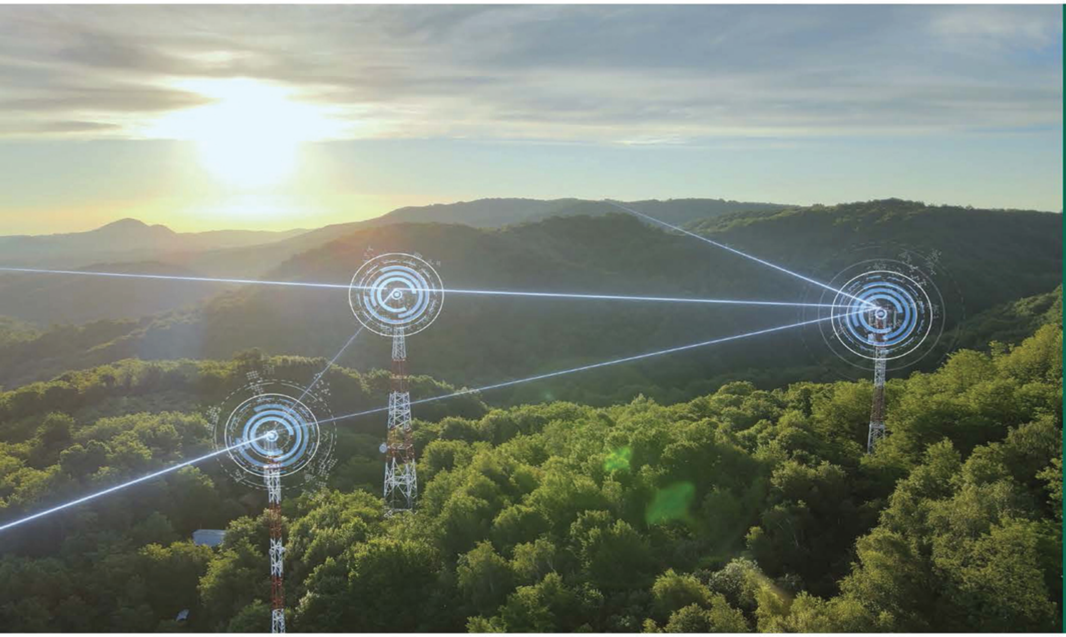
# Improving the Energy Efficiency of Mobile Networks

## Strategies for 5G and 6G Technologies



Josip Lorincz and Zvonimir Klarin

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# Improving the Energy Efficiency of Mobile Networks

This book provides an analysis of the problem of high energy consumption of mobile networks and describes methods for improving the energy efficiency of mobile networks. It explores new technologies and strategies that will enable mobile networks to operate with less energy and become more sustainable while not compromising service quality.

*Improving the Energy Efficiency of Mobile Networks: Strategies for 5G and 6G Technologies* is designed to help readers understand how to optimize energy consumption in mobile networks. It explores technical solutions for reducing the energy consumption with a focus on innovative solutions such as network energy consumption optimization using artificial intelligence (AI) in the management of network resources, energy harvesting (EH), software-defined networking, renewable energy sources, and implementation of advanced techniques and protocols for improving the energy efficiency of mobile networks. The book analyzes how the integration of different advanced technologies, network function virtualization, and non-orthogonal multiple access techniques, along with the implementation of AI, renewable energy sources, and EH, can contribute to the optimizing energy use of mobile networks, without compromising network performance. It offers an overview of concrete solutions, with an insight into future directions of development, which makes it particularly relevant at a time when industry is increasingly moving toward sustainability and the implementation of green technologies.

This book is ideal for researchers, industry professionals, and scholars who want to gain a deeper understanding of the excessive mobile network energy consumption and contribute to the development of energy-efficient and sustainable mobile networks.

# Improving the Energy Efficiency of Mobile Networks

## Strategies for 5G and 6G Technologies

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# *Preface*

The rapid evolution of mobile networks has placed improvement of mobile network energy efficiency at the forefront of research and technological development. With the increasing demand for higher data rates, lower latency, and seamless connectivity, mobile networks have expanded significantly, leading to a rise in energy consumption and environmental concerns. Today, mobile communication networks account for a substantial share of global electricity consumption, with user devices, base stations, and other network elements contributing to a growing carbon footprint. As the world moves toward sustainable digital transformation, optimizing energy use in mobile networks has become a global imperative. Governments, regulatory bodies, and industry stakeholders are emphasizing the need for green and energy-efficient mobile network implementations.

