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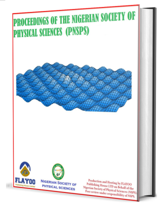

Optimizing energy efficiency in IoT networks for sustainable smart cities: a focus on energy-efficient communication protocols

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ABSTRACT

The rapid expansion of the Internet of Things (IoT) is driving the development of smart cities by improving connectivity and automation. However, the increasing number of IoT devices raises concerns about energy consumption, device longevity, and network sustainability. High energy demands lead to higher costs and limit large-scale deployments. To address these issues, energy-efficient protocols are essential for optimizing power consumption while maintaining network reliability. Key strategies include adaptive power control, duty cycling, and hybrid energy harvesting. The Hybrid Energy Harvesting-Based Energy Neutral Operation Medium Access Control (HENO-MAC) protocol integrates solar and wind energy to support energy-neutral operations. Additionally, advanced Medium Access Control (MAC) and routing protocols, such as the Routing Protocol for Low-Power and Lossy Networks (RPL), help minimize energy wastage. Emerging communication standards like Thread 1.4 further enhance energy efficiency and security. This study evaluates state-of-the-art energy-efficient IoT protocols in smart urban environments, analyzing technologies such as (Message Queuing Telemetry Transport) MQTT, RPL, and Constrained Application Protocol (CoAP). It also explores AI-driven energy management, edge computing, and energy-harvesting IoT systems. Through case studies from smart city initiatives in Barcelona and Singapore, the research highlights best practices for improving sustainability in IoT-driven cities.

Keywords: Energy-efficient IoT protocols, Smart city sustainability, Hybrid energy harvesting.

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1. INTRODUCTION

The rapid advancement of Internet of Things (IoT) technologies has become a cornerstone in developing smart cities, enhancing urban life through interconnected devices and intelligent systems. However, the extensive deployment of IoT devices poses significant challenges, particularly concerning energy consumption and sustainability. Estimates suggest that global IoT power consumption exceeds 100 TWh per year, substantially contributing to overall energy demand and raising concerns about long-term sustainability [1]. The high energy requirements of these networks diminish device lifespan, escalate operational costs, and impede sustainability initiatives [2]. Addressing these challenges necessitates the development and implementation of energy-efficient protocols that optimize power consumption while preserving network performance.

Recent research has underscored the imperative to implement

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energy-efficient solutions to mitigate power usage in IoT applications. For instance, Refs. [3, 4] emphasized the role of adaptive power control and duty cycling in reducing energy expenditure within smart city infrastructures. Their study demonstrates that employing strategies such as Adaptive Power Control and Network Topology Optimization can lead to significant reductions in energy consumption, ranging from 15% to 25%, thereby enhancing the sustainability of IoT deployments. Another successful deployment involves hybrid energy harvesting systems. Ref. [5] introduce the Hybrid Energy Harvesting-Based Energy Neutral Operation Medium Access Control (HENO-MAC) protocol, which integrates solar and wind energy sources to enable energy-neutral operations in delay-sensitive IoT scenarios. This protocol dynamically adjusts device duty cycles based on harvested energy availability, reducing reliance on conventional power sources and promoting sustainability.

Refining routing protocols has also been identified as a crucial strategy for minimizing energy consumption. Ref. [6] conducted a systematic review of energy-efficient routing protocols for IoT networks, highlighting methodologies that optimize energy usage and extend network lifespan. Their findings underscore the importance of developing protocols that balance energy efficiency with the Quality of Service (QoS) requirements of IoT applications.

Beyond protocol optimization, integrating advanced communication standards is vital for enhancing energy efficiency. The adoption of Narrowband IoT (NB-IoT) and LTE-M technologies has shown promise in optimizing energy consumption for IoT devices in smart cities [7]. These technologies offer low-power, wide-area connectivity solutions that are well-suited for IoT applications requiring extended battery life and reliable communication.

