engineering proceedings

MDPI

Proceeding Paper

Energy-Saving Techniques in the Next Generation of Mobile Communication Networks †

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† Presented at the 2nd International Electronic Conference on Processes: Process Engineering—Current State and Future Trends (ECP 2023), 17–31 May 2023; Available online: https://ecp2023.sciforum.net/.

Abstract: The generalized integration of new communication technologies is expected to improve the lives of humans and edge us closer to achieving the Sustainable Development Goals in the next ten years. People will benefit from the rapid exchange of information, high-speed data transfer, the high-quality protection of uploaded and transmitted information, greater accessibility to medicine, the development of smart cities and homes, etc. But there are factors that significantly hinder the spread of fifth-generation mobile networks, the most critical being the high energy consumption that comes with the rapidly growing number of devices, machines, and mobile subscribers. Most often, base stations always operate at full capacity, but there are statistics that show that the flow of base station clients is not always the same, so energy consumption may be managed. It was found that cell zooming algorithms that mostly consider client flow can save 14–80% of base station power consumption; however, not all studies pay attention to the quality of service. By balancing energy saving and the quality of service, base station energy savings of about 15% can be achieved. In modern research, dynamic network scaling algorithms are more often presented, and location management investigation has been identified as a solution that can help improve energy-saving techniques and keep the quality of service at the optimal level.

Keywords: energy efficiency; energy saving; cell zooming; traffic load; green wireless communication; 5 G

Citation: Kapustynska, V. Energy-Saving Techniques in the Next Generation of Mobile Communication Networks. *Eng. Proc.* **2023**, *37*, 97. https://doi.org/10.3390/ECP2023-14722

Academic Editor: Kuo-Lin Huang

Published: 25 May 2023

1. Introduction

Research conducted by mobile communication organizations such as Ericsson and the Next-Generation Mobile Networks (NGMNs) Alliance has demonstrated a growing trend in the number of mobile application users and subscribers. Consequently, the number of base stations required to cater to the growing user base is increasing, leading to the necessity of power conservation and meeting key performance indicators to ensure the quality of service and the quality of the user experience. Multiple scientific investigations have validated the feasibility of managing power consumption in a base station, and several effective techniques have been proposed to achieve this aim.

This literature review aims to present an analysis of the existing research related to energy-saving techniques in NGMNs, with a focus on traffic-driven cell zooming and advanced sleep modes that consider the impact of traffic load.

The present review is divided into the following sections. At the outset is a detailed summary of the prevailing trends in NGMNs and their impact on the energy efficiency of mobile networks. Subsequently, we present two key energy-saving techniques that consider the described traffic load, alongside conclusions on their effectiveness based on an analysis of the pertinent scientific literature. Finally, the paper concludes with a succinct summary of the key findings.

Overall, this literature review aims to provide an understanding of the latest research in energy-saving techniques in NGMNs. The identification of the principal trends and gaps in the existing literature serves as a potential roadmap for future research in this field.

2. The Present State and Future Prospects of Next-Generation Mobile Networks

According to Ericsson's Mobility Report [1], long-term evolution (LTE) in telecommunications has become the predominant technology in Central and Eastern Europe, comprising 75% of all mobile subscriptions as of 2022. Projections indicate that LTE will remain the dominant technology in that region, accounting for 56% of mobile subscriptions by 2028, while 5G subscriptions are estimated to constitute 43%. In contrast, the implementation of 5G technology in Western Europe is occurring at a faster rate, with an estimated 88% of all mobile subscribers expected to utilize 5G, while 12% are expected to use LTE.

Huawei's annual report [2] predicts that by 2030, there will be 200 billion global connections, of which around 100 billion will be wireless connections, including passive cellular connections, while the other 100 billion connections will be wired, Wi-Fi, and short-range connections. The industrial sector will account for a large portion of these connections, consisting of various sensors such as pressure, photoelectric, temperature, and humidity sensors, as well as intelligent cameras, autonomous vehicles, drones, and robots. To support the increasing number of connected devices, industrial networks will need to adopt universal broadband technologies that can replace different narrowband technologies, providing high-speed, reliable, and low-latency connectivity to various devices and applications.

