PhD school: Comprehensive Energy Consumption Analysis in Mobile Networks: Integrating Base Station and User Equipment Measurements

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Abstract

Mobile networks have become ubiquitous in our society, with a number of subscribers surpassing the entire world population [1]. The total global mobile world traffic reached 130 EB per month in 2023, with video content representing 73% of this number [1]. At the same time, new services, with challenging networking demands, are entering the market. For example, extended reality (XR) services are expected to trigger a further increase in mobile traffic demand before the end of the decade [1].

In this context, the energy consumption of user equipment (UE) plays a major role, for two main reasons. First of all, with the information and communication technologies (ICT) sector now representing 4% of the worldwide energy consumption [1], its contribution to the climate change phenomenon can no longer be neglected. While the radio access network (RAN) equipment is generally considered the main contributor of the sector in terms of energy consumption, the 8.5 billion mobile devices actually add up to a bigger overall impact [2]. Second, with UE generally battery-powered, a certain minimum energy autonomy is required for users to enjoy the expected experience. With more complex and immersive applications being developed, such as XR, understanding and reducing the energy consumption on mobile devices becomes an important objective.

Measuring UE energy consumption can be conducted using software probes [3], or hardware probes [4], with the second being considered more accurate. However, hardware measurement campaigns in the literature [4, 5] present two significant shortcomings. First, traditional power consumption measurements are typically taken at the battery connector, which provides the overall power usage of the entire device. This method captures the total UE energy consumption, hence it can obscure the specific power usage of individual components, such as the radio frequency (RF) module. This is because the total power reading includes, in this case, the consumption of all device components, such as the screen, the processor, the memory, etc. Such a measurement setup can lead to multi-layered power patterns that mask the specific energy consumption of the RF module. The second problem comes from the fact that whenever the RF module is isolated and its energy consumption measured [6], this is done for very specific (and rather exotic) UE models.

Our work starts with the measurement on the UE side. By measuring the power consumption of the RF module of a smartphone, this work provides insights into optimizing energy use for wireless connectivity, aiming to contribute to more sustainable network designs. The methodology used is highly original, using off-the-shelf mobile phones and providing significant added value for energy consumption analysis studies. It can uncover important network power consumption patterns that would otherwise be difficult to identify and measure. The proposed methodology involves hardware modifications, requiring advanced engineering skills. Nevertheless, it proves to be highly effective, circumventing operating system (OS) limitations in software energy profiling.

To obtain accurate measurements, hardware probes were employed to directly access the internal power rails of the logic boards of specific smartphone models, allowing for precise readings without affecting the power usage itself. This ensures that the measurements reflect the RF module energy consumption accurately, without introducing artifacts from other hardware modifications. Additionally, our hardware approach provides accurate measurements of the power consumption of all RF electronic components. This allows us to conduct a unique study on energy consumption at the network level. This brings a significant advantage over software measurement tools, which provide the total energy consumption of mobile applications, including non-network-related components (screen, CPU, NAND). It is well known that these software tools are based on assumptions and models that reduce measurement accuracy.

Three smartphone models were selected for these experiments: the iPhone 12 mini (A2399 EU version), which supports 4G, 5G NSA (sub-6GHz), and Wi-Fi 2.4GHz/5GHz; the iPhone X (A1865), which supports 3G, 4G, and Wi-Fi; and the Pixel 6 Pro, an Android smartphone that supports 4G, 5G SA/NSA, sub-6GHz, and mmWave technologies and Wi-Fi 2.4GHz/5GHz. These devices were chosen to cover a wide range of network technologies across both iOS and Android platforms.

Using these smartphones, we are able to precisely measure the RF module power consumption in a variety of scenarios.

Current experiments include measuring the power consumption during video streaming and voice call services, which already highlight differences in energy usage. Additional experiments are planned to investigate other network-related functions on the devices, potentially uncovering previously unknown operations that are particularly energy-intensive on the UE side.

Energy consumption tests have already been conducted on several iPhone models, focusing on the RF module power usage during video streaming on platforms such as Netflix, YouTube, Disney+, and Amazon Prime. Our study provided a detailed examination of energy consumption across multiple Radio Access Network (RAN) technologies, including Wi-Fi (2.4 GHz and 5 GHz), 3G (UMTS 900 MHz), 4G (LTE 2100 MHz), and 5G NSA (3500 MHz). We conducted these tests using two different smartphones, the iPhone X and iPhone 12 Mini, across both commercial networks and a private cellular network setup.

