International Journal of Information Science and Computing
Citation: *IJISC*: **11**(02): 95-109, December 2024
DOI: 10.30954/2348-7437.2.2024.3

INFORMATION SCIENCE AND TECHNOLOGY FOUNDATION

RESEARCH PAPER

5G with IoT: Progressive Trends in Energy Efficiency Integration

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Received: 11 Oct., 2024 **Revised:** 25 Nov., 2024 **Accepted:** 02 Dec., 2024

ABSTRACT

The convergence of fifth-generation (5G) wireless technology and the Internet of Things (IoT) is revolutionizing modern communication networks by enabling ultra-reliable, low-latency, and high-throughput connectivity. However, this rapid evolution raises critical concerns about energy consumption and sustainability, particularly as billions of interconnected devices become active. This paper investigates progressive trends in the integration of energy-efficient strategies within the 5G-IoT ecosystem. The study examines emerging technologies like edge computing, machine learning-based energy optimization, and energy harvesting techniques for their potential to balance performance and power consumption. The paper also discusses standardization efforts and green communication frameworks that guide the development of sustainable 5G-IoT infrastructures. Furthermore, real-world case studies and simulations are analysed to assess the impact of energy-efficient protocols and architectures on system performance. The results highlight that using a multi-layered strategy—mixing new network designs, energy management at the device level, and flexible protocols—is crucial for long-lasting sustainability. This research contributes to a more profound understanding of how next-generation IoT applications can align with global energy goals, paving the way for eco-friendly digital transformation. We also outline future directions for research and deployment, advocating for cross-disciplinary collaboration and policy support to enhance energy efficiency across the 5G-IoT spectrum.

Keywords: Fifth-generation network, IoT, Energy efficiency, Sustainability, Green computing

In the era of rapid technological advancements, the integration of 5G and the Internet of Things (IoT) has brought about a paradigm shift in the way we connect and communicate. The 5G technologies and the Internet of Things (IoT) are reshaping various industries, promising unprecedented connectivity, speed, and data exchange[1][2]. As these technologies continue to evolve, there is a growing need to address the present issue of energy efficiency. The efficient utilization of energy resources is not only crucial for reducing operational expenses but also for promoting sustainability in the digital ecosystem. The fifth generation of wireless communication technology offers unprecedented improvements over

How to cite this article: Ratnakar, M. and Kumar, A. (2024). 5G with IoT: Progressive Trends in Energy Efficiency Integration. *IJISC.,* **11**(02): 95-109.

Source of Support: None; **Conflict of Interest:** None

its predecessors, including higher data transfer speeds, ultra-low latency, and the capacity to connect a vast number of devices simultaneously[3]. Technologies like milli-meter-wave frequencies, massive MIMO (multiple input, multiple output), and network slicing enable these advancements. 5G's enhanced capabilities provide a robust and scalable platform for supporting the exponential growth of IoT devices and applications. The IoT refers to the interconnection of everyday objects via the Internet, enabling them to send and receive data. The IoT spans a wide range of applications, from smart home devices and wearable health monitors to industrial automation and smart cities. Advancements in sensor technology, data analytics, cloud computing, and wireless communication have driven the evolution of IoT. The 5G technologies and the IoT are reshaping various industries, promising unprecedented connectivity, speed, and data exchange. As these technologies continue to evolve, there is a growing need to address the present issue of energy efficiency. The efficient utilization of energy resources is not only crucial for reducing operational costs but also for promoting sustainability in the digital ecosystem. The fifth generation of wireless communication technology, offers unprecedented improvements over its predecessors, including higher data transfer speeds, ultra-low latency, and the capacity to connect a vast number of devices simultaneously. The Internet of Things (IoT) refers to the interconnection of everyday objects via the Internet, enabling them to send and receive data. IoT spans a wide range of applications, from smart home devices and wearable health monitors to industrial automation and smart cities. The evolution of IoT has been driven by advancements in sensor technology, data analytics, cloud computing, and wireless communication[4]. The integration of 5G with IoT is expected to catalyze the development of innovative applications and services. The main benefits of this synergy include:

- **Enhanced Connectivity:** 5G's ability to support a massive number of devices per square kilometer facilitates the widespread deployment of IoT devices, enabling seamless and reliable connectivity for smart cities, industrial IoT, and connected vehicles.

- **Low Latency:** Critical applications such as autonomous driving, remote surgery, and industrial automation require real-time communication. 5G's ultra-low latency ensures that data is transmitted and received with minimal delay, supporting these time-sensitive operations.

