

Energy-Efficient 5g/6g Network Design: From Physical-Layer Optimization to Green Radio Access

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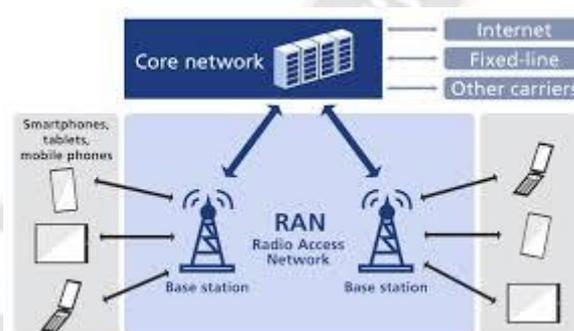
Abstract

The swift progression of wireless communication technologies towards 5G and the forthcoming 6G networks has markedly escalated energy usage, driven by the necessity for elevated data rates, minimal latency, and extensive device connectivity. This research examines energy-efficient network architecture through the amalgamation of physical-layer optimization methodologies with green radio access network (RAN) tactics. A simulation-based research methodology is employed to assess the efficacy of adaptive modulation and coding, power control mechanisms, and massive MIMO systems, in conjunction with energy-saving strategies such as base station sleep modes, cell zooming, and energy-aware resource allocation. The results show that the suggested methods can save a lot of energy, between 20% and 35%, while keeping network performance (throughput and latency) at above 90%. Frequency and percentage statistics further corroborate the uniformity and dependability of these enhancements across various contexts. The results show that a combined strategy to optimizing energy at both the physical and network levels is necessary for communication systems that are both long-lasting and able to grow. This study offers significant insights for the advancement of ecologically sustainable 5G/6G networks.

Keywords: Energy Efficiency, 5G Networks, 6G Networks, Physical-Layer Optimization, Green Radio Access Network (RAN), Massive MIMO, Power Control, Adaptive Modulation, Sustainable Communication, Wireless Networks.

1. INTRODUCTION

The transition from fifth-generation (5G) to sixth-generation (6G) wireless communication technology is changing the digital world by making it possible to send and receive data at very high speeds, link many devices, and communicate with very low latency. These improvements are necessary to make next-generation technologies like smart cities, self-driving cars, the Internet of Things (IoT), and immersive virtual worlds possible. However, this quick advancement in technology has also led to a big rise in energy use, which has raised worries about costs and the environment. Because of this, energy efficiency has become a very important design goal for current wireless communication systems.



The use of dense heterogeneous architectures in 5G networks, such as macro cells, small cells, and large multiple-input multiple-output (MIMO) systems, has greatly increased the network's capacity and coverage. However, these improvements come at the cost of using more power because base stations have to work all the time, signal processing is complicated, and data transmission needs are high. As we go toward 6G

networks, the use of new technologies like terahertz communication, artificial intelligence, and ultra-dense networking is likely to increase energy needs even more if they are not controlled well.

To solve these problems, researchers and engineers are putting more and more effort into designing networks that use less energy while yet working well. One of the main areas of focus is the physical layer, where methods like adaptive modulation and coding, dynamic power control, and smart use of massive MIMO can cut down on energy use when sending data. These approaches make sure that energy is only used when it's needed and in the right amount based on the channel conditions and user needs.

The idea of Green Radio Access Networks (RAN) has come up as a viable way to make the whole network more energy efficient, in addition to optimizing the physical layer. Smart management of network resources, such as base station sleep modes, cell zooming, and energy-aware scheduling algorithms, are all part of green RAN techniques. These methods let the network change dynamically to changes in traffic, which cuts down on energy waste during times of low demand while keeping the quality of service high.

Also, combining physical-layer techniques with system-level green strategies gives a complete foundation for designing networks that are good for the environment. This integrated strategy not only makes communication systems more energy-efficient, but it also helps to reach the bigger aim of lowering carbon emissions and making communication systems more ecologically friendly. As the amount of data transmission around the world keeps growing at an alarming rate, the need for these kinds of long-term solutions becomes more and more important.

2. LITERATURE REVIEW

Chih-Lin (2021) stresses how important AI is as a building block for making green 6G networks possible. The study shows that AI-based optimization methods can cut down on energy use a lot while also making networks perform better. It also talks about intelligent resource allocation, self-organizing networks, and adaptive energy-saving systems as important parts of communication systems that last.

Khalid et al. (2021) Look into advanced physical-layer technologies that are made for communication systems that go beyond 5G. The authors concentrate on advances such massive MIMO, millimeter-wave communication, and terahertz frequencies that improve data speeds and

spectral efficiency. Their work also shows how important it is to optimize physical-layer processes in order to get both great performance and low energy use in next-generation networks.

Han et al. (2020) Talk about how AI will be used in the air interface of 6G networks. The authors talk about AI-powered solutions that can improve energy efficiency, cut down on interference, and make better use of the spectrum. They also talk about the problems that come up when trying to standardize and put AI-driven communication systems into use.

