5G RedCap vs FullCap UEs: Energy Insights

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***Abstract*—The rapid growth of Internet of Things (IoT) deployments, mission-critical sensing, and unmanned systems requires wireless solutions with reduced complexity, improved energy efficiency, and reliable connectivity. While Fifth Generation Mobile Communication System (5G) Full-Capability (FullCap) User Equipment (UE) provides high performance, it often exceeds the power and cost constraints of large-scale sensor networks. 5G Reduced Capability (RedCap) devices offer a practical compromise with essential 5G functionalities and lower energy consumption. This paper presents a comparative study of the energy consumption of RedCap versus FullCap 5G devices. Measurement campaigns using smart plugs collected real-time power data under different configurations and were processed through an automated pipeline. Results show that RedCap devices significantly reduce energy consumption while maintaining reliable connectivity for large-scale IoT deployments.**

I. INTRODUCTION

The rapid expansion of Internet of Things (IoT) applications is driving the demand for wireless communication technologies that provide reliability, low energy consumption, and reduced device complexity [1], [2]. Traditional IoT networks often rely on Low Power Wide Area Network (LPWAN) technologies [3] such as Long Range (LoRa), Sigfox, and IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN). These solutions offer long-range connectivity and low power consumption, but are limited in throughput, latency, reliability, and Quality of Service (QoS) guarantees, with data rates typically limited to a few kilobits per second. As a result, LPWAN is generally unsuitable for real-time or high-data-rate IoT applications.

In contrast, Fifth Generation Mobile Communication System (5G) and New Radio (NR) introduce capabilities that address these limitations. 5G supports Enhanced Mobile Broadband (eMBB) for high-throughput applications such as video monitoring or industrial sensing, Ultra-Reliable Low-Latency Communications (URLLC) with sub-millisecond End-to-End (E2E) latency for critical services, and Massive Machine-Type Communications (mMTC) for massive device connectivity. Additional features such as network slicing and dynamic QoS management enable flexible resource allocation, which is not available in LPWAN [4]. However, these capabilities increase energy consumption for traditional Full Capability (FullCap) devices, motivating the development of Reduced Capability (RedCap) devices.

Defined in 3rd Generation Partnership Project (3GPP) 3GPP Release (Rel)-17, RedCap devices aim to maintain essential 5G functionalities while reducing complexity and power consumption [5]. Despite promising specifications, there is limited experimental validation of RedCap energy efficiency in real deployments compared to FullCap devices. Understanding the energy profile of RedCap is essential for dense IoT networks requiring extended autonomy and lower operational costs.

In this paper, we investigate the practical integration of 5G RedCap using a Quectel RG255C compared to a FullCap setup with the Quectel RM500Q-GL modem, both connected to a Raspberry Pi 4B via an M.2-to-Universal Serial Bus (USB) interface, interacting with an OpenAirInterface (OAI) Next Generation Node B (gNB) and Universal Software Radio Peripheral (USRP) B210. Power consumption was measured using an Athom 16A Power Monitoring Plug (PG01EU16A) [6] and a data pipeline that we name Energy Measurement and Analysis Platform (EMAP) leveraging Kafka, Logstash, Elasticsearch, and Kibana. Multiple test scenarios were executed, including different User Equipment (UE) radio modes (ECO and ACTIVE) and burst intervals, allowing comparison of RedCap versus FullCap under controlled traffic conditions over extended periods.

The contributions of this work are: (i) deployment of a functional RedCap and IoT testbed in a real 5G network; (ii) a measurement campaign comparing RedCap and FullCap energy consumption under different operating conditions; and (iii) quantitative insights into RedCap's potential for energy-efficient IoT deployments resulting in a large energy consumption dataset.

Section II provides background and reviews related work. Section III describes the EMAP platform and dataset. Section IV details the experimental setup. Section V analyzes results, and Section VI concludes the paper.