This book provides a comprehensive overview of strategies, technologies, and innovations aimed at improving the energy efficiency of mobile communication networks, particularly in the context of 5G and future 6G technologies. By exploring both foundational principles and emerging trends, this book serves as a guiding resource for addressing the energy sustainability challenges of mobile networks, while ensuring that future mobile networks remain high-performing and resilient.

Intended for scientists, scholars, practitioners, and professionals, this book serves as a valuable resource for understanding the challenges and advancements in energy-efficient mobile network design and implementation. It is structured to provide both theoretical foundations and practical insights, encouraging further research and innovation in this critical area.

The first chapter of the book, “Introduction to the Problem of Excessive Mobile Network Energy Consumption,” outlines the key motivations for improving mobile network energy efficiency, addressing environmental sustainability, operational costs, regulatory requirements, and technological advancements.

The second chapter of the book, “Evolution of Mobile Networks,” explores the transition from the first-generation (1G) to the future sixth-generation (6G) networks, emphasizing the role of heterogeneous networks, millimetre-wave technologies, and artificial intelligence in shaping next-generation networks.

Chapter 3 of the book, entitled “Energy Efficiency of Mobile Networks,” defines the metrics, factors, and standardization efforts related to energy efficiency in mobile communication networks. It also examines the impact of network interference, latency, spectral efficiency, and traffic variations on energy consumption.

Chapter 4 of the book, entitled "Optimization of Mobile Network Energy Consumption," presents various techniques for reducing mobile network energy consumption, including base station sleep mode strategies, intelligent base station transmit power control, massive multiple-input multiple-output technologies, cognitive radio techniques, and cloud-based radio access network architectures. Additionally, Chapter 4 discusses energy harvesting and renewable energy integration in the power supply of mobile networks and the impact of network slicing on the energy efficiency of mobile networks. The chapter ends with analyses of the impact of satellite-based mobile network constellations and reconfigurable intelligent surfaces on energy consumption improvements of mobile networks.

The final book chapter, "Future Challenges and Opportunities," explores emerging trends in mobile network energy management, such as AI-driven network optimization and the sustainability of 6G networks, emphasizing the importance of interdisciplinary collaboration and innovation in shaping the future of sustainable wireless communication. The final chapter provides a forward-looking perspective on the next generation of mobile networks, particularly in the transition toward 6G technologies and the global push toward carbon-neutral mobile networks.

This book is designed as an overview resource, aiming to illuminate new research directions in the field of energy-efficient mobile networks. By bridging theoretical advancements with practical implementations, it provides a foundation for further innovation, ensuring that future networks are not only high-performing but also sustainable.

# 1

# *Introduction to the Problem of Excessive Mobile Network Energy Consumption*

Regardless of a country's economic status or an industry sector's level of development, enhancing mobile network energy efficiency (EE) contributes to a global reduction in energy consumption (EC) and greenhouse gas (GHG) emissions. Achieving these reductions requires the effective implementation of information and communication technologies, which serve as a fundamental tool for driving EE improvements across all countries or industry sectors worldwide. The rapid proliferation of connected devices in the modern digital era, especially smartphones and Internet of Things (IoT) devices, has resulted in significant changes in the architecture and performance requirements of wireless communication networks. As a consequence, the operators of wireless communication networks now face the challenges of managing the problem of growing EC of mobile cellular networks.

One of the main reasons for this growth of network EC is due to the increase in the number of connected user devices, which also imposes numerous operational challenges for wireless communications networks. Smartphones as an example of typical user devices transfer significant amounts of data through mobile application updates, real-time video streaming, social media services, and other various user activities on the Internet. In addition, IoT devices are constantly collecting, processing, and transmitting data, thus increasing the need for the capacity of mobile networks. The Ericsson Mobility Report [1] predicts that by 2030 the number of IoT devices will reach 42.9 billion, while the number of mobile phone subscribers will exceed 9.5 billion. Furthermore, the global average monthly data transfer per smartphone is expected to reach 21.58 GB in 2025 and is projected to increase to 39.52 GB by 2030, indicating a significant increase in data traffic and the need for extremely large data capacities.

