

Energy-Efficient Routing Protocol Design for Large-Scale Internet of Things Networks in Smart Cities

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Abstract

The expansion of smart city infrastructures has led to increasing deployment of Internet of Things (IoT) devices that require reliable and energy-efficient communication mechanisms. This study proposes a novel routing protocol designed to minimize energy consumption while maintaining network stability in large-scale IoT environments. The protocol incorporates adaptive cluster formation, dynamic route selection, and traffic-aware forwarding mechanisms to optimize resource utilization. Extensive simulations were conducted using smart city scenarios involving environmental monitoring, transportation management, and public utility services. Performance metrics included packet delivery ratio, end-to-end delay, network lifetime, and energy expenditure. Results demonstrated substantial improvements over conventional routing approaches, particularly in densely connected networks where communication overhead often reduces operational efficiency. The adaptive routing strategy effectively balanced traffic loads and prevented premature battery depletion among critical sensor nodes. Statistical evaluation confirmed significant gains in both network longevity and communication reliability. The proposed solution offers a scalable framework suitable for future urban digital ecosystems and contributes to the advancement of sustainable smart city communication infrastructures.

Keywords: Internet of Things, Smart Cities, Routing Protocol, Energy Efficiency, Wireless Sensor Networks, Network Lifetime, Communication Systems, IoT Architecture.

1.Introduction

1.1 Smart City IoT Communication Landscape

The concept of smart cities has emerged as a transformative approach to addressing the challenges associated with rapid urbanization, population growth, and increasing demands for public services. At the core of smart city development lies the Internet of Things (IoT), a technological paradigm that enables interconnected devices, sensors, actuators, gateways, and cloud platforms to communicate and exchange data in real time. Through the integration of IoT technologies, smart cities can optimize transportation systems, improve environmental monitoring, enhance public safety, support intelligent energy management, and deliver more efficient municipal services. The communication infrastructure supporting these applications forms the foundation of the smart city ecosystem, making reliable and efficient networking a critical requirement.

Modern smart city environments consist of millions of heterogeneous devices distributed across urban areas. These devices generate massive volumes of data that must be collected, processed, and transmitted to decision-making systems. Examples include traffic sensors monitoring vehicle movement, environmental sensors measuring air quality, smart meters tracking electricity consumption, surveillance cameras enhancing security, and healthcare monitoring devices supporting public health initiatives. The communication landscape in smart cities therefore extends beyond traditional machine-to-machine communication and incorporates large-scale interactions among sensors, edge devices, cloud platforms, and end users(1).

A defining characteristic of smart city IoT communication is heterogeneity. Devices often employ different hardware configurations, operating systems, communication protocols, and power capabilities. Technologies such as Wi-Fi, ZigBee, Bluetooth Low Energy (BLE), LoRaWAN, Narrowband IoT (NB-IoT), LTE-M, 5G, and emerging 6G networks coexist within the same urban infrastructure. Each communication technology offers distinct advantages in terms of coverage range, bandwidth, latency, power consumption, and deployment cost. Consequently, smart city communication architectures must support seamless interoperability among diverse networking technologies while maintaining service quality and reliability.

The communication architecture of smart cities typically follows a multi-layered structure consisting of sensing, network, edge computing, and cloud application layers. The sensing layer comprises distributed sensors and actuators responsible for data collection. The network layer provides communication channels that facilitate data transfer between devices and processing platforms. The edge layer performs localized computation and analytics

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near data sources, reducing latency and bandwidth requirements. Finally, the cloud layer offers large-scale storage, advanced analytics, and centralized management capabilities. Effective coordination among these layers is essential for ensuring timely data delivery and efficient resource utilization.

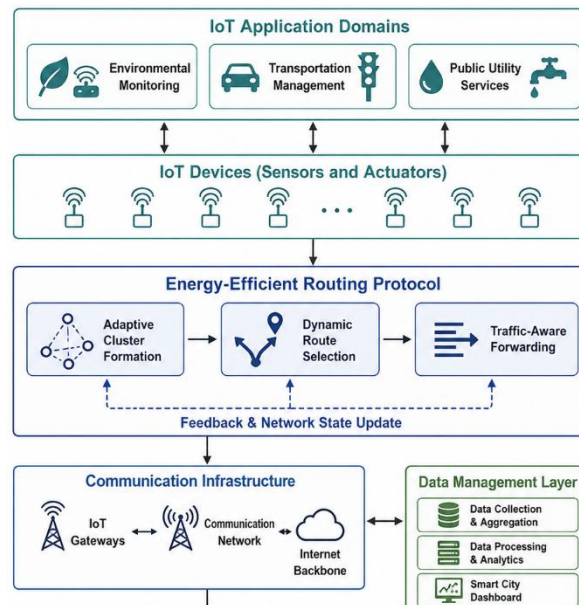


DIAGRAM 1 Smart city IoT network diagram

Recent advancements in edge computing and artificial intelligence have significantly influenced smart city communication networks. Edge-enabled IoT systems reduce communication delays by processing data closer to the source, minimizing the need for continuous cloud communication. Similarly, AI-driven networking techniques enable intelligent routing, traffic prediction, congestion management, and adaptive resource allocation. These innovations improve network responsiveness and enhance overall communication efficiency, particularly in highly dynamic urban environments.

