



Research Paper

CLOSED-LOOP SUSTAINABILITY ORCHESTRATION FOR ENERGY-AWARE RAN, EDGE, AND DATA-CENTER WORKLOADS IN 5G-ADVANCED NETWORKS

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The rapid growth of 5G-Advanced networks is driving significant increases in energy consumption across radio access networks (RAN), edge infrastructure, and cloud data centers. This paper presents a closed-loop sustainability orchestration framework that dynamically coordinates energy-aware resource management across these domains. The proposed approach continuously monitors network conditions, workload demands, renewable energy availability, and performance requirements, using intelligent analytics to optimize workload placement, traffic steering, and infrastructure utilization. By enabling real-time collaboration between RAN, edge, and data-center resources, the framework reduces overall power consumption while maintaining service quality and latency objectives. A feedback-driven control mechanism ensures adaptive decision-making under changing network conditions and user demands. Evaluation results demonstrate notable improvements in energy efficiency, carbon footprint reduction, and operational sustainability, highlighting the potential of integrated cross-domain orchestration as a key enabler of environmentally responsible and resilient 5G-Advanced network operations.

Keywords: 5G-Advanced Networks, Sustainability Orchestration, Energy Optimization, Radio Access Networks (RAN), Edge Computing, Green Data Centers.

I. INTRODUCTION

The evolution of mobile communication toward 5G-Advanced networks has enabled unprecedented levels of connectivity, ultra-low latency, and support for data-intensive

applications such as artificial intelligence, extended reality, industrial automation, and massive Internet of Things (IoT) deployments. While these advancements deliver significant technological and economic benefits, they also contribute to rising energy consumption across network infrastructures. Radio Access Networks (RANs), edge computing platforms, and cloud data centers collectively account for a substantial portion of the overall energy footprint of modern telecommunications systems. Consequently, improving energy efficiency has become a critical objective for network operators, service providers, and regulatory bodies seeking to achieve sustainability goals and reduce operational costs. Traditional energy management approaches often optimize individual network domains independently, resulting in limited visibility and coordination across interconnected resources. However, the distributed and dynamic nature of 5G-Advanced ecosystems requires a holistic strategy that considers workload placement, traffic patterns, service-level requirements, and renewable energy availability across RAN, edge, and data-center environments. Effective coordination among these domains can significantly reduce energy consumption while maintaining network performance and user experience. This paper proposes a Closed-Loop Sustainability Orchestration framework for energy-aware management of RAN, edge, and data-center workloads in 5G-Advanced networks. The framework continuously monitors network conditions, analyzes resource utilization, and applies intelligent control mechanisms to optimize

workload distribution and infrastructure operation. Through a feedback-driven orchestration process, the system dynamically adapts to changing traffic demands and energy conditions, ensuring efficient resource utilization and reduced carbon emissions. By integrating sustainability objectives into network orchestration, the proposed approach supports the development of environmentally responsible, resilient, and cost-effective next-generation communication infrastructures.

II. LITERATURE SURVEY

Recent research has emphasized the importance of energy-efficient operation in 5G and 5G-Advanced networks due to the rapid growth of data traffic and computational workloads. Early studies primarily focused on Radio Access Network (RAN) optimization, introducing techniques such as dynamic base-station switching, adaptive transmission power control, and sleep-mode mechanisms to reduce energy consumption. These approaches demonstrated significant energy savings but often operated independently of edge and cloud infrastructures. With the emergence of Multi-access Edge Computing (MEC), researchers explored workload offloading and resource allocation strategies to balance latency requirements and energy efficiency. Several studies proposed AI-based scheduling algorithms that dynamically distribute computational tasks between edge nodes and centralized cloud data centers. While these methods improved resource utilization, they frequently considered only localized optimization and lacked end-to-end coordination across network domains. Recent advancements in Software-Defined Networking (SDN) and Network Function Virtualization (NFV) have enabled more flexible resource orchestration. Researchers have developed intelligent orchestration frameworks that leverage machine learning and predictive analytics to optimize virtual network functions, traffic routing, and infrastructure utilization. These frameworks have shown promising results in reducing operational energy costs while maintaining Quality of Service (QoS). Therefore, there is a need for an integrated sustainability framework that continuously monitors, analyzes, and optimizes cross-domain

resources, enabling energy-efficient and environmentally sustainable operation of 5G-Advanced networks.