By employing hardware-level power measurement techniques, we were able to obtain precise, granular data on the energy consumption of wireless network modules during video streaming sessions. Interestingly, the findings reveal that the choice of streaming platform has a more significant impact on power consumption than the underlying network technology or even the quality of the video being streamed. In fact, power consumption patterns varied significantly among platforms like Netflix, YouTube, and Disney+, suggesting that the way these applications manage network resources, buffer content, and optimize video delivery plays a critical role in the energy footprint of a mobile device.

The study encompassed nearly 50 hours of streaming sessions, offering a comprehensive look at how different application behaviors influence power consumption. These results emphasize the need for developers and service providers to optimize the energy efficiency of their platforms, as platform-specific behaviors can have a more pronounced effect on UE power usage than the RAN technology itself. These insights are particularly valuable for future research and development, guiding efforts to reduce energy consumption in mobile devices, especially in data-heavy applications like video streaming.

The second experiment focuses on measuring the energy consumption of voice call services, which represent the core functionality of RAN and the primary reason for the existence of UE. Specifically, this study examines Voice over LTE (VoLTE), Voice over Wi-Fi (VoWiFi), and Circuit-Switched (CS) voice calls across different RAN technologies, including 3G, 4G, and 5G NSA. Given that voice communication has historically been the most essential service on mobile networks, understanding its energy consumption is critical for optimizing the overall efficiency of smartphones.

Using precise hardware-based measurements, the study seeks to compare the energy consumption of each voice service type, aiming to determine which technology—VoLTE, VoWiFi, or CS—is the most energy-efficient. Additionally, the experiment explores whether there are significant differences in power usage between these voice services when operating on different RAN technologies (3G, 4G, 5G NSA).

Preliminary findings suggest that VoWiFi may offer better energy efficiency compared to other technologies, particularly in scenarios where strong and stable Wi-Fi coverage is available. However, the study remains open to the possibility that factors such as poor signal strength or high network load could reduce these efficiency gains. Moreover, VoWiFi limitations—such as its dependence on Wi-Fi range and lack of mobility support—make it less ideal for situations requiring seamless handover, where RAN-based services like VoLTE excel. Nevertheless, VoWiFi could still be an efficient alternative for indoor environments where mobility is not a concern.

Since voice call services are the most fundamental and widely used function of mobile devices, this research is essential for identifying any power-hungry operations or inefficiencies that can be optimized. By doing so, the study aims not only to improve energy efficiency for voice services but also to contribute to the development of more sustainable smartphone usage, aligned with the ongoing advancements in RAN technologies.

As part of our future work, we will shift the focus toward measuring the power consumption of base stations. This research will aim to identify the key factors contributing to energy usage at the base station level, which plays a critical role in the overall efficiency of mobile networks. While current experiments have concentrated on the energy consumption of UE, understanding power consumption at the base station is equally important for optimizing the energy performance of the entire RAN.

The planned experiments will examine power usage under different network conditions, traffic loads, and RAN technologies (3G, 4G, 5G NSA). By conducting detailed measurements across various base station configurations, the study will aim to uncover the operations that consume the most energy, whether related to high data traffic, signal processing, or network demand fluctuations.

Ultimately, the goal of this research is to obtain accurate measurements of energy consumption on both the base station and UE sides. By combining these insights, we can develop a comprehensive energy model that captures the power usage patterns across the entire RAN. This holistic approach will enable us to understand the interplay between base station operations and UE behavior, providing a complete picture of energy consumption within the mobile network.

By measuring energy consumption at both ends, we can identify inefficiencies, optimize network configurations, and enhance overall energy efficiency. This will not only contribute to lowering operational costs for network operators but also support efforts to create more sustainable telecommunication infrastructure. The findings from this research will serve as a valuable resource for stakeholders aiming to improve energy management strategies and minimize the environmental impact of mobile communications.

CCS Concepts

• **Networks** → **Network measurement**; **Network experimentation**; **Wireless access points, base stations and infrastructure**; *Network mobility*; *Mobile networks.*

Keywords

mobile networks; energy measurement; video streaming; voice calls

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