An Energy Measurement Framework for 5G RAN Using USRP and Real-Time Monitoring

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***Abstract*—Beyond 5G (B5G) networks, expected to support applications requiring ultra-low latency, high data rates, and dense connectivity, may increase energy consumption, especially in the Radio Access Network (RAN), which accounts for about 75% of total mobile network energy usage. We present an architecture for precise measurement of RAN energy consumption by monitoring the gNB radio interface implemented with Universal Software Radio Peripheral (USRP) and OpenAirInteraface (OAI). Real-time measurements from the GW Instek GPM-8213 power meter allowed us to analyze energy consumption patterns during various gNB operation phases. Our results show precise measurement and differentiation of energy usage during user transmission, enabling exact operational cost quantification. This architecture enables energy measurements in other mobile scenarios, paving the way for advanced network management use cases and more energy-efficient B5G operations.**

***Index Terms*—Energy Efficiency, Energy Footprint, Power consumption, Sustainability, RAN.**

I. Introduction

The United Nations (UN) General Assembly has introduced seventeen interrelated *Sustainable Development Goals* aimed at promoting a sustainable future by 2030 [1]. The Information and Communication Technologies (ICT) sector, with a particular focus on wireless networks, plays a crucial role in facilitating the achievement of these objectives. Research on Beyond 5G (B5G) networks directly supports these initiatives, especially in reducing energy consumption and carbon emissions. The ICT sector accounts for an estimated 1.8% to 2.8% of global greenhouse gas emissions, underscoring the need for effective measurement solutions to enhance network performance and sustainability.

As B5G networks evolve, these introduce a wider variety of data-hungry applications — Augmented Reality (AR) and Virtual Reality (VR), remote surgery, autonomous vehicles, and many other —, complicating network operations and increasing energy demands [2]. The Radio Access Network (RAN) faces the challenge of accommodating diverse use cases and a growing number of connected devices while maintaining stringent Quality of Service (QoS) standards. Consequently, the RAN is responsible for approximately 75% of the overall energy consumption within mobile networks, making it critical in assessing the environmental impact of ICT infrastructure.

Monitoring and managing energy consumption in mobile networks is crucial for operators. Effective energy management reduces Operating Expenses (OPEX) and lowers Carbon Dioxide (CO2) emissions. By optimizing RAN operations, operators not only diminish their carbon footprint but also gain economic benefits. This highlights the pressing need for advanced software and hardware tools to measure and monitor energy consumption in the RAN, ensuring that the sustainability objectives of B5G networks are met and fostering a more efficient ICT ecosystem.

Advanced tools for measuring and monitoring energy consumption are essential for operators to identify increases in power usage, indicating higher energy draw from network resources. Effective energy monitoring enables operators to track and reduce carbon emissions while ensuring compliance with regulatory requirements and promoting sustainable practices.

These innovative solutions provide critical insights into capacity planning, performance optimization, and early issue detection, all vital for maintaining operational excellence. By focusing on power consumption over shorter intervals, operators can implement strategic measures to lower energy usage. This approach aligns with the long-term objectives of B5G use cases, supporting sustainability in rapidly evolving telecommunications infrastructures.

The work presented in [3], evaluates power consumption during user registration and authentication processes across various deployed open-source 5G Core Network (CN), including free5GC, open5GS, and OAI. Another study in [4], employs the Meross MSS310 hardware tool[1] to measure power consumption within the 5G CN. Another study proposed in [5] presents an optimization method aimed at reducing power consumption in the RAN, while in [6], the authors assess the energy consumption of individual RAN components (e.g., Radio Unit (RU) and Baseband Unit (BBU)), contributing to overall network energy usage. Also, in [7], the authors propose novel approaches to minimize power consumption across various components of both the 5G CN and the RAN. Whereas works in [8], [9] introduce software power measurement tools across various deployments of the RAN — Monolithic, Disaggregated, and Control Plane and User Plane Separation

[1]https://www.meross.com/en-gc/smart-plug/smart-plug-google-home/6

(CUPS). In contrast, the proposed work integrates the GW Instek GPM-8213 digital power meter into the RAN setup to obtain precise, real-time energy consumption metrics directly from the physical hardware.

