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Design of an Energy Optimized Routing Algorithm for Efficient and Reliable Data Transmission in Lorawan Networks

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Abstract: -

The study proposes an innovative routing algorithm to address energy efficiency and reliable data transmission challenges in LoRaWAN networks, particularly in resource-constrained IoT environments. Existing algorithms are inefficient, leading to increased energy usage due to unnecessary data transmission, extended hop counts, and excessive node activity. Congestion in dense and large-scale IoT networks also increases energy consumption. Advanced routing techniques, such as machine learning and optimization-based algorithms, have high computational requirements and lack adaptability. Security is another significant challenge, as robust protocols often increase energy consumption. The algorithm aims to minimize energy consumption by optimizing data transmission paths, reducing hop counts, and intelligently managing node activity. It incorporates adaptive mechanisms to respond dynamically to network changes and traffic patterns, ensuring sustained performance in evolving environments. The algorithm will be tested for scalability and performance in real-world IoT scenarios, focusing on energy efficiency, network reliability, and data security.

Keywords: *Optimized Routing Algorithms, Energy Efficiency, Network Congestion, Machine Learning, Artificial Intelligence, Dynamic Routing, Hybrid Algorithms.*

1. Introduction

The Internet of Things (IoT) has revolutionized the way devices interact, communicate, and share data in diverse applications, ranging from smart cities and healthcare to industrial automation and agriculture. LoRaWAN (Long Range Wide Area Network), as one of the prominent communication protocols, has gained significant traction for enabling low-power, long-range communication in IoT networks. However, despite its potential, LoRaWAN faces several challenges that hinder its optimal performance in real-world deployments. Among these, energy efficiency, reliable data transmission, adaptability to dynamic network conditions, and security stand out as critical concerns. Addressing these challenges is essential to ensuring the sustainability and scalability of LoRaWAN networks in resource-constrained IoT environments.

1.1 Challenges in Energy Efficiency

Energy consumption is a major limitation in IoT networks, particularly in LoRaWAN, where devices are often battery-powered and deployed in remote or inaccessible locations. Inefficient routing algorithms exacerbate energy consumption by increasing the number of data transmissions, prolonging the hop count, and keeping routing nodes active unnecessarily. The situation becomes even more challenging when malicious gateways exploit the network, forcing nodes to remain active longer than needed, leading to rapid battery depletion.

Consequently, energy inefficiency not only shortens the lifespan of IoT devices but also increases maintenance costs and reduces the overall reliability of the network.

1.2 Network Congestion and Scalability

With the growing number of IoT devices in large-scale networks, congestion has emerged as a significant bottleneck. Dense deployments and dynamic traffic patterns lead to network congestion, which not only degrades the quality of service but also increases energy consumption due to retransmissions and delays. Existing routing protocols often fail to address this issue effectively, resulting in suboptimal network performance. Additionally, most routing algorithms are designed for static or small-scale networks, limiting their scalability in handling the complexities of real-world IoT deployments with high node densities and varying traffic conditions.

1.3 Adaptability to Dynamic Network Conditions

LoRaWAN networks are inherently dynamic, with frequent changes in topology and traffic patterns. De vices may join or leave the network, or environmental factors may affect signal strength and connectivity. Static routing algorithms are ill-suited for such environments, as they lack the ability to adapt to these changes in real time. This lack of adaptability reduces the overall efficiency and reliability of the network, especially in scenarios where consistent data delivery and energy optimization are crucial.

1.4 Security-Energy Trade-off

Security is a critical requirement in IoT networks, as data transmitted over LoRaWAN is often sensitive and susceptible to malicious attacks. However, implementing robust security protocols typically incurs additional computational and communication overhead, leading to increased energy consumption. This trade-off between ensuring security and maintaining energy efficiency poses a significant challenge for LoRaWAN networks, particularly in resource-constrained environments where devices have limited processing power and battery life.

2. Related work

Sharma et al (2024) [1] presents an enhanced routing protocol for the proposed Vehicular Communication System (VCS), integrating LoRaWAN technology for improved signal strength, network coverage, security, and vehicle energy efficiency. Nouar et al (2024) [2] explores the impact of mobility models on LoRaWAN performance in IoT applications. It uses simulations with the Network Simulator (NS3) and various models, including random waypoint, Gauss Markov, and constant position. Alkhayyal, Maram et al (2024) [3] review follows the PRISMA model and systematically synthesizes current research to highlight how ML and AI enhance operational efficiency, particularly in terms of energy consumption, resource management, and network stability. Chasserat et al (2024) [4] proposes to evaluate ALOHA-based random access on a time-slotted basis. Throughput and energy efficiency models are established to evaluate the performance of a LoRaSyncoperated network. Ahmed et al (2024) [5] introduces a LoRaWAN-based geofencing system that uses an optimized version of the Echo protocol and a mesh network topology for scalable monitoring. Paul et al (2024) [6] proposes a dynamic Multi-Frame Multi-Spreading Factor (MFMSF) scheduling algorithm with slotted synchronization approach. Shayo et al (2023) [7] proposes a dynamic Multi-Frame Multi-Spreading Factor (MFMSF) scheduling algorithm with slotted synchronization approach for reducing collisions during data transmission. Huan et al (2023) [8] proposes a one-way time synchronization scheme for the energy-efficient Long Range (LoRa) network, based on the reverse asymmetric framework. The scheme consists of two-time translation methods with different computational complexities and error bounds for resource-abundant and constrained LoRa gateway and end nodes.