- **Improved Energy Efficiency:** 5G networks incorporate advanced power management techniques and energy-efficient hardware, which help mitigate the increased energy demands of dense IoT deployments[7]. Additionally, IoT devices themselves can benefit from energy-efficient communication protocols supported by 5G.

- **Optimal Resource Allocation:** This 5G feature allows the creation of virtual networks tailored to specific requirements, such as high reliability for healthcare applications or high bandwidth for video surveillance[6]. Network slicing ensures optimal resource allocation and performance for diverse IoT use cases[5].

However, the deployment of these technologies comes with significant energy consumption concerns. As 5G networks and IoT devices proliferate, the demand for energy-efficient solutions becomes critical to sustain their growth and minimize environmental impact. This paper highlights the significance of energy efficiency in the context of 5G and IoT deployments. It sets the stage for understanding the challenges and opportunities associated with optimizing energy consumption in these interconnected systems. By focusing on energy efficiency, we can mitigate the environmental impact, extend battery life, and ensure the long-term viability of these transformative technologies[8].

The paper also emphasizes the potential benefits of energy-efficient practices in 5G and IoT[9]. These include reduced carbon emissions, improved network performance, enhanced scalability, and cost savings. By optimizing energy consumption, businesses and individuals can contribute to a greener future while reshaping the advantages of seamless connectivity and data-driven insights. Furthermore, the introduction acknowledges the complexities and obstacles involved in achieving energy efficiency in 5G and IoT[10]. It highlights the need for innovative solutions, collaborative efforts, and standardized protocols to overcome these challenges. By exploring strategies such as network optimization, device design, and data management, we can pave the way for sustainable and efficient 5G and IoT deployments.

It involves optimizing network infrastructure, reducing power consumption in devices, and implementing smart management systems. By addressing these energy challenges, the industry can ensure that the benefits of 5G and IoT are realized sustainably, paving the way for a more connected and efficient future. In conclusion, this introduction provides a comprehensive overview of the importance of energy efficiency in the context of 5G and IoT. It sets the foundation for further exploration and research into the development and implementation of energy-efficient solutions, ultimately leading to a more sustainable and connected future.

LITERATURE REVIEW

This section highlights various IoT-driven model components, energy efficiency model in 5G and state-of-the-art research publications. It provides a comprehensive overview of how IoT technologies are integrated into 5G networks to optimize energy consumption and enhance overall performance. Additionally, it showcases the latest advancements in research related to IoT-driven energy efficiency models in the context of 5G networks.

IoT-Driven Energy Efficiency Model

Fig. 1 shows the "IoT-Driven Energy Efficiency Model," which is positioned at the center of a circular diagram and connected to six key components. These components embody the essential strategies that collectively enhance energy efficiency via the integration of the Internet of Things (IoT). Each component addresses a distinct aspect of energy management, illustrating how IoT technologies can enhance sustainable and optimized energy systems.

Power Management Technique: This component highlights the significance of intelligent power control systems that oversee and manage energy consumption in real time. IoT-enabled sensors and actuators can automate energy consumption according to demand, occupancy, and environmental conditions, thereby minimizing unnecessary power waste and enhancing overall efficiency.

Demand Response and Load Management: IoT technologies play a critical role in adjusting energy demand in response to supply conditions. Smart meters and IoT devices can gather data to facilitate dynamic pricing, encourage consumer participation, and shift or reduce energy usage during peak demand times. Such action not only alleviates stress on the grid but also allows for more stable and cost-effective energy distribution[29].

Dynamic Resource Allocation: The integration of IoT in dynamic resource allocation allows energy systems to intelligently assign and reassign resources where they are most needed. By analyzing data in real-time, energy distribution can be optimized based on consumption patterns, helping to avoid bottlenecks, underutilization, or overloading of energy resources[30].

Optimize Communication Protocols: Efficient communication between IoT devices is essential for energy efficiency. Optimized protocols minimize energy consumption by reducing data transmission frequency, compressing data, and implementing low-power communication standards like ZigBee, LoRaWAN, or NB-IoT. This approach ensures that IoT networks are energy-conscious while maintaining performance.

Fig. 1: IoT-Driven Energy Efficiency Model

Energy-Aware Edge Computing: It refers to the processing of data near its source, rather than transmitting it to centralized cloud servers. By reducing the amount of data transmitted over networks and performing computations locally, edge computing significantly reduces energy consumption, enhances latency, and improves decision-making efficiency in IoT systems[20][28].

