

EFICIÊNCIA ENERGÉTICA EM REDES 5G: UM PANORAMA ATUAL

ENERGY EFFICIENCY IN 5G NETWORKS: A CURRENT OVERVIEW

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Resumo – A crescente expansão do tráfego de dados móveis intensificou a demanda por soluções de rede mais eficientes e sustentáveis. As redes móveis de quinta geração (5G) introduziram avanços inéditos em velocidade, capacidade e conectividade; contudo, também apresentam desafios significativos relacionados ao consumo de energia. Diante do aumento dos custos energéticos e das preocupações ambientais, a melhoria da eficiência energética dos sistemas 5G tornou-se essencial. A eficiência energética é hoje reconhecida como um Indicador-Chave de Desempenho (KPI) fundamental para o projeto, a implantação e a operação das redes 5G. Este artigo oferece um panorama atual das estratégias e tecnologias emergentes voltadas para a melhoria da eficiência energética nas infraestruturas 5G. Focalizando inovações como Massive MIMO, técnicas de modos de dormência, Superfícies Inteligentes Reconfiguráveis (RIS) e o gerenciamento energético baseado em Inteligência Artificial (IA), destaca-se como a indústria de telecomunicações está se adaptando à necessidade de redes mais verdes e sustentáveis.

Palavras-chave: Redes 5G. Eficiência de energia. Comunicações móveis sustentáveis.

Abstract - The increasing expansion of mobile data traffic has intensified the demand for more efficient and sustainable network solutions. Fifth-generation (5G) mobile networks have introduced unprecedented advancements in speed, capacity, and connectivity; however, they also present significant energy consumption challenges. As energy costs and environmental concerns grow, improving the energy efficiency of 5G systems has become essential. Energy efficiency is now recognized as a critical Key Performance Indicator (KPI) for the design, deployment, and operation of 5G networks. This article provides an up-to-date overview of strategies and emerging technologies aimed at enhancing energy efficiency in 5G infrastructures. Focusing on innovations such as Massive MIMO, sleep mode techniques, Reconfigurable Intelligent Surfaces (RIS), and AI-driven energy management, highlighting

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how the telecommunications industry is adapting to the imperative of greener, more sustainable networks.

Keywords: 5G networks. Energy efficiency. Sustainable mobile communications.

I. INTRODUCTION

1.1 – Contextualization of 5G and Energy Consumption

The exponential growth of mobile data traffic, driven by the proliferation of connected devices, high-definition streaming, and emerging applications such as augmented reality and autonomous vehicles, has placed extraordinary demands on wireless networks. In response, fifth-generation (5G) networks have been developed to deliver higher throughput, ultra-reliable low-latency communication, and massive device connectivity. However, the technological enhancements introduced by 5G also come with significant energy consumption challenges. The deployment of dense network architectures, the adoption of new frequency bands, and the increasing complexity of network operations contribute to higher energy requirements. Consequently, although 5G advances network capabilities, it simultaneously raises critical concerns regarding environmental impact and operational sustainability.

The need for sustainable network operations is increasingly urgent. Energy consumption not only influences the operational expenses (OPEX) of mobile operators but also has direct implications for global carbon emissions. Efficient energy management is essential to support the financial and ecological viability of 5G networks. Recognizing these factors, energy efficiency has been formally established as a vital Key Performance Indicator (KPI) for 5G network design and operation. Optimizing energy use across network components — from radio access networks (RANs) to core networks — is fundamental to achieving the ambitious goals of both technological advancement and environmental responsibility.

1.2 – Objective of the Paper

The objective of this paper is to provide a current and comprehensive overview of energy efficiency in 5G networks. We aim to analyze key strategies, technologies, and real-world implementations focused on reducing energy consumption without compromising network performance. Special attention is given to technological innovations such as Massive MIMO, energy-saving sleep modes, Reconfigurable Intelligent Surfaces (RIS), and AI-driven network optimization as promising solutions toward achieving sustainable 5G deployments.

II. LITERATURE REVIEW

2.1 – Energy Challenges in 5G Networks

Base Stations (BSs) continue to be responsible for a significant portion of energy consumption in mobile networks, accounting for more than 50% of the energy used by the Radio Access Network (RAN) infrastructure (NGMN ALLIANCE, 2023). Recent studies show that the RAN can consume up to 75% of a mobile network's total energy, with a major contribution from RF circuits, digital processing systems, and especially cooling systems, which can represent up to 40% of the energy consumption at a BS site (NGMN ALLIANCE, 2023).

The technological advancements introduced by 5G have contributed to the increase in energy consumption at BSs. According to GSMA (2023), a 5G BS can consume between two and three times more energy than a 4G BS, driven by the use of high-power amplifiers, Massive MIMO systems, and intensive processing to support high data rates and multiple simultaneous connections. Even during periods of reduced traffic, energy consumption remains high due to the need to maintain control signals and the continuous operation of critical components.