II. BACKGROUND AND RELATED WORK

This section introduces the RedCap paradigm and reviews related work on energy-efficient IoT communications.

A. Redcap

3GPP Rel-17 introduced RedCap NR devices [7] to reduce UE complexity and power consumption while preserving core 5G functionalities. RedCap limits Frequency

Range 1 (FR1) bandwidth to 20 MHz, disables carrier aggregation and dual connectivity, and typically restricts devices to 1–2 receive antennas, reducing Radio Frequency (RF) and baseband processing requirements. At the protocol level, the number of supported bearers and optional features is also reduced, lowering memory and signaling overhead. These design choices reduce energy consumption and cost while maintaining 5G-level connectivity and latency. Compared to FullCap NR UEs, RedCap provides a compromise between Narrowband (NB)-IoT/Long Term Evolution for Machines (LTE-M) and eMBB devices, offering better performance than LPWAN technologies while requiring less power and silicon resources.

B. *State of the Art*

Energy efficiency has been widely studied in wireless IoT communications, particularly through low-power cellular technologies such as LTE-M and NB-IoT, which reduce bandwidth, transmission power, and protocol complexity to extend battery lifetime [8]. However, their limited throughput and latency restrict them to low-data-rate sensing applications.

With 5G NR, research has focused on energy-aware IoT support using protocol optimization, adaptive resource allocation, and service differentiation. Nevertheless, studies show that conventional FullCap 5G devices remain over-dimensioned for many IoT scenarios, resulting in unnecessary energy consumption and higher device cost [2]. This highlights the gap between low-power cellular solutions and high-performance 5G devices.

3GPP introduced RedCap in Rel-17 to address this gap for mid-rate IoT and industrial applications. Existing work mainly focuses on standardization, architecture, and security aspects [5], identifying potential energy savings through simplified radio configurations and reduced monitoring requirements.

However, only a limited number of experimental studies have evaluated RedCap energy efficiency in realistic deployments. Existing results are mostly scenario-specific, short-term, or limited to particular protocol optimizations [9]–[11]. Comprehensive measurement-based comparisons between RedCap and FullCap devices under realistic 5G Standalone (SA) conditions, including both active and idle modes, remain largely missing.

To the best of our knowledge, no publicly available dataset currently quantifies the energy performance of RedCap UEs compared with FullCap counterparts in a realistic 5G SA environment. Addressing this gap is essential to assess the practical energy efficiency of RedCap for real-world IoT deployments and motivates the experimental study presented in this paper.

III. PROPOSAL

A. *Holistic Perspective*

The proposed EMAP architecture (Figure 1) is conceived as a multi-layer energy monitoring and analytics framework for 5G infrastructures. The system provides fine-grained energy telemetry and dataset generation for heterogeneous 5G equipment, including UEs, Radio Units (RUs), and Core Networks (CNs). EMAP is structured around three architectural layers:

a) 5G Layer: This upper layer comprises the operational 5G components (Radio Access Network (RAN) and CN), deployed as Containerized Network Functionss (CNFs) on the underlying infrastructure layer. It provides access to network-level information (traffic load, radio state transitions, Physical Layer (PHY) metrics) through internal logging and service interfaces. These network metrics are collected independently and are not directly exchanged with the energy metering subsystem; correlation is performed later with the monitoring layer.

b) Infrastructure Layer: The infrastructure layer aggregates all hardware and physical network elements participating in the experiment, including 5G UEs (RedCap and FullCap), RF front-end modules, sensors, and the power-monitored computing platforms as Single-Board Computer (SBC) (e.g., Raspberry Pi). The smart energy plug and metering equipment are integrated at this layer to provide high-resolution active-power measurements. It also hosts the compute resources on which both the 5G containerized functions and the monitoring layer services are deployed. The layer integrates smart plugs and metering equipment to capture high-resolution energy consumption, providing the monitoring layer with telemetry from the underlying hardware.

c) Monitoring Layer: The monitoring and analytics layer hosts EMAP services as containerized components (e.g., Kafka broker, Elasticsearch, Kibana) and collects telemetry exclusively from the infrastructure layer (power measurements, sensor data). It provides real-time visualization, long-term storage, and automated dataset generation. The monitoring layer operates independently from the 5G layer, enabling external analytics to correlate network telemetry with power consumption from the infrastructure layer, without directly interacting with the 5G control or user-plane functions.