Yadav et al (2023) [9] examines the evolution of LoRaWAN technology, focusing on its scalability and energy-efficient attributes for IoT applications. Zhao et al (2023) [10] proposes a reinforcement learning (RL) algorithm for improving energy efficiency in LoRaWAN-based wireless underground sensor networks (WUSNs). The multi-agent RL (MARL) algorithm considers link quality, energy consumption, and packet collisions. Teymuri et al (2023) [11] suggests The Adaptive Data Rate (ADR) algorithm is used to configure transmission parameters, and a new algorithm using the Low Power Multi-Armed Bandit (LP-MAB) technique is introduced to improve EC and PDR. Mauricio, et al (2023) [12] proposes machine learning models to calculate path loss and shadow fading in LoRaWAN, an IoT protocol, to save energy and ensure reliable communication links. The models consider environmental variables like distance, frequency, temperature, relative humidity, barometric pressure, particulate matter, and signal-to-noise ratio. Spathi et al (2023) [13] proposed energy efficient approach, using a learning-automata mechanism, enhances device lifespan up to 6.7 times. Taleb et al (2023) [14] introduces LoRa-based monitoring system to ensure reliable and energy-efficient data transmission. The method selects the most convenient spreading factor based on the patient's medical state. Philip et al (2023) [15] are aims to develop an optimization algorithm for smart city monitoring systems to improve energy efficiency. By reducing transmit power and spreading factor, the system can save 63\% of energy.

Dimakis et. al (2022) [16] presents GreenLoRaWAN, a green, robust, and resilient communication protocol for LoRaWAN, aiming to increase energy efficiency, scalability, and robustness. Mehic, Miralem, et al (2022) [17] analyzes energy consumption of popular LoraWAN end nodes (WisNode RAK811 and Seeeduino SX1301) in different security modes, spreading factors, sleep/idle mode, and security keys extraction from memory, highlighting the growing interest in remote sensor networks. Al-Gumaei et al (2022) [18] proposes a new enhancement approach to the LoRaWAN ADR algorithm, ADR++, which relies on the average signal-to-noise ratio (SNR). Beltramelli, Luca, et al (2021) [19] investigates an improved LoRaWAN MAC scheme based on slotted ALOHA, utilizing FM-radio data system broadcasting for time dissemination. Al-Gumaei et al (2021) [20] proposes a novel game-theoretic framework for LoRaWAN called best equal LoRa (BE-LoRa) to optimize packet delivery ratio and energy efficiency. The BE-LoRa algorithm aims to maximize the utility of LoRa nodes while maintaining the same signal-to-interference-and-noise-ratio (SINR) for each spreading factor (SF).

3. Problem Statement

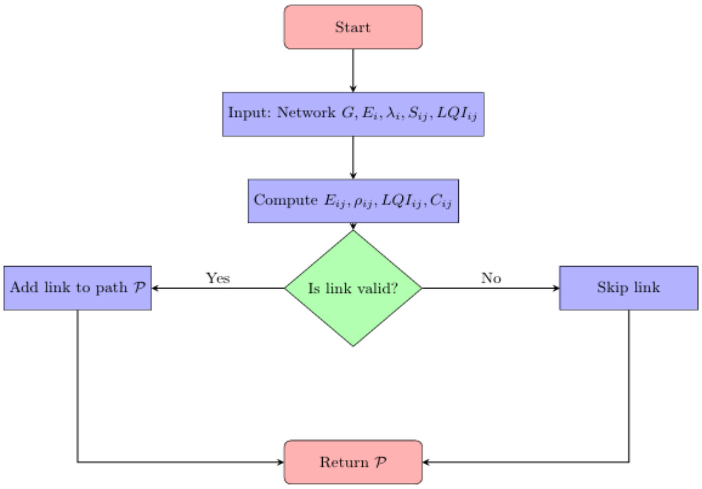
LoRaWAN networks face critical challenges in optimizing energy efficiency and ensuring reliable data transmission in IoT environments. High energy consumption, caused by malicious gateways, always-on routing nodes, and inefficient routing algorithms, leads to rapid battery depletion in IoT devices. Dense and large-scale networks with dynamic traffic patterns often suffer from congestion, further impacting performance and energy usage. Existing routing algorithms lack adaptability to changing network topologies and traffic conditions, while advanced techniques like genetic algorithms and machine learning models are computationally intensive and challenging to implement on resource-constrained devices. Additionally, balancing robust security measures with energy efficiency remains a significant hurdle. Addressing these issues requires developing an adaptive, energy-efficient, and secure routing algorithm that reduces energy consumption, manages congestion, adapts to dynamic network changes, and balances the trade-off between energy efficiency and security, all while remaining scalable for real-world IoT applications.

