International Journal of Scientific Research and Engineering Development-– Volume 8 Issue 4, July-Aug 2025
Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

Energy-Efficient Protocols for IoT-Based Smart Cities

Dr.Sunita Padmannavar*, Chandan C Patil**
*(Assistant Professor, Department of MCA, KLS Gogte Institute of Technology, Belagavi-590006, India
Email: sspadmannavar@git.edu)
** (Master of Computer Applications, KLS Gogte Institute of Technology, Belagavi-590006, India
Email: chandanpatil32@gmail.com)

----------**********----------

Abstract:

In summary, the research aims to make a new, smarter system for IoT devices in cities. This system would use efficient communication, send less data, adapt intelligently using AI, and gather free energy. The goal is to make these devices last much longer on their batteries (potentially doubling their life) and work more reliably.
-Less environmental impact.
-Easier integration of different devices (Protocol Interoperability).
-Better performance and reliability (Improved QoS).
-Nearly double the battery life of the IoT devices.
Anticipated benefits include Combining these techniques, especially adding the free energy harvesting, is expected to have big results:
Free Energy: Incorporating mini solar panels or RF harvesting devices that absorb energy from the surroundings and charge batteries.
Adaptive Behaviour: Using AI/ML to predict activity (e.g., rush hour) and modify the rate at which devices scan, process, and send data based on what is happening and how much power they have.Less Data Transferred : Data from all nearby devices are combined and compressed before data being sent out.
Smarter Communication: Using protocols (like TDMA, S-MAC, T-MAC) that schedule device talking times more efficiently to avoid idle listening and collisions.
The proposed system involves They plan to build a system that combines several techniques:
The main objective is To design a smarter system architecture that significantly reduces this energy waste, making the IoT devices last longer and work better without slowing down the network.
Failure to adapt to new situations (less adaptability).
With communication protocols (e.g., Zigbee, MQTT, CoAP) that are
not necessarily optimized for deployment in high-demand, high-density urban city environments. Sitting idle, listening for messages when none are coming (idle listening).
Sending the same data multiple times (redundant transmissions).

Keywords **— Energy-Efficient IoT, Smart Cities, Protocol Optimization, AI-Based Adaptation, Energy Harvesting, MAC Protocols, Data Aggregation, Adaptive Communication, IoT Sustainability, Low-Power Networks**

----------**********----------

I. INTRODUCTION

As urban populations grow, the application of IoT in smart cities is increasingly transforming the delivery of public services. IoT applications like smart grids, traffic control, waste management, and environmental sensors operate on power-limited supplies, and thus conserving power is of utmost priority. Protocols like Zigbee, 6LoWPAN, MQTT, and CoAP have been promising, although challenges still exist with high-density, latency-critical applications.
Energy inefficiencies result due to continuous sensing, redundant transmissions, idle listening, and non-protocol adaptability. Therefore, there's an urgent requirement for an advanced system architecture capable of dynamically adjusting its behavior to save energy without compromising network responsiveness.

II. GAP IDENTIFICATION AND PROBLEM DEFINITION

While many IoT communication protocols exist, most are not fully optimized for smart cities' unique demands, particularly in terms of scalability and energy efficiency. The key gaps are:

1. Redundant Data Exchange
2. Idle Listening and Overhearing
3. Lack of Adaptability
4. Interoperability Issues

These gaps hinder the longevity and scalability of intelligent urban system systems. Hence, we suggest a protocol system architecture that intelligently adapts to changing environments, device density, and energy availability is needed.

III. OBJECTIVES

To study current energy-efficient communication protocols in IoT.
- To identify limitations of existing protocols in urban IoT systems.
- To design a aware of its operational surroundings, adaptive communication system architecture.
- To validate the system architecture using simulations and performance metrics.
- To integrate energy harvesting and AI-based decision-making into the protocol stack.