B. *Detailed View*

Now, we focus on the EMAP-based detailed view, encompassing the data collection pipeline and the dataset description.

1) Data Collection: The EMAP energy monitoring platform shown in Figure 2 implements a containerized measurement pipeline capable of generating high-resolution active power traces of 5G UEs under both RedCap and FullCap configurations. In the current setup, the UE are

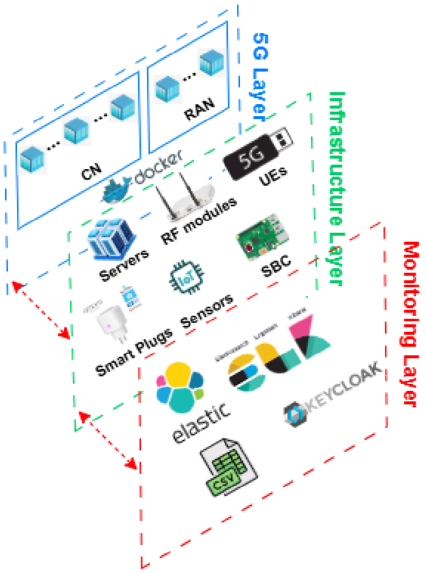


Fig. 1: EMAP Architecture (Global View).

attached as USB modems to a Raspberry Pi 4B, which acts as the execution host for the UE software stack while being physically powered through a Tasmota-enabled smart plug. Consequently, EMAP captures the electrical consumption of the entire UE execution chain (modem, host Central Processing Unit (CPU), USB subsystem, and driver stack), providing representative E2E energy profiles.

At the hardware measurement level, Tesmota connects to the Local Area Network (LAN) via IEEE 802.11 Wireless Local Area Network (Wi-Fi) and exposes instantaneous electrical parameters (voltage, current, power, apparent power and power factor) through an Message Queuing Telemetry Transport (MQTT) telemetry stream. EMAP integrates a custom middleware that recomputes active power from raw voltage and current measurements, correcting Tasmota-reported values and ensuring physical consistency. The middleware performs topic filtering, timestamp normalization and message enrichment before forwarding structured messages to Logstash.

At the data management level, the platform is implemented through a modular Elasticsearch, Logstash, and Kibana (ELK) stack deployed as independent Docker containers. Logstash pipelines ingest the measurement streams and index them in Elasticsearch with time-series semantics, enabling fine-grained querying and long-term persistence. Kibana dashboards provide real-time visualization of UE energy dynamics, RAN procedures and traffic-induced variations. Authentication and access control are enforced through Keycloak and OpenID Connect (OIDC), securing experiment data and dashboards.

This architecture enables reproducible energy measurement campaigns while providing precise correlation between 5G software execution, UE radio capabilities (RedCap vs FullCap), and the resulting active power consumption observed at the physical power source. The resulting dataset forms the basis for quantitative energy benchmarking, model training and energy-aware evaluation of 5G devices.

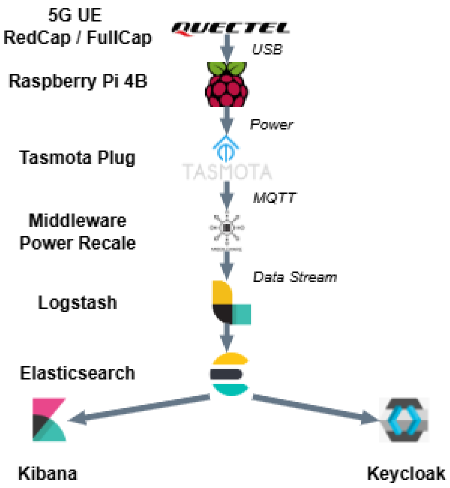


Fig. 2: EMAP Energy Monitoring Pipeline for 5G UEs.

