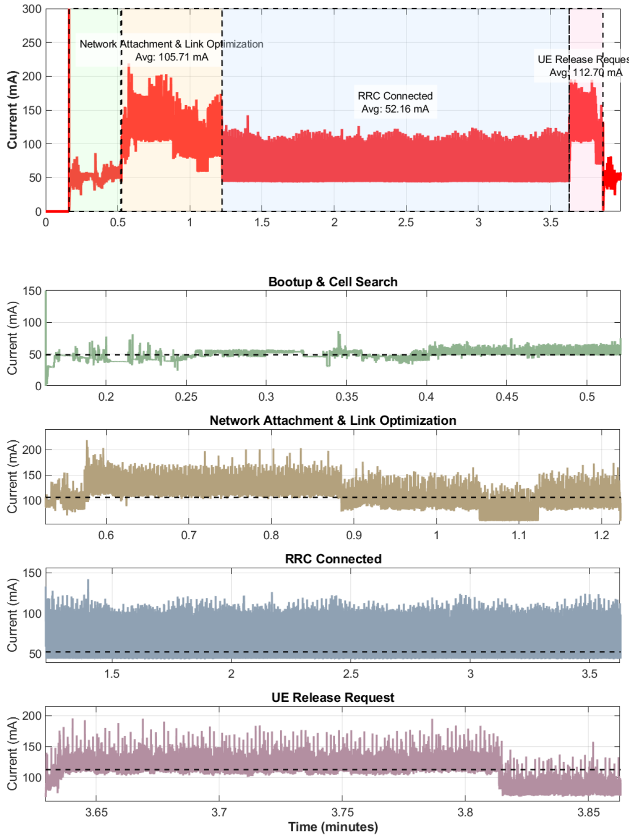

Figure 2: Current consumption during bootup, initial network attachment, RRC-connected state, and release request.

consumption behavior across bootup, registration, connected, and release states. The UE KPIs are logged only after the UE appears on the network dashboard, so the KPIs are not logged for the bootup and cell search duration, but only for network attachment, stable connected phase and release phases. During bootup and cell search, the module draws an average current of approximately 54.59 mA looking for a cell to attach, and it takes approximately 27 seconds for the UE to appear on the network. During this entire time, the UE performs its initial procedure, sets up RRC, and contention resolution - these are the phases involved in the initial registration of the UE to the network.

Upon successful connection, we can observe from Fig. 2 that the current rises to an average of 105 mA. This elevated consumption corresponds to the period where the UE attempts to balance the block error rate (BLER) and resource usage, which results in the assignment of a high MCS. As the BLER converges to zero and the traffic flow stabilizes, the network maintains optimal MCS values as shown in the Fig. 3. During this stable RRC-connected phase, the UE enters an energy-optimized state, drawing an average of 52.28 mA.

In the RRC release process, the UE initiates a controlled transition from RRC_CONNECTED to RRC_IDLE by exchanging signaling messages with the network, temporarily increasing the processing load and current draw. As shown in Fig. 2, this results in the peak current of 113.02 mA before the release completes. The session is properly terminated using the AT command 'AT+QPOWD', the network releases the radio bearers and fully detaches the UE. This process contributes to the 13-second delay before complete shutdown. In subsequent experiments, the stable 52.28 mA current observed in the RRC_CONNECTED phase will serve as the baseline for comparative analysis of dynamic current fluctuations during state transitions. All current measurements were captured with 1 ms resolution.

5.2 Uplink Current Consumption

We investigated two data transmission protocols: UDP and TCP. In the case of DL, the UE acts as a client and sends data to the server installed within the OAI BOX network. It is observed that the TCP protocol draws a higher current than UDP, given that the testing conditions (throughput and signal strength) are kept the same, as shown in Fig. 4. The evaluation of transmission in TCP UL and UDP UL highlights that the current consumption of the RedCap UE exhibits clear differences, primarily influenced by protocol behavior and the utilization of radio resources. On both UDP and TCP, the DL MCS varied dynamically between 14 and 16, optimally assigned by the network, and the average throughput of 12 Mbps was maintained. However, in the TCP case, a high DL MCS was also assigned, primarily for the reception of TCP acknowledgments, whereas the UDP scenario maintained a much lower DL MCS, around 9, indicative of minimal DL signaling activity Fig. 4. The DL bitrate further illustrates this difference: TCP maintained a steady DL throughput of approximately 3 Mbps due to frequent acknowledgment packet exchanges, whereas UDP showed zero DL traffic as shown in the Fig. 4. The lack of acknowledgments in UDP allows the UE to remain idle in the DL direction, thus reducing current consumption. Both TCP and UDP maintained near-zero DL BLER. However, DL BLER, although comparable (ranging from 5–18%), impacts TCP more substantially. Due to its reliable, connection-oriented nature, TCP triggers retransmissions, increasing DL airtime and processing load, as shown in Fig. 4. TCP UL resulted in an increase of 29.35 mA over the baseline (52.21 mA), which corresponds to a 56.2% increase, while the UDP UL showed a less significant increase of 24.82 mA or 47.5%, as shown in Table 2.

