Improving Energy Efficiency in Mobile Networks: Techniques for Sustainability

Saving Energy in Mobile Systems

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***Abstract*—As mobile networks expand and user demands continue to rise, concerns about high levels of energy consumption are becoming a critical issue. Creative solutions must be developed to ensure sustainable and efficient energy performance moving forward. By exploring five core areas, this investigative paper delves into different approaches on how to improve existing technologies while examining new designs aimed at creating more energy-efficient mobile networks. Through simulations, these techniques have demonstrated significant improvements in energy efficiency over baselines. In this paper, an evaluation has been made to determine the efficiency of proposed techniques and their practicability. The findings of these techniques revealed that their utilization can remarkably enhance energy efficiency and energy savings in mobile networks, often without compromising service quality.**

Keywords—mobile networks; energy efficiency, sustainability, green technology, network design, packet processing, artificial intelligence, fog-based cloud computing

I. Introduction

Despite the numerous benefits of mobile networks, the rapid expansion and upgrading of these networks have led to a surge in energy consumption. In addition to environmental concerns, the increasing energy costs associated with mobile networks have become a challenge for network operators, and energy-efficient solutions are necessary to maintain the viability of these networks.

Moreover, energy efficiency in mobile networks has become a priority for governments and regulatory bodies around the world. Energy efficiency regulations and standards have been implemented to reduce the energy consumption of mobile networks and promote sustainable practices, of which the European Union is an example of doing this [1].

Companies and researchers in the telecommunications industry are constantly exploring innovative approaches to energy efficiency, such as optimizing network infrastructure and implementing advanced technologies. Energy efficiency is a crucial aspect of mobile networks since it has significant implications for both cost and sustainability. Reducing energy consumption results in reduced operational expenses for mobile network operators. These cost savings can then be reinvested in improving the network infrastructure, making it possible to upgrade hardware to newer generations, ultimately saving even more energy because of the techniques like the ones that will be discussed in this paper.

II. Use of Artificial Intelligence

M. Masoudi's Ph.D. dissertation, titled "Data Driven AI Assisted Green Network Design and Management" (2022) [2], focuses on the need to improve energy efficiency in mobile networks as they account for 1-2% of global energy consumption according to the author, which is expected to increase with the advent of 5G and beyond. The paper presents a two-part contribution to improving energy efficiency: AI-assisted green mobile networks and AI-assisted network architecture design and management. The first part addresses the energy consumption of base stations (BSs) by putting them into a sleep state when idle while maintaining the quality of service (QoS) for users.

The author proposes a network management framework with a digital twin to analyze and monitor risk while utilizing machine learning (ML) to make sleep mode decisions. The study shows that more than 50% of energy consumption can be saved with the proposed method. The second part focuses on network architecture design and migration to new energy-efficient architectures to meet the requirements of 5G and beyond systems. Masoudi addresses the deployment cost of different cloud radio access network (C-RAN) architectures and proposes an AI algorithm for optimal fronthaul design to minimize energy consumption while meeting user delay requirements.

The author writes that the total electricity consumption of mobile networks increased by almost 60 percent from 2007 to 2020, owing to the increasing number of devices, subscribers, services, and network expansion. With the ongoing deployment of 5G, it would therefore be highly probable that the electricity consumption will keep increasing as traffic demand does as well, with higher speeds and a larger number of devices connected.

A. *Energy savings at the base stations*

Masoudi proposes a framework for generating user arrivals based on real data and develops a deep-learning algorithm to determine the appropriate sleep mode to use at different times. The algorithm aims to maximize a reward function based on energy savings and delay reduction. Delay refers to the time it takes for user data to be transmitted between devices over the mobile network. Simulation results demonstrate significant energy savings can be achieved with the proposed approach. During busy periods or when the delay is prioritized, the algorithm tends to choose shallower sleep modes, while during low traffic hours or when energy saving is prioritized, deeper sleep modes are chosen. The author argues that compared to traditional methods like SARSA, the proposed approach performs better at saving energy with a similar priority for energy savings and minimizing delay, indicating that it is better at adapting to the dynamic nature of the network.