2) Data Description: The dataset collected via the EMAP platform provides high-resolution, timestamped energy telemetry of 5G UEs under controlled experimental conditions. Each record corresponds to a measurement capturing the electrical state of the UE and its execution environment. Table I summarizes the key fields of the dataset.

TABLE I: Key EMAP Dataset Fields for Energy Telemetry.

Field	**Description**
`@timestamp`	UTC timestamp (ms)
`E.Power`	Instantaneous active power P [W]
`E.ApparentPower`	Apparent power S [VA]
`E.ReactivePower`	Reactive power Q [VAR]
`E.Current`	Current I [A]
`E.Voltage`	Voltage V [V]
`E.Factor`	Power factor PF
`E.Period`	Measurement interval Δt [s]
`E.Today`	Cumulative energy consumed today [kWh]
`E.Yesterday`	Cumulative energy consumed yesterday [kWh]
`E.Total`	Cumulative total energy E_{total} [kWh]
`dev.id`	Unique device ID
`dev.type`	Device type (e.g., Tasmota)

The dataset provides both instantaneous and cumulative measurements that can be formally described as follows:

a) Active Power: The instantaneous active power P represents the rate at which electrical energy is converted to useful work and is computed as:

$$P(t) = V(t) \cdot I(t) \cdot \mathrm{PF}(t) \tag{1}$$

where $V(t)$ is the instantaneous voltage, $I(t)$ is the instantaneous current, and $\mathrm{PF}(t)$ is the power factor.

b) Apparent and Reactive Power: Apparent power S quantifies the combination of active and reactive power:

$$S(t) = V(t) \cdot I(t) \tag{2}$$

Reactive power Q measures the energy oscillating between the source and reactive components:

$$Q(t) = \sqrt{S(t)^2 - P(t)^2} \tag{3}$$

c) Power Factor: The power factor PF indicates the efficiency of power usage:

$$\mathrm{PF}(t) = \frac{P(t)}{S(t)}, \quad 0 \leq \mathrm{PF} \leq 1 \tag{4}$$

d) Cumulative Energy Consumption: The total energy consumed over a period Δt is obtained by integrating the active power over time:

$$E_{\mathrm{total}}(t) = \int_{t_0}^{t} P(\tau)\, d\tau \tag{5}$$

Fields such as `E.Today`, `E.Yesterday`, and `E.Total` correspond to energy values computed in this manner over specific intervals.

e) Device-Level Granularity: Each UE is monitored individually through a Tasmota-enabled smart plug connected to its execution host (Raspberry Pi). This ensures that $P(t)$ represents the E2E electrical consumption of the entire UE execution chain, including modem, host CPU, USB subsystem, and driver stack.

f) Temporal Resolution and Structure: Measurements are timestamped with millisecond accuracy, allowing reconstruction of fine-grained energy profiles. The structured dataset stored in Elasticsearch enables correlation with 5G network Key Performance Indicators (KPIs), such as radio state transitions, traffic load, and UE configuration (RedCap vs FullCap).

This mathematically formalized dataset serves as the foundation for quantitative energy benchmarking, modeling, and energy-aware optimization of 5G devices.

IV. METHODOLOGY AND TESTBED

This section presents the methodology adopted to evaluate the EMAP platform under realistic 5G SA conditions. We detail the execution workflow and the hardware/software constituents and the test cases forming the E2E experimental infrastructure. The objective is to reproduce representative RedCap and FullCap 5G NR capabilities in controlled laboratory conditions.

A. Experimental Setup

The evaluation follows a controlled and repeatable procedure. Several energy-related operating states are triggered on different UE categories (i.e., RedCap andFullCap), while continuously collecting electrical quantities and connectivity metrics.