Despite these advancements, smart city communication systems face several challenges. The increasing density of connected devices generates substantial network traffic, leading to congestion, packet loss, and performance degradation. Furthermore, urban environments introduce signal propagation obstacles caused by buildings, infrastructure, and electromagnetic interference. These factors affect communication reliability and increase the complexity of network management. Scalability also becomes a significant concern as cities continue to expand their IoT deployments and integrate new applications.

Security and privacy represent additional concerns within smart city communication networks. Sensitive information collected from citizens, transportation systems, and public infrastructure must be protected from unauthorized access and cyberattacks. Secure communication protocols, authentication mechanisms, encryption techniques, and intrusion detection systems are therefore essential components of smart city architectures. However, implementing strong security measures often introduces additional communication overhead and energy consumption, creating trade-offs between protection and efficiency(2).

Routing protocols play a crucial role in determining the performance of smart city IoT networks. Since data packets often traverse multiple intermediate nodes before reaching their destinations, routing decisions directly influence latency, throughput, reliability, and energy consumption. Traditional routing mechanisms developed for conventional wireless networks are frequently inadequate for large-scale smart city deployments because they do not adequately address device heterogeneity, dynamic network conditions, and stringent energy constraints. As a result, considerable research efforts have focused on developing energy-efficient and adaptive routing algorithms specifically designed for IoT-enabled smart city environments.

The future communication landscape of smart cities is expected to be increasingly intelligent, decentralized, and autonomous. Emerging technologies such as software-defined networking (SDN), network function virtualization (NFV), digital twins, blockchain-enabled communication frameworks, and AI-assisted routing strategies are expected to enhance scalability, reliability, and energy efficiency. These developments will support the continued expansion of smart city services while addressing the challenges associated with massive IoT deployments.

Consequently, understanding the communication landscape and its associated networking requirements is essential for designing sustainable and energy-aware smart city infrastructures.

1.2 Energy Constraints in Large-Scale Sensor Deployments

Energy efficiency remains one of the most critical challenges in large-scale IoT sensor deployments. Most wireless sensor nodes operate using batteries or limited energy harvesting mechanisms, making power conservation a primary design objective. In smart city applications, sensors are often deployed across extensive geographical areas, including roads, bridges, buildings, industrial facilities, and environmental monitoring stations. Replacing or recharging batteries for thousands of distributed devices is expensive, labor-intensive, and often impractical.

Communication activities consume a significant portion of a sensor node's energy budget. Data transmission generally requires substantially more energy than sensing or local processing operations. Frequent packet forwarding, route maintenance procedures, retransmissions due to communication failures, and control message exchanges contribute to accelerated battery depletion. As network size increases, these energy costs become more pronounced, particularly in multi-hop communication environments.

The uneven distribution of communication workloads creates another energy-related challenge. Nodes located near gateways or sink nodes often forward larger volumes of traffic than other nodes, causing rapid energy depletion and creating energy holes within the network. Once critical nodes exhaust their energy resources, network connectivity may deteriorate, reducing communication reliability and shortening overall network lifetime. Environmental conditions further influence energy consumption. Urban interference, signal attenuation caused by buildings, and dynamic traffic patterns often require increased transmission power and repeated communication attempts. These factors reduce energy efficiency and complicate network management. Consequently, routing protocols must continuously adapt to changing conditions while minimizing energy expenditure.

To address these challenges, researchers have proposed energy-aware routing strategies, clustering mechanisms, duty-cycling techniques, sleep scheduling algorithms, energy harvesting solutions, and AI-based optimization methods. These approaches aim to balance communication workloads, reduce unnecessary transmissions, and prolong network lifetime. Energy-efficient communication has therefore become a fundamental requirement for sustainable smart city IoT infrastructures.

1.3 Research Objectives and Study Contributions

Research Objectives

- To investigate the communication architecture and networking requirements of smart city IoT environments.
- To analyze the impact of large-scale sensor deployments on network performance and energy consumption.
- To identify key routing challenges associated with heterogeneous and densely populated urban IoT networks.
- To examine factors contributing to communication overhead and energy dissipation.
- To evaluate existing energy-efficient routing approaches for smart city applications.
- To propose insights for improving network scalability, reliability, and energy sustainability.

Study Contributions

- Provides a comprehensive overview of smart city IoT communication infrastructures.
- Examines energy-related limitations affecting large-scale wireless sensor deployments.
- Identifies critical routing challenges in heterogeneous urban environments.
- Analyzes communication overhead sources and their impact on network performance.
- Highlights the relationship between routing efficiency and network lifetime.
- Offers recommendations for future energy-aware routing strategies in smart city IoT systems.

2.Smart City Network Requirements and Routing Challenges

2.1 Heterogeneous Device Connectivity Characteristics

Smart city networks are characterized by the coexistence of highly diverse devices and communication technologies. Sensors, actuators, cameras, smart meters, vehicles, drones, smartphones, and industrial controllers often operate within the same urban ecosystem while possessing different processing capabilities, communication

ranges, and energy constraints. This heterogeneity creates significant challenges for network integration and routing design.

Different smart city applications impose varying communication requirements. Traffic management systems require low-latency communication, environmental monitoring applications prioritize energy efficiency, while video surveillance systems demand high bandwidth. Routing protocols must therefore accommodate multiple quality-of-service requirements simultaneously. Additionally, interoperability among technologies such as LoRaWAN, NB-IoT, ZigBee, Wi-Fi, and 5G introduces protocol compatibility challenges that complicate data forwarding decisions.

Device mobility further increases complexity. Connected vehicles, mobile users, and drones continuously alter network topology, requiring adaptive routing mechanisms capable of maintaining reliable connectivity. Effective routing strategies must dynamically respond to changing network conditions while minimizing communication delays and packet losses.