Another relevant factor is network densification, intensified by the deployment of small cells to meet capacity and coverage demands in urban and indoor environments. According to a report by 5G Americas (2022), while the addition of small cells is essential for improving spectral efficiency, it also increases the overall network energy consumption, since each small cell has its own fixed energy cost regardless of the traffic transmitted. In ultra-dense networks, the increase in energy consumption becomes inevitable unless intelligent strategies such as sleep modes, dynamic BS shutdown, and AI-based optimization are adopted (ETSI, 2022). These energy challenges highlight the need for innovative solutions, including energy-efficient Massive MIMO, Reconfigurable Intelligent Surfaces (RIS), and AI-based techniques, which will be discussed in the next section.

2.1.1 – Massive MIMO: Spectral and Energy Efficiency

The expansion of 5G networks has introduced new challenges related to energy consumption. To minimize environmental and operational impacts, several technologies and strategies have been developed, aiming to optimize efficiency without compromising service quality (NGMN ALLIANCE, 2023). Among the main solutions are Massive MIMO, sleep modes, Reconfigurable Intelligent Surfaces (RIS), and the application of Artificial Intelligence (AI). Massive MIMO is a key technology for enhancing spectral and energy efficiency in 5G networks. By using dozens or even hundreds of antennas per base station (BS), it is possible to transmit multiple data streams simultaneously over the same frequency spectrum, increasing network capacity without requiring higher transmission power (NGMN ALLIANCE, 2023).

This approach reduces the power consumed per bit transmitted, resulting in significant energy efficiency gains. However, increasing the number of antennas brings considerable challenges. The intensive processing required to manage multiple signals leads to increased energy consumption by digital circuits and processors (GSMA, 2023). In systems with more than 128 antennas, it is estimated that over 50% of the total energy consumption is associated with signal processing (5G AMERICAS, 2022). Therefore, to fully realize the benefits of Massive MIMO, it is crucial to develop efficient processing algorithms and invest in specialized low-power hardware.

2.1.2 – Sleep Modes

The introduction of sleep modes in 5G networks has proven to be highly effective in reducing energy consumption. During periods of low demand, BS components can be placed into low-power states or shut down entirely, conserving energy without affecting service quality (ETSI, 2022).

Micro-sleep techniques, applied over millisecond intervals between transmissions, and deep sleep modes during very low-traffic periods, such as overnight, have shown significant savings. According to 5G Americas (2022), implementing dynamic carrier shutdown strategies can result in energy savings of up to 23% in clusters of BSs, without noticeable degradation in user experience.

2.1.3 – Reconfigurable Intelligent Surfaces (RIS)

Reconfigurable Intelligent Surfaces (RIS) are emerging as an innovative solution to optimize signal propagation in mobile networks. Composed of nearly passive elements capable of controlling the behavior of radio waves, RIS can redirect, reflect, or refract signals, enhancing coverage and link quality without requiring additional transmission power (IEEE COMSOC, 2022).

The deployment of RIS on building facades or indoors reduces the need for installing new small cells or increasing transmitter power. Although real-time control of RIS still presents technical challenges, the prospects are promising for significantly reducing energy consumption in dense and complex urban environments (IEEE COMSOC, 2022).

2.1.4 – Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) has played a central role in managing energy consumption in 5G networks. AI algorithms enable dynamic adjustments to network parameters such as transmission power, beamforming, and cell activation/deactivation based on traffic patterns and environmental variables (ITU, 2022). Techniques like reinforcement learning are being applied to define optimal strategies for cell shutdown and resource adjustment in real-time, maximizing energy efficiency without compromising service quality (NGMN ALLIANCE, 2023). Initiatives as "AI for Green Networks" led by ITU, show that intelligent demand forecasting can reduce energy consumption by up to 20% in 5G networks (ITU, 2022). Furthermore, commercial solutions like ZTE's "Power Pilot" enhanced in 2022, are already operating in several global networks, demonstrating real-world energy reductions of between 18% and 22% through automatic network optimizations based on AI (RCR WIRELESS, 2022).

2.2 – Case Studies and Real-World Implementations

The implementation of energy efficiency solutions in 5G networks has advanced rapidly through strategic partnerships between operators and vendors. An example is the collaboration between Ericsson and Telefónica, which conducted tests in Spain and Brazil between 2021 and 2022, focusing on strategies to reduce energy consumption in next-generation networks. The application of techniques such as ultra-lean design and the minimization of unnecessary signaling resulted in up to a 90% reduction in energy consumption per unit of traffic compared to traditional 4G networks (ERICSSON, 2022). The dynamic adaptation of radio parameters and the intelligent shutdown of carriers during low-demand periods achieved up to a 23% reduction in access network energy consumption without compromising the user experience (ERICSSON, 2022).