The 5G SA network is deployed using OAI containerized components and an NR-Time Division Duplex (TDD) gNB configured in band n78. Two UE modem families are evaluated: a RedCap module (Quectel RG255C) and a FullCap 5G module (Quectel RM500Q). Power measurements are collected through a Tasmota-enabled smart plug and processed offline.

The following operational conditions are executed: idle (Radio Resource Control (RRC)_Idle State (Idle)), connected (RRC_Connected), periodic sensing, and uplink data reporting. The evolution of active power P, and energy consumption $E(t)$ are tracked along the experiment.

B. Experimental Platform

The testbed is composed of: (i) an OAI 5G SA Core, (ii) an OAI gNB connected to a USRP B210, (iii) Raspberry-Pi-based UE hosting Quectel modems, and (iv) a Tasmota power monitoring device. A third server is dedicated to the EMAP software stack (MQTT broker, Kafka bus, Kibana dashboard, and related Docker services). A schematic overview is shown in Fig. 1.

a) UE: A Raspberry Pi 4B (Advanced RISC Machine (ARM) Cortex-A72, Debian 12) alternately hosts: (i) Quectel RG255C (5G RedCap), (ii) Quectel RM500Q (5G FullCap). The modem is interfaced via USB using Qualcomm MSM Interface (QMI); kernel modules (QMI_Wireless Wide Area Network (WWAN), Communications Device Class (CDC)_Windows Driver Model (WDM), option) are manually loaded. Access Point Name (APN), Public Land Mobile Network (PLMN), and operational mode parameters are configured using Attention Command (AT) commands. Power is measured at the Alternating Current (AC) input using a Tasmota-based smart plug.

b) gNB and RF: The OAI gNB (develop branch) is connected to a USRP B210 using USRP Hardware Driver (UHD) drivers, operating in TDD mode at 3.6 GHz (n78). The configuration enables both Rel-17 RedCap and Rel-15 FullCap, enabling direct comparison under identical RF conditions.

c) 5G Core: The 5G SA Core uses OAI CN v2.1.0 containers (Access and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Unified Data Management (UDM), Authentication Server Function (AUSF), Unified Data Repository (UDR), Network Repository Function (NRF)) deployed using docker-compose. Default OAI routing and UPF behavior are preserved without external traffic generator.

d) EMAP Services: A separate x86 server hosts EMAP containerized services including MQTT broker, Kafka message bus, and Kibana visualization, enabling real-time telemetry ingestion and processing.

C. *Test Cases*

This section describes the test cases executed on the EMAP platform in order to assess the energy behavior of RedCap and FullCap UEs under representative 5G SA conditions. The objective is to quantify how RRC activity, RF availability and uplink periodicity influence the instantaneous active power $P(t)$ and the accumulated energy for 24 hours $E_{24\text{h}} = \int_{t_0}^{t_0+24\text{h}} P(\tau)\, d\tau$.

Uplink traffic is generated using `iperf3` toward a server located inside the 5G Core data network and reachable through the UPF user-plane. The `iperf3` server runs on the CN host and listens on the configured port, thus enabling periodic uplink bursts throughout the 24 h experiment window for each test. in Total we have 16 test, 8 for each UE type(i.e., RedCap, or FullCap).

The complete campaign is organized according to the following configuration items and shown in table II:

- **UE Category:** each experiment is executed with two modem classes: a RedCap device (Quectel RG255C) and a FullCap device (Quectel RM500Q), connected over USB (QMI) to the same Raspberry Pi host.
- **RAN Behaviour:** two operating modes are considered: *ACTIVE*, where the RF remains continuously attached for 24 h, and *ECO*, where RF attach (`AT+CFUN=1`) is performed only during each burst and disabled afterwards (`AT+CFUN=0`).
- **Traffic Periodicity:** uplink IoT bursts of duration $T_{\text{burst}} = 2$ s are generated every $\Delta \in \{60,\ 10,\ 5,\ 1\}$ minutes using `iperf3` with a reporting interval of 1 s.
- **Execution Duration:** every configuration is executed for a continuous 24 h, storing power telemetry, modem traces and traffic statistics for offline processing.

