IRO Journal on Sustainable Wireless Systems (ISSN: 2582-3167)
www.irojournals.com/irosws/

Green Wireless Communications: A Review of Sustainable Architectures and Protocols

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Abstract

The rapid growth of wireless communication systems and devices has increased global energy consumption in wireless communication networks. Therefore, wireless communication technologies are advancing towards the development of fifth-generation wireless communication systems and beyond, i.e., towards the development of sixth-generation wireless communication systems. It is important that the energy efficiency of wireless communication systems considered a significant parameter along with data rate, delay and reliability. Green wireless communication systems aim to reduce the power consumption of wireless communication systems minimize carbon emissions and make wireless communication systems environmentally sustainable. This paper presents a comprehensive review of sustainable wireless communication systems and energy-efficient protocols for green wireless communication systems. This study discusses various architectural strategies such as energy-efficient base stations, heterogeneous and ultra-dense networks, cloud radio access networks, adaptive networks, renewable energy and their role enables wireless networks to modify their behavior according to the nature of the data and availability of resources. Further, the paper discusses the role of sustainable wireless protocols in all layers of wireless communication, where techniques like power control, duty cycle, energy-efficient routing and transport protocols are playing a significant role in removing the unnecessary communication and utilizing resources efficiently. It also discusses enabling technologies that can be utilized in energy-efficient network operation including energy harvesting, cognitive radio, artificial intelligence, edge computing and network virtualization. Moreover, some of the major challenges in energy-efficient wireless communication including decisions, complexity, security, cost, and regulatory issues, are addressed. This study provides an sustainable wireless

DOI: https://doi.org/10.36548/jsws.2026.1.001
Received: 20.01.2026, received in revised form: 18.02.2026, accepted: 07.03.2026, published: 16.03.2026

communication can be achieved based on recent developments and existing research gaps in wireless communication particularly in future 5G and 6G networks.

Keywords: Green Wireless Communications, Energy Efficiency, Sustainable Networks, 5G, 6G, Wireless Protocols, Network Architectures.

1. Introduction

Green wireless communications aim at designing and using wireless networks that conserves energy and limits the impact of these networks on the environment. Wireless technology is becoming an integral part of life. Consequently, the number of devices connected using these technologies and the amount of data communicated through these devices are growing at a rapid rate. The energy consumption of these networks has increased at a rapid rate. Additionally, suggesting high operating costs for service providers, high energy consumption, high carbon emissions, and this involves a major impact on climate change. [1].

The conventional wireless networks were primarily developed with the aim of enhancing coverage, data rate and reliability. Energy efficiency was not a major concern during the development of conventional wireless networks. Therefore, many conventional wireless networks are wasting energy unnecessarily. The major cause of energy consumption is the base station, which is always active even during periods of low usage [9]. In many cases, the base stations are operating with full power during the day despite large fluctuations in the volume of traffic [2]. In addition, conventional communication protocols are characterized by frequent signalling, repeating data transmission and resource allocation are responsible for energy consumption. The networks are densely implemented with the aim of demands for large data transfer, thereby resulting in increased power consumption and energy costs.

Another challenge associated with traditional wireless networks is that the energy efficiency of consumer devices doesn't receive any considerations. Most mobile devices, sensors and Internet of Things devices are powered by batteries. The use of inefficient wireless communication methods can cause a rapid depletion of device batteries. Consequently, this increases the rate of battery replacement or recharging, which is harmful to the environment. The aforementioned challenges are a visible indication of the drawbacks of traditional wireless networks [14]. The increase in the need for wireless services and environmental protection has provided a high source to create sustainable wireless systems and protocols. Sustainable wireless systems helps to improve efficiency in power usage across all tiers of a network infrastructure from base stations to user devices. This involves designing a network structure that is able to change conditions to enable unused components to be put to sleep in situations where they are not required. Additionally, there is a need to improve communication protocols to reduce data communication where possible and vary power usage based on conditions [3].

