Smart Internet of Things

www.siot.reapress.com

Smart. Internet. Things.Vol. 1, No. 3 (2024) 191–197.

Paper Type: Original Article

Energy-Aware Network Management for IoT Devices in Smart Cities

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Citation:

Received: 27 May 2024 *Revised: 18 July 2024* *Accepted: 22 September 2024*	Thakur, B. (2024). Energy-aware network management for IoT devices in smart cities. *Smart internet of things*, *1*(3), 191-197.

Abstract

In the modern era of rapid urbanization, smart cities are emerging as data-driven ecosystems where Internet of Things (IoT) devices play a crucial role in enhancing efficiency across urban services. However, the proliferation of these devices has resulted in significant energy consumption, posing challenges for sustainable city development. Effective energy management in IoT networks is thus essential to achieve long-term sustainability goals. This paper addresses the issue of energy inefficiency within IoT networks in smart cities by proposing an Energy-Aware Network Management (EANM) framework. Our methodology integrates an adaptive clustering algorithm and a predictive analytics model, forecasting network load and energy demands based on historical data patterns. By leveraging machine learning, the framework enables the real-time adaptation of network protocols, including sleep scheduling and data transmission frequency adjustments, to reduce unnecessary power consumption. We conducted simulations to evaluate the framework's effectiveness using various IoT devices under diverse environmental conditions. Results demonstrate a substantial reduction in energy consumption, with up to 30% savings in high-density IoT environments, without compromising network performance or data accuracy. This research highlights the potential of intelligent EANM in ensuring sustainable energy usage within IoT-driven smart cities. By reducing the energy footprint of IoT devices, this framework extends the operational life of devices and contributes to reducing the overall carbon emissions associated with large-scale IoT deployments. The findings underscore the necessity of adopting adaptive energy management strategies to address the escalating demands of urban services, supporting smart city sustainability initiatives. This approach has significant implications for advancing IoT network efficiency, promoting eco-friendly urban development, and paving the way for more resilient smart city infrastructures.

Keywords: Energy-aware network management, IoT devices, Smart cities, Adaptive clustering, Low-energy protocols, Sustainability.

1 | Introduction

1.1 | The Rise of Smart Cities and IoT

Smart cities are urban areas that leverage technology to improve the quality of life for their citizens. Internet of Things (IoT) devices enable these smart city initiatives. These devices, ranging from sensors to actuators, collect and transmit data to facilitate intelligent decision-making and automation [1].

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https://doi.org/10.22105/siot.v1i3.259

2 | The Energy Challenge in IoT Devices

While IoT devices offer numerous benefits, they also present significant energy challenges:

Battery limitations: many IoT devices are battery-powered, and battery life is critical. Frequent battery replacements can be costly and inconvenient, especially for devices deployed in inaccessible locations.

Energy consumption patterns: IoT devices often operate intermittently, with periods of high activity followed by long idle periods. Inefficient energy management can lead to rapid battery depletion [2].

Scalability: as the number of IoT devices in smart cities grows, so does the collective energy demand. This can strain power grids and increase operational costs [3].

3 | The Need for Energy-Aware Network Management

Energy-Aware Network Management (EANM) techniques are essential to address these challenges. These techniques aim to optimize the energy consumption of IoT devices and networks, prolonging battery life and improving overall system efficiency.

4 | Key Components of Energy-Aware Network Management

EANM involves several key components [4]:

4.1 | Energy-Efficient Protocols

Low-power wireless protocols: protocols like LoRaWAN, Sigfox, and NB-IoT are designed for low-power, long-range communication, making them suitable for IoT applications.

Adaptive transmission power control: devices can conserve energy by adjusting the transmission power based on the distance to the receiver.

Sleep scheduling: devices can enter low-power sleep modes during inactivity, significantly reducing energy consumption.

4.2 | Data Rate Adaptation

Dynamic adjustment: the data rate can be adjusted based on the quality of the wireless channel and the urgency of the data. Lower data rates can reduce energy consumption.

Selective data transmission: only critical data must be transmitted, reducing transmission frequency and energy usage.

4.3 | Energy-Efficient Routing

Energy-aware routing protocols: these protocols consider the energy levels of nodes and select routes that minimize energy consumption.