Addtionally, the Ericsson Mobility Report [1] predicts that global mobile data traffic will reach 303 EB per month by 2030. Taking into account the traffic generated by user devices via fixed wireless access (FWA) technology, the predictions estimate that total mobile network traffic will reach 473 EB per month by the end of 2030 (Figure 1.1). The growth in mobile network traffic is mainly attributed to an increase in the amount of video content, which is estimated to account for 74% of total mobile data traffic at the end of 2024.

With such expected exponential growth of connected devices and data volumes by 2030, the practical realization of more energy-efficient mobile

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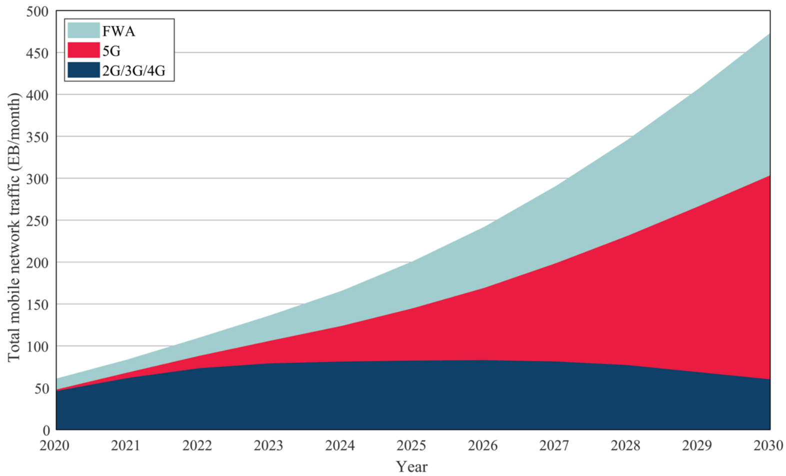


**FIGURE 1.1**
The projected growth of total global mobile network traffic from 2020 to 2030 [1]

networks becomes challenging. This challenge is primarily related to the need for deployment of additional base stations (BSs), the improvement of existing network EE, and the introduction of new types of services and applications which are mostly more throughput intensive than the previous ones. The main solution for satisfying this challenge is seen in the ongoing deployment of fifth-generation (5G) and future deployment of sixth-generation (6G) mobile networks. Although 5G mobile network technology in comparison with previous generations of mobile networks can provide improved EE per unit of transferred data, the total mobile network EC may increase due to the increase in the number of installed BSs. Namely, each newly installed BS requires additional energy for operation, maintenance, and, in specific implementations, cooling. This challenge thus highlights the importance of matching network EE with the growing capacity requirements of modern mobile networks.

In addition, the nonnegligible GHG emissions of mobile network equipment have also become a concern in the telecommunications sector, which is also driven by the increase in the number of connected devices and the continuous growth of network traffic volumes. As a result, improving mobile network EE and the consequent reduction of GHG emissions have become a priority for mobile network operators. In light of this, the 5G technology can offer significant potential for network EE improvements that can help mobile operators achieve sustainability goals and more effectively reduce the negative impact of the contribution of telecommunication network equipment to global GHG emissions. Thus, the implementation of 5G networks sets new benchmarks for the improvement of network EE through the optimization of network resources and the introduction of specific technologies that can contribute to significant improvements in the optimization of mobile network EC.

Due to the abovementioned reasons, EE has been defined as a critical performance metric for 5G networks and different energy-efficient technologies have been integrated into all recent standards related to the development of 5G technology [2–4]. The mobile network EE is formalized as a key performance indicator, thus imposing new standards in the future development of mobile networks. Accordingly, the behavior of mobile networks in terms of EE requires careful analysis during the planning, deployment, operation, and even disposal phases of the mobile network [2].