The motivation for green wireless communications is not limited to the reduction of energy consumption alone. Reduced energy consumption means lower operational costs for the network providers. It also means the availability of alternative sources of power. In addition, reduced energy consumption helps in the control of the impact of the increasing wireless communication networks on the environment [17]. Future global communication demands have been satisfied in a way that maintains the environment with the basic concept of green wireless communications being the importance of energy efficiency in the development of wireless communication networks.

2. Literature Review

Recent studies have focused more on the significance of sustainability in future wireless networks, especially with the advent of 6G wireless networks. Li et al. [4] provides a detailed discussion regarding future green wireless networks for the advent of 6G networks, focusing on energy efficiency as a fundamental aspect rather than an additive feature. The study highlights that future 6G wireless networks need to fulfil the demands of providing high data rates, ultra-low latency and massive connectivity while minimizing the energy consumption and carbon footprint of the networks. The study further discusses the importance of intelligent control in green wireless networks for the advent of sustainable 6G communication networks.

Wireless sensor networks (WSNs) and Internet of Things (IoT) systems have been identified as significant contributors to energy consumption. Salama et al. [5] presented an overview of green networking techniques for wireless sensor networks in the context of 6G communications. The authors of the paper emphasize the importance of energy-efficient routing protocols and low-power communication protocols for the efficient lifetime of the network. Additionally, the authors of the paper emphasize the importance of adaptive duty cycling. Further, the authors of the paper emphasize the importance of supporting massive energy-constrained devices in the context of future 6G communications.

Flexible and open architectures for radio access networks have also attracted interest in addressing energy efficiency. In the research by Khan et al. [6], the authors propose an architecture referred to as ORAN-B5G, which combines open radio access networks and machine learning for the purpose of supporting beyond-5G industrial applications. This architecture is significant in its ability to support data-driven optimization for energy efficiency. This research is significant in its ability to show how open and intelligent wireless networks can be used for a greener wireless network.

Another research area for green wireless communications is the use of intelligent reflecting surfaces (IRS). Shi et al. [7] proposed intelligent reflection as an enabling technology for integrated and green Internet of Everything systems beyond 5G networks. The authors investigated the potential of intelligent reflection technology and its implications for green communications. The research indicated that intelligent reflection technology has the potential to enhance the propagation of communication signals without the need to actively transmit them. This will lead to energy-saving opportunities. Additionally, the authors proposed the potential of intelligent reflection technology to support communication, sensing, and security in an integrated way. This research demonstrates the potential of new physical layer technology for green communications.

Machine learning and distributed intelligence have also been studied as potential solutions for reducing energy consumption in wireless networks. In [8], Kim et al. explore green and quantized federated learning over wireless networks. The authors are concerned with designing efficient wireless networks by focusing on energy-efficient training of models. The authors propose quantization as a solution to the problem of energy cost related to data transmission and computation during federated learning. The results show that intelligent learning models can be adapted to work efficiently in wireless networks, making them suitable for green 5G/6G networks.

Table 1. Comparison of Existing Studies and Identified Research Gaps

Ref.	Focus Area	Limitations	Research Gap
[4]	6G Green Network Vision	Provides a conceptual sustainability roadmap but lacks detailed quantitative evaluation. The study does not present measurable energy-saving models or protocol-level validation.	There is a need for integrated evaluation frameworks that combine architectural design, protocol optimization, and measurable energy performance metrics under realistic 6G scenarios.
[5]	Wireless Sensor Networks and Green 6G	Primarily focused on low-power sensor networks. The analysis does not extend to full-scale cellular infrastructure or heterogeneous deployments.	Future work should investigate how energy-efficient routing and duty cycling strategies can scale to large 5G/6G macro–small cell environments with mixed traffic types.
[6]	ORAN-B5G Architecture with ML	Emphasizes open RAN and machine learning but provides limited discussion on the energy cost of model training and real deployment feasibility.	Research is needed on the trade-off between machine learning optimization gains and the computational energy cost of AI integration in large-scale networks.
[7]	Intelligent Reflecting Surfaces (IRS)	Focuses mainly on physical-layer improvements and theoretical signal gains. System-level energy modeling and long-term operational analysis are limited.	There is a need for comprehensive system-level studies evaluating how IRS affects total network energy consumption, including control overhead and hardware cost.
[8]	Federated Learning for Energy Efficiency	Addresses communication energy reduction but does not fully quantify the energy overhead of repeated training rounds in large networks.	Future studies should develop lightweight distributed learning frameworks with measurable energy-benefit validation under real traffic conditions.