Renewable Energy Integration: Integrating renewable energy sources like solar, wind, and hydro into IoT ecosystems is essential for sustainable energy strategies. The Internet of Things enables real-time oversight and administration of renewable resources, guaranteeing their optimal utilization and integration with current power grids. It allows for better forecasting, load balancing, and storage management, enhancing the reliability and efficiency of renewable energy systems[19][21].

Energy consumption in the 5G era

The demand for communications service providers (CSPs) to diminish their energy consumption has been progressively intensifying, elevating this concern to a primary position on their corporate agendas. In this report, Caroline Gabriel, Research Director of Networks at Analysis Mason, explores how AI is critical to operators' bid to reduce energy consumption in the 5G era. Several principal reasons are delineated below:

- Without intervention, the present fuel price spike could put OPEX efficiency programs at risk by increasing energy costs.
- Consumers are progressively apprehensive about environmental matters and are keen on the sustainability qualifications of the companies from which they buy.
- National and supranational goals are filtering through to specific regulatory policies in the telecoms market, such as India's mandate for renewable energy sources to be used in rural cell towers.

An increasing number of CSPs are prioritizing environmental, social, and governance (ESG) issues in their long-term strategic agendas as a result of these cumulative pressures. The central axis of our strategy requires innovative, intelligent, and sustainable technology solutions that generate a positive impact on the environment and help manage the digital transition[22][23]. Fig. 2 highlights the energy consumption rate in various modules of 5G network.

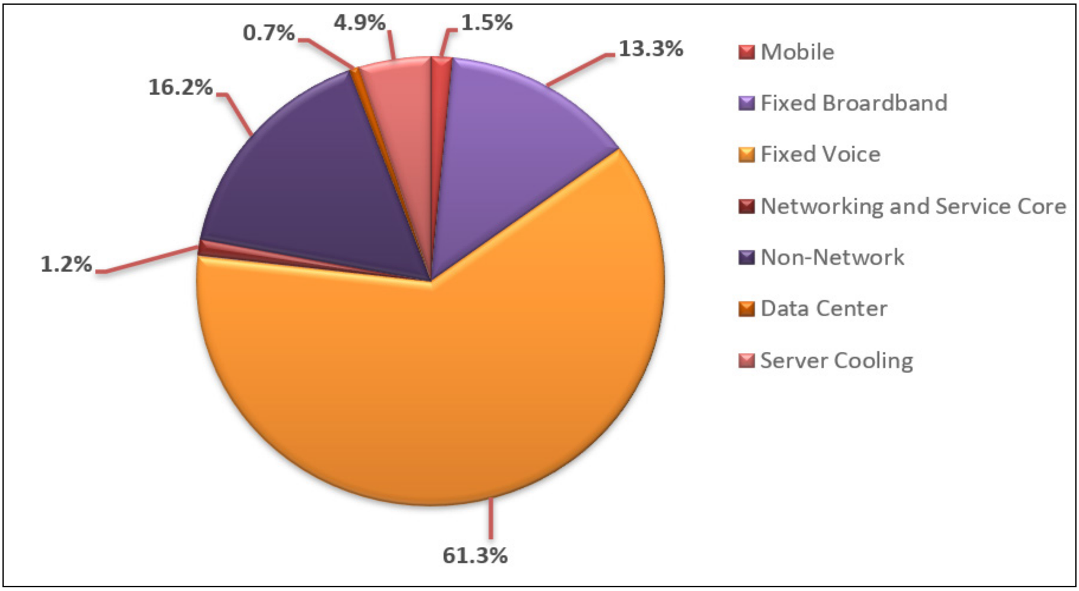

Fig. 2: Energy consumption rate in 5G networks

Related Research Publications

The 5G and IoT technology combined give greatly advanced connectivity and automation. These technologies have significant issues due to their increased energy consumption. In the Internet of Things (IoT)-based fifth generation (5G) networks, the coexistence of various network technologies, low latency, efficient spectrum usage, and high data rates are critical factors. Authors (Javaid *et al.* 2018[12]) examines the literature on several tools and techniques for improving energy efficiency in 5G networks and Internet of Things systems. New future challenges have been identified in the area of energy efficiency, which has recently been the focus of research aimed at improving performance measurements and design constraints for 5G communication networks[14]. In particular, artificial intelligence and machine learning will improve 5G's power efficiency and, more crucially, its ability to dynamically adapt its network components to any type of energy demand[21].