Works in [8]–[10], focused on software-based approaches for measuring power consumption in virtualized and containerized environments. Despite advancements in integrating software power measurement tools with the RAN, there remains a pressing need for dedicated hardware solutions. These tools offer precise, real-time measurements that accurately capture the dynamic power consumption patterns of RAN components. By enabling operators to identify specific sources of energy waste, hardware tools facilitate targeted optimization strategies. This capability is essential for effectively managing energy efficiency and sustainability in the rapidly evolving landscape of B5G networks.

The main contributions of this paper are as follows:

- Integration of hardware-based power measurement tools with the RAN to analyze energy and power consumption.
- Experimental evaluation of a Monolithic RAN with USRP, focusing on monitoring energy consumption.
- Discussion about various advanced use cases in the field of sustainable RAN.

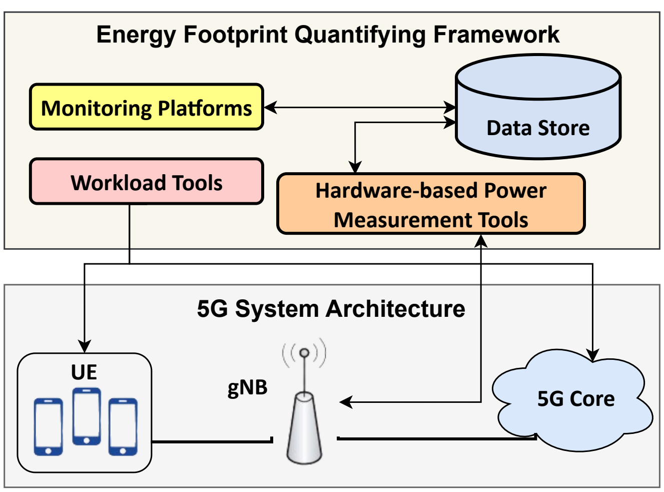

Fig. 1. Illustration of the System Architecture.

II. System Model

This section outlines the system model, comprising two key elements: the 5G system architecture and our Energy Footprint Quantifying Framework (EFQF).

The 5G system architecture is made up of three primary subcomponents: User Equipments (UEs), RAN, and 5G CN, as illustrated in Fig. 1. These components collaborate to deliver the full range of 5G network functionalities. The UE acts as the user's device for network access, the RAN enables wireless communication between the UE and the gNB, and the 5G CN handles data routing, network operations, and a variety of services, required to operate the network.

On the other hand, the EFQF, as shown in Fig. 1, incorporates hardware-based power measurement tools and is able to track energy consumption across various 5G deployments and save values into a data store. This provides critical insights into power usage, enabling the evaluation of the associated carbon emissions. The data store is used to collect and store power consumption information, facilitating detailed analysis through multiple monitoring platforms like Grafana or python-based custom solutions. These platforms can offer real-time visibility into energy metrics and system performance.

The framework's interaction with the 5G system architecture enable to measure power consumption across both the RAN and UE, with the gathered data stored in a common repository. In a real scenario, the UE, usually a smartphone, is able to measure itself those values, while on the gNB site it is needed to install additional hardware as documented in our architecture. Monitoring platforms then utilize this data to deliver a comprehensive understanding of the energy usage of 5G components and may be used to take real time decision on how to cut energy consumption.