Artificial Intelligence (AI) driven approaches are also being explored to improve energy efficiency in IoT networks. Ref. [8] investigates AI-based strategies, employing machine learning techniques such as neural networks and reinforcement learning to forecast and optimize energy consumption trends. The study indicates notable enhancements in energy consumption, leading to longer battery life, decreased operational expenses, and reduced environmental impact.

Given these challenges and advancements, this study aims to quantify the impact of IoT energy consumption on sustainability and establish performance benchmarks for evaluating energy-efficient IoT networks. Specifically, it will assess cutting-edge protocols, including hybrid energy harvesting techniques, optimized routing protocols, and AI-driven approaches, to enhance sustainability, improve energy efficiency, and ensure the long-term functionality of IoT-enabled urban systems. Performance metrics such as energy savings in joules per transmitted bit, network lifetime improvements, and reductions in power draw per device will be examined to provide a comprehensive evaluation of sustainable IoT deployments.

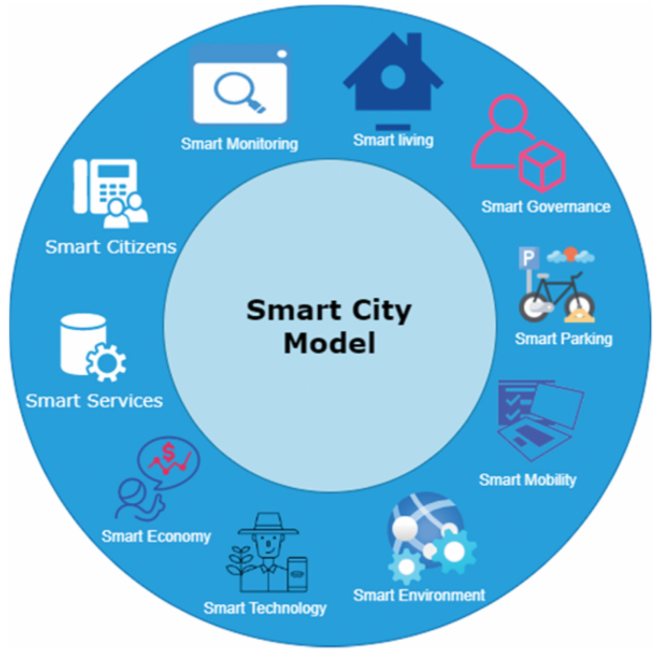

Figure 1. Features of a smart city.

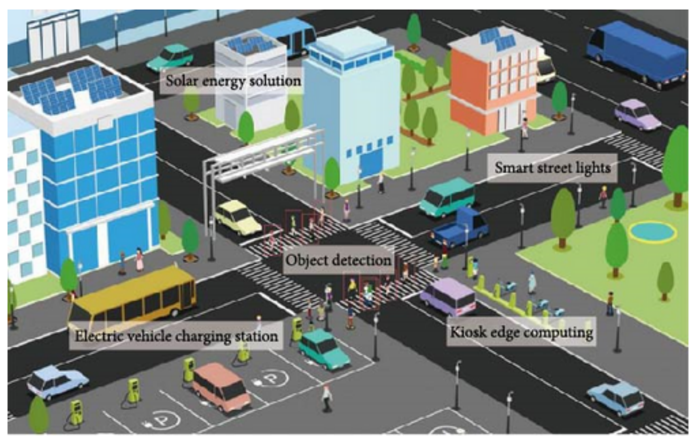

Figure 2. A sophisticated smart city scenario with conceptual levels of ICT infrastructure.

2. LITERATURE REVIEW

2.1. MESSAGE QUEUING TELEMETRY TRANSPORT (MQTT)

The swift development of smart cities relies heavily on the effective incorporation of IoT networks, with energy efficiency playing a vital role in achieving sustainability. Advanced communication protocols, particularly the MQTT, are key to optimizing energy use while maintaining dependable data transmission [9].