In authors (Ejaz, W. *et al.* 2016[13]) have demonstrated that deploying small cells and dense network topologies can reduce energy consumption by bringing network resources closer to end-users, thereby reducing transmission power and enhancing spectral efficiency. The well-known paper authored by Dhar Dwivedi, A. 2024[16] highlights the effectiveness of incorporating sleep modes in base stations and utilizing energy-aware communication protocols to minimize power usage during low-traffic periods. The (Li, S., Da Xu, L. & Zhao, S. 2018[15]) discussed how machine-to-machine communication became fast and ultra-reliable, through-put effecting transmission by enabling new 5G and IoT technology. And also focuses on several challenges such as a large number of connections of nodes, security, and main research trends. The authors (Shafique, K. *et al.* 2020[17]) present the device-to-device communication, centralized radio access network (CRAN), and cognitive radios (CRs) enabling and emerging technology in IoT -5G scenario[18]. Also discussed is how massive Multiple Input Multiple Output (MIMO) technology can improve energy efficiency by focusing transmission power more precisely, thus requiring less energy for the same data throughput. The implementation of strong authentication mechanisms for both devices and users accessing the network. It ensures that only authorized entities can access and control IoT devices and 5G network resources. The convergence of 5G and IoT promotes innovation in renewable energy integration, electric vehicle charging infrastructure, and demand-response systems, driving sustainability initiatives and reducing carbon footprints. However, amid these opportunities, ensuring the security, privacy, and reliability of 5G-IoT ecosystems[19].

In recent years, companies and researchers have paid more and more attention to mobile networks' energy usage and efficiency. Mobile data traffic is growing quickly, and a number of devices which are surrounding and connecting to smart cities, healthcare, transportation industry, etc. over the next 10 years, there are plans for even faster increases. Because of this, mobile networks' energy efficiency needs to drastically increase the internet of Things in order to security that future transfer levels are both economically and environmentally sustainable. The fifth-generation mobile networks are supposed to be the future standard network that will handle the invasion of IoT device updates and links while preserving the required quality of services (QoS).

THE PROPOSED PROGRESSIVE APPROACH

The proposed model

5G will continue to provide secure connectivity and high-value services, enabling a complete range of IoT solutions for consumers and businesses. This proposed model aims to control the interference between 5G and IoT is based on using the Smart Energy Optimization (SEO) technique to reduce interference and maximize the energy efficiency and reliability of the IoT and cellular networks in fifth-generation systems[24]. The proposed Smart Energy Optimization harnesses the power of 5G and IoT technologies to revolutionize energy efficiency. Figure 3 shows the proposed model of IoT-driven 5G progressive trends for energy efficiency.

The platform gathers real-time data on energy consumption through the deployment of IoT-enabled smart meters and sensors. This allows for the use of AI algorithms and advanced analytics to improve usage patterns[25]. The system's 5G connectivity makes it possible for utility companies and end users to communicate quickly, allowing for the smooth integration of renewable energy sources and dynamic demand-response management. SEO gives customers the tools they need to make wise decisions, save energy expenses, and contribute to a more sustainable future through tailored recommendations and predictive maintenance features. By putting strong security measures in place, the platform protects sensitive energy data's integrity and privacy, opening the door for a sustainable energy economy[27].