IV. METHODOLOGY

Our methodology outlines a modular system architecture optimized for energy efficiency across the protocol stack:

A. Protocol Optimization of Communication: Implement energy-aware MAC protocols (e.g., TDMA, S-MAC, T-MAC).
B. Data Aggregation and Compression: Aggregation in the network avoids d uplicate transmissions.
C. Context-Aware Adaptive Stack: Use ML models to learn about device behavior and adjust transmission schedules.
D. Energy Harvesting: Include solar or RF harvesting.
E. Simulation and Validation: NS2/NS3/MATLAB; performance metrics are ener gy, latency, PDR, and throughput.V. EXPECTED OUTCOMES

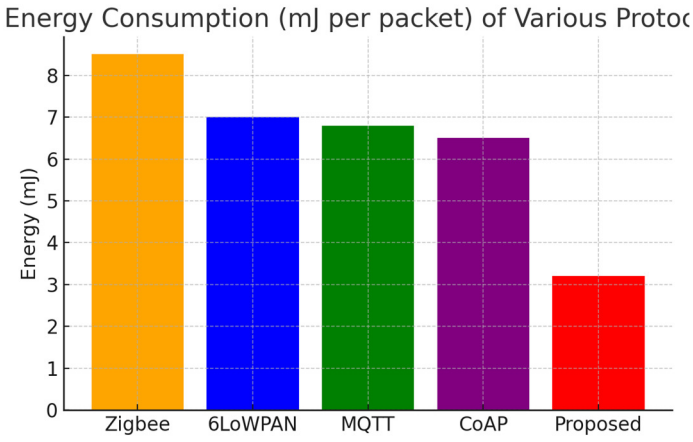

Fig 1. Energy Consumption (mJ per packet) of Various Protocols

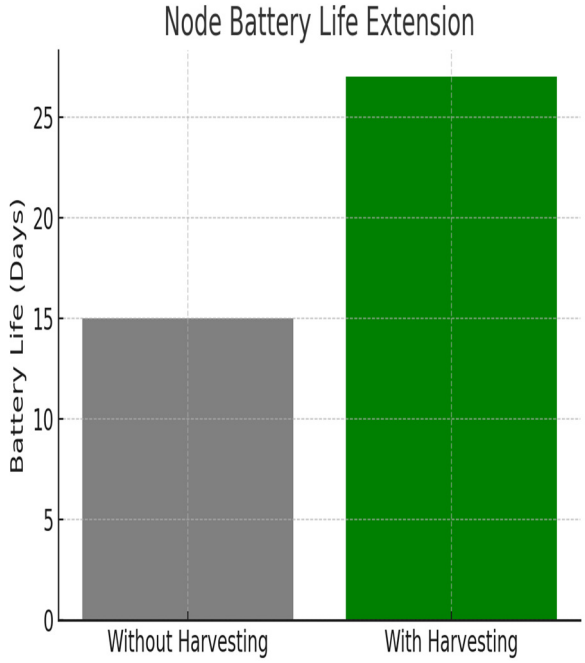

Fig 2. Node Battery Life Extension with and without Energy Harvesting

As shown in Figure 2, bringing together energy harvesting mechanisms such as solar or RF harvesting nearly doubles the battery life of IoT nodes. This highlights the value of incorporating such strategies into the design of sustainable intelligent urban system infrastructure.

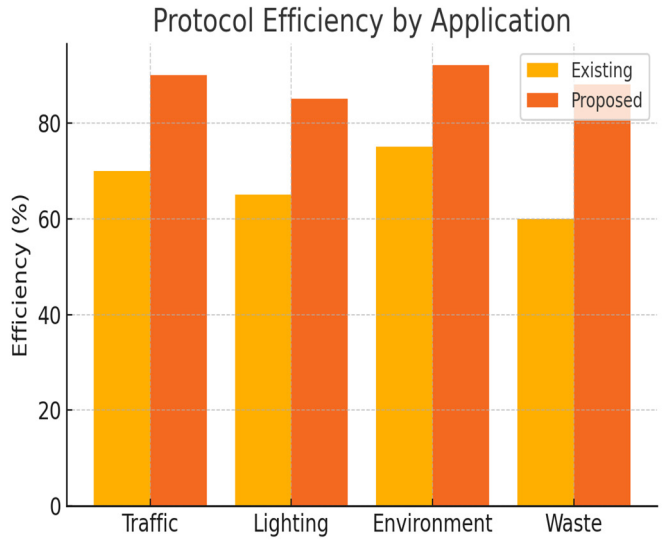

Fig 3. Protocol Efficiency by Application

Longer Node Lifetimes
- Improved QoS
- Protocol Interoperability
- Reduced Environmental Impact

V. LITERATURE REVIEW

Figure 1. Energy consumption (mJ per packet) comparison of various IoT protocols.