Overall, existing literature demonstrates a high change towards integrating sustainability into wireless network design. Prior studies have addressed green wireless communications from multiple perspectives, including network architecture, protocol optimization, intelligent control, and emerging technologies (Table 1). However, most works focus on specific aspects or technologies highlighting the need for a comprehensive review that combinedly examines sustainable architectures and protocols across different network layers.

This motivates the present study aims to deliver a comprehensive overview of green wireless communications focusing on identifying major challenges and outlining potential future research directions in this field.

3. Green Wireless Network Architectures

The necessary performance in modern wireless systems allows green wireless network architecture aims to reduce energy usage. Energy efficiency has become an essential design feature for the 5G and future 6G networks with high data rates, low latency and massive connectivity [13]. When compared with traditional network designs, green architectures are smart, adaptive and flexible in their management of network resources and depends on high-demand allocation and static operation. The networks will be able to change their operations based on user distribution, energy availability and traffic demand due to these designs.

3.1 Energy-Efficient Base Station Architectures

The key contributors of energy consumption for base stations are cellular networks impact the total power usage in 5G systems with advanced technologies such as beamforming, massive MIMO, bandwidth transmission increases the demand. The green architecture base station addresses by increasing the hardware efficiency and facilitate smart operational models [6]. A common method implements sleep and low-power modes deactivates the base station components during the low traffic. Additionally, the adaptive transmission power control allows output power based on user distance and channel. conditions. This method aligns 5G New Radio (NR) standards promotes dynamic resource allocation for energy efficiency. In this research, the 6G mainly focused on ultra-power transceivers and the integration of artificial intelligence for smart energy management [11].

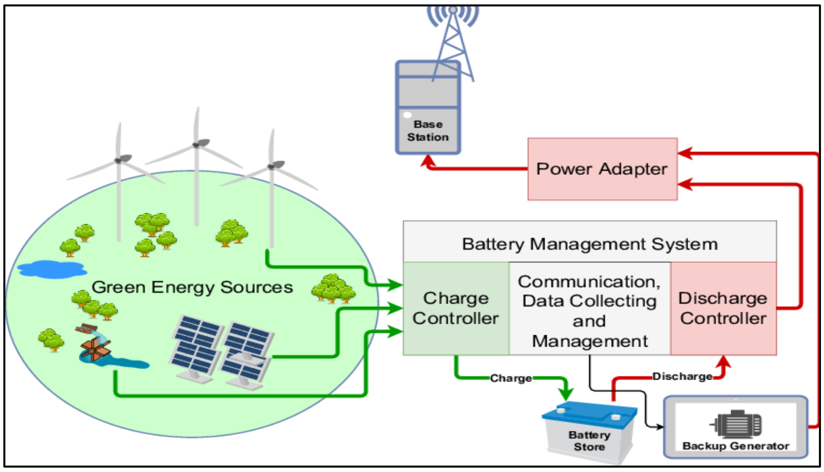

Figure 1. Energy-Efficient Base Station Architecture [10]

The figure 1 illustrates a green base station with adaptive power control, sleep modes for inactive components and smart traffic-aware resource management to reduce energy consumption.