The integration of energy-efficient technologies into the standardization of 5G networks offers numerous benefits. One of the main benefits is related to the reduction of operational expenditure (OPEX) costs for telecommunications service providers, which are directly reduced by decreasing network equipment EC and can, in turn, lead to lower service prices for end users. Furthermore, reducing GHG emissions through the improvement of mobile network EE contributes to the mitigation of negative environmental impacts of GHG emissions.

In addition to the ongoing implementation of 5G networks, the upcoming 6G mobile network technology will further enhance network performance, and it is expected to additionally contribute to the improvement of mobile network EE [5, 6]. Compared to 5G networks, the 6G networks are expected to bring faster data rates, reduced latency, and increased capacity [7]. Besides these benefits, the 6G networks are expected to have higher network EE compared to 5G networks, which will be achieved through the use of artificial intelligence (AI)-based solutions dedicated to the optimization of network EE that can thus significantly reduce the negative environmental impact of mobile networks. However, these goals will be challenged with enabling new applications and use cases that are expected to be characteristic for 6G networks, such as the implementation of services related to autonomous driving and robotics, unmanned aerial vehicles, virtual reality, augmented reality, and the Internet of Everything in everyday life. This will consequently result in a continuation of the increase in demand for data capacity, as all of these applications require the transmission of large amounts of data due to their complexity and resource-intensive nature. Therefore, issues related to the improvement of mobile network EE will continue even with the proliferation of 6G networks, and special attention will need to be paid to optimization of network EE, in order to optimize network EC and keep GHG emissions at acceptable levels [8].

Considering the presented advantages that new generations of mobile networks bring and issues related to the problem of excessive EC, it is clear that improving EE in 5G and future 6G networks has considerable potential to positively impact both society and the environment. Hence, improving the EE of mobile networks will be crucial for addressing excessive energy consumption and GHG emissions of mobile networks. However, with the support of 5G and 6G technologies, mobile network operators will need to meet the growing demands for high data transfer rates and capacity and, at the same time, ensure the sustainable development and deployment of current and upcoming generations of mobile networks.

## 1.1 Motivation for Improving Mobile Network Energy Efficiency

Research in the field of improving EE of wireless communication networks started intensively during the 2010s. It was motivated by increased environmental awareness related to the evident climate change, the need for sustainable development of society, and the necessity for reducing OPEX of mobile network operators. This was followed by national, regional, or global regulatory demands that started to include improvement of mobile network EE in their recommendations and standards. Hence, these motivations foster technological advancements that will result in the development of new hardware solutions, algorithms, techniques, and strategies that are dedicated to improving mobile network EE, while simultaneously meeting the demands for increasing network capacity, ensuring quality of service (QoS) and performance requirements of wireless communication networks.

### 1.1.1 Environmental Awareness and Sustainability

As awareness of climate change and the need for sustainable development rises, there is increasing pressure on mobile network operators (MNOs) and network equipment manufacturers to reduce GHG emissions and energy consumption of mobile networks. Improving the EE of mobile communication networks is a key step toward achieving these goals. Climate change represents one of the most important global challenges of our time, and an increasing number of scientific studies and reports emphasize its seriousness and the need for urgent intervention [9]. Growing awareness of climate change has increased demands on industries, especially the telecommunications sector, to take measures to reduce their impact on the environment [10]. This transition is forcing the telecommunications sector to adopt sustainable practices and technologies that reduce these negative environmental impacts.

### 1.1.2 Operating Expenses

Energy accounts for a substantial portion of the OPEX of mobile network operators. According to a GSMA report [11], energy accounts for an average of 20%–40% of total OPEX in the telecommunications sector. This is why the telecommunications industry must pay close attention to reducing its overall EC in order to increase competitiveness and achieve global economic sustainability. The continuous power supply of BSs, cooling systems, data centers, and other networking equipment that enable mobile networks to operate generates high energy costs. Furthermore, the continuous demands for ensuring faster data rates and the emergence of more throughput-demanding services additionally contribute to the increase in the energy requirements of mobile networks, leading to higher OPEX of MNOs. Also, mobile network designs based on the installation of a vast amount of new equipment when deploying every new generation of mobile networks, whose operation also relies on constant, uninterrupted power supply sources, significantly contribute to the increase in capital expenditures (CAPEX) of MNOs. This presents an important challenge for the strategic financial planning of network service providers. In the future, this problem will be further emphasized by the deployment of ultra-dense 5G networks and the expected implementation of 6G networks, which will require an increase in the number of BSs and significantly faster data processing capabilities of mobile network equipment [12, 13]. Consequently, the increasing complexity and amount of mobile network infrastructure will contribute to the further increase of network EC and MNOs' OPEX, forcing MNOs to seek more sustainable and energy-efficient solutions for the realization of radio, backhaul, and core parts of mobile networks.