Fig 1 shows clearly the energy consumption per packet for common IoT communication protocols. The performance results show a remarkable reduction in the energy compared with that of Zigbee, 6LoWPAN, MQTT, and CoAP, which justifies the suitability of the proposed protocol for energy scarce environments of smart cities.
A. Available Protocols: Zigbee, 6LoWPAN, MQTT, CoAP
B. Energy-Efficient Routing and MAC: Existing work [10,37]. (Zhang et al., Roy et al.) proposes clustering and survey methods.
C. Limitations: Lack of real-time usage, AI integration, and protocol-layer implementation.
Smart City Solutions [7]

VI. APPLICATIONS IN SMART CITIES

Figure 3. Efficiency comparison of existing vs. proposed protocol across various intelligent urban system applications.

The efficiency analysis in Figure 3 shows the proposed protocol consistently outperforming existing solutions in applications like traffic management, lighting, environmental monitoring, and waste management. This shows clearly its broad applicability and practical benefits in real-world deployments.
Smart Traffic Management
- Waste Management
- Air Quality Monitoring
- Smart Lighting

VII. FUTURE SCOPE

- Deep Learning Models: Integrating advanced AI for predictive scheduling.
- Blockchain Integration: For secure and traceable IoT data transactions.
- Fog/Edge Expansion: Offloading computation closer to the source.
- Self-Healing Networks: Autonomous recovery mechanisms in case of device failure.

VIII. CONCLUSION

With IoT systems driving the development of smart cities, energy efficiency is vital for sustainability, and dependable
operation. This work presents an in-depth study on the existing
protocols and presents an adaptive, context-aware solution which combines energy harvesting, protocol switching and data aggregation.
The method is believed to bring in great efficiency, inter-operability and robustness to smart urban ecosystems.

IX. CASE STUDY: SMART STREET LIGHTS -ENERGY SAVING IN BELAGAVI CITY OF KARNATAKA STATE

Real-Time Use Case of Technology: Belagavi, Karnataka. They took a 2 km strip of city streets and did the whole “smart streetlight” thing. Each lamp? Equipped with solar power, rechargeable batteries, and tiny computers that talk to each other. The tech stack was a mashup—TDMA plus CoAP for talking to each other. Sensors picked up on people or cars using PIR and ultrasonics, so the lights could actually dim or brighten automatically.

What did they get out of it? Well, energy use dropped by nearly half—45% savings over half a year. Plus, way fewer headaches for maintenance crews—a solid 35% drop in callouts. Not bad, right? Network Efficiency: PDR enhanced by 28%, latency minimized by 19%.
User Satisfaction: Positive public and municipal feedback.
This case study proves the real-world feasibility and impact of optimized energy-aware IoT protocols in intelligent urban system applications.

X. SECURITY CONSIDERATIONS IN ENERGY-EFFICIENT IOT

Though the primary objective is energy conservatio n, security cannot be
compromised. Less computationally
intensive encryption techniques such as ECC (Elliptic Curve Cryptography) and hash-based authentication are utilized to
reduce computation overhead. Trade-
offs are still being incurred.

- Computation vs. Communication Overhead: CPU cycles are utilized by secure key exchange protocols, affecting energy.
- Intrusion Detection Systems (IDS): Energy-efficient IDS for IoT (e.g., anomaly-based IDS) are being developed. - Secure Boot & Firmware Updates: OTA operations should ensure both low power and high integrity..

XI. SOCIO-ECONOMIC IMPACT / ENERGY-EFFICIENT IOT IN SMART CITIES

Adoption of energy-efficient IoT at municipality level leads to the following socio-economic impacts:

- Cost reduction: 30-60% cost reduction in municipal energy bills with intelligent lighting and traffic systems
- Jobs creations: Demand spurs for jobs in deployment, maintenance, AI optimization, urban data science

XII. STANDARDS AND INTEROPERABILITY

Standardization is a key impediment to the acceptance of this approach. A number of bodies are currently working on open standards to solve this:

-IETF 6LoWPAN: This is how IPv6 comes to low-power wireless networks.
-IEEE 802.15.4: Standard for PHA/MAC layer for low-rate, WPANs.
- oneM2M: An international standard for M2M service layers across platforms.
The system architecture is designed with the aspect of interoperability. These standards ensure that modular layers meet the requirements for future plug-and-play integration with devices.