MQTT functions on a lightweight publish-subscribe framework, which diminishes the necessity for constant data polling and reduces energy consumption in IoT devices with limited resources [10]. This approach improves network efficiency by allowing devices to send data only when required, thus saving power.

In contrast to conventional request-response protocols like HTTP, MQTT significantly decreases bandwidth requirements and computational demands, making it particularly suitable for battery-operated sensors in smart city environments [11]. Studies have demonstrated that MQTT can reduce energy consumption by approximately 6% to 8% compared to HTTP. Specifically, experiments using the MQTT protocol with Quality of Service (QoS) levels 0 and 1 resulted in power savings of 6.03% and 8.33%, respectively, compared to HTTP, thereby extending battery life in IoT devices [12]. Another study found that MQTT's power consumption is notably lower than that of HTTP, highlighting its suitability for energy-constrained IoT applications [13]. These findings underscore MQTT's efficiency in reducing energy usage, which is critical for the longevity and reliability of battery-powered sensors in smart city deployments.

A significant aspect of MQTT that promotes energy efficiency is its QoS levels, which allow devices to find a balance between reliability and energy use [14]. By choosing an appropriate QoS level, IoT systems can enhance data transmission according to network conditions and specific application needs. Furthermore, MQTT's lightweight design alleviates the processing load on devices, contributing to additional energy savings [15].

In extensive smart city deployments, MQTT's support for edge computing further boosts energy efficiency. By facilitating local processing and decision-making at edge devices, MQTT minimizes the need for frequent cloud communications, which in turn reduces power consumption and enhances network responsiveness.

Additionally, MQTT's application in public safety systems provides benefits such as real-time communication, effective data sharing, and scalability. For example, emergency services can leverage the ability to swiftly and reliably exchange information during critical incidents, thereby improving overall public safety [16].

2.2. ROUTING PROTOCOL FOR LOW-POWER AND LOSSY NETWORKS (RPL)

The RPL is a distance-vector-based routing protocol standardized by the Internet Engineering Task Force (IETF) for networks characterized by low power and high loss, particularly those utilizing IPv6 technology [17]. It constructs a Destination-Oriented Directed Acyclic Graph (DODAG) anchored at a sink node, facilitating efficient data routing while supporting customizable objective functions that optimize routing based on metrics such as energy consumption, latency, link quality, and reliability [15, 18, 19].

Despite its flexibility, RPL presents several trade-offs that impact its performance in resource-constrained IoT environments. One major trade-off exists between energy efficiency and routing overhead. RPL is designed to be energy-efficient, minimizing control packet exchanges and selecting parent nodes based on residual energy and link quality. However, maintaining the DODAG structure introduces routing overhead, particularly in large-scale networks where frequent topology updates and control messages such as DODAG Information Object (DIO) and Destination Advertisement Object (DAO) consume bandwidth and computational resources. Another key trade-off is adaptability versus stability. While RPL is highly adaptable and supports different routing strategies for static and dynamic environments, it struggles with mobility management. In static networks like environmental monitoring systems, RPL ensures stable paths and optimized energy use. However, in mobile settings, frequent topology changes lead to route inconsistencies, increased packet loss, and performance degradation, as RPL was not initially designed for highly mobile scenarios [20].

Additionally, RPL's focus on low power consumption can lead to increased latency. The protocol employs mechanisms such as trickle timers to reduce unnecessary control transmissions, thereby conserving energy. However, limiting message propagation delays network updates, which can be problematic in time-sensitive applications such as real-time industrial monitoring. To address these challenges, various enhancements have been proposed. Backpressure RPL (BRPL) introduces dynamic routing adjustments based on network congestion, improving throughput and adaptability in mobile IoT environments [20]. Other enhancements focus on energy-aware RPL variants, which modify the parent selection process to balance energy consumption among nodes, extending network lifespan [19]. Additionally, hybrid RPL approaches incorporating machine learning and reinforcement learning techniques help optimize routing decisions dynamically, reducing overhead while maintaining network efficiency.