TABLE II: Executed Test Configurations (24 h Each).

UE Type	Mode	Period (Δ)	Duration
RedCap	ACTIVE	60,10,5,1 min	24 h
RedCap	ECO	60,10,5,1 min	24 h
FullCap	ACTIVE	60,10,5,1 min	24 h
FullCap	ECO	60,10,5,1 min	24 h

All campaigns are automated through a shell script controlling the modem (AT/QMI), executing the periodic `iperf3` bursts, toggling RF in ECO mode, and timestamping results. This ensures fully repeatable energy measurements across modem category, RF strategy and traffic periodicity.

V. PERFORMANCE

In this section, we present the results of our 24-hour measurement campaign regarding active power $P(t) = V(t) \cdot I(t) \cdot \text{PF}(t)$ and the accumulated energy $E_{24\text{h}} = \int_{t_0}^{t_0+24\text{h}} P(\tau)\, d\tau$. We focus on the influence of UE category (RedCap vs. FullCap), UE radio mode (ACTIVE vs. ECO), and traffic burst period $\Delta \in \{1, 5, 10, 60\}$ minutes.

a) Active Power: Figure 3 shows the *average instantaneous* power in Watt (W) of RedCap and FullCap UEs under identical bandwidth and single-packet burst traffic, representative of IoT sensing, for various burst periods Δ and both ACTIVE and ECO radio modes. In ACTIVE mode (Figure 3a), with the UE radio continuously ON, power consumption is consistently higher and weakly dependent on Δ, as baseline RF and baseband circuitry dominate. RedCap devices consume 1–1.4 W, while FullCap UEs consume 1.7–2 W due to more complex RF chains, despite identical spectrum allocation. Power decreases slightly with increasing Δ, reflecting reduced instantaneous draw for less frequent transmissions. In ECO mode (Figure 3b), with the UE radio OFF between bursts, consumption drops: RedCap devices consume 0.7–1 W and FullCap devices 1.4–1.7 W. The ACTIVE–ECO gap highlights the energy-saving potential of duty-cycling, especially for RedCap UEs. Notably, power reduction is most pronounced at short burst periods (e.g., $\Delta = 1$ min), showing ECO mode effectively mitigates frequent-transmission costs.

b) Cumulative Energy: Figure 4 shows the 24-hour cumulative energy in Watt-hour (Wh) for all UE configurations. RedCap UEs consume significantly less energy than FullCap UEs across all Δ, with ECO mode providing the largest savings. For example, RedCap ECO uses 22.90–17.91 Wh compared to FullCap ECO's 39.58–35.09 Wh, corresponding to energy reductions of $\sim$ 42–49% across Δ. Similarly, RedCap ACTIVE reduces consumption by $\sim$ 32–40% compared to FullCap ACTIVE, and RedCap ECO achieves up to $\sim$ 57% savings relative to FullCap ACTIVE. Energy consumption further decreases as Δ increases, with the lowest value observed for RedCap ECO at $\Delta = 60$ min (17.91 Wh).