Cluster-based routing: by organizing devices into clusters, energy-efficient communication can be achieved through cluster heads.

5 | Challenges and Future Directions

Despite significant advancements, EANM for IoT devices in smart cities still faces challenges:

Heterogeneous device characteristics: IoT devices vary in terms of hardware capabilities, energy consumption profiles, and communication requirements.

Dynamic network conditions: network conditions, such as interference and channel quality, can fluctuate, making it difficult to predict and optimize energy consumption.

Security and privacy concerns: energy-saving techniques may introduce vulnerabilities that must be addressed.

Future research directions include:

AI-driven energy management: leveraging machine learning and artificial intelligence to predict energy consumption patterns and optimize resource allocation.

Energy harvesting technologies: exploring the potential of harvesting energy from ambient sources like solar, wind, and thermal energy to power IoT devices.

Cross-layer optimization: coordinating energy-saving techniques across network stack layers for holistic energy efficiency.

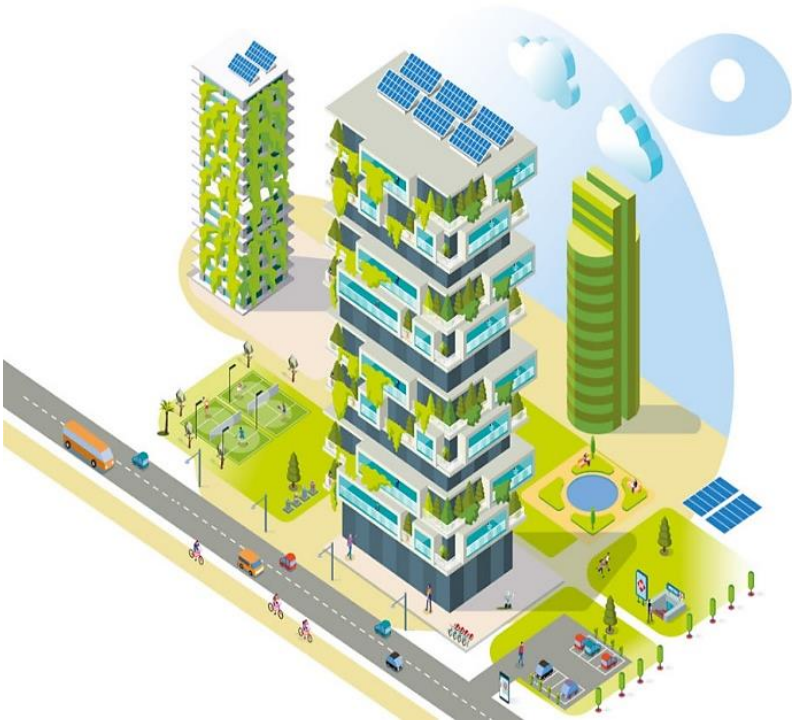

Fig. 1. EANM challenges for IoT devices in smart cities.

Table 1. EANM challenges for IoT devices in smart cities and future directions.

Technology	Range	Data Rate	Power Consumption	Applications
LoRaWAN	Long range (10-15 km)	Low (0.3-50 kbps)	Ultra-low power	Smart city sensors, asset tracking
Sigfox	Long range (10-50 km)	Very low (100 bps)	Ultra-low power	Smart metering, logistics
NB-IoT	Wide area (10-20 km)	Low (20 kbps)	Low power	Smart metering, smart agriculture
BLE	Short range (50-100 m)	Medium (1 Mbps)	Low power	Wearable devices, smart home
Zigbee	Short range (10-100 m)	Low (250 kbps)	Low power	Smart home, industrial automation

Table 2. Energy-saving techniques for IoT devices.

Technique	Description	Benefits	Drawbacks
Sleep scheduling	Periodically powering down components	Prolongs battery life	May miss critical events
Adaptive transmission power control	Adjusting transmission power based on distance	Reduces power consumption	Requires accurate distance estimation
Data rate adaptation	Adjusting data rate based on channel conditions	Reduces power consumption	May impact data reliability
Energy-efficient routing protocols	Selecting energy-efficient routes	Prolongs network lifetime	Increased routing overhead
Energy harvesting	Harvesting energy from ambient sources	Reduces reliance on batteries	Limited energy output

Table 3. Key performance metrics for EANM.