2.3. CONSTRAINED APPLICATION PROTOCOL (COAP)

The CoAP is an application-layer protocol specifically designed to address the communication challenges faced by resource-constrained devices in IoT environments. These devices, which often operate with limited processing power, memory, and energy resources, require an efficient protocol that minimizes overhead while maintaining interoperability with web-based systems. CoAP meets these requirements by providing a lightweight communication interface, similar to HTTP, but optimized for constrained devices and networks [21, 22].

CoAP employs a request/response model while utilizing the User Datagram Protocol (UDP) instead of Transmission Control Protocol (TCP). This choice significantly reduces communication overhead, improves energy efficiency, and minimizes latency, making it particularly suitable for low-power and lossy networks [23]. Unlike traditional protocols, CoAP also supports asynchronous communication, which allows IoT devices to exchange data without maintaining persistent connections. This feature is particularly beneficial for battery-powered sensors and actuators that need to operate intermittently to conserve energy.

Another critical advantage of CoAP is its seamless integration with the Representational State Transfer (REST) architecture. This allows IoT applications to interact with web-based services efficiently, enabling interoperability between IoT networks and cloud-based platforms [20]. By leveraging RESTful principles, CoAP enables devices to expose resources using uniform resource identifiers (URIs) and supports methods such as GET, POST, PUT, and DELETE, simplifying communication and data exchange across heterogeneous IoT ecosystems.

Despite its advantages, security remains a key concern, especially in large-scale deployments where devices communicate over open and potentially vulnerable networks. To mitigate risks, CoAP can be secured using Datagram Transport Layer Security (DTLS), which provides encryption and authentication to protect data integrity and confidentiality. However, the overhead introduced by DTLS can be a challenge for extremely resource-constrained devices, prompting ongoing research into lightweight security mechanisms tailored for CoAP-based systems [24].

Recent advancements in CoAP focus on enhancing scalability, reliability, and adaptability to evolving IoT frameworks. Researchers are exploring hybrid transport mechanisms, congestion control strategies, and improved resource discovery techniques to optimize CoAP's performance in dynamic IoT environments [25]. As IoT applications continue to expand across domains such as smart cities, industrial automation, and healthcare, CoAP's role in enabling efficient, low-power communication will remain pivotal in shaping the future of interoperable and sustainable IoT solutions.

2.4. CHALLENGES IN ENERGY EFFICIENCY FOR IOT IN SMART CITIES

Energy efficiency is a critical challenge in smart city IoT networks due to device heterogeneity and resource constraints. Wireless communication, a major energy consumer, becomes inefficient in large deployments without optimized protocols [26]. Techniques like duty cycling and adaptive transmission power control help mitigate this issue.

Scalability further impacts energy consumption as more devices increase transmission and processing demands. High node density can cause interference, worsening energy usage [27]. Adaptive clustering techniques such as LEACH and SEP improve data aggregation and reduce redundant transmissions, enhancing efficiency [28].

Environmental factors also affect energy harvesting. Solar and kinetic energy sources provide alternative power, but their efficiency varies by climate, requiring hybrid energy management strategies [29].

Security adds to energy constraints. Encryption and authentication are crucial but demand processing power. Lightweight encryption methods balance security and energy use, making them suitable for low-power IoT devices [30].

3. CASE STUDIES AND REAL-WORLD APPLICATIONS

The exploration of energy-efficient IoT protocols has gained significant traction in real-world smart city initiatives. Numerous case studies illustrate the effectiveness of these protocols in optimizing energy consumption, enhancing network performance, and promoting sustainability. However, these implementations also present challenges that offer valuable lessons for future smart city deployments.