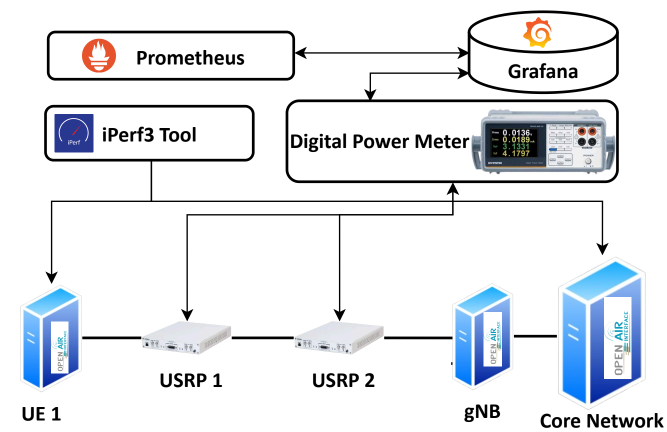

Fig. 2. Detailed overview of the applied Experimental Setup.

III. Experimental Setup and Results

This sections describes the experimental setup built to implement the reference architecture depicted in Fig. 1.

A. Experimental Setup

Fig. 2 shows the considered experimental setup primarily consisting of three different parts that are the RAN, the EFQF and CN.

Radio Access Network (RAN)

The RAN utilizes the OAI open-source RAN software stack [11]. An OAI-based UE, designated as *UE 1*, is deployed on a physical machine and connects to the RAN via a National Instrument X310 Universal Software Radio Peripheral (USRP). The USRP on the UE side links to the USRP on the gNB side. The OAI gNB operates at various bandwidths — 40, 60, and 80 MHz — to facilitate a comprehensive analysis of energy consumption across these different configurations.

Energy Footprint Quantifying Framework

We selected the *GW Instek GPM-8213* power meter to measure the energy consumption of our gNB and UE, both implemented by a USRP device with a standard power supply running OAI gNB and UE. This power meter is particularly suited for measuring single-phase AC power, and its high accuracy in voltage, current, and power measurements aligns well with our needs. The standard power supply of the USRP can be connected directly to the meter's input terminals, enabling precise monitoring of power consumption during our experiments. Additionally, the GPM-8213 features network connectivity through RS-232, USB, and LAN interfaces, allowing for remote control and data acquisition, which enhances the efficiency and flexibility of our measurement process, allowing us to automatize the most of the measurement tasks.

Energy consumption data from the USRP2 which works as gNB is collected and stored in a dedicated data store using a custom python script. This can enable real-time monitoring through a Grafana dashboard, or time-series storage through Prometeus.

Core Network

The OAI-based 5G CN is designed for scalability and follows the 5G service-based architecture, allowing for easy adaptation to various 5G use cases [12]. It employs a containerized approach leveraging Docker container engine, encompassing all necessary Virtual Network Functions (VNFs) to support core operations effectively. Evaluating the core energy consumption is out of the scope of this work because depends on many factors like the deployment of choice (monolithic, disagregated, CUPS) and has been already discussed in previous work [9].

B. Theoretical considerations on energy

In our experimental setup depicted in Fig. 3, we have identified three distinct levels of energy consumption for the gNB, based on its operational state:

- **System Idle:** This is the base level of energy consumption, recorded when the USRP is powered on but the gNB has not yet been initialized. At this stage, the USRP is essentially consuming energy to stay operational, without executing any network-related tasks;
- **gNB Idle:** This intermediate level represents the energy consumed by the gNB when it is fully initialized and the control plane is active, but there is no user data transmission, nor any associated UE. The network is in a ready state, handling only control traffic necessary to associate new UEs or to keep connected the associated ones. No UE is transmitting data at this stage;
- **Data Transmission:** This is the highest energy consumption level, observed when a UE is associated with the gNB and transmitting data through the network. The data load is generated using iperf3, simulating real-world data transmission scenarios. At this stage, the gNB consumes additional energy to manage both control and data plane activities.