3.2 Heterogeneous and Ultra-Dense Network Architectures

An essential component of 5G and 6G architecture is Heterogeneous Networks (HetNets). It combines the extensive coverage will be provided by macro cells with local area high-capacity access provided for micro, femto and pico cells [15]. When it is possible, the heterogeneous network architecture allows the provision of services with low-power small cells compared to high-power macro base stations. In the case of ultra-dense HetNets, the urban areas with high density of users, a number of small cells are implemented. This result increases the energy efficiency. The mentioned problems will be handled by using the green network architecture allows dynamic activation of cells. This will allow the active small cells when users are detected. This is further addressed in 5G architecture with the help of self-organizing networks. It is also further addressed in 6G architecture with the help of AI [6].

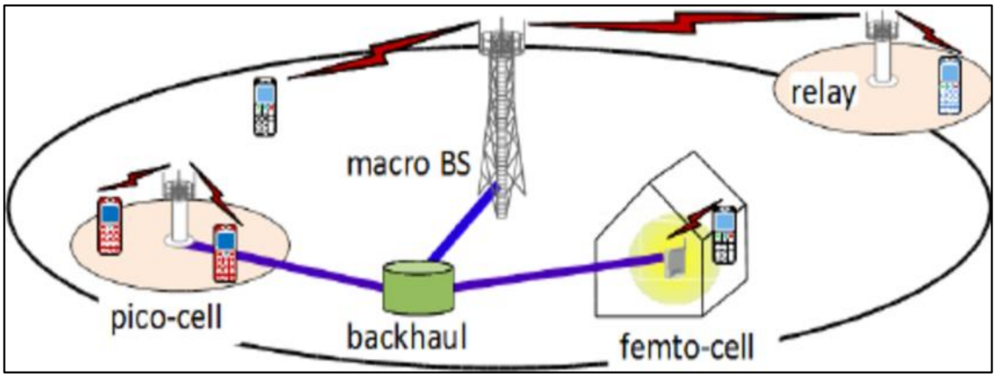

Figure 2. Heterogeneous and Ultra-Dense Network Architecture [15]

The figure 2 shows a macro cell providing wide-area coverage with multiple small cells serving local users, enabling traffic offloading and reduced transmission power.

3.3 Cloud Radio Access Networks and Virtualized Architectures

Cloud Radio Access Networks (C-RAN) and virtualized network architecture is pivotal for promoting green wireless communications in 5G and future generations [18]. C-RAN centralizes the baseband processing units within cloud data centers with remote radio heads positioned are cell sites facilitates resource sharing among multiple base stations [9]. This method improves the resource utilization by decreases the hardware redundancy. Additionally, Network Function Virtualization (NFV) and Software-Defined Networking (SDN) is essential to the 5G system to boost energy efficiency by enables the dynamic creation, scaling and deactivation of network functions as per the demand [14]. These technologies improve flexible network management and help to minimize the energy waste during the low traffic. The cloud and AI based architecture are evaluated to achieve the significant energy optimization in 6G [19].

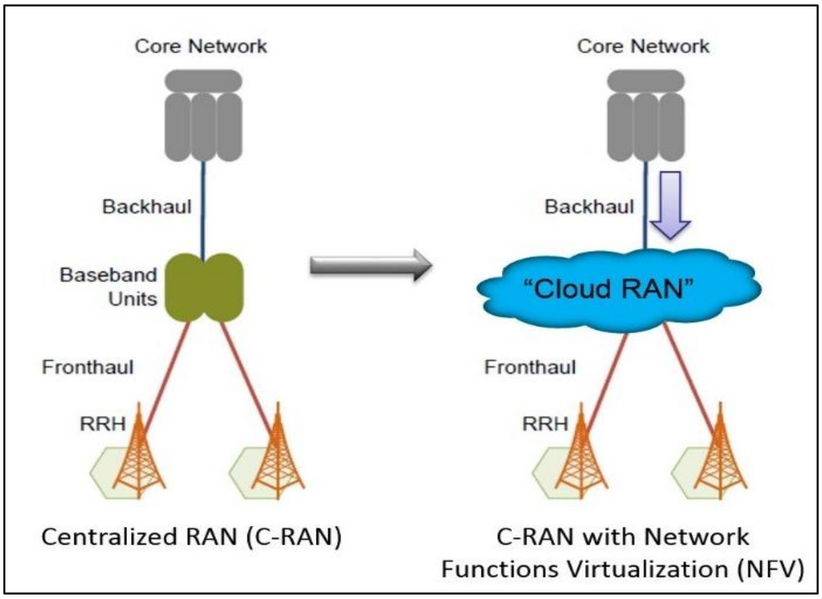

Figure 3. Cloud-Based and Virtualized Radio Access Network Architecture [20]