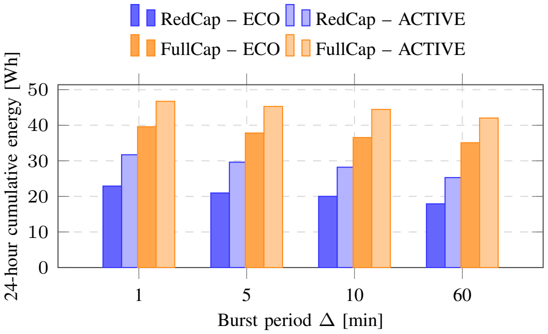
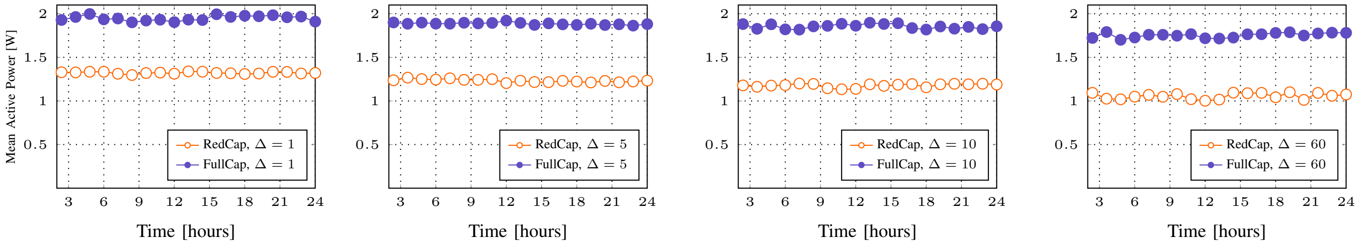
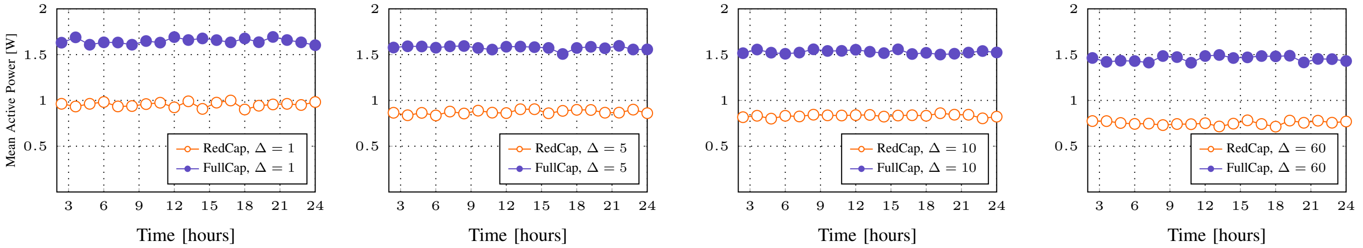


Fig. 4: 24-Hour Cumulative Energy of RedCap and FullCap UEs for Different Burst Periods Δ in ECO and ACTIVE Modes.

c) Summary: Overall, our results show that UE category, radio mode, and traffic periodicity strongly influence both instantaneous power and cumulative energy consumption. RedCap UEs consistently consume less power than FullCap UEs, with ECO operation and longer burst periods yielding the largest energy savings—up to 57% compared



(a) ACTIVE UE Radio Mode — UE Radio Always ON.



(b) ECO UE Radio Mode — UE Radio OFF Between Bursts.

Fig. 3: Average Active Power Obtained Under ACTIVE and ECO UE Radio Modes for Different Burst Delays.

to FullCap ACTIVE. Duty-cycling and lower hardware complexity are therefore key enablers for energy-efficient 5G-IoT deployments.

VI. CONCLUSION

This paper presents a comprehensive experimental evaluation of power and energy consumption for RedCap and FullCap UEs in a real-world 5G SA network under different radio modes (ACTIVE, ECO) and burst periods. Our results demonstrate that RedCap UEs in ECO mode achieve the lowest energy footprint, with FullCap UEs consuming up to ~ 42–49% more with the same configuration, and that energy use increases with burst frequency. These findings highlight the critical role of radio duty-cycling and traffic shaping for energy-efficient 5G-IoT deployments. Future work will extend this study to multi-UE scenarios, heterogeneous traffic, and energy-aware radio management techniques—such as Discontinuous Reception (DRX)/Extended DRX (eDRX), Bandwidth Part (BWP) adaptation, and dynamic power control—to further optimize 5G and Beyond (5G&B) networks for low-power IoT applications.

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