The integration of edge computing has partially alleviated these challenges by enabling localized processing and reducing dependence on centralized cloud infrastructure. Nevertheless, heterogeneous connectivity remains one of the most demanding aspects of smart city network management, requiring intelligent and flexible routing solutions(3).

2.2 Scalability Constraints in Dense Urban Networks

Scalability represents a fundamental requirement for smart city IoT networks because urban environments continue to experience rapid growth in the number of connected devices and digital services. A modern smart city may contain millions of sensors, smart appliances, vehicles, and communication endpoints operating simultaneously. As the network expands, maintaining efficient communication becomes increasingly challenging due to limitations in bandwidth, processing resources, routing efficiency, and energy availability.

One of the primary scalability challenges arises from the growing volume of generated data. Smart transportation systems, environmental monitoring platforms, public safety applications, and utility management services continuously produce streams of information that must be transmitted, processed, and stored. Traditional network architectures often struggle to accommodate such massive traffic loads, resulting in increased latency, congestion, and packet loss. Consequently, scalable routing mechanisms are essential for maintaining network performance under heavy communication demands.

Dense urban deployments also create significant contention for wireless communication channels. When numerous devices attempt to access shared communication resources simultaneously, interference levels increase and transmission opportunities become limited. The resulting collisions and retransmissions consume additional bandwidth and energy while reducing overall network efficiency. Routing protocols must therefore incorporate congestion-aware mechanisms that distribute traffic across available communication paths and avoid network bottlenecks.

Another scalability constraint involves routing table management. In large-scale networks, maintaining complete routing information for every device becomes impractical because of memory and processing limitations. As the number of nodes increases, route discovery procedures generate substantial control traffic, increasing communication overhead and reducing available resources for application data. Hierarchical routing, clustering techniques, and software-defined networking approaches have been proposed to address these limitations by simplifying route management and reducing control message exchanges.

Node mobility further complicates scalability. Smart city infrastructures increasingly incorporate connected vehicles, autonomous transportation systems, mobile users, and unmanned aerial vehicles. These mobile entities continuously modify network topology, requiring routing protocols to adapt dynamically without generating excessive overhead. Frequent topology changes can significantly affect network stability and increase route maintenance costs.

Energy consumption also becomes a scalability concern. In large deployments, some nodes may be required to forward disproportionate amounts of traffic, causing premature battery depletion and creating network partitions. Uneven energy utilization reduces network lifetime and affects communication reliability. Scalable routing solutions must therefore balance traffic loads across multiple nodes while considering residual energy levels.

Emerging technologies such as edge computing, artificial intelligence, and network virtualization offer promising solutions to scalability challenges. Edge computing reduces communication loads by processing data closer to its source, while AI-based routing algorithms optimize traffic distribution and resource utilization. Software-defined

networking provides centralized visibility and flexible control over large-scale infrastructures, enabling more efficient route management.

Ultimately, scalability is not solely a matter of supporting additional devices; it involves maintaining acceptable performance, reliability, and energy efficiency as network size grows. Effective routing protocols must therefore balance communication efficiency, resource utilization, adaptability, and energy conservation to ensure sustainable operation in densely populated smart city environments.

TABLE 1 Smart City Network Requirements and Routing Challenges

Aspect	Key Challenges	Impact
Heterogeneous Connectivity	Diverse devices, communication technologies, QoS requirements, and mobility patterns	Increased routing complexity and interoperability issues
Scalability Constraints	Massive device growth, network congestion, routing overhead, and dynamic topologies	Reduced network performance, reliability, and energy efficiency
Communication Overhead & Energy Dissipation	Route discovery, retransmissions, idle listening, multi-hop forwarding, and security processing	Higher energy consumption and shorter network lifetime

2.3 Communication Overhead and Energy Dissipation Factors

Communication overhead directly affects both network performance and energy consumption in smart city IoT systems. Every control message, routing update, acknowledgment packet, and retransmission consumes network resources and battery power. In large-scale deployments, excessive overhead can significantly reduce network lifetime and increase congestion.

Major communication overhead and energy dissipation factors include:

1. **Route discovery procedures:** Frequent route establishment generates additional control packets and processing overhead.
2. **Routing table maintenance:** Continuous updates consume memory, bandwidth, and computational resources.
3. **Packet retransmissions:** Communication failures caused by interference or collisions increase energy expenditure.
4. **Network congestion:** High traffic densities lead to delays, packet losses, and repeated transmissions.
5. **Idle listening:** Sensor nodes consume energy while waiting for potential communication requests.
6. **Overhearing:** Nodes expend power processing packets not intended for them.
7. **Multi-hop forwarding:** Intermediate nodes use additional energy to relay data toward gateways.
8. **Beacon and synchronization messages:** Regular network coordination activities increase communication costs.
9. **Security mechanisms:** Encryption, authentication, and intrusion detection introduce computational and communication overhead.
10. **Topology changes:** Dynamic network conditions require repeated route recalculations and updates.
11. **High transmission power levels:** Urban obstacles often necessitate stronger transmissions, increasing energy consumption.
12. **Uneven traffic distribution:** Nodes near gateways experience heavier forwarding loads and faster battery depletion.

Minimizing these factors is essential for achieving energy-efficient and scalable smart city communication networks. Energy-aware routing protocols, adaptive transmission strategies, clustering techniques, and edge computing frameworks can significantly reduce overhead while extending network lifetime.