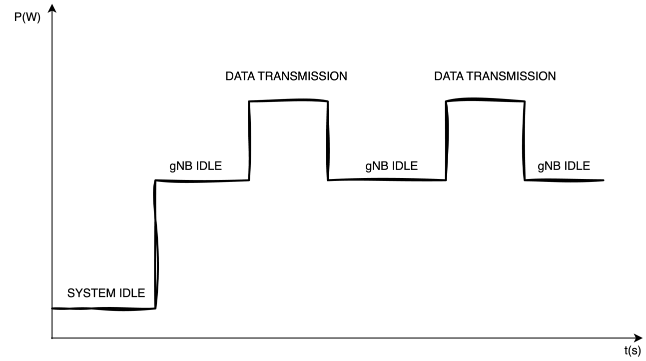

Fig. 3. Theoretical Power Consumption trend

When we stop data transmission, we expect to fallback to the gNB Idle level.

C. Results

Fig. 4 illustrates the power consumption profile of the monolithic RAN as a function of experiment time, with both current and average power readings captured by the GW Instek GPM-8213 tool. Current power refers to the real-time power consumption at a specific moment, providing instantaneous insights into how the system reacts to dynamic events. On the other hand, average power is the cumulative measurement of power consumption over a period of time, offering a more generalized view of energy usage across the entire experiment.

The power consumption of the monolithic gNB with an attached USRP is measured using the GPM-8213 power meter, as shown in Fig. 4. The experiment spans a duration of $600\ sec$, with the workload generated using the iperf3 tool between the interval of $[240 - 360\ sec]$. In this setup, the *SYSTEM IDLE* state refers to the condition where none of the RAN components are operational, reflecting the baseline power consumed by the USRP attached to the gNB. During *SYSTEM IDLE*, the current power is measured at $43.8\ W$, while the average power is $43.9\ W$.

When the gNB is initially started, represented as *STARTUP gNB*, both the current and average power increase by approximately 3.5% compare to the *SYSTEM IDLE*. Following the startup, the UE association shows a minor rise in power consumption as the gNB transitions to an *IDLE* state, where power consumption stabilizes. Subsequently, a workload is generated during the *START DATA TRANSMISSION* phase using iperf3, lasting between $[240\ - 360\ sec]$. During this period, both current and average power levels rise to $45.6\ W$ and $45.5\ W$, respectively, driven by increased data traffic and the corresponding system resource allocation. The experiment concludes with the *STOP DATA TRANSMISSION*, where the power levels return to baseline as traffic diminishes.

IV. Enabled Use Cases

The architecture realized in this work enables precise measurement of energy consumption in the RAN and supports