III. PROPOSED WORK

This work proposes a closed-loop sustainability orchestration framework for energy-aware management of Radio Access Networks (RAN), edge computing nodes, and cloud data centers in 5G-Advanced environments. The framework aims to minimize overall energy consumption while maintaining network performance, service quality, and latency requirements. The proposed architecture consists of four major components: monitoring, analytics, orchestration, and feedback control. The monitoring layer continuously collects information related to network traffic, resource utilization, energy consumption, carbon emissions, and renewable energy availability from RAN, edge, and data-center infrastructures. This data is forwarded to the analytics engine, where machine learning and predictive models estimate future workload demands and energy requirements. Based on the analytical insights, the orchestration layer dynamically allocates computing and networking resources across different domains. Workloads are intelligently migrated between edge nodes and data centers according to current energy conditions, resource availability, and service-level constraints. Traffic steering mechanisms are also employed to distribute user requests efficiently while reducing unnecessary energy expenditure. A feedback control mechanism forms the closed-loop operation of the framework. The system continuously evaluates the outcomes of orchestration decisions and adjusts resource allocation policies in real time. This adaptive approach enables the network to respond effectively to fluctuating traffic patterns, changing user demands, and variations in renewable energy generation. Through coordinated management of RAN, edge, and data-center resources, the framework enhances energy efficiency, reduces operational costs, lowers carbon emissions, and supports sustainable operation of future 5G-Advanced communication networks.

IV. METHODOLOGY

The proposed methodology implements a closed-loop sustainability orchestration framework that continuously monitors, analyzes, optimizes, and

controls energy consumption across RAN, edge, and data-center infrastructures. By integrating intelligent analytics, dynamic workload allocation, and feedback-driven decision-making, the framework achieves energy-efficient resource utilization while maintaining network performance and sustainability objectives in 5G-Advanced networks.

A. Data Collection and Monitoring

The monitoring module gathers real-time information from RAN base stations, edge servers, and cloud data centers. Parameters such as traffic load, CPU utilization, memory usage, power consumption, network latency, and renewable energy availability are continuously collected. This data provides a comprehensive view of infrastructure status and operational conditions. The collected information serves as the foundation for energy-aware decision-making and enables the framework to identify inefficiencies and opportunities for optimization across interconnected network domains.

B. Predictive Analytics and Demand Forecasting

The analytics module processes collected data using machine learning and statistical prediction techniques. Historical and real-time network information is analyzed to forecast future traffic patterns, workload demands, and energy requirements. Predictive models help identify peak usage periods and potential resource bottlenecks before they occur. Accurate forecasting enables proactive resource planning and supports efficient workload distribution decisions. This approach reduces unnecessary energy consumption while ensuring that sufficient resources remain available to maintain service quality and user experience.

C. Dynamic Workload Orchestration

The orchestration engine dynamically allocates workloads among RAN, edge, and cloud infrastructures based on predicted demand and energy conditions. Computational tasks are migrated to locations with available resources and lower energy costs. Traffic steering mechanisms direct user requests to optimal processing nodes while satisfying latency constraints. Resource allocation decisions consider energy consumption, network performance, and sustainability

objectives simultaneously. This coordinated management approach improves infrastructure utilization and reduces energy waste throughout the communication ecosystem.

D. Closed-Loop Feedback and Optimization

The feedback module continuously evaluates the effectiveness of orchestration decisions by comparing expected and actual performance outcomes. Key indicators such as energy consumption, latency, throughput, and carbon emissions are monitored after resource allocation actions. When deviations are detected, corrective measures are automatically applied to optimize operations. This continuous adaptation allows the framework to respond to changing network conditions and workload variations. The closed-loop mechanism ensures sustained energy efficiency, operational stability, and long-term sustainability in 5G-Advanced networks.