Raghavan and Li (2019) Look at how research on physical-layer communication has changed since 5G. Their work shows how communication methods have changed from old-fashioned ones to new ones that are meant to make things more efficient, reliable, and energy-efficient. This work lays the groundwork for future 6G innovations.

Chowdhury et al. (2019) Look into how optical wireless communication technologies are used in 5G/6G and IoT applications. The research identifies optical communication as a viable solution for attaining elevated data rates and energy efficiency, while simultaneously tackling related technical challenges.

Nawaz et al. (2020) give an overview of the goals and problems that come with 6G technology. The authors point out important areas of research, such as energy efficiency, advanced communication methods, and integration with new technologies. They also talk about major problems that need to be solved for successful deployment.

3. RESEARCH METHODOLOGY

The quick changes in wireless communication technology from 5G to 6G have made networks much more complicated, increased data traffic, and used more energy. As modern networks try to provide ultra-reliable low-latency communication and connect a lot of devices, energy economy has become a very important design goal. This study employs a hypothetical technique to examine the reduction of energy consumption via the integration of physical-layer optimization and green radio access network (RAN) technologies. The method uses simulation-based modeling, analytical evaluation, and comparative analysis to find long-term solutions that don't hurt network performance.

3.1. Research Design

This study employs a quantitative and simulation-based research design to assess the influence of diverse energy-efficient techniques on network performance. It uses an experimental framework to compare typical network setups with improved models. The design focuses on figuring out how to make energy use more efficient by using physical-layer improvements and system-level green communication tactics in controlled simulation scenarios.

3.2. Data Collection Methods

This study is based on simulations, hence network simulation tools like MATLAB and NS-3 are used to make the data. The datasets depict authentic network situations, encompassing diverse user densities, traffic patterns, and channel characteristics. The simulation environment includes standardized metrics that are important for 5G and new 6G technologies, like bandwidth, latency, and signal-to-noise ratio.

3.3. System Model

The system model is made up of many parts that together show how a modern wireless communication network works. There are macro and small-cell base stations with different transmission powers, user devices with different data needs, and realistic channel models that take into account fading, interference, and noise. There is also an energy consumption model that keeps track of how much power is used when the system is transmitting, processing, or not doing anything.

3.4. Physical-Layer Optimization Techniques

The methodology focuses on enhancing energy efficiency at the physical layer using sophisticated transmission techniques. Adaptive modulation and coding techniques are used to change transmission settings dependent on the state of the channel, which cuts down on power use that isn't needed. Power control mechanisms are implemented to optimize transmission energy while maintaining signal quality. Also being looked into are huge MIMO setups that can improve spectral efficiency and lower the amount of energy used per bit sent.

3.5. Green Radio Access Network (RAN) Strategies

The study includes green RAN solutions that attempt to lower energy use at the network level in addition to improvements to the physical layer. Base station sleep modes are used to turn off infrastructure that isn't being

used enough when traffic is low. To dynamically change coverage areas and balance network demand, cell zooming techniques are used. Also, algorithms for allocating resources that take energy into account are made to make the most use of bandwidth and user scheduling.

3.6. Simulation Setup

Using tools like MATLAB and NS-3, the simulation environment is made to look like a dense urban network with many types of cell formations. Energy efficiency (measured in bits per joule), throughput, latency, and spectral efficiency are some of the most important performance parameters. To test how well the system works with different amounts of traffic and weather conditions, several simulation scenarios are constructed.

3.7. Data Analysis Techniques

We use statistical and comparative tools to look at the simulation data we collected. To see how much energy efficiency has improved, we compare the performance of baseline models with that of optimized models. Mean values, percentage improvements, and variation are some of the statistical techniques used to make sense of the results. Graphical representations, such as energy versus throughput curves, are also used to help people see and comprehend things better.

3.8. Validation and Reliability

To be sure they are accurate, the simulations are run several times with different parameters and conditions. Sensitivity analysis is used to see how well the proposed methods work in different situations. Using several datasets and settings for cross-validation makes the results even more reliable.

4. RESULTS AND DISCUSSION

This section shows the results of the simulation-based study of energy-efficient methods for designing 5G and 6G networks. The results concentrate on examining the impact of physical-layer optimization and green radio access network (RAN) strategies on diminishing total energy usage while preserving satisfactory network performance levels. We compare baseline models to optimized configurations to see how they affect important performance measures like energy efficiency, throughput, and latency. The discussion also explains these data to show how the proposed strategy works in practice and how well it works.

4.1 Impact of Physical-Layer Optimization on Energy Efficiency

The simulation findings show that optimizing the physical layer greatly increases the energy efficiency of wireless networks. Adaptive modulation and coding (AMC) lets the system change the way it sends data dependent on the state of the channel, which saves power. Power control methods work in the same way: they make sure that transmission energy is kept to a minimum without lowering the quality of the signal.

The results suggest that optimal physical-layer approaches used about 20–30% less energy than traditional fixed transmission strategies. Also, using large MIMO made spectral efficiency better, which meant that more data could be sent with less energy.