Beyond partnership initiatives, innovative commercial solutions have also gained prominence. One example is the evolution of Power Pilot, a platform from ZTE enhanced in 2022, which leverages artificial intelligence (AI) and big data to dynamically manage energy consumption in 4G and 5G networks. This solution has demonstrated the capability to reduce energy consumption by between 18% and 22% through the automatic optimization of resource allocation based on traffic patterns (RCR WIRELESS, 2022). These case studies reinforce the practical viability of the approaches discussed earlier, such as the use of AI, sleep modes, and energy-efficient network design. The success of these implementations demonstrates that it is possible to align the expansion of mobile network capacity with sustainable practices and operational cost reductions. To measure and evaluate these improvements, it is essential to use metrics such as bit/Joule, which quantify the amount of data transmitted per unit

of energy consumed, and assessment models that consider both the static and dynamic energy consumption of BSs (NGMN ALLIANCE, 2023).

2.3 – Metrics and Evaluation Models

The assessment of energy efficiency in mobile networks is crucial for guiding optimization strategies and ensuring sustainable operations. The primary metric used is energy efficiency (bit/Joule), which measures the amount of data transmitted per joule of energy consumed. The higher the bit/Joule value, the more efficient the network is, indicating that more data is transmitted for each unit of energy used (NGMN ALLIANCE, 2023). This metric is widely adopted to compare different technologies and to evaluate improvements in efficiency over time.

In addition to the efficiency metric, energy consumption models are applied to understand the behavior of Base Stations (BSs) and other network components. The classical model separates consumption into two parts: static and dynamic. Static consumption refers to the energy required to keep the station operational regardless of traffic volume, including energy used for RF circuits, minimal processing, and cooling systems. Dynamic consumption, on the other hand, varies according to the amount of data traffic, increasing as the number of connected users or the amount of data transmitted grows (PMCC, 2021). This behavior can be represented by the following equation (1):

$$P = P_1 + (\alpha \times C) \quad (1)$$

Where P is the total energy consumption, P_1 is the base (static) consumption, α is the coefficient representing the increase in energy consumption relative to the load, and C is the traffic load. This model helps estimate the impact of traffic increases on BS energy consumption. More complex models may include nonlinear terms or multiple operational states, such as sleep modes, to adjust energy consumption according to network demand (PMCC, 2021). These metrics and models are fundamental to optimizing energy consumption and ensuring that networks operate more efficiently.

III. CONCLUSION

The deployment of 5G networks has brought advancements in speed, capacity, and connectivity, but it has also introduced significant energy challenges that demand new solutions. As addressed, base stations (BSs) are major contributors to the energy consumption of radio access networks, driven by technologies such as Massive MIMO, infrastructure densification, and the uninterrupted operation of components even during periods of low demand. To tackle these challenges, certain technologies have proven effective in improving energy efficiency. Massive MIMO significantly contributes to enhancing spectral and energy efficiency, though it requires optimized algorithms to manage the energy costs of signal processing (GSMA, 2023). Techniques based on sleep modes allow the deactivation of network elements during periods of low utilization, yielding energy savings, while Reconfigurable Intelligent Surfaces (RIS) improve signal propagation, minimizing the need for increased transmission power (IEEE COMSOC, 2022). Furthermore, Artificial Intelligence (AI) enables dynamic network adaptation through intelligent resource management, and real-world implementations, such as industry collaborations and AI-based solutions.

The adoption of sustainable technologies is considered essential for the long-term viability of 5G networks. Energy efficiency, classified as one of the primary key performance indicators (KPIs), directly impacts operational costs and environmental

sustainability (NGMN ALLIANCE, 2023). The implementation of energy efficiency solutions must occur from the initial planning stages, through highly lean network architectures, to the operational phase, via AI-based optimizations, to meet performance requirements with the smallest possible environmental footprint (NOKIA, 2024). This approach not only reduces operational expenses (OPEX) but also contributes to convergence with global decarbonization goals, as the telecommunications sector accounts for a significant share of global energy consumption (NOKIA, 2024).

Looking ahead, research should explore the integration of renewable energy sources, such as solar and wind, to power 5G infrastructure, aiming to reduce reliance on fossil fuels (HUAWEI, 2024). In parallel, advancements in AI and machine learning algorithms hold the potential to further elevate energy efficiency by improving demand forecasting and optimizing resource allocation in real-time (IEEE JSAC, 2025). These initiatives will be fundamental in ensuring that 5G networks, as well as their future generations, evolve into truly sustainable systems, capable of supporting the growing demands of an increasingly connected world.

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