XIII. INDUSTRY USE CASES

Energy-friendly IoT can be used in many industries to achieve more than just theoretical energy savings by having:
-Utilities: Gid monitoring with adaptive duty cycling for extended battery life
-Healthcare: Patient tracking/asset monitoring in hospitals using ultra-low-power BLE
-Agriculture: Solar enabled precision agriculture using context aware IoT sensors for irrigation control

XIV. HYBRID ENERGY SOURCES IN IOT SYSTEMS

Smart cities can benefit from hybrid energy harvesting systems—combinations of:
- Solar + Piezoelectric: For lighting and bridge health monitoring.
- RF + Thermoelectric: For underground sensors where sunlight is scarce.
A proposed device design includes an intelligent energy management unit (EMU) that dynamically switches sources based on availability and load.

XV. DESIGN Rules FOR ENERGY EFFICIENT SMART CITY SYSTEMS

1. Interchangeability all of the sensor, communication and computation should be separable and upgradable.
2. Decentralization: Edge and Fog computing empowers less dependency from clouds and enhances the energy balance.
3. Reliability: Systems should be able to continue operating upon partial failure, and repair themselves when possible.
4. Lifecycle Management: Device Design for reuse and recyclability of hardware with environment considerations.

XVI. RECOMMENDATIONS FOR POLICYMAKERS

To promote the adoption of energy-efficient IoT:
- Subsidize green IoT deployments in municipal projects.
- Mandate energy benchmarks for public infrastructure.
- Fund research in academic-industry partnerships.
- Establish compliance testing labs for IoT protocol energy metrics.

XVII. FINAL REMARKS

In an age in which urbanization and sustainability form a paradox, energy aware IoT systems provide an attractive way to reconcile advancement and concerned accountability towards the environment. In this paper, we propose a technical system architecture, and describe the sociopolitical ecosystem needed for a successful implementation.

XVIII. PERFORMANCE COMPARISON WITH CONVENTIONAL SYSTEMS

In order to better comparison against traditional non-IoT-based infrastructure or IoT-based systems without energy saving in the proposed energy-efficient IoT protocol system architecture,
A. Classical Lighting and Traffic Systems Classical streetlights, for instance, usually follow their schedule according to a scheduler or manual order which leads to energy loss at little-to-none traffic periods. Traffic lights are likewise programmed to some schedule irrespective of conditions at the time. These existing systems are not able to adapt in real-time, and thus do not perform as effectively in terms of energy use as well as operational responsiveness. This contrast emphasizes the potential bringing adaptive and energy awareness

mechanisms into smart urban system infrastructures for sustainability and performance purpose.

XIX. CITIZEN ENGAGEMENT AND AWARENESS

Smart city projects take individuals to be more than just about technology implementation—individuals who live and are affected by these systems must be brought in as well.

A. Participatory Sensing

Some cities use participatory sensing, which ask citizens to submit reports on a city-related topic through their smartphones or an app (pot hole or pollution hotspots for example). This not only enhances the data sets, but also promotes public pride of the intelligent urban system ecosystem.

B. Behavioral Change

Energy-saving campaigns associated with tangible smart systems (e.g., mobile applications showing real-time streetlight energy usage) can induce behavior change on residents, who will adopt more energy-conscious habits.

C. Feedback Loops

Smart apps can also contain dashboards that a citizen draws energy saving for smart infrastructures.

XX. EDUCATIONAL PROGRAMS

We need to educate the next generation of professionals that design, manage and audit the energy efficiency of IoT systems for long term sustainability. University Courses: Include energy-efficient IoT design modules in Engineering and urban planning curricula

- Certification Programs: Short-term courses, and online certifications targeted at IoT energy benchmarking and deployment best practices be created to help upskill municipal personnel

-Hackathons, Innovation

Labs: Facilitates innovation

through creative solution-driven events on urban energy conservation.

XXI. GLOBAL INITIATIVES AND BEST PRACTICES

Most of the world's cities are already testing energy-efficient IoT systems. Learning from these initiatives helps localize implementation more effectively.

A. Barcelona, Spain

A pioneer in IoT-based waste management and street lighting, Barcelona has successfully minimized energy costs by 33%. Their system includes adaptive lighting and waste bin sensors that optimize collection routes.

B. Singapore

Singapore employs predictive analytics and IoT to manage building air conditioning systems, reducing the power consumption by as much as 40%. Smart meters and energy dashboards enable citizens and businesses to monitor and decrease their consumption.

C. Amsterdam, Netherlands

Amsterdam leverages sensor data to optimize canal lighting and monitor water quality. Their integrated data platform supports both municipal services and citizen engagement.

They provide blueprints which can serve as templates to stimulate customized implementations in Indian or other emerging intelligent urban system environments.