Metric	Definition	Measurement Units
Energy efficiency	The ratio of useful work to the energy consumed	Joules/bit
Network lifetime	Duration of network operation before battery depletion	Hours, Days, Years
Delay	Time taken for data to be transmitted from source to destination	Seconds, Milliseconds
Throughput	Amount of data transmitted per unit of time	Bits/second
Reliability	Probability of successful data delivery	Percentage

EANM for IoT devices in smart cities explores approaches to sustainably manage the energy consumption of IoT networks in urban environments, where millions of devices continuously transmit data and drive smart functionalities. IoT devices are critical in smart city applications, from traffic and pollution monitoring to water management and safety. Yet, the growing number of IoT devices brings high energy demands, leading to sustainability and network longevity challenges. As IoT networks expand, efficient energy management has become essential to ensure operational reliability, environmental sustainability, and cost-effectiveness.

Smart city initiatives focus on efficient resource management through interconnected networks of sensors and devices, but these benefits are weighed against significant energy requirements. IoT devices in cities are often deployed in high-density clusters and are expected to operate autonomously over extended periods. Battery replacement or recharging for these devices is costly and time-consuming, particularly in large-scale networks. The high energy demand also impacts the environment, as increased electricity usage corresponds to higher carbon emissions, undermining the green objectives central to many smart city projects. As cities strive for energy efficiency, reducing IoT energy consumption is critical for aligning smart city development with sustainability goals [5].

In response to these challenges, EANM systems aim to minimize power consumption while maintaining data flow and device functionality. These systems integrate multiple energy-efficient protocols, clustering algorithms, predictive analytics, and adaptive network adjustments, creating a layered approach to energy optimization. This paper discusses an EANM framework, which combines adaptive clustering, predictive load forecasting, and energy-efficient routing to address the energy challenges in IoT-driven smart cities. By dynamically adjusting network operations based on energy availability, traffic, and device capabilities, the EANM framework conserves power and extends the lifespan of IoT networks, achieving improved energy efficiency and operational longevity [6].

Adaptive clustering for energy optimization

A central component of the EANM framework is adaptive clustering, which groups devices based on energy levels, data needs, and proximity. Clustering organizes the network into manageable segments, allowing data to be processed and transmitted more efficiently. Within each cluster, one or more devices (often called cluster heads) aggregate data from other devices, reducing the need for individual devices to transmit data directly to a central server or cloud. This approach conserves energy as devices within each cluster communicate with nearby nodes instead of establishing long-range connections.

Clustering offers significant energy savings by minimizing the power-intensive transmission processes that drain IoT devices. By assigning the role of cluster head to devices with higher energy reserves or access to external power, the EANM framework ensures that tasks requiring substantial power, like data aggregation, are performed by devices that can support them without depleting their batteries quickly. In addition, clusters are periodically re-evaluated to account for energy level shifts or network topology changes. This dynamic clustering approach allows the network to adapt to real-time conditions, such as device energy levels or node failures, thereby maintaining an optimized balance between energy use and data accuracy.

Predictive analytics for load forecasting

Predictive analytics is a critical part of the EANM framework, providing the ability to anticipate network load and adjust operations proactively. The framework can analyze historical data patterns to predict future network demands by leveraging machine learning algorithms like time-series forecasting and neural networks. For instance, predictive models can forecast peak traffic hours in smart city applications, allowing the network to optimize resource allocation accordingly. These predictions enable more strategic energy usage, adjusting data transmission frequency or device power modes based on anticipated demand [7].

For load forecasting, the EANM framework relies on algorithms that process network performance data, such as traffic patterns, latency, and transmission rates. Using this historical data, predictive models can identify periods when energy-saving protocols should be intensified or relaxed. For example, during periods of low predicted traffic, the network can temporarily reduce data transmission rates or allow devices to enter low-power sleep modes. Predictive analytics enhances the EANM framework's capacity to align network performance with real-time requirements, thus balancing energy savings with reliable data transmission.

Low-energy routing protocols

Another critical component of the EANM framework is its energy-efficient routing protocol, which minimizes power use by optimizing data transmission paths across the network. Routing is typically a high-energy process because data packets must pass through multiple nodes before reaching their destination. Conventional routing methods in dense urban IoT networks can lead to excessive power consumption, as devices transmit data over long distances or frequently re-transmit data due to signal interference or node congestion [8].