Given the competitive market environment, MNOs are facing pressure to reduce OPEX in order to remain profitable and competitive in the telecom market. Thus, increasing mobile network EE has become one of the key strategies for reducing OPEX, enabling MNOs to optimize their operations and increase profitability. Ultimately, the reduction of OPEX through the optimization of network EE strengthens the economic resilience and competitiveness of mobile operators on the global market.

### 1.1.3 Regulatory Requirements

More and more countries are introducing stricter regulations related to energy consumption and GHG emissions. Mobile operators must comply with these requirements to avoid sanctions and additional costs associated with non-compliance. For example, the European Union has introduced a series of regulations to reduce greenhouse gas emissions, including a target of reducing emissions by 40% by 2030 compared to 1990 levels [14]. This decision is part of a broader strategy that also includes increasing the share of renewable energy and improving energy efficiency in order to achieve climate neutrality by 2050.

In the United States, many states are also adopting targets to reduce greenhouse gas emissions and implementing market-based policies. According to a report by the National Conference of State Legislatures, at least 16 states have adopted legislative goals to reduce GHG emissions [15]. These goals often include emissions monitoring and reporting systems, as well as a cap-and-trade system to regulate emissions in the energy and transportation sectors. These efforts are aimed at reducing GHG emissions and encouraging the use of renewable energy sources, thus supporting the broader goals of sustainability and environmental protection.

Additionally, improving mobile network energy efficiency aligns with several of the United Nations Sustainable Development Goals [16], which include a contribution to:

- Goal 7: affordable and clean energy – by reducing the energy consumption per unit of data transmitted and thus lowering GHG emissions and promoting sustainable energy use,
- Goal 9: industry, innovation, and infrastructure – through integrating advanced, energy-saving technologies like renewable-powered base stations and efficient network design,
- Goal 11: sustainable cities and communities goal – by reducing the carbon footprint of urban telecommunications infrastructure, supporting cleaner and more sustainable cities,
- Goal 12: responsible consumption and production – by conserving network resources and encouraging telecom operators to adopt sustainable practices, from manufacturing to operations and disposal, and
- Goal 13: climate action – by reducing GHG emissions which enables mitigating climate change effects and aligning with national and international climate goals.

The telecommunications sector must adapt to such a regulatory framework, through reducing the EC and GHG emissions of mobile networks. However, the introduction of green policies and energy-efficient technologies in mobile networks is becoming imperative not only due to regulatory requirements but also due to MNOs' economic profitability and environmental sustainability. Hence, the goal dedicated to optimizing EE of wireless mobile networks is not only a response to regulatory requirements but also a key step toward long-term environmental preservation and reduction of OPEX.

### 1.1.4 Technological Advancement

Technological progress plays a key role in increasing the EE of wireless communication networks. The development of new technologies in the frame of 5G and the upcoming 6G networks can bring significant changes in the way networks are designed and their EC is managed [17, 18]. It is expected that these technologies will enable the implementation of advanced solutions that optimize mobile network EC and reduce OPEX. Technological progress enables the possibility of using sophisticated systems that can ensure more precise management of mobile network EC. This will be particularly fostered through the development of new AI-based solutions for dynamic adjustment of network resources in real time, which can result in more energy-efficient operation of mobile networks. Considering the growing demands for higher network capacity and improved performance, technological progress enables EE to be achieved without compromising the QoS. Such technological innovations are crucial for the sustainable development of wireless communication networks and the reduction of their ecological footprint.

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## Future Challenges and Opportunities

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