5.3 Downlink Current Consumption

In a DL throughput test for both protocols, the DL MCS reaches and maintains the maximum value of 27, indicating excellent radio conditions and maintaining a high throughput of 70 Mbps, as depicted in the Fig. 5. However, the operational dynamics of the protocols differ. In the TCP DL case, the DL MCS fluctuates between 13 and 17, suggesting ongoing DL activity. This activity corresponds to the continuous exchange of TCP acknowledgment packets, which generate frequent DL transmissions. Conversely, in the UDP DL scenario, the DL MCS remains consistently high, near 27, where networks have a clean channel and can support a high data rate in the DL direction. This distinction becomes clearer when examining BLER. While both scenarios show zero or near-zero DL BLER, DL behavior diverges notably as shown in Fig. 5. In the TCP case, the DL BLER frequently spikes, ranging between 5% and 17%, indicating packet losses and triggering retransmissions. These retransmissions directly results in the current consumption increase. In contrast,

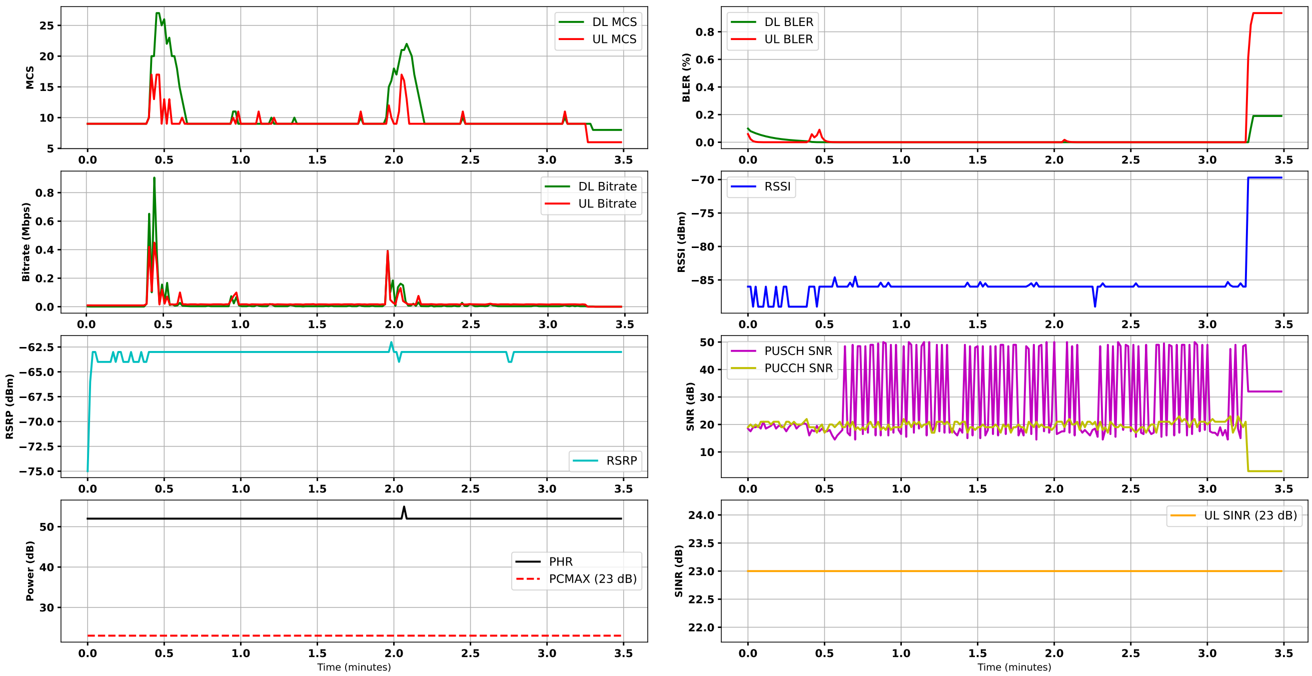

Figure 3: Measured UE KPIs during bootup, initial network attachment, RRC-connected state, and release request.

UDP shows substantially lower DL BLER, typically below 7%, and does not incur retransmission overhead due to its connectionless nature. The bitrate analysis further supports this conclusion. Looking at Fig. 5, TCP maintains a sustained DL bitrate of approximately 68–70 Mbps, driven by the continuous data flow and receipt of acknowledgment packets. The DL bitrate, while lower (2–3 Mbps), reflects the persistent TCP control signaling and retransmissions. UDP also achieves a similar DL bitrate (70 Mbps), but the DL bitrate is zero since there are no acknowledgment packets in the UDP case. For the DL tests, TCP DL caused the highest increase in current consumption, an average of 81.23 mA, as shown in Table 2, recorded during the experiment.