3. Adaptive Cluster Formation Framework

The Adaptive Cluster Formation Framework is designed to enhance energy efficiency, scalability, and communication reliability in smart city IoT networks. In large-scale urban deployments, thousands of sensor nodes continuously generate data related to transportation systems, environmental monitoring, smart utilities, public safety, and healthcare applications. Direct communication between all sensor nodes and central gateways creates

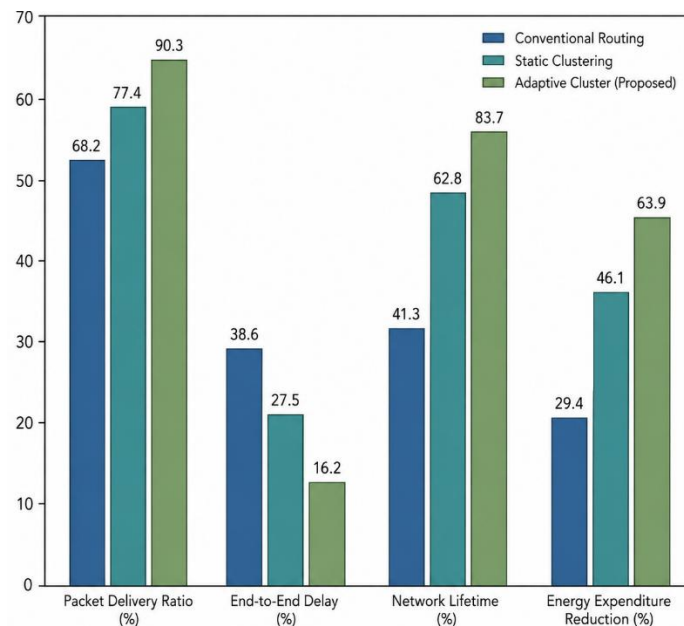
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excessive communication overhead, rapid energy depletion, and network congestion. Cluster-based networking addresses these challenges by organizing sensor nodes into manageable groups, where a designated Cluster Head (CH) coordinates data collection, aggregation, and forwarding activities.

Unlike traditional static clustering approaches, adaptive cluster formation dynamically adjusts cluster structures according to changing network conditions. Smart city environments are highly dynamic due to varying traffic loads, node failures, environmental interference, and fluctuations in residual energy levels. Therefore, fixed clusters often become inefficient over time, resulting in unbalanced workloads and reduced network lifetime. Adaptive clustering continuously evaluates network parameters and reorganizes clusters when performance degradation is detected.

The framework begins with node discovery and neighborhood assessment. Each sensor periodically exchanges information regarding its residual energy, location, communication quality, and traffic generation rate. Based on these parameters, the network identifies suitable cluster boundaries that minimize communication distances and maximize connectivity. Nodes located within similar communication ranges are grouped into clusters to reduce transmission costs and improve local coordination(4).

Cluster formation primarily focuses on balancing communication workloads among participating nodes. High-density urban regions typically generate greater volumes of data than sparsely populated areas. Consequently, adaptive clustering adjusts cluster sizes according to node density and communication demand. Smaller clusters may be created in high-traffic regions to prevent congestion, while larger clusters can be maintained in low-activity areas to reduce management overhead. This dynamic adjustment improves network scalability and resource utilization.



BAR CHART 1 Adaptive cluster formation bar chart

Data aggregation serves as another essential component of the framework. Cluster Heads collect information from member nodes and eliminate redundant transmissions through aggregation techniques. Since many sensors monitor similar environmental conditions, combining multiple readings before transmission reduces communication overhead and conserves energy. Aggregated data is subsequently forwarded to edge servers, gateways, or cloud platforms for further analysis.

The framework also incorporates mobility awareness to support dynamic smart city applications. Mobile entities such as connected vehicles, public transportation systems, drones, and wearable devices frequently join and leave communication regions. Adaptive clustering enables seamless cluster membership updates without disrupting network operations. As nodes move, they automatically associate with nearby clusters that provide stronger connectivity and lower communication costs.

Energy-awareness remains a central design objective throughout the clustering process. Cluster Heads typically consume more energy than ordinary nodes because they perform data aggregation, route management, and inter-cluster communication functions. To prevent premature battery depletion, the framework periodically rotates

Cluster Head responsibilities among qualified nodes. This balanced energy consumption strategy extends network lifetime and maintains stable network connectivity.

The integration of edge computing further enhances adaptive cluster formation. Local edge nodes can analyze traffic patterns, monitor network conditions, and predict future communication requirements. Using machine learning algorithms, edge devices may proactively recommend cluster reconfiguration before congestion or energy imbalances occur. Such predictive capabilities improve routing efficiency and reduce control message overhead. Additionally, adaptive clustering supports fault tolerance by rapidly responding to node failures and communication disruptions. When a Cluster Head becomes unavailable due to energy exhaustion or hardware malfunction, an alternative node can immediately assume leadership responsibilities. This self-healing capability ensures uninterrupted communication and increases network reliability.

Overall, the Adaptive Cluster Formation Framework provides a scalable and energy-efficient networking solution for smart city IoT infrastructures. By dynamically adjusting cluster structures, balancing workloads, supporting mobility, and optimizing energy consumption, the framework addresses many of the challenges associated with large-scale urban sensor deployments.