The impact of mobile networks on global electricity use and carbon emissions is relatively small—0.6% and 0.2%, respectively—but the industry faces challenges in managing energy use, costs, and carbon emissions due to the need for constant network expansion. However, Ericsson believes that 5G can be scaled up while reducing overall energy consumption.

According to [3], about 60% to 80% of the energy consumed by wireless mobile networks comes from base stations (BSs). The NGMN Alliance reported [4] (p. 15) that the primary equipment consisting of a radio unit, baseband, and the main control is the biggest power consumer at a site, accounting for roughly 50% of the total power consumption. Air conditioning is the second biggest power consumer, representing around 40% of the total; the radio processing component is also responsible for 40%. This component converts the digital signal from the baseband into amplified radio waves. As the power amplifier in the radio unit consumes the most power, it is the primary determinant of the unit's efficiency.

An analysis of emerging trends in NGMNs suggests that improving the energy efficiency of base stations is critical due to their high energy consumption in mobile networks. As base stations operate at maximum power continuously, it is essential to investigate energy-saving technologies that optimize energy usage based on traffic load analysis.

3. Sustainable NGMN: A Survey of Energy-Saving Techniques

According to the findings of the NGMN Alliance [5] (p. 6), there are numerous organizations that assess either the performance and user experience delivered by a particular network operator (referred to as "performance benchmarks") or the wider environmental, social, and governance (ESG) and sustainability standards without considering the particular service they offer.

Disregarding quality-of-service considerations in favor of enhancing the energy efficiency of a network is not an optimal strategy. The importance of quality of service (QoS) in real-time applications cannot be overstated, as even slight deviations from the expected level of performance can result in a significant degradation in the quality of a user's experience (QoE).

Several energy-saving techniques use traffic load analysis to achieve the optimal QoS and improve energy efficiency in BSs. These techniques include user association, traffic variation, cell load, cell zooming, and on–off switching control, as shown in Figure 1.

Additionally, other techniques from Figure 1 can also impact the energy efficiency of the base station.

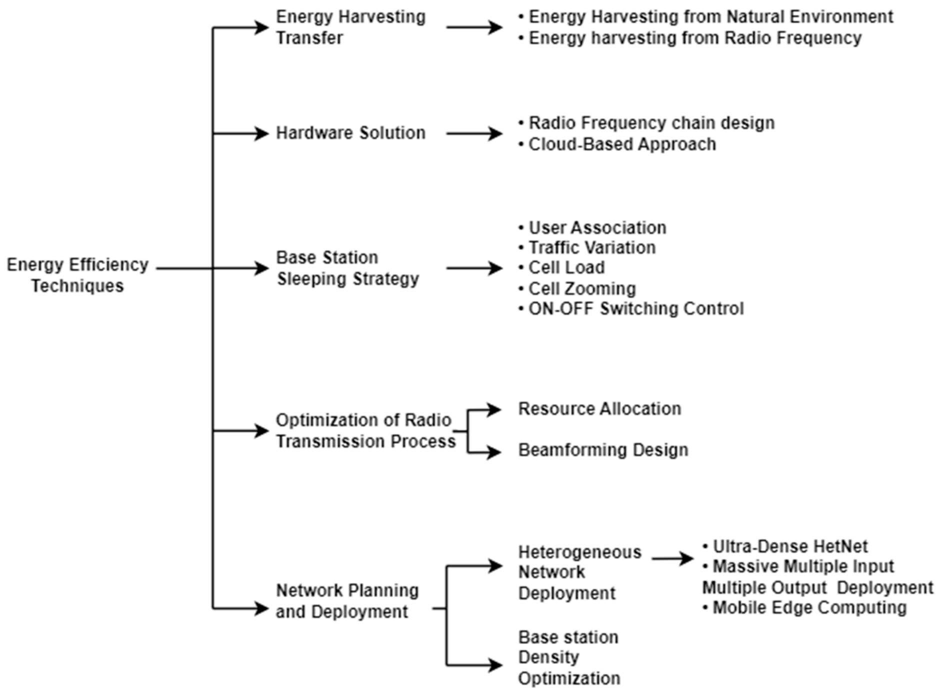

Figure 1. Illustration of energy efficiency techniques. Note: adapted from [3].