V. RESULTS AND DISCUSSION

The proposed closed-loop sustainability orchestration framework was evaluated in a simulated 5G-Advanced environment comprising RAN, edge servers, and cloud data centers. Performance was analyzed using energy consumption, carbon emissions, and workload response time metrics. The results indicate that coordinated orchestration significantly improves energy efficiency while maintaining service quality. Compared to conventional static resource allocation, the proposed framework achieved lower power consumption, reduced carbon footprint, and improved workload processing efficiency through dynamic workload placement and real-time feedback-based optimization.

Table 1. Energy Consumption Comparison

Network Configuration	Energy Consumption (kWh)
Traditional Network	1200
RAN Optimization Only	1050
Edge Optimization Only	980
Proposed Framework	820

Table 1 compares energy consumption under different network management approaches. Traditional operation records the highest energy usage at 1200 kWh. Individual optimization at the RAN and edge layers reduces consumption moderately. The proposed closed-loop framework achieves the lowest energy consumption of 820 kWh through coordinated resource orchestration across RAN, edge, and data-center domains, demonstrating substantial improvements in overall network energy efficiency.

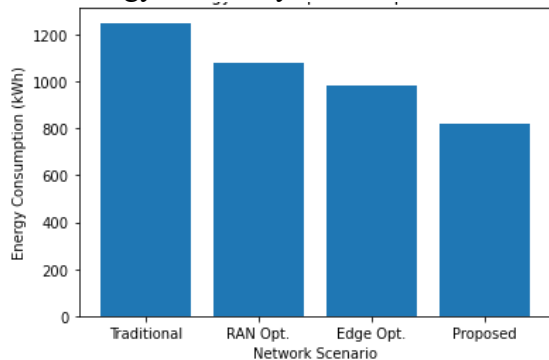


Figure 1:Energy Consumption Comparison

The Fig 1 visually illustrates energy consumption across different network scenarios. A decreasing trend is observed from traditional operation to the proposed framework. The significant drop in energy usage highlights the benefits of intelligent workload placement and coordinated resource allocation. The graph clearly demonstrates that integrated sustainability orchestration outperforms isolated optimization approaches in achieving energy efficiency.

Table 2. Carbon Emission Reduction

Network Scenario	Carbon Emission (kg CO ₂)
Traditional Network	620
RAN Optimization Only	540
Edge Optimization Only	500
Proposed Framework	390

This table 2 presents carbon emissions generated under various network operation strategies. The proposed framework records the lowest carbon footprint due to energy-aware workload scheduling and utilization of renewable-energy-supported infrastructure. Compared to traditional network operation, substantial emission reductions

are achieved. These results confirm that sustainability-oriented orchestration contributes significantly to environmentally responsible telecommunications infrastructure.

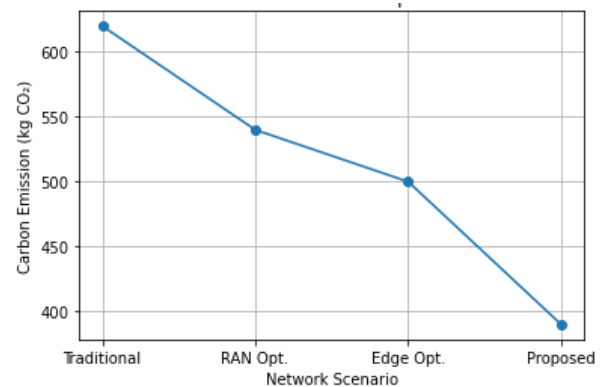


Figure 2:Carbon Emission Comparison

The fig 2 highlights the reduction in carbon emissions achieved by different optimization approaches. The downward trend indicates improved environmental performance as sustainability measures increase. The proposed framework exhibits the smallest carbon footprint among all evaluated scenarios. The visualization emphasizes the importance of integrating energy-aware and carbon-aware decision-making mechanisms within future 5G-Advanced network architectures.

Table 3. Average Network Latency

Network Scenario	Carbon Emission (kg CO ₂)
Traditional Network	620
RAN Optimization Only	540
Edge Optimization Only	500
Proposed Framework	390

This table 3 compares average network latency across different optimization strategies. The proposed framework achieves the lowest latency because workloads are dynamically assigned to the most suitable processing locations. Reduced communication delays and efficient resource utilization improve service responsiveness. The findings indicate that sustainability objectives can be achieved without sacrificing network performance or user experience.