B. *Efficiently allocating network resources*

The author explores the design of mobile network architecture, focusing on the C-RAN architecture for 5G networks. Three main topics are covered: the end-to-end delay and power model, the cost of migrating from RAN to C-RAN architecture, and methods for improving QoS for users. The study finds that the conventional C-RAN architecture is most cost-efficient for fiber-rich network operators, while C-RAN with functional splitting can benefit fiber-short operators. Two methods for improving QoS are proposed: caching files at the edge cloud and creating customized network slices for different services.

By caching files at the edge cloud, closer to the user, it is possible to reduce content delivery delay to the users and save energy in the network by turning off extra processing units. The method optimizes the power consumption of the network by finding the best location for each file.

End-to-end network slicing involves creating multiple service-based customized networks (known as slices) on top of the same physical infrastructure and assigning end-to-end resources to each slice. The author writes that by customizing each network slice to meet the specific QoS requirements, it is possible to optimize the use of resources and reduce overall energy consumption. Masoudi concludes that end-to-end network slicing can save more energy compared to only RAN slicing.

C. *Discussion and limitations*

The need to improve energy efficiency in mobile networks is highlighted in Masoudi's research. Masoudi's research offers a practical solution to reduce energy consumption while maintaining QoS by proposing AI-assisted frameworks for green mobile network design and management. While the research shows promising results, some limitations and challenges need to be addressed. For example, the proposed frameworks may require significant computational resources and may not be suitable for all types of mobile networks. There may also be trade-offs between energy savings and QoS, particularly during busy periods or for certain types of services.

III. MOBILE FOG-BASED CLOUD

While many studies have focused on optimizing network infrastructure and cloud computing, it is also important to consider the energy efficiency of the devices that enable this connectivity. Mobile devices are ubiquitous and play a critical role in accessing and processing data. However, their limited battery life often limits their utility. In this context, exploring energy-efficient solutions for the Internet of Things (IoT) is an important research area that can have a significant impact on both individual users and the wider network ecosystem.

Mobile fog-based cloud (MFBC) computing is a popular framework for the IoT that allows for fast and cost-effective data sharing while reducing network traffic loads and latency. However, the environments for mobile fog-based clouds are constantly changing, leading to unpredictable energy consumption and a loss of control for fog cloud providers. The article "Energy-efficient and secure mobile fog-based cloud for the Internet of Things" (2022) [3] proposes a solution to address these challenges; as the authors write it, an energy-efficient and secure hybrid algorithm (EESH) for the MFBC to support the IoT. The authors continue to describe that the EESH algorithm utilizes a voltage scaling factor to reduce energy consumption. It is further secured with a malicious data detection algorithm (MDD) using blockchain technology to protect the identity of mobile cloud users. The article also analyzes and improves the performance of processors on the server side of the MFBC and compares the performance of the proposed algorithms with that of known algorithms in terms of security, energy efficiency, throughput, and latency.

The authors describe that the proposed solution for an energy efficient MFBC system requires different operational levels to increase energy efficiency and successful job scheduling. The system involves several modules: energy consumption, MFBC power, minimum task scheduling, and malicious data detection using blockchain technology. The authors explain that the energy consumption module focuses on the hardware-level devices, and the states of MFBC energy consumption involve static and non-static energy consumption. They write that its energy efficiency can be determined using a formula that considers the total capacity of the MFBC, the number of requests, and the response from the MFBC. The authors continue to explain that the MFBC power module estimates the power of the system, which depends on the number of functional fog servers, cloud servers, and mobile users connected. The power module also computes the power consumption of each active virtual machine (VM). The minimum task-scheduling module aims to minimize the make-span completion time by assigning the task set to a VM. Parallel VM scheduling is used to execute the tasks in parallel to minimize the entire execution time, according to the authors.