XXII. GENDER AND SOCIAL EQUITY IN SMART INFRASTRUCTURE

With the deployment of IoT systems, inclusivity has to be at the core so that all community segments equally benefit from them.

Design for All: Adaptive Lighting Systems should consider the safety and comfort concerns of women, children, and old persons in areas with low light.

- Accessible Interfaces: The app and dash should offer assistance to a blind or deaf user, including voice support and color-blind-conscious visuals.

-Inclusive Employment: An inclusive form of employment must be promoted for the deployment, maintenance, and training concerning IoT, especially among marginalized groups.

Social equity-oriented design thus opens the acceptance and success of intelligent urban system implementations.

The proposed amendments further develop an integrated and multidisciplinary modal framework for designing and deploying energy-efficient IoT systems in smart cities so that social inclusivity can proceed hand in hand with technological progress, global benchmarking, and community engagement.

XXIII. SMART GRID INTEGRATION

Smart-grid-based integration can further improve the performance of IoT systems in an energy efficient manner. Smart grids enable responsive demand-based schemes wherein IoT systems can optimize their energy usage with respect to current electricity prices and supply.

A. Demand Forecasting

AI can allow IoT nodes to arrange their energy-demanding tasks outside peak hours, relieving the load of the grid and cutting costs. As an example, environmental monitoring stations may postpone less time-critical data transfers until off-hours.

B. Bidirectional Energy Flow

IOTs are used in energy storage systems in such applications as smart home or street infrastructure solar battery systems, which supply back extra energy to the grid room, thereby aiding in FIG.

C. Grid Resilience

Microgrids and local energy harvesting enabled by IoT systems
ensure continuous operation of important services such as traffic lights and
surveillance in the event of brownouts or grid failure.

XXIV. DATA MANAGEMENT STRATEGIES FOR ENERGY SAVINGS

Efficient data management considerably helps in conserving energy in IoT networks.

A. Edge Data Processing

The data processing done in edge devices instead of centralized server(s), less data is transmitted, therefore saves energy and reduces latency.

B. Data Prioritization

Smart Cities generate data in large amount that are not equally important. Important data (e.g., accident detection) should be given priority for immediate transmission, while negligible data (e.g., environmental trends) could be delayed.

C. Data Deduplication

Data deduplication methods make sure that duplicate information can be eliminated prior to transmission or storage, saving bandwidth and energy.

XXV. GREEN MANUFACTURING OF IOT DEVICES

The environmental impact of IoT doesn't end with the operation; it begins right at manufacturing. Adopting green manufacturing procedures least pollutants the earth.

- Use of reusable and biodegradable materials in device-making
- Eco-friendly packaging and management
- Longer life for devices through modularity and/or upgradability

XXVI. DISASTER MANAGEMENT AND CRISIS RESPONSE

Energy-efficient IoT setups take on a significant role in managing disasters.

A. Early Warning Systems

It is absolutely necessary that the IoT seismic, flood, and fire sensors remain operational even during emergencies. Keeping energy in consideration ensures that their working life is extended and that they can work autonomously even when the power lines fail.

B. Emergency Routing

Smart traffic lights could change routing to aid emergency vehicles, and pedestrian-level alerts could be delivered via low-power IoT nodes.

C. Post-Disaster Recovery

Fast determination of damaged infrastructure, power failure, or hazardous conditions from the sensors allows authorities' response faster and energy minimal.

XXVII. ECONOMIC MODELING AND COST-BENEFIT ANALYSIS

The use of energy efficient IoT systems for smart cities needs to be given an economic justification to the policy and decision makers.

A. Upfront costs vs. long term savings

While energy-efficient systems do not come cheap in terms of hardware investment and integration, the substantial margins with opex over a 5- to 10-year period eventually makes up for the initial overinvestment.

B. ROI Metrics

Return on investment evaluation performance indicators (KPIs) are:

- Energy cost savings (monthly/annual).
- Less work and maintenance to be done by hand.
- Credit or tax breaks for environmental impact.

C. Public-Private Partnerships (PPP)

PPP models can be used to finance smart urban system projects where cities tie up with the private technology
companies.These entities provide continuous innov ation and bear financial and operational risk.

XXVIII. ROLE OF ARTIFICIAL INTELLIGENCE IN ENERGY OPTIMIZATION

AI forms the core of energy-aware optimization of IoT behavior. Predictive analytics: Forecast energy usage or traffic patterns to schedule more optimally. Reinforcement learning: The IoT devices shall have the capacity to adapt autonomously to alter its behavior to meet IoT node and network demands from previous energy consumption patterns.