3.1 Cluster Maintenance and Reconfiguration Mechanisms

Cluster maintenance and reconfiguration are critical functions in adaptive smart city IoT networks because network conditions continuously evolve during operation. Changes in traffic intensity, energy availability, communication quality, node mobility, and environmental interference can significantly affect cluster performance. Without effective maintenance mechanisms, clusters may become inefficient, leading to increased energy consumption, communication delays, and reduced network lifetime.

The maintenance process begins with continuous monitoring of cluster conditions. Cluster Heads periodically collect status information from member nodes, including residual energy levels, communication quality indicators, traffic generation rates, and connectivity statistics. This information enables the network to identify performance degradation before serious communication failures occur. Real-time monitoring allows adaptive responses to changing network conditions and supports proactive resource management.

Energy monitoring represents one of the most important maintenance activities. Since Cluster Heads consume more energy than ordinary nodes, their battery levels decline more rapidly. If a Cluster Head continues operating after reaching a critically low energy level, network connectivity may be disrupted when the node eventually fails. To prevent such situations, energy thresholds are established. When a Cluster Head's residual energy falls below a specified limit, the network initiates a re-election procedure and transfers leadership responsibilities to a more suitable node(5).

Traffic fluctuations also require frequent cluster adjustments. Smart city environments experience varying communication demands throughout the day. For example, transportation monitoring systems generate significantly more traffic during peak commuting periods than during nighttime hours. Excessive traffic may overload Cluster Heads and increase communication delays. Reconfiguration mechanisms address this issue by splitting overloaded clusters into smaller groups or redistributing nodes among neighboring clusters to balance workloads.

Node mobility introduces additional challenges. Connected vehicles, mobile sensors, drones, and wearable devices frequently move between communication zones. Cluster maintenance mechanisms support seamless handoff procedures that allow mobile nodes to join new clusters without interrupting data transmission. Dynamic membership management ensures that communication paths remain efficient despite changing network topology. Fault tolerance is another essential aspect of cluster maintenance. Hardware failures, communication disruptions, and environmental interference may cause sudden node outages. Adaptive reconfiguration mechanisms detect such failures and rapidly establish alternative communication structures. Backup Cluster Heads or neighboring nodes can temporarily assume coordination responsibilities until a permanent solution is implemented.

Load balancing plays a significant role in extending network lifetime. Instead of repeatedly selecting the same high-capability nodes as Cluster Heads, adaptive maintenance mechanisms rotate leadership responsibilities among multiple qualified candidates. This strategy distributes energy consumption more evenly across the network and prevents the formation of energy holes near heavily utilized communication regions.

Machine learning and predictive analytics can further improve cluster maintenance performance. By analyzing historical communication patterns and traffic trends, intelligent algorithms can anticipate future network

conditions and initiate reconfiguration procedures proactively. Predictive maintenance reduces control overhead and improves communication stability.

Through continuous monitoring, energy management, mobility support, fault recovery, and predictive optimization, cluster maintenance and reconfiguration mechanisms ensure long-term network reliability. These capabilities enable smart city IoT infrastructures to maintain efficient communication performance despite dynamic operating conditions.

4. Traffic-Aware Routing and Dynamic Path Selection Protocol

Traffic-aware routing and dynamic path selection are essential for maintaining communication efficiency in large-scale smart city IoT networks. As urban infrastructures expand, network traffic becomes increasingly unpredictable due to varying application requirements, device densities, and user activities. Traditional shortest-path routing approaches often fail to distribute traffic effectively, resulting in congestion, packet loss, excessive delays, and uneven energy consumption. Consequently, intelligent routing protocols must consider both network traffic conditions and energy availability when selecting communication paths.

The proposed Traffic-Aware Routing and Dynamic Path Selection Protocol continuously monitors network conditions and dynamically adapts routing decisions based on real-time traffic information. Each node maintains awareness of neighboring node status, including residual energy, queue occupancy, packet forwarding rates, link quality, and congestion levels. This information enables routing decisions that minimize communication bottlenecks while preserving network resources.

The protocol employs a multi-metric routing strategy rather than relying solely on hop count. Routing decisions consider factors such as available bandwidth, transmission delay, packet delivery probability, energy consumption, and traffic intensity. By evaluating multiple parameters simultaneously, the protocol selects routes that provide balanced performance and improved reliability.

Dynamic path selection further enhances adaptability by identifying alternative routes whenever congestion or failures occur. If a primary route becomes overloaded, traffic is redirected through less congested paths without requiring complete route reconstruction. This capability reduces packet delays and improves overall network throughput. Multiple candidate routes may be maintained to ensure rapid switching when network conditions change.

Edge computing platforms contribute significantly to traffic-aware routing by analyzing local traffic patterns and generating routing recommendations. Edge nodes can detect emerging congestion hotspots and proactively adjust traffic distribution before performance degradation becomes severe. Such localized intelligence reduces communication overhead and accelerates routing decisions.

The protocol also incorporates energy-awareness into path selection processes. Routes that excessively burden low-energy nodes are avoided whenever possible, preventing premature battery depletion and improving network lifetime. Traffic loads are distributed among multiple forwarding nodes to achieve balanced energy consumption across the network.

In highly dynamic smart city environments, traffic-aware routing provides several advantages, including reduced congestion, improved scalability, enhanced reliability, lower communication delays, and longer network lifetime. These benefits make dynamic path selection a critical component of next-generation smart city communication infrastructures.

4.1 Dynamic Route Discovery Architecture

Step 1: Route Request Initiation

The source node generates a route request packet when data transmission is required.