The article presents the results of a study comparing the proposed EESH algorithm with contending algorithms such as WEED, DAP, PFBS, HFCC and FLRPE in terms of performance optimization goals related to energy efficiency, latency reduction and secure communication. The results of a performance analysis show that the EESH algorithm consumes the least energy of all the mentioned algorithms, consuming

379.5 J in 72 hours compared to the least energy-efficient algorithm WEED, consuming 471.2 J in 72 hours.

A. Discussion and limitations

For energy efficiency in mobile fog-based cloud computing, the solution provided in the article is appropriate for larger packet sizes and longer service durations. However, as the authors claim themselves, the proposed EESH algorithm may not show optimal results in transactions of smaller packages and shorter durations. Nevertheless, in today's high-speed global internet where large amounts of data are sent constantly, the algorithm proves to be energy efficient according to the authors' studies. Integration of these techniques in IoT solutions and the larger global internet may contribute to significantly reduced energy consumption, lower costs, and better QoS for users.

IV. Packet processing, micro-sleeps, and hardware offloading

Ericsson researchers P. Holmberg, L. Johansson, and R. Skog propose a new method to reduce energy consumption in communication service providers' networks in their article "Energy-efficient packet processing in 5G mobile systems" (2022) [4]. The authors explain that there are existing energy-saving mechanisms that a communication service provider (CSP) may use to reduce energy consumption in their networks. Upgrading to hardware (HW) that consumes less energy than the previous generation is one of them. In addition, the authors clarify that regardless of the energy-saving mechanism it is essential that there is no negative impact on real-time characteristics such as jitter and packet latency. However, the researchers' latest findings suggest that micro-sleeps in packet processing nodes can save additional energy in CSPs' data centers while still having better performance than existing methods, even at high loads.

The researchers state that the effects of micro-sleeps are notably significant in the user plane function (UPF), which main purpose is to forward packets to and from the internet. They reference the definition of UPF in 3GPP, stating that the UPF links the RAN to the internet (or similar networks).

A. Two methods of packet processing

The authors discuss two methods of packet processing. Kernel packet processing and kernel-bypass packet processing, and their impact on energy efficiency. The authors state that kernel packet processing is a built-in, native networking support implemented as part of the operating system (OS) kernel, which uses the POSIX socket as its standard application programming interface (API). They write "In kernel packet processing, user-mode application programs use the POSIX socket API to send and receive packets, while the kernel driver/scheduler handles the interaction with the network interface card (NIC)". The authors continue to explain that this method has several disadvantages, including high overhead of the OS calls and copying of packets to and from kernel space, making it hard to scale to high networking speeds and high packet rates. The researchers state that it is also challenging to perform power management in the kernel at high networking speeds. Kernel-bypass packet processing eliminates kernel execution overhead by moving packet processing directly to user space. The authors detail that this method involves the use of the Data Plane Development Kit (DPDK), where packets are received directly in user-space memory without kernel interaction, and all network-related interrupts are disabled. They explain that a DPDK-based application checks the packet ring buffer in busy-waiting mode, where the complete core is assigned to the application thread to avoid packet drops and reduce packet latency. However, it seems that the busy-waiting technique of packet reception consumes more power than necessary when waiting for work. The authors write that to solve these issues, power management actions must be fast, controlled directly from the packet processing application, and executed in user mode. They elaborate that this is possible because "server processors now have support for entering power-saving sleep states directly from applications in user mode". The authors explain that the latest release of the DPDK library at the time of writing includes options to avoid problems associated with the busy-waiting loop.

B. Hardware offload and power management

The article also discusses the hardware offloading technique used to achieve energy efficiency in packet processing. It explains that the technique involves transferring the handling of selected flows from the processor to the NIC. The authors state that the technique frees up CPU cores, allowing for more effective use of micro-sleep technology. Additionally, the authors write that a complementary method for "achieving the best efficiency over longer periods of lower processing" is scaling down CPU core voltage and frequency when the packet rate drops for a period. They present the results showing that the two sets of experiments indicate that the power-saving methods are stable and efficient, with negligible impact on packet latency even in worst-case conditions. According to the authors, the experiments used synthetic benchmarks and realistic workloads to measure the energy gain when using HW offload and power management. They conclude that the techniques resulted in a significant reduction in processor power consumption, with potential energy savings of up to 68% at idle load and up to 24% at maximum load. The authors state that no packets were dropped during the measurements.