Figure 3 illustrates centralized cloud processing supporting distributed radio units through virtualized network functions, enabling flexible and energy-efficient operation

3.4 Adaptive Network Operation and Intelligent Control

Adaptive network management plays a vital role in green wireless architecture. It is important in 5G wireless networks by slicing and spectrum sharing can be managed. When the network is required, the adaptive management can minimize the energy consumption [8]. The network slices require less data rate managed by minimizing the power and resource. In 6G, the machine learning is expected to play an important role in wireless network architecture. It can be used in 6G wireless networks for the prediction of user traffic patterns, user mobility and energy availability in network [1]. These predictions are capable of proactive measures to save energy for removing the unused network components [15].

3.5 Integration of Renewable Energy in Network Architecture

Green network architecture uses solar or wind energy to improve base stations in rural areas [9]. Each storage systems like batteries enable storage of excess energy. In 5G technology and future 6G technology, the energy-aware network designs considers both quality of communication and the availability of energy [11]. Smart energy management system uses renewable energy sources, electricity grid for efficient usage and storage systems to minimize the usage of fossil fuels for green environment [16].

3.6 Architectural Trade-Off Analysis

The green architectures will improve energy efficiency involves technical and operational trade-off. Energy reduction cannot be evaluated independently from cost, latency, reliability and complexity. Therefore, the advantages and limitations of each architecture is required for real-time implementation. Table 2 represents the architectural analysis for green wireless networks.

Table 2. Architectural Trade-Off Analysis for Green Wireless Networks

Architecture	Advantages	Limitations	Suitable Deployment Scenario
Energy-Efficient Base Stations [2]	Direct reduction in transmission and circuit power; improves long-term operational cost	Requires hardware upgrades; limited savings if traffic remains high	Urban and suburban macro deployments
Heterogeneous Networks (HetNet) [18]	Reduced transmission distance; improved spectral efficiency; better coverage in dense areas	Increased coordination complexity; higher interference management overhead	Dense urban and high-capacity areas
Ultra-Dense Networks with Dynamic Cell Activation [9]	Significant idle energy reduction; traffic-aware operation	Risk of coverage gaps; handover increase; signaling overhead	Smart cities and variable traffic zones
Cloud Radio Access Network (C-RAN) [20]	Centralized processing improves resource utilization; reduced hardware redundancy	High fronthaul bandwidth requirement; latency sensitivity	Centralized metropolitan deployments
Network Function Virtualization (NFV) & SDN [14]	Flexible scaling; dynamic activation of network functions	Increased software complexity; potential cybersecurity risks	5G core and cloud-native networks

Renewable Energy Integration [17]	Reduces fossil fuel dependency; sustainable long-term operation	Intermittent energy supply; storage cost; weather dependence	Rural and off-grid base stations
AI-Driven Adaptive Architecture [16]	Traffic prediction; intelligent resource optimization	Training energy cost; model maintenance overhead	Large-scale 5G/6G networks

4. Sustainable Wireless Protocols

Sustainable wireless protocols play a significant role in reducing energy consumption in wireless networks by controlling how data is transmitted, received and managed across different network layers. The traditional protocols are mainly focused on throughput, latency and reliability compared to green protocols considers energy efficiency as a key performance objective [12]. These protocols aim to minimize unnecessary transmissions, reduce listening, adapt communication behavior to traffic demand and network conditions., Significant energy savings can be achieved without compromising service quality by optimizing protocol operation at each layer of the communication stack [19]. Table 3 represents the sustainable wireless protocols across different network layers.