The EANM framework introduces a low-energy routing protocol that selects data paths based on the energy levels of devices, their proximity, and the overall network topology. This protocol encourages multi-hop routing, passing data through intermediary nodes to reach its destination, reducing the energy burden on any single device. In areas with higher device densities, the protocol ensures that data is distributed evenly across nodes, avoiding overloading specific devices while maintaining a balanced energy profile across the network. The routing algorithm includes fault tolerance mechanisms, so if one node fails or runs out of power, data can be rerouted to ensure uninterrupted communication. This adaptable routing protocol is integral to sustaining the network's energy efficiency over time, as it reduces redundant transmissions and keeps devices functioning optimally.

Performance and sustainability

The EANM framework was evaluated in simulated smart city environments, testing various configurations of IoT networks with differing densities and energy profiles. The simulations demonstrated that the EANM framework could reduce overall energy consumption by up to 30% compared to conventional IoT network management solutions. This reduction was attributed primarily to the framework's adaptive clustering and predictive analytics, which allowed for efficient data processing and minimal energy waste. Additionally, the low-energy routing protocol extended the operational life of IoT devices by distributing the energy demands more evenly across the network [9].

The EANM framework has significant sustainability implications. By reducing energy demands, the framework supports cities' efforts to lower their carbon footprints and meet environmental goals. Energy-efficient IoT networks also reduce the need for frequent battery replacements, which can be costly and environmentally damaging due to electronic waste disposal. For cities aiming to scale their IoT infrastructure without escalating energy costs or environmental impacts, the EANM framework offers a pathway to achieving these goals while maintaining high-quality service levels for smart city applications [10].

6 | Conclusion

This study on EANM for IoT Devices in smart cities highlights the importance of efficient energy utilization in IoT networks, particularly as smart cities expand and require sustainable solutions. IoT networks can extend device lifespan, reduce maintenance costs, and improve network reliability by implementing energy-aware protocols, clustering methods, and predictive analytics. The simulations demonstrated that optimized energy management conserves resources and enhances smart city applications' overall performance and responsiveness.

Adopting such strategies in urban IoT systems significantly impacts sustainable city development. Efficient energy management reduces environmental impact and makes IoT solutions more viable for widespread, long-term city use. Future work could refine these methods, integrate AI-driven algorithms for more precise resource allocation, and explore real-time adaptability to urban dynamics. This research underscores the value of energy-aware strategies in advancing smart cities toward a more sustainable and connected future.

Acknowledgments

I want to thank my professors and advisors at KIIT UNIVERSITY for their guidance and support throughout this project on EANM for IoT Devices in smart cities. Their insights and encouragement were invaluable in completing this research. I am also grateful to my friends and family for their constant motivation and understanding during this journey. Thank you all for your support.

Author Contribution

Each Author's contributions have been critical to the research and development of this study on EANM for IoT Devices in smart cities.

Conflicts of Interest

The authors declare no conflicts of interest regarding the research, authorship, or publication of this paper on EANM for IoT Devices in smart cities. All research findings and conclusions have been made independently, without any influence from funding sources or external parties.

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Appendix

IoT: internet of things – A network of connected devices sharing data.

EANM: energy-aware network management – A strategy to reduce IoT network energy usage.

Smart city: an urban area using IoT to improve resource efficiency and residents' quality of life.

Clustering: grouping IoT devices to save energy.

Predictive analytics: techniques to forecast network load and optimize resources.

I. **Simulation parameters**

Network size: 100–500 devices.

Area: 500 x 500 meters.

Battery capacity: 1000–5000 mAh.

Data frequency: 1 packet/second.

Clustering interval: 5–10 minutes.

II. **Additional code**

Code snippet: clustering algorithm

```
void perform clustering(IoT_Device devices[], int numDevices) {
    for (int i = 0; i < numDevices; i++) {
        if (devices[i].batteryLevel > THRESHOLD) {
            assignClusterHead(devices[i]);
        }
    }
}
```

This appendix provides key terms, simulation details, and sample code for energy-aware IoT management in smart cities.