C. Discussion and limitations

As techniques for saving energy in mobile networks are continuously researched and improved globally, the Ericsson researchers' solutions in this article may be a valid addition. The use of periods of sleep in HW seems to be a recurring method, and the challenge is in making it work with different parts of the network while also maintaining QoS. In this article, the proposed way of potential energy savings is the combination of three things. Micro-sleep, hardware offloading, and frequency scaling. The authors' results of tests with the proposed solutions indicate a pronounced improvement in energy efficiency compared to existing methods. Therefore, we can argue that versions of sleep periods in HW will most probably be continued to be researched and implemented in real-time network solutions.

V. MOBILE AD-HOC NETWORKS

According to Wikipedia, a mobile ad-hoc network (MANET) is a de22 type of wireless network that has no pre-existing infrastructure. A MANET is dynamically structured and self-organizing with nodes forwarding data as per the routing algorithm used and network connectivity [5]. Achieving better energy efficiency in MANETs is a relevant topic to the paper as a whole as it expands the scope of our analysis beyond traditional cellular networks. As MANETs can provide ad-hoc network connectivity, it is important to consider their energy efficiency as they may be used in situations where traditional networks are unavailable or unreliable. Energy efficiency in MANETs is closely related to the battery life of mobile devices which ties directly to sustainability because of the tear-down of batteries.

In the article "Improving the Energy Efficiency in Mobile Ad-Hoc Network Using Learning-Based Routing" V. Aroulanandam et. al. propose a solution for improving the efficiency of energy consumption in MANETs (2020) [6]; a combination of the two supposedly incompatible methods Dynamic Range Clustering (DRC) with Learning-based Routing (LR). The authors explain that in a mobile ad-hoc network the devices move around freely within a certain area.

Therefore, because of the dynamic nature of the devices, the network faces challenges related to scalability and data transmission. The authors write that clustering is used to address these challenges, a technique where the devices are divided into small groups called clusters. Each cluster has a cluster head (CH) and cluster members (CM). The CH is responsible for communication, scheduling, and maintaining the network's endurance.

A. Dynamic range clustering

The first part of the authors' solution simplifies clustering and introduces range. According to the authors, dynamic range clustering (DRC) simplifies the collection of CHs across a set of learning processes. They write that the algorithm does this by using a neural network evaluation for the optimal selection of CHs and determining the number of CMs required to handle the network traffic. The authors state that "two explicit and hidden constraints are applied for each of the learning iterations performed", and that they "are assessed using neighboring density and use of bandwidth". Additionally, the authors consider the energy expenditure of the CH as a dependence factor, using the average energy of the cluster members to determine if the CH has enough energy for the communication process. The range of the CH is variable, and it depends on the number of nodes involved in the communication with the minimum and maximum hops between the nodes being updated based on the availability of energy. They use a weight function to resolve inequalities in the decision of the CH node.

B. Learning-based routing for efficient load balancing

The second part of the authors' solution is using learning-based routing (LR) for efficient load balancing in the network. It is important to ensure that network resources are used efficiently and that no one node or path becomes overwhelmed with traffic. The authors motivate the proposal of learning-based routing to "reduce the disadvantages of data dissemination". The LR scheme uses a transmission matrix to schedule transmissions and prevent congestion and considers the probability of packet loss to communicate with available neighbors. The authors write that the learning process is repeated until a node is categorized as optimal, and the process is updated before the next communication begins. If a node fails to learn, "the next set of neighbors is identified through a news broadcast". LR aims to reduce the disadvantages of data dissemination and improve energy efficiency by avoiding inadequate or defective load handling that degrades network resources and output.

C. Results of simulating the DRC-LR solution

The article includes a table of the simulation parameters and values. Some include the following:

- Network region: 1000m x 1000m
- Range: 250m
- Packet size 512kb
- Simulation time 300s

The simulation is run with three other clustering methods than DRC-LR. As the authors reference them: REA-MAODV, QUACS, and EE-MBOC. The results of the simulations show that the proposed DRC-LR method outperforms QUACS and REA-MAODV in terms of remaining energy, with the remaining energy in them being 42.66% lower and 18.27% lower than that in DRC-LR, respectively.