The effectiveness of energy-saving techniques may depend on network deployment characteristics, traffic patterns, and optimization algorithms. Therefore, comprehensive evaluations are necessary before deploying them in production environments.

3.1. Traffic-Driven Cell Zooming

Cell zooming is a system-level technique that can be implemented within a geographical area served by multiple base stations without requiring any hardware changes. It involves adjusting the size of cells based on the network's traffic load and user needs. This energy-saving technique monitors the network's traffic load and enables cell zooming when the load falls below the set traffic threshold to reduce the power consumption of the base station. However, if the load exceeds the threshold, cell zooming is not enabled to avoid compromising the QoS.

Cell zooming algorithms can be classified into two principal categories based on their fundamental similarity: regular or static switch-off algorithms and dynamic switch-off algorithms. In regular algorithms, cells are switched off in a predefined pattern by the network control server during a predefined time period when low traffic arrival is expected [6]. However, the limitation of this algorithm is that it cannot be used for full-day operation, where time-dependent traffic fluctuation and traffic spatial distribution are high or when traffic arrival patterns are inconsistent day by day. Despite these limitations, the regular switch-off algorithm is advantageous due to its simplicity and power-saving benefits during low-traffic hours.

Dynamic algorithms involve the real-time monitoring of traffic conditions and sharing that information among collaborating base stations to make decisions about cell zooming. This can save power and solve traffic congestion problems if they occur. Dynamic algorithms can be implemented in a distributed or centralized plan. However, the challenge in dynamic switch-off algorithms is how to manage the requirement of massive information exchange among mobile users, base stations, and control servers [6].

In work [7], a traffic-driven cell zooming strategy was implemented in a homogeneous network, which regulated the radiation radius of an individual base station to reduce the energy consumption. The proposed algorithm adjusts the number of base stations (BSs) in a cluster based on real-time traffic load, switching off BSs with no traffic to achieve zero dynamic power consumption while ensuring service quality. When traffic increases, neighboring cells handle it until a control signal triggers a switched-on BS. The transmitted power is increased, extending the cell radius. Compared to the business-as-usual scenario, the algorithm is more energy-efficient, balances load, and maintains coverage and service. This traffic-driven cell zooming saves energy and resolves load imbalances [7]. The power consumption saving was measured in a real-time environment and found to be 20%, confirming the previously simulated results, which showed that an energy saving of 14.4% could be obtained. The author mentions that load balancing is the key task in cell zooming.

3.2. Advanced Sleep Modes

The implementation of sleep modes represents a means of reducing power consumption, as it does not necessitate any alterations to the underlying hardware. Consequently, this technique can be readily deployed on existing architectures, facilitating its widespread adoption.

As indicated in [8], the sleep mode approaches aim to conserve energy by observing the network's traffic load and determining which network components to power off or on. By implementing such sleep mode techniques, wasteful energy consumption such as running air conditioning in underutilized BSs can be prevented. These approaches typically entail toggling various components—including, but not limited to, power amplifiers, signal processing units, cooling equipment, entire BSs, or the entire network—between sleep mode and active mode.

On a research level, four different levels of sleep modes, called advanced sleep modes (ASMs), can be extracted. The ASMs are exclusively determined by the time it takes for the BS's components to transition, but there is no clarity on the duration of sleep for individual components. In [9], it was assumed that the minimal sleep duration in each sleep level is in the same time scale of the transition time corresponding to that level, and that both the activation and deactivation delays are half of this transition time. These ASM levels are shown in Table 1.

Table 1. Sleep mode levels with minimum sleep time and depth required for their activation [9].