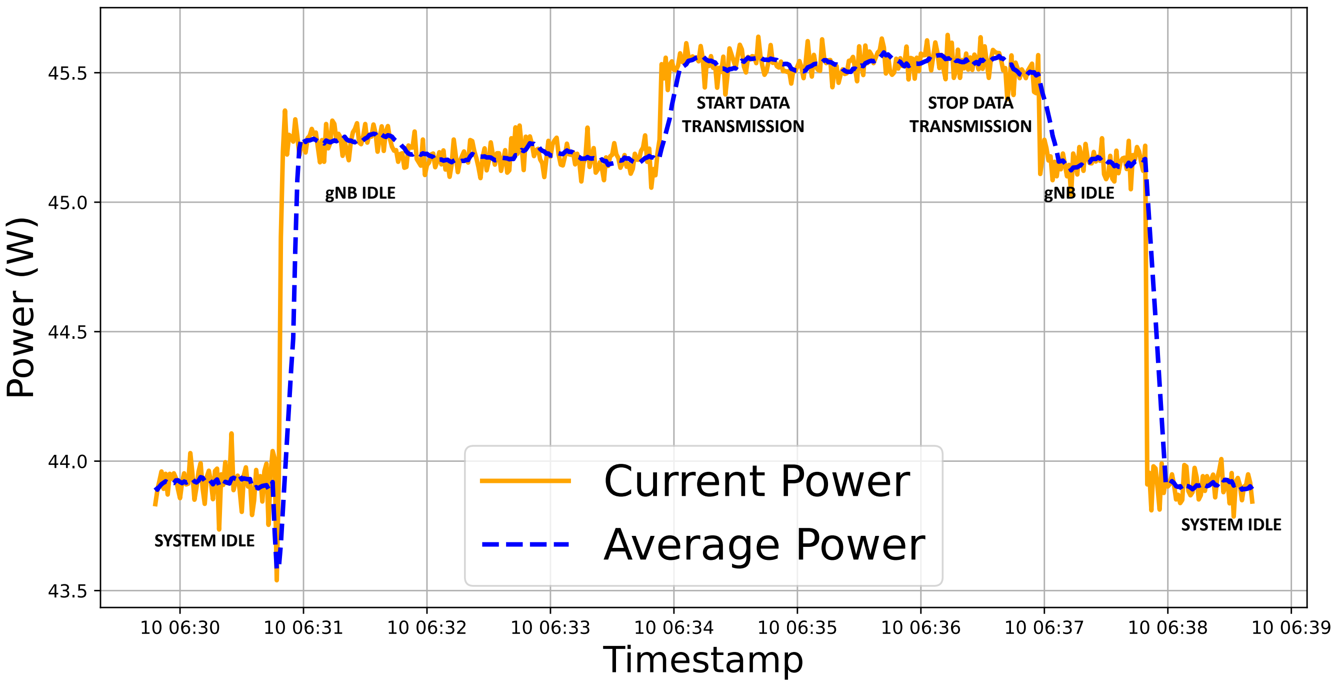

Fig. 4. Power consumption measurement using *GW Instek GPM-8213* for monolithic gNB

advanced use cases for managing next-generation mobile networks. These use cases are vital for optimizing network performance, energy efficiency, and security in 5G and beyond.

a) RAN Configuration Comparison: Our framework measures energy consumption across different RAN configurations, such as the separation of Radio Unit (RU), Distributed Unit (DU), and Central Unit (CU). By analyzing the energy associated with virtualizing these elements (e.g., vDU and vCU), operators can identify the most energy-efficient configurations. This analysis is essential for designing sustainable RAN architectures that balance performance and energy use.

b) Core Network Power Consumption Assessment: The architecture allows measurement of core network energy consumption in various scenarios: monolithic deployments where core elements are consolidated; disaggregated deployments with distributed services; and CUPS. Assessing energy in each scenario helps operators evaluate trade-offs between complexity, scalability, and efficiency, leading to more sustainable networks.

c) Energy-Aware Open Radio Access Network (O-RAN) Control: Real-time energy observation enables energy-aware network control via O-RAN interfaces. By incorporating energy metrics into decision-making, it is possible to optimize consumption through adaptive radio resource assignment and adjustments of physical parameters like bandwidth parts and numerology. This enhances overall energy efficiency while maintaining the required Quality of Service (QoS).

d) Anomaly Detection via Energy Observation: Energy consumption data stored in Prometheus can be used for anomaly detection with Artificial Intelligence (AI) and Machine Learning (ML) techniques. By identifying deviations from expected patterns, the system can detect malfunctions or cyber-attacks in real time, improving network reliability and reducing downtime.

V. Conclusions and Future Work

We developed an architecture enabling precise measurement of energy consumption in the RAN, focusing on the gNB's power usage using USRP, OAI, and the GW Instek GPM-8213 digital power meter. Our analysis identified distinct phases in the device lifecycle, allowing exact quantification of energy consumption and operational costs during data transmission. This architecture can measure energy consumption in additional mobile network scenarios, supporting use cases like RAN configuration comparison, core network power assessment, energy-aware O-RAN control, and anomaly detection via energy observation.

Future work will expand this analysis to develop automated systems that detect the energy cost per bit, enabling efficient resource allocation and reduced energy consumption. This contributes to the sustainability goals of B5G networks, offering environmental and economic benefits to operators.

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