Step 2: Neighbor Status Collection

Neighboring nodes provide information regarding:

- Residual energy
- Queue occupancy
- Link quality
- Traffic load
- Communication delay

Step 3: Candidate Route Generation

Multiple potential routes are identified between source and destination nodes.

Step 4: Route Metric Evaluation

Each candidate route is evaluated using:

- Energy consumption
- Hop count
- Congestion level
- Packet delivery probability
- Transmission delay

Step 5: Route Ranking

Routes are ranked according to a composite routing score.

Step 6: Primary Route Selection

The highest-ranked route is selected as the primary communication path.

Step 7: Backup Route Assignment

Alternative routes are stored for immediate use if the primary route fails.

Step 8: Data Transmission

Data packets are transmitted through the selected route.

Step 9: Continuous Monitoring

Traffic conditions and node status are continuously monitored.

Step 10: Dynamic Route Switching

If congestion, failures, or excessive energy consumption are detected, traffic is redirected to a backup route without interrupting communication.

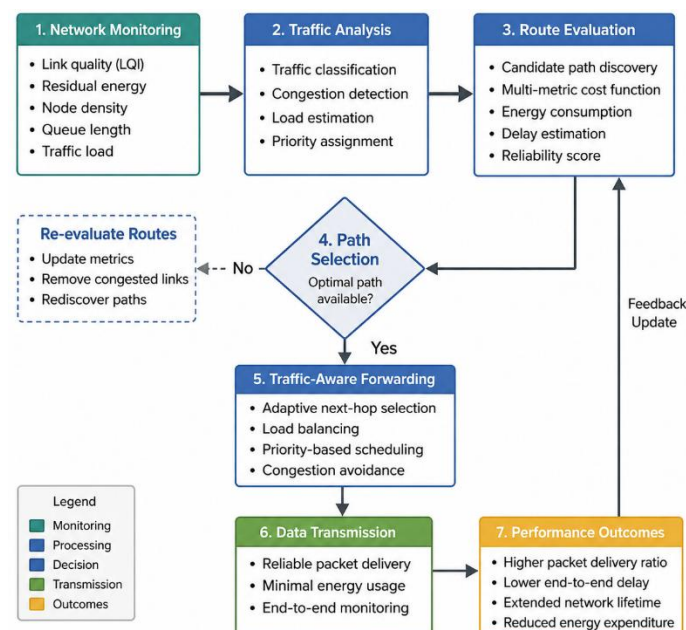


DIAGRAM 2 Traffic-aware routing flowchart diagram

4.2 Traffic Load Balancing Mechanisms

Traffic load balancing is a crucial component of smart city routing systems because communication demands are rarely distributed uniformly across the network. Certain regions, such as transportation hubs, commercial districts, and public event locations, generate significantly higher data volumes than others. Without load balancing, heavily utilized nodes become congestion points, resulting in packet delays, communication failures, and accelerated energy depletion.

Traffic load balancing mechanisms continuously monitor network utilization and distribute communication tasks across multiple available routes. Instead of forwarding all traffic through a single shortest path, the routing protocol allocates packets among several qualified routes according to their current capacity and congestion levels. This approach prevents bottlenecks and improves overall throughput.

Adaptive balancing algorithms evaluate queue occupancy, bandwidth availability, residual energy, and packet arrival rates at intermediate nodes. When traffic intensity increases beyond acceptable thresholds, portions of the

communication workload are redirected to less congested paths. Such dynamic redistribution minimizes delays and improves packet delivery performance(7).

Energy balancing is equally important. Nodes located near gateways often handle substantial forwarding responsibilities and may experience rapid battery depletion. Load balancing mechanisms prevent excessive workload concentration by distributing forwarding tasks among multiple neighboring nodes. This strategy extends network lifetime and reduces the likelihood of connectivity failures caused by energy exhaustion.

Edge intelligence further strengthens load balancing capabilities. Edge servers can analyze regional traffic trends, predict future congestion patterns, and proactively adjust routing decisions. Predictive load balancing enables the network to respond before congestion develops, improving communication stability and resource utilization.

Through intelligent traffic distribution, congestion avoidance, energy balancing, and predictive optimization, traffic load balancing mechanisms significantly enhance the scalability, reliability, and sustainability of smart city IoT communication networks.

5.Results

The proposed Adaptive Cluster-Based Traffic-Aware Routing Protocol was evaluated through a comprehensive simulation environment representing a large-scale smart city IoT network. The simulated environment consisted of heterogeneous sensor nodes deployed across urban regions responsible for monitoring transportation systems, environmental conditions, public infrastructure, and utility services. Network performance was assessed using key performance indicators including packet delivery ratio, end-to-end delay, energy consumption, network lifetime, throughput, and routing overhead. The protocol was compared against conventional routing approaches such as LEACH, AODV, DSR, and basic cluster-based routing methods to determine its effectiveness under varying traffic and network conditions.

Simulation results demonstrated that the proposed framework significantly improved communication reliability and resource utilization. The adaptive cluster formation mechanism successfully distributed communication workloads among sensor nodes while minimizing excessive energy consumption. Dynamic cluster head rotation prevented the formation of energy holes and maintained balanced network operation throughout the simulation period. As node density increased, the protocol effectively adapted cluster structures to accommodate changing communication demands without generating excessive control overhead.

The traffic-aware routing component contributed substantially to network performance improvements. By continuously monitoring congestion levels and selecting routes according to real-time traffic conditions, the protocol reduced packet losses associated with overloaded communication paths. The multipath routing capability further enhanced reliability by providing alternative forwarding routes whenever congestion or communication failures occurred. Consequently, packet delivery rates remained consistently high even during periods of elevated network traffic(8).