Level of Sleep	Description	Sleep Time (min. Duration)
SM_1	Primarily deactivates the radio unit power amplifiers.	71 µs
SM_2	Deactivates more BS components that may be retrieved from the radio frequency (RF)-integrated circuit or from the digital processing unit.	1 ms
SM_3	Foresees the deactivation of more BS components than both the previous levels for a longer duration. Similar to the second level, the components to switch off at this level may be retrieved from the RF-integrated circuit or from the digital processing unit.	10 ms
SM_4	This level of sleep mode foresees the deactivation of more BS components than all the previous levels. This level of sleep typically cannot be used without a loss of connectivity.	~1 s

As was shown in work [10], the energy consumption can be reduced up to 90 % while there is very low load. However, the delay increase may be up to 5 ms, which is critical for some 5G use cases. For this reason, a delay-sensitive orchestration of the different ASM levels is needed in order to determine how much each of them is allowed to be used depending on the length of the idle periods of a BS and according to the network operator's needs with respect to latency [9].

In work [11], a self-adaptive sleep and wake-up scheduling approach for small BSs was proposed. The author suggests that the current approach to network power saving is not significant due to active small cells in distant areas from the macrocell, and proposes a new approach that combines adaptive small-cell expansion and a small-cell sleeping mechanism to use range-expanded small cells to cover the traffic system from nearby sleeping small cells in the edge area of the macrocell and save more power. This differs from existing small-cell sleeping mechanisms, where all the traffic from a sleeping small cell is handed over to the macrocell to decrease power consumption.

3.3. Hybrid Energy-Saving Technique

While both cell zooming and sleep mode techniques are effective at reducing energy consumption, they can also have an impact on the QoS provided by the network. For example, cell zooming can lead to increased interference in neighboring cells, while sleep modes can result in delays when devices need to be reactivated. To overcome these challenges, some researchers have proposed combining cell zooming and sleep modes to achieve network energy efficiency while maintaining the QoS. This can be carried out by dynamically adjusting the size of cells based on user demand and activity levels, and putting idle devices into sleep mode when they are not needed.

In a more recent study [12], a power consumption model as a function of the traffic was developed for macrocell base stations based on measurements on an actual base station. This model allows developing energy-efficient wireless access networks using the author's green radio access network design (GRAND) tool, which develops an always-on network with minimal power consumption for a predefined area, and an algorithm that introduces sleep modes and cell zooming to reduce power consumption. Green field deployments and the optimization of existing networks were investigated. It was found that introducing sleep modes and cell zooming in a network can reduce the power consumption by up to 14.4% compared to networks without sleep modes and cell zooming. Optimizing existing networks by applying the GRAND tool (without sleep modes and cell zooming) results in a power consumption reduction of 34.5% compared to the original network. The authors conclude that, for forthcoming network implementations, supporting sleep modes and cell zooming techniques is advisable. In addition, future research should consider incorporating adaptive capacity demands to further optimize network performance.

The authors of [13] propose a joint cell zooming and sleeping strategy for a downlink two-tier heterogeneous network modeled under the Poisson point process. The cell zooming scheme uses game theory to adjust the cell zooming factor, improving the association probability of each BS and allowing more users to connect to a micro-BS instead of a macro-BS, resulting in a better network experience. The two-step sleeping strategy includes analyzing the energy consumption of candidate base stations to ascertain which ones are kept and measuring the overall overlapping degree of each base station to make different sleep decisions based on the radius of the area covered by the MBS, resulting in more energy savings. The proposed strategy balances user benefits and communication system operating costs. The simulation results demonstrate an enhancement in both QoE and energy savings.

Overall, the combination of cell zooming and sleep mode techniques has the potential to significantly reduce energy consumption in wireless networks while still providing a high-quality service to users.

4. Summary

This literature review discusses the current state and future prospects of next-generation mobile networks (NGMNs) and describes energy-saving approaches for base stations (BSs). The review highlights cell zooming and sleep modes as effective algorithms for reducing energy consumption by up to 20% on real equipment, but also mentions their limitations. Based on the literature analysis, combining these techniques can help address these limitations, with load balancing being a key task in cell zooming. The approach that combines adaptive small-cell expansion and the small-cell sleeping mechanism is a possible method worthy of further research.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

Conflicts of Interest: The author declares no conflict of interest.

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