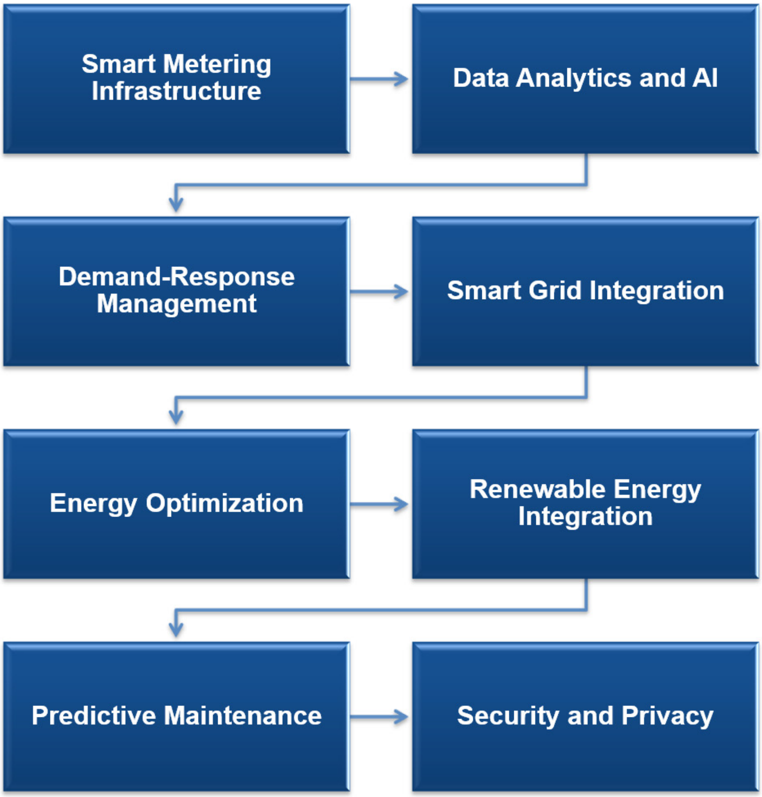

Fig. 3: Proposed progressive approach model towards energy optimization

Mathematical formulation of energy optimization model

To optimize the performance of IoT devices in a 5G network, we consider a model that integrates energy consumption, interference, and reliability. Let E_i represent the energy consumption of the i^{th} IoT device, and I_{ij} denote the interference between the i^{th} IoT device and the j^{th} 5G cell. The primary objective is to minimize total interference, expressed as;

$$\min \sum_{i=1}^{N} \sum_{j=1}^{M} I_{ij}$$

where N is the total number of IoT devices and M is the number of 5G cells. Here, we aim to maximize the reliability of the system, defined by where R_i is the reliability of the i^{th} device. To combine all three performance factors — reliability, energy efficiency, and interference, we define a single objective function as:

$$\min\left[\alpha\sum_{i=1}^{N} R_i - \beta\sum_{i=1}^{N} E_i - \gamma\sum_{i=1}^{N}\sum_{i=1}^{M} I_{ij}\right] \quad \ldots(1)$$

Where α, β, γ are positive constraints that reflect the relative importance of each term.

Energy Constraint:

$$0 \leq \sum_{i=1}^{N} E_i \quad \ldots(2)$$

Interference Constraint:

$$0 \leq \sum_{i=1}^{N}\sum_{j=1}^{M} I_{ij} \quad \ldots(3)$$

Reliability Constraint:

$$0 \leq \sum_{i=1}^{N} R_i \quad \ldots(4)$$

This optimization is subject to the following constraints: energy consumption must be non-negative, interference must also be non-negative, and the total reliability must be non-negative as well. The optimization problem aims to find the values of energy consumption, interference, and total reliability that maximize a certain objective function while satisfying the given constraints. The constants α, β, and γ play a crucial role in determining the trade-offs between these different factors in the optimization process. This optimization model provides a trade-off between-Reducing interference, saving energy and improving reliability. The use of weights α, β, and γ allows system designers to prioritize one factor over others, depending on the application requirements.

Experimental Parameters

To evaluate the proposed energy optimization model, several key experimental parameters must be defined to simulate a realistic IoT and 5G network environment. First, the number of IoT devices (N) and 5G base stations (M) are chosen based on the scale of the network-common values might range from tens to hundreds for IoT devices and a smaller number of 5G cells depending on coverage. Each IoT device is assigned an initial energy level and a specific data transmission requirement, which influences its energy consumption E_i. The interference values I_{ij} are typically computed based on spatial distance, signal strength, and channel overlap between devices and 5G cells, and may also incorporate stochastic noise to reflect real-world variability. Similarly, reliability scores R_i are modelled based on factors such as successful transmission rate, latency tolerance, and network stability for each device. These network-specific inputs, the optimization process depends heavily on the tuning of the weighting coefficients *α, β,* and *γ* in the objective function. These parameters are selected experimentally to reflect the relative importance of reliability, energy efficiency, and interference reduction. For instance, in scenarios where energy conservation is critical (e.g., battery-powered sensors), a higher value of β may be chosen. Conversely, in latency-sensitive applications, a greater emphasis may be placed on α\alphaα to prioritize reliability. Furthermore, baseline constraints such as maximum allowable energy consumption or interference thresholds may also be set to ensure realistic simulation conditions. Performance metrics such as total interference, average reliability, and energy usage before and after optimization are then recorded to evaluate the effectiveness of the model.