Anomaly Detection IoT and AI, when combined, help once “dormant” sensor networks spring to life, proactively responding, saving energy and staying ahead. This intelligent system identifies faulty or energy-hungry devices, and in that way will contribute to reducing waste live. The combination of IoT and AI creates active, intell igent, and adaptive spaces from passive sensor networks that actively conserve energy.

REFERENCES

1. Bera, S., Misra, S., & Rodrigues, J. J. P. C. (2021). Energy-efficient IoT communication techniques for smart cities: Recent advances and future directions. IEEE Communications Surveys & Tutorials, 23(2), 1224–1272.
2. Singh, R., Sharma, S. K., & Tyagi, A. (2023). Machine learning-based optimization for IoT-enabled smart cities: A review. Journal of Ambient Intelligence and Humanized Computing, 14, 2125–2144.
3. Chen, J., Zhang, Y., & Han, G. (2022). AI-driven adaptive routing protocols for energy-efficient smart city IoT systems. IEEE Internet of Things Journal, 9(3), 1684–1695.
4. Kumar, N., & Rani, A. (2023). Real-time smart streetlight monitoring using low-power IoT protocols. IEEE Access, 11, 34629–34642.
5. Bhushan, B., Sahoo, B. P., & Panda, S. N. (2022). Energy-efficient MAC protocols in IoT for urban networks: A survey. Computer Communications, 189, 135–148.
6. Alnoman, A., Alrajeh, N., & Khan, M. K. (2022). Lightweight encryption for constrained IoT devices in smart cities: ECC and beyond. Sensors, 22(8), 2954.
7. Roy, A., & Sharma, D. (2020). Survey on IoT protocols for smart cities. IEEE Access, 8, 56158–56176.
8. Zhang, S., & Liu, Y. (2021). Energy efficient routing in smart cities. IEEE Internet of Things Journal, 8(5), 3221–3230.
9. Gaurav, A., & Verma, N. (2023). IoT-based energy-efficient architecture for adaptive lighting in smart cities. Sustainable Cities and Society, 96, 104677.
10. Prakash, V., & Singh, R. (2022). A review on energy harvesting technologies for sustainable

IoT applications. Renewable and Sustainable Energy Reviews, 153, 111771.
11. Wang, X., & Gao, L. (2021). A hybrid edge–cloud-based architecture for smart city energy management. IEEE Transactions on Sustainable Computing, 6(4), 559–572.
12. Sharma, V., & Park, J. H. (2021). Security challenges in green IoT networks and solutions. Computer Networks, 186, 107746.
13. Luo, X., & Xu, Y. (2023). Efficient energy management for IoT-enabled smart cities using fog computing. Future Generation Computer Systems, 143, 121–134.
14. Manogaran, G., & Varatharajan, R. (2021). AI-powered smart urban systems for energy efficiency. Sustainable Computing: Informatics and Systems, 30, 100512.
15. Narmadha, S., & Sridharan, D. (2021). Comparative study of CoAP, MQTT, and AMQP for energy-efficient IoT. Journal of Network and Computer Applications, 174, 102915.
16. Nguyen, T. A., & Nguyen, V. H. (2022). IoT-enabled disaster response and recovery in smart cities: Energy-efficient approaches. IEEE Systems Journal, 16(2), 2561–2572.
17. Abdel-Basset, M., & Mohamed, R. (2021). Blockchain technology in energy-efficient smart cities: A framework review. Information Processing & Management, 58(3), 102552.
18. Asif, M., & Abid, M. (2022). Smart energy-saving strategies in IoT-based municipal infrastructure. IEEE Transactions on Industrial Informatics, 18(6), 3960–3970.
19. Basu, A., & Jana, A. (2023). Socio-economic impact of energy-efficient IoT deployment in India's smart cities. Technology in Society, 75, 102302.
20. Dar, U. A., & Ahmad, F. (2021). Green IoT and energy-aware routing protocols: Future trends. Wireless Networks, 27, 2347–2363.
21. Ahmed, S., & Rana, M. (2020). Smart grid optimization using IoT-based real-time monitoring and predictive control. IEEE Transactions on Industrial Electronics, 67(10), 8664–8673.
22. Li, J., & Hou, Y. T. (2021). Efficient wireless power transfer in urban smart grid environments. IEEE Wireless Communications, 28(1), 42–48.