Table 3. Summary of Sustainable Wireless Protocols Across Different Network Layers [13]

Layer / Protocol	Protocol Objective	Representative Protocols / Techniques	Energy-Saving Mechanism	Relevance to 5G/6G
Physical Layer / Energy-Efficient Protocols	Reduce transmission power while maintaining reliable communication	Adaptive Modulation and Coding (AMC), Power Control, Beamforming, Massive MIMO	Adjusts signal strength and modulation based on channel conditions to avoid excessive power usage	Core feature of 5G NR; extended in 6G with ultra-low-power waveforms and AI-based adaptation

MAC Layer Protocol	Minimize idle listening, collisions, and retransmissions	S-MAC, T-MAC, IEEE 802.15.4, Energy-aware scheduling	Uses duty cycling, sleep scheduling, and coordinated access to reduce unnecessary radio activity	Supported by flexible frame structures and dynamic scheduling in 5G; enhanced in 6G IoT
Network Layer / Routing Protocols	Optimize routing and data forwarding for energy efficiency	LEACH, PEGASIS, Energy-aware routing, SDN-based routing	Selects routes based on energy cost, residual battery, and traffic load	SDN-enabled routing in 5G core; global energy-aware routing in 6G
Transport Layer Protocol	Reduce energy waste from congestion and retransmissions	TCP Westwood, TCP Vegas, UDP with CoAP	Adapts congestion control and reduces retransmissions in wireless environments	Lightweight transport increasingly important for 5G IoT and 6G massive connectivity
Application Layer Protocol	Minimize data transmission and communication overhead	MQTT, CoAP, Data aggregation, Edge caching	Reduces payload size, aggregates data, and processes data locally	Edge computing and service-aware protocols are central to 5G/6G
Cross-Layer / Intelligent Protocol	Joint energy optimization across multiple layers	Cross-layer power control, SON protocols, AI-driven optimization	Shares information across layers to enable coordinated energy-saving decisions	AI-native cross-layer design is a key expectation for 6G

5. Enabling Technologies for Green Wireless Communications

Energy harvesting decreasing the dependence on traditional power sources for wireless devices. This concept enables wireless devices to operate for a longer time with minimal power supply from their environment, such as sunlight, wind, or radio signals. This concept is useful for sensor network and Internet of Things applications [19], where devices are often deployed in large numbers in inaccessible locations. Wireless power transfer is a further extension of this concept, where devices are powered or charged using electromagnetic waves [12].

Another important enabling technology for green wireless communications is cognitive radio. Cognitive radio is defined as a radio that is able to sense its environment and adapt [1]. When compared to the current wireless systems that transmit with a constant power level and frequency, cognitive radio is able to sense the environment and choose the better transmission parameters to send the signal [6]. The principles of cognitive radio are important in the current wireless systems to enable dynamic spectrum access. This feature is more important in the future as wireless systems will be required to support a wide range of applications with a limited number of available resources.

Artificial intelligence and machine learning have emerged as key drivers in achieving energy efficiency in wireless networks [8]. Machine learning and artificial intelligence can help wireless networks process large datasets and make rational decisions without human involvement. In green wireless communication networks, machine learning and artificial intelligence can be applied for predicting traffic patterns and controlling power consumption. When moving towards the 6G wireless communication networks, Artificial intelligence is expected to play a vital role in the design and development of wireless networks. The wireless network can perform tasks autonomously and efficiently in terms of energy consumption [16].

Artificial intelligence techniques can be further classified as offline learning and online learning techniques. In offline learning techniques, a high amount of training data and high computational power are required. Hence, the energy consumption in the initial phase is high. Once the model is trained, the energy consumption is low. In online learning techniques, the model is updated during runtime. Hence, the energy consumption during runtime is high. Centralized intelligence or cloud-based AI has high processing power but high energy consumption during data transmission. Distributed intelligence or edge-based AI has low energy consumption during data transmission but low processing power [7].