RESULTS AND DISCUSSION

The Fig. 4 represents the energy consumption (E_i) of 50 IoT devices. The data is uniformly distributed between 10 and 100 units, simulating a diverse set of devices with varying power requirements. From the graph, we observe that energy consumption is fairly spread across this range, with a slight concentration in the mid-range, indicating that most devices consume a moderate amount of energy. This diversity in energy profiles reflects a realistic IoT environment, where some devices (like low-power sensors) use minimal energy, while others (such as cameras or gateways) consume significantly more. The Fig. 5 illustrates the total interference experienced by each IoT device, calculated by summing up the interference values (I_{ij}) from all 10 nearby 5G cells for each device. The interference values are randomly generated between 0 and 1 for each IoT–5G pair, leading to a total interference per device that generally falls between 2 and 8 units. This pattern is realistic in dense networks where channel overlap and spatial proximity to multiple 5G cells contribute to varying interference levels. The Fig. 6 shows the reliability scores (R_i) of the IoT devices, with values uniformly distributed between 0.7 and 1.0. This distribution reflects a generally high level of reliability across the devices, which is typical in well-maintained or quality-controlled networks.

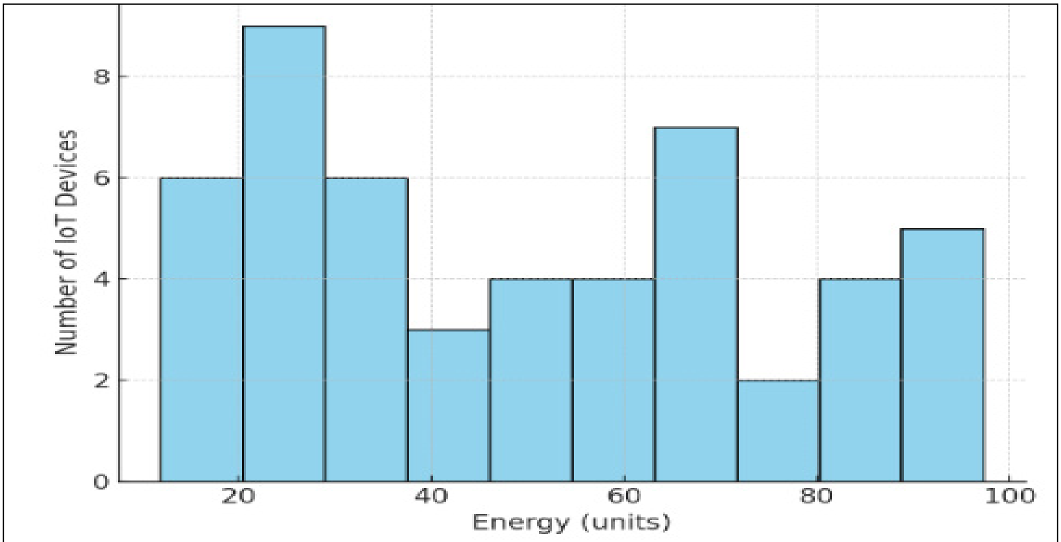

Fig. 4: Energy Consumption (E_i): Most IoT devices consume energy in the mid to high range, with a spread between 10 and 100 units

The histogram shows a noticeable clustering toward higher reliability scores (e.g., above 0.85), indicating that most devices maintain stable communication and meet required performance thresholds. This high reliability is crucial for mission-critical or latency-sensitive applications in an IoT-5G ecosystem.