3.1. CASE STUDY: SMART CITY INITIATIVE IN BARCELONA

Barcelona has integrated IoT-driven smart solutions for energy-efficient street lighting, traffic management, and waste collection. The city utilizes LEACH-based clustering methods within its sensor networks to enhance data transmission efficiency, resulting in a 30% reduction in energy usage and an extension of sensor lifespan. The smart lighting system, which combines LED lights with motion and environmental sensors, has led to annual energy savings exceeding €36 million [31].

Despite these successes, Barcelona faced challenges in scaling its IoT infrastructure. Initial deployment costs and interoperability issues between legacy systems and new technologies required strategic investments and policy adjustments. Lessons from Barcelona highlight the necessity of modular IoT frameworks that can adapt to evolving urban needs.

3.2. CASE STUDY: SINGAPORE'S SMART NATION PROGRAM

Singapore's Smart Nation program employs RPL-based routing protocols to improve the efficiency of its environmental monitoring and traffic management systems. By implementing adaptive power control strategies, the city has reduced energy expenditure by 35% while maintaining high data accuracy. Singapore's motion-sensor-based smart street lighting system has enhanced remote monitoring capabilities, reduced maintenance costs and improving overall operational efficiency [32].

One of the primary challenges Singapore encountered was cybersecurity risks associated with interconnected smart infrastructure. To address these concerns, the government introduced robust encryption standards and multi-tier authentication mechanisms. This case study underscores the importance of integrating security measures alongside energy-efficient protocols to maintain the resilience of smart city networks.

3.3. CASE STUDY: TSCH-BASED SMART FACTORY IN GERMANY

Germany's Industry 4.0 factories have adopted the Time-Slotted Channel Hopping (TSCH) protocol to enhance communication reliability while conserving energy. A comparative analysis demonstrated that TSCH-based networks achieved up to 40% energy savings over conventional wireless systems by reducing retransmissions and interference [33]. These networks have also improved real-time monitoring of industrial processes, increased productivity and reducing downtime.

However, integrating TSCH into existing industrial IoT systems presented compatibility issues with older hardware. Retrofitting legacy equipment required custom firmware updates and standardized industrial protocols. This case study highlights the need for industry-wide collaboration to develop scalable, energy-efficient IoT solutions.

4. COMPARATIVE ANALYSIS OF IOT SOLUTIONS IN SMART CITIES: BARCELONA VS. SINGAPORE

Smart cities leverage IoT technologies to enhance urban infrastructure, improve energy efficiency, and promote sustainability. Barcelona and Singapore provide notable examples of these implementations, as shown in the following comparisons.

Table 1 illustrates the deployment of smart street lighting in Barcelona and Singapore, featuring sophisticated LED lighting systems that incorporate motion and environmental sensors. These innovations lead to substantial energy savings, with Barcelona realizing a 30% reduction and Singapore achieving 35%. Furthermore, the economic and operational advantages are impressive Barcelona notes annual savings surpassing €36 million, while Singapore utilizes remote monitoring to enhance maintenance efficiency and prolong the lifespan of its systems.

Table 2 offers a comparison of various smart traffic management initiatives. In Barcelona, the implementation of smart parking sensors allows for real-time updates on parking availability through mobile apps, resulting in decreased congestion and reduced emissions. Conversely, Singapore utilizes an Intelligent Transport System (ITS) along with Electronic Road Pricing (ERP), which combines real-time data to facilitate dynamic congestion pricing and effective traffic oversight. Both cities successfully leverage IoT-driven solutions to improve urban mo-

Table 1. Smart street lighting comparison.