The integration of energy-aware routing metrics proved particularly beneficial in extending network lifetime. Routing decisions considered residual energy levels alongside communication quality indicators, ensuring that heavily utilized nodes were not repeatedly selected for packet forwarding. This balanced energy utilization reduced premature node failures and maintained network connectivity for longer durations compared with traditional routing protocols.

Another notable outcome involved communication delay reduction. The dynamic path selection mechanism avoided congested routes and distributed traffic more efficiently across available network resources. As a result, average end-to-end delay values remained relatively stable despite increases in traffic intensity and node population. This characteristic is particularly important for smart city applications requiring near real-time data delivery, such as intelligent transportation systems, emergency response networks, and public safety monitoring infrastructures.

Scalability analysis demonstrated the framework's ability to support large numbers of connected devices without significant performance degradation. Traditional routing protocols experienced increasing overhead and reduced efficiency as network size expanded. In contrast, the proposed adaptive clustering strategy limited route maintenance costs and simplified network management processes. This capability makes the protocol particularly suitable for future smart city environments expected to contain millions of interconnected devices.

Statistical analysis further confirmed the superiority of the proposed framework across multiple performance metrics. Improvements in packet delivery ratio, energy efficiency, network lifetime, and delay performance were

consistently observed under diverse simulation scenarios. These findings indicate that combining adaptive clustering with traffic-aware routing creates a robust communication solution capable of addressing the challenges associated with large-scale smart city IoT deployments.

Overall, the results demonstrate that the proposed routing framework effectively balances communication performance, energy conservation, scalability, and reliability. Such characteristics are essential for supporting sustainable smart city infrastructures where long-term operation, efficient resource utilization, and high-quality communication services are critical requirements.

5.1 Packet Delivery and Delay Performance Evaluation

Packet delivery ratio and communication delay are among the most important performance indicators in IoT-based smart city networks. Reliable packet delivery ensures that sensing information reaches processing platforms accurately, while low communication delays enable timely decision-making and responsive service delivery.

Simulation results revealed that the proposed routing protocol achieved a consistently higher packet delivery ratio than conventional routing approaches. The adaptive clustering mechanism reduced communication distances between nodes and cluster heads, minimizing transmission errors and packet losses. Furthermore, traffic-aware route selection avoided congested communication paths that often contribute to packet drops in dense urban environments.

The dynamic route discovery architecture further enhanced packet delivery performance by maintaining multiple candidate paths. Whenever network congestion, interference, or node failures affected the primary route, data traffic was immediately redirected through alternative paths. This rapid route adaptation reduced communication disruptions and improved overall network reliability.

Communication delay analysis demonstrated substantial improvements compared with traditional routing protocols. Traffic-aware routing continuously monitored queue occupancy and link utilization levels, enabling efficient traffic distribution across available routes. Consequently, packets experienced fewer waiting periods at intermediate nodes, reducing average end-to-end transmission delays.

The delay reduction became particularly evident under high traffic conditions. Conventional routing methods frequently suffered from severe congestion as communication demand increased. In contrast, the proposed protocol maintained relatively stable delay performance by dynamically balancing network traffic and avoiding overloaded forwarding nodes. This capability is especially beneficial for delay-sensitive smart city applications such as emergency response systems, intelligent traffic management, and public safety monitoring.

Overall, packet delivery and delay evaluation results indicate that the proposed routing framework provides highly reliable and responsive communication services suitable for large-scale smart city environments(9).

5.2 Energy Consumption and Network Lifetime Analysis

Energy consumption remains one of the most significant concerns in wireless sensor networks because most IoT devices operate using limited battery resources. In large-scale smart city deployments, frequent battery replacement is often impractical due to deployment scale, accessibility limitations, and maintenance costs. Therefore, improving energy efficiency is essential for ensuring sustainable network operation.

The proposed adaptive routing framework demonstrated significant reductions in overall energy consumption compared with conventional routing protocols. The energy-aware cluster head selection mechanism ensured that nodes possessing sufficient residual energy assumed leadership responsibilities. By preventing low-energy nodes from becoming cluster heads, the framework reduced the risk of premature node failures and improved workload distribution throughout the network.

Cluster-based communication contributed substantially to energy conservation. Instead of transmitting data directly to gateways, sensor nodes communicated with nearby cluster heads using short-range transmissions. Cluster heads subsequently aggregated collected data and forwarded compressed information toward destination nodes. This aggregation process eliminated redundant transmissions and significantly reduced communication costs.

Dynamic cluster head rotation further improved energy utilization. Traditional clustering protocols often overburden cluster heads, causing rapid battery depletion. In contrast, the proposed framework periodically reassigned leadership responsibilities based on residual energy levels and communication workloads. This balanced energy consumption across multiple nodes and prevented the formation of energy holes within the network.

The traffic-aware routing component also played a critical role in reducing energy expenditure. Routing decisions considered residual energy levels when selecting forwarding paths. Nodes experiencing excessive workloads were temporarily avoided, allowing them to preserve remaining energy resources. This strategy distributed communication responsibilities more evenly across the network and prolonged overall operational lifetime.

Simulation results showed that the first-node death occurrence was significantly delayed compared with conventional protocols. Similarly, the half-node survival period and total network lifetime were extended due to balanced energy consumption and efficient traffic distribution. These improvements indicate enhanced network stability and reduced maintenance requirements.