5.4 GNSS Subsystem Impact

To assess the impact of GNSS on power consumption, we switched on the GNSS receiver. GNSS is activated via the AT command AT+QGPS=1 and can be turned off with the AT command AT+QGPSEND. We have noticed that the device's current consumption has increased noticeably. In particular, GNSS activation resulted in a 30 mA increase in current, as listed in Table 2, a 62.1% increase over the baseline current of 52.22 mA. This increase underscores the importance of carefully managing GNSS usage in power-constrained devices. It is worth noting that the measurement carried out for GNSS was at a cold start when it was looking for a satellite.

5.5 Sleep mode

The RG255C-GL mode supports sleep mode, where the device's current consumption goes to an ultra-low level. It is activated using AT commands. In this state, the RedCap UE transitions to the RRC inactive state, not fully detaching itself from the network, but

Figure 4: TCP and UDP Uplink iperf throughput test.

instead entering an intermediary state. The UE can enter the RRC connected mode using RRC resume operation, which allows the UE to avoid the initial connection establishment process, thereby reducing current consumption. When the module enters sleep mode, the RF light (D0108) on the EVB board blinks at regular intervals, indicating that the RF module is active and monitoring paging messages. Since the network lacks CEDRX support, no paging messages are sent. Average sleep mode current was 18.84mA. Fig. 6 shows periodic current spikes, each representing a UE wake-up to

Figure 5: TCP and UDP Downlink iperf throughput test.

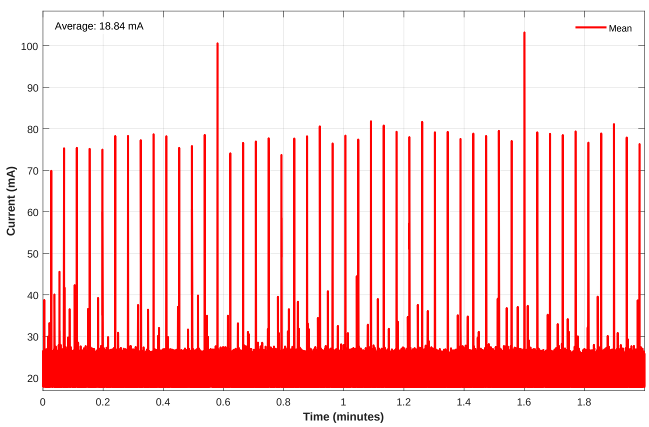

Figure 6: Sleep mode: ultra low current consumption.

check for paging. Table2 summarizes current consumption across all experiments, with TCP/UDP statistics relative to the baseline in Fig.2.

Table 2: Current Consumption and Statistics (Baseline = 52.22 mA)

Mode	Avg. (mA)	Δ (mA)	Change (%)	Std. Dev.
Baseline (Idle)	52.22	–	–	–
TCP UL	81.56	+29.34	+56.2%	16.79
UDP UL	77.03	+24.81	+47.5%	19.47
TCP DL	91.51	+39.29	+75.3%	14.19
UDP DL	88.12	+35.90	+68.7%	11.94
GNSS Enabled	84.65	+32.43	+62.1%	–
Sleep Mode	18.84	-33.38	-63.9%	–

6 CONCLUSION

In this work, the experimental current consumption of the RedCap UE is measured using a 5G network emulator. For the channel model, an RF cable is used to ensure channel repeatability. The testbed evaluated the current consumption pattern for comparative analysis among different data transmission protocols, which provided sufficient insight into which application purpose the RedCap device would be best suited for. Our measurement identifies that when the GNSS subsystem is active, the increase in the current consumption is 62% from the baseline current consumption, which is 52 mA, thus showing that GNSS activities have a significant effect on the current consumption of the device. Current consumption was the lowest in sleep mode, which indicates that if periodic sleep mode is activated during no active reception or transmission, it can significantly reduce energy consumption and hence can be used for applications that require longer battery life. Our 5G base station didn't support eDRX mode; in the future, measurements for this mode will be carried out with an advanced 5G base station. The attenuation was constant at 20 dB for these experiments, but in the future, a variable attenuator will be applied to see the effect of different attenuations on the current consumption pattern. For end-to-end energy measurement, the energy consumption of the RedCap base station will also be measured in a future experiment.

Acknowledgments

This research was supported by Business Finland through the 6G-SatMTC Project and by the Research Council of Finland 369116 (6G Flagship) grant.

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