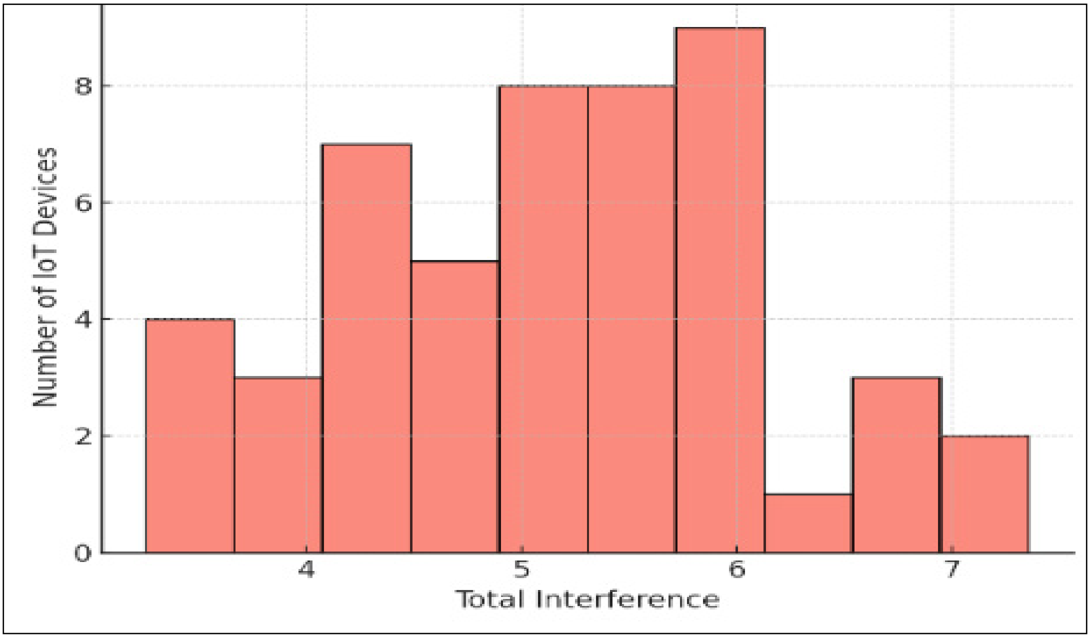

Fig. 5: Total Interference per Device: Interference values vary, but most devices experience moderate total interference from the 5G cells

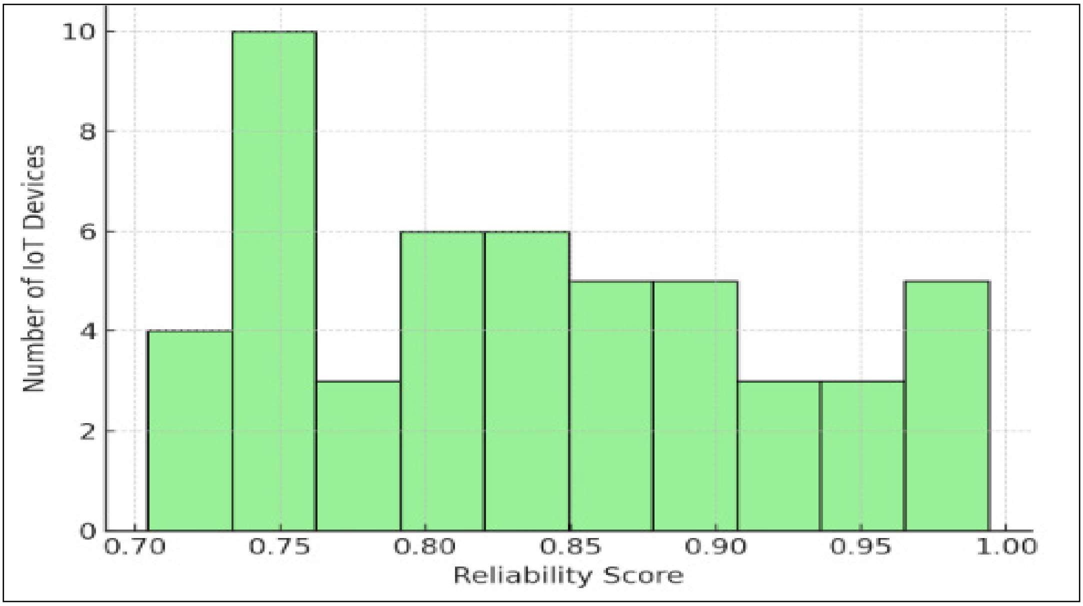

Fig. 6: Reliability (R_i): The reliability scores are fairly high across devices, with most values between 0.7 and 1.0