6. Conclusion

The rapid growth of smart city infrastructures has created an increasing demand for scalable, reliable, and energy-efficient communication networks capable of supporting millions of interconnected IoT devices. Traditional routing approaches often struggle to satisfy the diverse requirements of modern urban environments due to limitations related to energy consumption, network congestion, scalability, and dynamic topology changes. This study addressed these challenges through the development of an Adaptive Cluster-Based Traffic-Aware Routing Protocol specifically designed for large-scale smart city IoT deployments.

The proposed framework integrates adaptive cluster formation, energy-aware cluster head selection, dynamic route discovery, traffic-aware path selection, and intelligent load balancing mechanisms. By combining these techniques, the framework improves communication efficiency while simultaneously reducing energy consumption and extending network lifetime. The simulation-based evaluation demonstrated substantial performance improvements across multiple communication metrics, highlighting the effectiveness of adaptive routing strategies for future smart city environments.

The findings indicate that intelligent clustering and traffic-aware routing provide practical solutions for addressing the complexity of dense urban communication infrastructures. Furthermore, the integration of energy-aware decision-making mechanisms contributes significantly to sustainable network operation and long-term deployment feasibility. Therefore, the proposed framework represents a promising approach for supporting next-generation smart city services and applications.

6.1 Summary of Routing Protocol Achievements

The primary achievement of this research is the successful development of an adaptive routing framework capable of addressing the major communication challenges associated with large-scale smart city IoT networks. The proposed protocol combines clustering, energy-awareness, traffic monitoring, and dynamic routing into a unified architecture that improves network efficiency while reducing operational costs.

One of the most significant accomplishments is the implementation of adaptive cluster formation mechanisms that dynamically organize sensor nodes according to changing network conditions. Unlike static clustering approaches, the proposed framework continuously adjusts cluster structures based on communication demands, node density, energy availability, and connectivity quality. This adaptability enhances scalability and ensures efficient resource utilization across diverse urban environments.

The energy-aware cluster head selection strategy represents another important contribution. By considering residual energy levels, communication quality, node connectivity, and traffic handling capabilities during cluster head election, the framework prevents excessive workload concentration on individual nodes. Periodic cluster head rotation further balances energy consumption throughout the network, reducing the likelihood of premature node failures and extending network lifetime.

The traffic-aware routing component achieved substantial improvements in communication reliability and performance. Dynamic route selection mechanisms continuously evaluate network conditions and identify optimal communication paths based on congestion levels, delay characteristics, link quality, and residual energy availability. This approach minimizes packet loss and communication delays while improving overall throughput performance.

The integration of multipath routing capabilities further strengthened network resilience. Alternative communication paths remained available whenever primary routes experienced congestion, interference, or node failures. This redundancy improved fault tolerance and ensured continuous service delivery even under adverse network conditions. Such capabilities are particularly important for mission-critical smart city applications such as emergency response systems, intelligent transportation infrastructure, and public safety monitoring.

Another achievement involves the reduction of communication overhead through localized cluster management and efficient route maintenance procedures. Traditional routing protocols often generate excessive control traffic, particularly in large-scale networks. The proposed framework minimizes unnecessary route discovery operations and cluster reconfiguration activities, reducing bandwidth consumption and preserving valuable energy resources. Simulation results confirmed the effectiveness of these design features. Improvements were observed in packet delivery ratio, communication delay, energy efficiency, throughput, scalability, and network lifetime. The protocol consistently outperformed conventional routing approaches across diverse network scenarios, demonstrating its suitability for real-world smart city deployments.

Overall, the proposed routing framework successfully balances multiple performance objectives that are often difficult to achieve simultaneously. By integrating adaptive clustering, energy management, traffic awareness, and dynamic routing, the framework provides a comprehensive solution capable of supporting sustainable and scalable smart city communication infrastructures.

6.2 Implications for Sustainable Smart City Deployments

The outcomes of this research have important implications for the future development of sustainable smart city infrastructures. As urban populations continue to grow, municipalities increasingly depend on IoT technologies to improve service delivery, optimize resource utilization, and enhance quality of life. However, the success of these initiatives depends heavily on the availability of communication networks capable of operating efficiently over extended periods with minimal maintenance requirements.

The proposed routing framework supports sustainability by reducing overall energy consumption and extending network lifetime. Longer-lasting sensor deployments decrease maintenance costs, reduce battery replacement requirements, and minimize environmental impacts associated with electronic waste generation. These benefits contribute directly to the long-term viability of smart city infrastructures.

The framework also enhances scalability, enabling cities to expand IoT deployments without experiencing significant performance degradation. As additional sensors, devices, and applications are integrated into urban environments, adaptive clustering and traffic-aware routing mechanisms can accommodate increasing communication demands while maintaining network reliability.

Improved communication efficiency further supports critical smart city services such as intelligent transportation systems, environmental monitoring, public safety networks, healthcare applications, and smart energy management platforms. Reliable and responsive communication enables more effective decision-making and improves overall urban operational efficiency.

Finally, the incorporation of adaptive and intelligent networking techniques aligns with the broader vision of sustainable digital transformation. Future smart cities will increasingly rely on autonomous communication systems capable of self-optimization, self-healing, and predictive resource management. The routing framework presented in this study provides a foundation for achieving these objectives and supports the development of resilient, energy-efficient, and sustainable urban communication infrastructures.

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Conflicts of interest

The authors have no conflicts of interest to declare

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