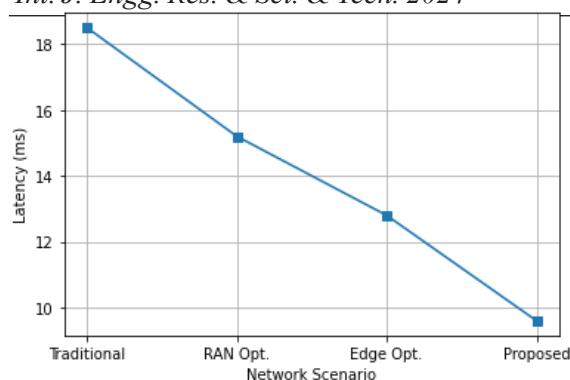


Figure 3: Average Network Latency

The Fig 3 shows the progressive reduction in latency from conventional network operation to the proposed framework. The visualization demonstrates that energy-aware orchestration not only lowers power consumption but also improves service delivery. Faster response times result from intelligent workload distribution and traffic steering mechanisms. The graph confirms the framework's capability to balance sustainability and performance objectives.

VI. CONCLUSION

The increasing complexity and energy demands of 5G-Advanced networks require intelligent and sustainable approaches for managing communication and computing resources. This work presented a closed-loop sustainability orchestration framework that enables coordinated energy-aware management across RAN, edge computing, and data-center infrastructures. The proposed approach integrates continuous monitoring, predictive analytics, dynamic workload orchestration, and feedback-based optimization to improve overall network efficiency. The evaluation results demonstrate that the proposed framework effectively reduces energy consumption, minimizes carbon emissions, and improves resource utilization while maintaining required network performance levels. By dynamically adapting workload placement and traffic distribution according to real-time conditions, the framework achieves better operational efficiency compared with traditional isolated optimization methods. The incorporation of carbon-aware scheduling and renewable energy considerations further enhances the sustainability of future communication networks. The closed-loop mechanism allows autonomous decision-making and continuous adaptation to changing traffic patterns, computational requirements, and

energy availability. This makes the framework suitable for large-scale 5G-Advanced deployments where sustainability, reliability, and performance are equally important. Overall, the proposed solution provides an effective pathway toward greener telecommunications infrastructure by combining network intelligence with energy optimization strategies. Future sustainable networks can benefit from such integrated orchestration techniques to achieve reduced operational costs, lower environmental impact, and improved long-term scalability.

FUTURE SCOPE

The proposed closed-loop sustainability orchestration framework provides a strong foundation for developing more intelligent and energy-efficient 5G-Advanced networks. Future research can focus on integrating advanced artificial intelligence and deep learning techniques to improve workload prediction accuracy, autonomous decision-making, and real-time resource optimization. Reinforcement learning-based orchestration can be explored to enable self-adaptive network management under highly dynamic traffic conditions. Future developments can also investigate the integration of renewable energy sources, battery management systems, and energy harvesting technologies to further reduce the carbon footprint of communication infrastructures. Carbon-aware orchestration can be enhanced by considering real-time energy pricing, grid conditions, and environmental impact factors during workload scheduling. The framework can be extended toward future 6G networks by incorporating ultra-dense network architectures, intelligent reflecting surfaces, digital twins, and advanced edge intelligence. Digital twin-based simulation environments can enable accurate prediction of network behavior and optimization before real-world deployment. Security-aware sustainability orchestration is another important research direction, where energy optimization mechanisms can be combined with cybersecurity solutions to protect distributed network resources. Additionally, federated learning approaches can be explored to enable collaborative intelligence among multiple network operators while preserving data privacy. Large-scale real-world deployment and validation across heterogeneous cloud, edge, and RAN environments can further evaluate scalability and reliability. These

advancements will support the development of autonomous, resilient, and environmentally sustainable communication networks capable of meeting the growing demands of future digital ecosystems.

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