City	Technology Used	Energy Savings (%)	Additional Benefits
Barcelona	LED lights with motion & environmental sensors	30%	Annual savings exceeding €36 million [31]
Singapore	Motion-sensor-based smart street lighting	35%	Remote monitoring for improved maintenance [32]

Table 2. Smart traffic management comparison

City	IoT System Used	Key Features	Outcome
Barcelona	Smart parking sensors	Real-time parking availability via mobile apps	Reduced traffic congestion and lower emissions [31]
Singapore	Intelligent Transport System (ITS) & Electronic Road Pricing (ERP)	Real-time data integration for congestion pricing and traffic monitoring	Efficient traffic flow and reduced congestion [32]

Table 3. Smart waste management comparison

City	Technology Used	Efficiency Gains	Environmental Impact
Barcelona	Sensor-based waste bins (Smart Waste Management System)	20% reduction in garbage truck trips	Lower carbon emissions [31]
Singapore	Pneumatic waste conveyance system	Reduced labor and collection costs	Minimal environmental footprint [32]

bility, minimize travel durations, and lessen their environmental footprint.

Table 3 highlights innovative waste management practices in smart cities. In Barcelona, the implementation of sensor-enabled waste bins within its Smart Waste Management System has resulted in a 20% decrease in garbage truck trips, thereby reducing carbon emissions. Similarly, Singapore's Pneumatic Waste Conveyance System enhances waste collection efficiency by cutting down on labor and operational expenses while also lessening the environmental impact. These strategies demonstrate how technology-based solutions can enhance both efficiency and sustainability in urban environments.

Barcelona and Singapore serve as benchmarks for integrating IoT-driven energy-efficient solutions in smart cities. While their strategies differ Barcelona focusing on sensor-based improvements and Singapore emphasizing automation and data analytics both cities have demonstrated significant energy savings and operational efficiencies. However, their experiences also highlight key challenges, including infrastructure scalability, cybersecurity risks, and initial deployment costs.

5. ADVANCING SUSTAINABLE AND SECURE SMART CITY INFRASTRUCTURE

5.1. AI-DRIVEN ENERGY MANAGEMENT

Future smart cities should integrate AI-driven optimization, such as predictive analytics for power consumption and adaptive routing algorithms, to enhance efficiency. Case studies in smart grids have shown AI reducing energy waste by up to 25% [34].

5.2. ENERGY-HARVESTING IOT (EH-IOT)

Deploying self-sustaining sensors powered by solar, kinetic, or thermoelectric energy can further improve sustainability. For instance, smart meters in the UK using solar panels have reduced dependency on grid power by 40% [35].

5.3. SCALABLE POLICY FRAMEWORKS

Governments should introduce standardized IoT policies that facilitate interoperability and cybersecurity while encouraging public-private partnerships to fund energy-efficient smart city projects [36].

5.4. FURTHER RESEARCH ON 6G AND BLOCKCHAIN SECURITY

Future studies should explore 6G-enabled IoT solutions and blockchain-based encryption techniques to enhance security and efficiency in large-scale smart city deployments [36].

6. EMERGING TRENDS AND TECHNOLOGIES

The rapid advancement of IoT networks has led to the development of innovative technologies aimed at improving energy efficiency, reliability, and scalability in smart urban environments. One of the most impactful trends is the integration of Artificial Intelligence (AI) and Machine Learning (ML) into IoT-driven energy management systems. AI-driven optimizations enable real-time adjustments in data transmission, device scheduling, and routing, significantly reducing power consumption. For instance, Google's DeepMind AI has successfully optimized energy usage in data centers, cutting cooling costs by 40%, a principle that is now being applied to IoT-based smart grids and building automation systems to enhance energy efficiency. Similarly, AI-powered traffic management systems in cities like Singapore dynamically adjust traffic signals to minimize congestion and lower fuel consumption, thereby reducing overall energy waste [36].

Additionally, Edge and Fog Computing have emerged as crucial technologies that process data closer to IoT devices rather than relying solely on cloud computing. This approach minimizes latency, conserves bandwidth, and reduces energy consumption, making IoT networks more sustainable. In applications like smart manufacturing, AI-driven edge computing has improved real-time decision-making in predictive maintenance, optimizing energy use in industrial machinery.