D. Discussion and limitations

Judging by the simulations and comparison results, the proposed solution of combining DRC and LR shows to be substantially more effective compared to the other mentioned methods. In the simulations, the authors gathered data about more than just energy efficiency; however, the energy information is of most relevancy to this paper, so the other data will not be presented. The positive results of DRC-LR outperforming other clustering methods in terms of remaining energy raise questions about the implications of these findings. One question is how they might be applied in real-world MANETs. It could also lead to discussions about the limitations of the simulations and the need for further research to validate the findings of the researchers in the article.

The authors of the article highlight that achieving better energy efficiency is a relevant topic for analysis. In situations where traditional networks are unavailable or unreliable, MANETs may be a choice for communications. In those cases, energy efficiency is of utmost importance, considering that mobile devices rely solely on batteries.

VI. INSIGHTS FROM A LARGE TELECOM COMPANY

The sources discussed previously in this paper are research papers; they are proposals for solutions for improvements in existing technology and new innovative ideas to reduce energy consumption in mobile networks. An interesting discussion of the subject is how these types of solutions are implemented in real-time network infrastructures. Therefore, an inquiry was sent to a leading company in the telecommunications industry. Headquartered in Germany, Deutsche Telekom is an Internet Service Provider (ISP), with a presence in many European countries. According to Wikipedia, Deutsche Telekom is the world's 3rd largest telecom company by revenue [7].

The inquiries sent were the following:

- Can you describe Deutsche Telekom's approach to energy efficiency in its mobile network infrastructure, including any specific techniques used?
- What measures does Deutsche Telekom employ to ensure both energy efficiency and high levels of quality and network reliability in its mobile network operations?
- Can you provide any information about current or upcoming projects or initiatives aimed at enhancing energy efficiency in Deutsche Telekom's mobile networks?

Answering the inquiries was the Team Group Corporate Responsibility of Deutsche Telekom (DT). They recommended DT's Corporate Responsibility Report of 2022 and a recent presentation that they held about sustainability within the company's operations. It is understandable that the company cannot directly provide advanced technical information about its network solutions as that would probably be against limitations on disclosure and confidentiality. Despite not receiving detailed information about the solutions, it is still relevant to discuss the public information available on Deutsche Telekom's company website, which was recommended by the Team Group Corporate Responsibility via e-mail.

The company had a Sustainability Day in October 2022 – where a lot of interesting information about the company in relation to sustainability was presented [8]. During the presentation, a Board Member by the name of Srini Gopalan talked about DT's energy in networks. Gopalan explains that the energy used in DT's networks worldwide has been 100% green since 2021. Furthermore, Gopalan mentions that DT is working hard toward reducing energy consumption, considering that there is a 25% growth in data consumption every year. One of the most impactful ways Deutsche Telekom will work to reduce energy consumption is by retiring old technology and modernizing to more digital less energy-intensive platforms. Gopalan also mentions that the company over the next decade will scale its solar panels to meet roughly 10% of the energy requirements for the network.

In the 2022 Corporate Responsibility report of Deutsche Telekom section "Energy consumption & efficiency" [9], the writers mention that since 2016, they have reported on "Energy Intensity" in addition to "Energy consumption". The reason behind this is that the total energy consumption increases by a small percentage every year. Energy intensity shows "energy consumption in proportion to the transmitted data volumes". Therefore, a fair assumption about energy intensity is that it is tied to energy efficiency. Lower energy intensity means higher energy efficiency. The company reported an energy intensity of 91 kWh/Terabyte in 2022, 102 kWh/Terabyte in 2021, 119 kWh/Terabyte in 2020, and 119 kWh/Terabyte in 2019.

The writers explain that DT is pursuing various approaches to ensure energy-efficient networks; removing equipment they do not need, such as 3D antennas which were turned off in Germany on June 30, 2021. Also, removing legacy systems and replacing them with newer, more energy-efficient technologies. Furthermore, the writers explain that Deutsche Telekom is aiming for better energy efficiency and stabilization of energy consumption by 2024, despite their network expansion. A technique they propose to optimize energy in mobile networks is developing innovative solutions for generating and storing renewable energy for use at mobile base stations.

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