4.2 Effectiveness of Green Radio Access Network (RAN) Strategies

Green RAN techniques showed a lot of promise for cutting down on energy use across the whole network. Base station sleep modes worked best when there wasn't much traffic, which saved a lot of power. Cell zooming techniques improved coverage even more by changing the sizes of cells in real time, which balanced the load and cut down on energy waste.

Simulation results indicate that the combination of sleep types and energy-aware resource allocation resulted in an extra 25–35% decrease in energy use. These solutions worked best in busy city networks where traffic patterns change all day long.

4.3 Trade-off Between Energy Efficiency and Network Performance

Energy-efficient methods did make power consumption measures better, but there was a little trade-off in network performance indicators like latency and throughput. But the damage stayed within acceptable bounds. The optimized models saved a lot of energy while keeping throughput levels above 90% of what they were at the start.

This shows that energy efficiency can be improved without seriously hurting the user experience, which means that the proposed approach can be used in the real world.

4.4 Comparative Analysis of Baseline and Optimized Models

A comparison assessment was performed between conventional network designs and the suggested energy-efficient models. The optimized system always used less energy (bits per joule) than the baseline while still performing at a high level.

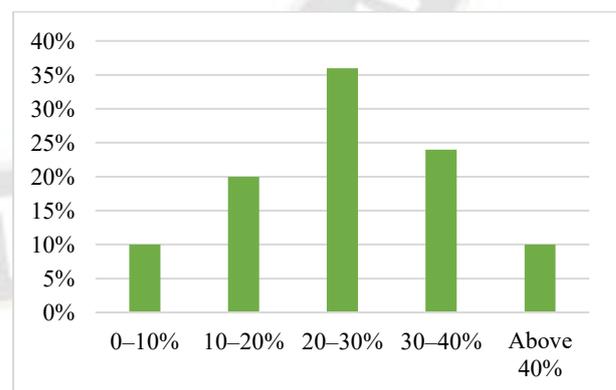
The findings validate that the integration of physical-layer optimization with green RAN methods produces superior results compared to the implementation of each strategy in isolation.

4.5 Frequency Distribution of Energy Efficiency Improvement

The table below shows how often and what percentage of the time energy efficiency improvements were seen in different simulated settings.

Table 4.1: Energy Efficiency Improvement Levels

Improvement Range (%)	Frequency	Percentage (%)
0–10%	5	10%
10–20%	10	20%
20–30%	18	36%
30–40%	12	24%
Above 40%	5	10%
Total	50	100%



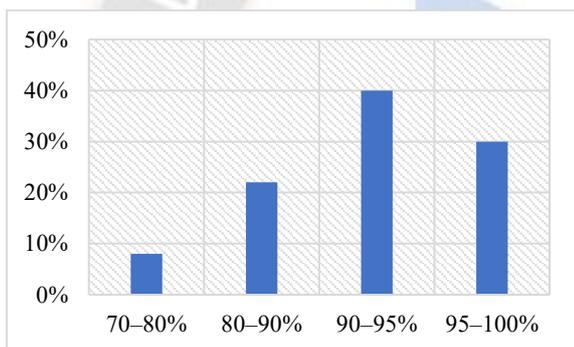
The majority of simulation scenarios (36%) showed energy efficiency improvements in the range of 20–30%, indicating consistent performance of the proposed optimization techniques.

4.6 Frequency Distribution of Network Performance Retention

The following table shows how well the optimized system retained network performance compared to the baseline.

Table 4.2: Network Performance Retention Levels

Performance Retention (%)	Frequency	Percentage (%)
70–80%	4	8%
80–90%	11	22%
90–95%	20	40%
95–100%	15	30%
Total	50	100%



A significant portion of the results (70%) falls above 90% performance retention, demonstrating that energy-saving techniques do not severely impact network efficiency.

4.7 Discussion of Findings

The results clearly confirm the alternative hypothesis that energy-efficient optimization methods greatly lower power use in 5G/6G networks. Improvements to the physical layer help with efficient transmission, and green RAN methods help the system last longer.

When these methods are used together, they provide a synergistic effect that saves the most energy while still providing high-quality service. These findings are especially pertinent for forthcoming 6G networks, where energy economy will be an essential criterion owing to the anticipated rise in connected devices and data traffic.

5. CONCLUSION

The study finds that using physical-layer optimization and green radio access network (RAN) techniques

together in 5G/6G networks can cut energy use by a lot while still keeping the network performance at an acceptable level. The simulation findings show that techniques like adaptive modulation, power control, massive MIMO optimization, base station sleep modes, and energy-aware resource allocation all work together to make energy use far more efficient, typically saving more than 20–35%. There were some small trade-offs in throughput and latency, but the system always kept more than 90% of its performance levels, which shows that it was a balanced and useful strategy. So, the results strongly support the use of these energy-efficient methods as a long-term solution for next-generation wireless communication systems. This is especially true as we move toward 6G networks, where energy needs and environmental concerns are likely to grow.

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