Energy-harvesting IoT (EH-IoT) is also gaining momentum, utilizing renewable energy sources to power sensors and devices. Solar-powered environmental monitoring sensors are widely deployed in smart agriculture, where they collect and transmit data on soil moisture and weather conditions without requiring frequent battery replacements. Similarly, kinetic energy-powered wearables, such as self-charging fitness trackers, harness motion to generate power. Thermoelectric-powered sensors, used in industrial settings, convert heat waste into usable energy, making them ideal for remote monitoring in high-temperature environments.

Innovations in 6G networks and Ultra-Low Power (ULP) wireless communication are further enhancing IoT connectivity. Technologies like Backscatter Communication, which enables IoT devices to transmit data using ambient radio waves, and Reconfigurable Intelligent Surfaces (RIS), which optimize signal propagation, are significantly reducing energy consumption while maintaining reliable communication.

7. CONCLUSION AND RECOMMENDATION

Enhancing energy efficiency in IoT networks is vital for smart city sustainability. HENO-MAC achieves up to 40% energy savings by optimizing medium access control and reducing idle listening, extending IoT device lifespan. Other protocols like LEACH, RPL, and CoAP contribute to power optimization, while cross-layer approaches improve efficiency by minimizing redundant transmissions. However, scalability, security, and network diversity remain key challenges. The recommendations are:

1. Smart Energy Management: Nigerian cities should adopt IoT-enabled smart grids and adaptive street lighting, which can cut energy use by 50% [37]. AI-driven analytics can further optimize power distribution, while energy-harvesting smart meters minimize maintenance needs.
2. IoT-Based Traffic Solutions: IoT-driven traffic management can reduce congestion and fuel consumption by 25%. Smart signals and predictive maintenance in connected vehicle systems can improve mobility and lower emissions in cities like Lagos and Abuja [38].
3. Waste Management Optimization: Sensor-equipped waste bins and automated collection systems can cut operational costs by 30% by optimizing pickup schedules. AI-driven analytics can further enhance recycling efficiency, following successful models from Barcelona and Singapore [39].
4. Renewable Energy & Energy Harvesting: Solar, wind, and kinetic energy can sustain IoT infrastructure in Nigerian cities. Hybrid energy-harvesting sensors ensure reliable operation under fluctuating conditions, improving air quality monitoring and urban sustainability [40].
5. Enhancing Public Safety: AI-powered IoT surveillance enhances security through real-time anomaly detection. Blockchain and lightweight encryption, such as ECC-based cryptography, can protect large-scale IoT networks while maintaining energy efficiency [41].

8. CHALLENGES AND FUTURE DIRECTIONS

Advancements in energy-efficient IoT protocols have not eliminated the challenges associated with optimizing power consumption while ensuring performance and security. A significant hurdle is scalability, as the size and complexity of IoT networks continue to expand. Effectively managing energy-efficient communication among a vast number of interconnected devices remains a pressing concern.

Moreover, security and privacy issues present considerable obstacles. Many energy-efficient protocols aim to minimize computational demands, which can inadvertently increase susceptibility to cyber threats. Future developments may involve the integration of lightweight encryption and blockchain-based security frameworks to bolster protection without incurring excessive energy costs.

Another critical challenge is network heterogeneity, characterized by the coexistence of diverse IoT devices with differing power capacities and communication protocols. Achieving seamless interoperability while ensuring energy efficiency necessitates the implementation of adaptive and AI-driven network management strategies.

In the future, research is expected to concentrate on self-sustaining energy solutions, including energy-harvesting IoT systems and ultra-low-power wireless communication technologies. Furthermore, AI-driven predictive analytics and edge computing will be essential in dynamically optimizing energy usage. The emergence of 6G-enabled IoT networks is anticipated to further improve energy-efficient communication, contributing to the sustainability and resilience of smart cities.

DATA AVAILABILITY

We do not have any research data outside the submitted manuscript file.

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