Another important development towards green wireless networking is edge computing. The use of edge computing technology reduces the energy consumption associated with data transmission to distant cloud servers. The use of edge computing technology in green wireless networks is important in improving the response time in wireless networks. The use of edge computing technology in green wireless networks allows unnecessary data transmissions to be avoided by processing and filtering data before transmission [8] [12].

The use of network virtualization and software-defined networking technologies offers the required flexibility for efficient green wireless networking. The use of these technologies allows network resources to be shared in green wireless networks. The use of these technologies in green wireless networks reduces energy consumption and lowers the costs associated with network operation. The use of network virtualization and software-defined networking technologies in 5G wireless networks has already shown the potential for efficient network operation. The use of these technologies in future wireless networks is expected to increase.

6. Challenges and Open Research Issues

Despite significant progress in green wireless communications, several challenges remain that limit the full realization of energy-efficient and environmentally sustainable wireless networks. These challenges arise from technical, operational and practical constraints must be addressed to support the long-term evolution of wireless systems particularly as networks move toward 6G. Table 4 illustrates the key challenges in green wireless communications.

Table 4. Key Challenges in Green Wireless Communications [17]

Challenge Area	Description	Potential Solutions and Research Directions
Energy Efficiency vs. Network Performance Trade-off	Reducing energy consumption may negatively affect data rate, latency, reliability, and coverage if not carefully managed.	Develop adaptive and cross-layer optimization techniques that dynamically balance energy efficiency and performance based on traffic and service requirements.
Increasing Network Complexity	Modern wireless networks involve heterogeneous cells, virtualization, massive MIMO, edge computing, and intelligent control, increasing system complexity and overhead.	Design scalable and simplified energy-aware network management frameworks supported by automation and intelligent control mechanisms.

Lack of Standardized Energy Metrics	Different studies use different metrics, making it difficult to compare energy-efficient solutions and assess environmental impact.	Establish unified energy efficiency and sustainability metrics that consider energy consumption, carbon emissions, and network lifecycle impact.
Integration of Renewable Energy Sources	Renewable energy availability is variable and unpredictable, which can affect network reliability and planning.	Develop intelligent energy management systems with energy storage, predictive control, and hybrid power supply models.
Security and Privacy Concerns	Lightweight and energy-efficient protocols may reduce security strength, and data-driven energy optimization may raise privacy issues.	Design secure and privacy-preserving energy-aware protocols and lightweight encryption methods tailored for low-power devices.
Energy Cost of AI-Based Optimization	Machine learning techniques improve energy efficiency but may require high computational power for training and inference.	Develop lightweight, distributed, and explainable AI models optimized for low-power and real-time network operation.
Economic and Deployment Constraints	High deployment costs and uncertain financial benefits slow the adoption of green wireless technologies.	Promote cost-effective solutions, long-term economic analysis, and supportive policies that encourage energy-efficient network deployment.
Regulatory and Policy Limitations	Existing regulations may not fully support energy-aware network operation or renewable energy integration.	Encourage collaboration between regulators, industry, and researchers to develop policies that support sustainable wireless networking.

7. Conclusion

The study discusses the different methods to support the green wireless communication systems include green network architectures, green technology and the green communication protocols. Green network architectures include energy-efficient base stations, cloud-based radio access networks, heterogeneous network implementation and renewable energy resources. In green communication protocols has various network layers helped in reducing the irrelevant transmissions and improves the lifespace of devices. This review explains the potential of new technologies such as artificial intelligence, edge computing, cognitive radio and energy harvesting supporting the adaptive and energy-aware network operations. However, few challenges are addressed such as balance between energy efficiency, system complexity, security and privacy, network performance and economic problems. The future research should be implementing the development of integrated energy management techniques includes architectural design, smart resource management and standardized evaluation criteria. This will develop the sustainable and energy-efficient wireless communication systems for supporting the 5G and 6G networks.

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