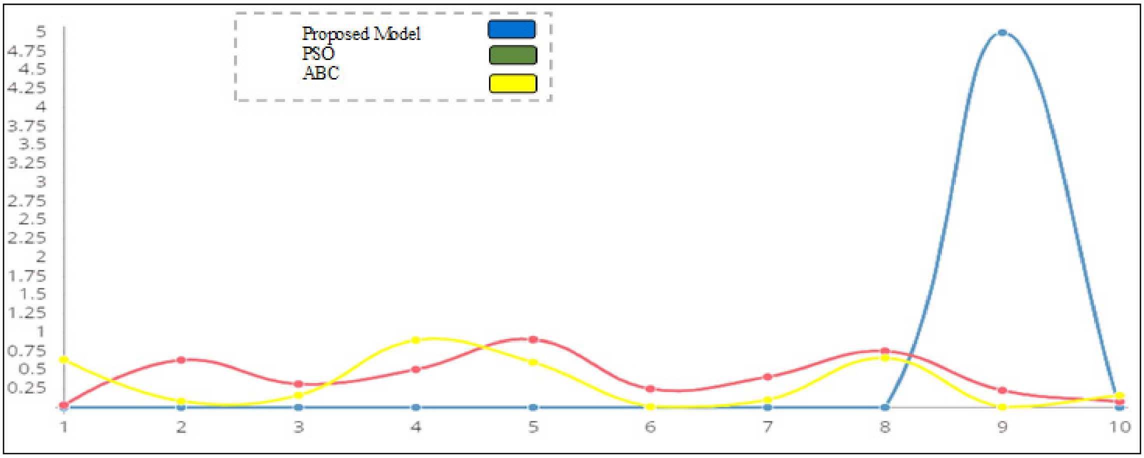

Fig. 7: Comparative results with Proposed model, PSO and ABC

The 5G enable devices to leverage the cloud more effectively, reducing dependency on internal memory and the accumulation of data. 5G has lower latency and it provides quick response times. This means new experiences associated with multiplayer mobile gaming, sophisticated factory robots and machinery, self-driving vehicles, and more. In addition, 5G will be able to accommodate more devices operating on the same network. This will impact IoT deployments across the spectrum, from smart devices operating inside homes, offices, and other commercial and private residences, to those comprising sophisticated Smart City solutions and services. Now, the outcomes and insights gained from testing two meta-heuristic models i.e. PSO & ABC with the proposed model are discussed here[26].

Table 1: Comparative results of model's reliability

Models	Mean	Std. Dev	Min	Max
Proposed Model	0.5000	1.5811	0.0000	5.0000
PSO	0.4119	0.2887	0.0314	0.9076
ABC	0.3333	0.3310	0.0092	0.8986

Table 2: Comparative results of model's energy optimization

Models	Mean	Std. Dev	Min	Max
Proposed Model	5.0000	15.8114	0.0000	50.0000
PSO	30.5790	15.0549	8.0611	46.4849
ABC	0.5637	0.2230	0.2243	0.8492

The proposed approach is to find models trained with optimization problems in our experiments. The testing dataset is used to compare the models' performance in terms of reliability and energy consumption as well as other metrics. Table 1 and 2 reported statistical data of comparative results of model's reliability and energy optimization respectively.

FUTURE RESEARCH DIRECTIONS

Based on the findings of this manuscript, we can identify several promising avenues for future research and development:

- *Advanced Energy Harvesting Mechanisms:* Research should focus on the design and implementation of novel energy harvesting materials and technologies, particularly those suited for low-power IoT devices operating under diverse environmental conditions.
- We need detailed research on methods that improve energy efficiency by working together across the physical, network, and application layers in different 5G-IoT settings.
- *Standardization and Policy Frameworks:* Future efforts should aim to develop global standards and regulatory policies that mandate or incentivize energy-efficient practices, ensuring that sustainability becomes an integral part of 5G-IoT deployment strategies.
- *Scalable Edge Computing Architectures:* As edge computing continues to evolve, new architectures that can scale efficiently while minimizing power consumption must be designed, particularly for supporting massive IoT networks.
- *Interdisciplinary Collaboration:* Finally, fostering collaboration between communication engineers, data scientists, environmental researchers, and policymakers will be crucial to creating holistic, sustainable 5G-IoT ecosystems.

These future trends emphasize the necessity for a comprehensive, interdisciplinary strategy that harmonizes technical progress with environmental stewardship, guaranteeing that the forthcoming generation of wireless communication is both robust and sustainable. Furthermore, continuous monitoring and assessment of 5G-IoT systems will be crucial to verify their compliance with environmental and social objectives. By uniting specialists from several disciplines, we can confront possible difficulties and devise new solutions for a more sustainable future.

CONCLUSION

The 5G enables devices to leverage the cloud more effectively, reducing dependency on internal memory and the accumulation of data. 5G has lower latency, and it provides quick response times. The result means new experiences associated with multiplayer mobile gaming, sophisticated factory robots and machinery, self-driving vehicles, and more. These changes will impact IoT deployments across the spectrum, from smart devices operating inside homes, offices, and other commercial and private residences to those comprising sophisticated Smart City solutions and services. The paper highlights significant advancements and ongoing research aimed at enhancing the energy efficiency of 5G networks and IoT systems. Strategies range from optimizing network infrastructure and hardware to developing innovative energy harvesting and low-power communication techniques. Continued focus on these areas is essential to support the sustainable growth of 5G and IoT technologies, ensuring their economically and ecologically viable deployment. The IoT has significant potential to improve energy efficiency, reduce energy consumption, and promote sustainability. However, challenges associated with integrating IoT in energy management include scalability, reliability, security, and privacy concerns.

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