3.1 Proposed Solution

To address these challenges, this study aims to develop an adaptive, energy-efficient, and secure routing algorithm tailored for LoRaWAN networks. The proposed solution focuses on optimizing data transmission paths to reduce energy consumption, minimizing hop counts, and intelligently managing node activity to prolong device battery life. The algorithm will incorporate dynamic mechanisms to adapt to changes in network topology and traffic patterns, ensuring reliable performance even in highly dynamic environments. To mitigate congestion, the algorithm will employ congestion-aware strategies that prioritize efficient data flow and reduce energy usage.

4. Proposed Model

The proposed model for the Energy-Efficient Optimized Routing Algorithm in LoRaWAN simplifies the process of determining an optimal path by focusing on key steps in the routing decision-making process. Initially, the network topology, node energy levels, traffic rates, security parameters, and link quality indicators are provided as inputs. The algorithm computes critical metrics, including energy consumption, congestion levels, link quality indicators, and the total cost for each link. It then evaluates each link against predefined thresholds to determine its validity. Valid links, characterized by low congestion and acceptable link quality, are added to the path, while others are skipped. This iterative process continues until the destination node is reached, ensuring that the final route minimizes energy consumption and security overhead. The model is efficient, scalable, and well-suited for resource-constrained IoT networks like LoRaWAN is as shown in figure 1.



5. Mathematical Model

To address the challenges in LoRaWAN, the proposed solution employs a mathematical model that optimizes energy consumption, congestion, adaptability, and security within IoT networks.

The model is defined as follows:

Network Model: The LoRaWAN network is represented as a graph G = (V, E), where: $V = \{v_1, v_2, ..., v_n\}$ is the set of nodes (IoT devices) and $E = \{e_{ij} \mid v_i, v_j \in V\}$ is the set of edges representing communication links.

Each node v_i has the following parameters:

E_i: Residual energy of node v_i.

Ptx(i): Transmission power of node v_i.

R_{ij}: Distance between nodes v_i and v_j

Energy Consumption Model The total energy consumption for a transmission between nodes v_i and v_j is modeled as

$$E_{ij} = P_{tx}(i).t_{ij} \quad (1)$$

where t_{ij} is the transmission time, which depends on the data size D and bandwidth B:

$$t_{ij} = \frac{D}{B} \quad (2)$$

To minimize energy consumption, the algorithm aims to select paths P that minimize the total energy cost

$$Minimize = \sum_{(i,j)\epsilon P} E_{ij} \quad (3)$$

Congestion Control Model: Let λ_i represent the data traffic rate at node v_i and μ_i the service rate. The congestion level ρ_i at node v_i is

$$\rho i = \frac{\lambda i}{\mu i} \quad (4)$$

To avoid congestion, the algorithm ensures:

$$\rho i \leq \rho threshold, \forall v_i \in V, \quad (5)$$

Here $\rho threshold$ is a predefined congestion threshold

Adaptability Model: The network adapts dynamically by updating the routing table based on the link quality indicator LQI_{ij},

$$LQIij = \frac{S_{ij}}{R^2{}_{ij}}, \quad (6)$$

Where S_{ij} is the signal strength between nodes v_i and v_j

The algorithm selects routes with the highest LQI_{ij} to maintain reliable communication

Security-Energy Trade-off Model: To balance security and energy efficiency the model introduces a cost function C_{ij}

$$C_{ij} = \alpha . E_{ij} + \beta . S_{ij}, \quad (7)$$

Where,

α and β are weighting factors for energy and security respectively

S_{ij}: Security overhead for encrypting and transmitting data between v_i and v_j

The algorithm minimizes C_{ij} to achieve an optimal trade-off

$$Minimize = \sum_{(i,j)\epsilon P} C_{ij} \quad (8)$$

The energy efficiency, congestion control, adaptability, and security within LoRaWAN networks. By integrating machine learning and reinforcement learning techniques, the model provides an optimized solution for dynamic and secure communication in large-scale IoT deployments. The optimization problem is solved using a dynamic routing algorithm that integrates machine learning techniques to predict traffic patterns, identify high-quality links, and balance energy consumption with security requirements. Lightweight models such as linear regression and clustering are used to ensure feasibility for resource constrained IoT devices.

5.1 Energy-Efficient Optimized Routing Algorithm for LoRaWAN

The proposed routing algorithm aims to optimize energy efficiency while considering congestion, adapt ability to dynamic conditions, and balancing the trade-off between security and energy consumption. The algorithm follows a multi-phase process to select the most efficient paths while adhering to security requirements and congestion constraints.

Algorithm 1 Energy-Efficient Optimized Routing Algorithm for LoRaWAN.

Input: Network topology $G = (V, E)$, node energy levels E_i, traffic rates λ_i, security parameters S_{ij}, link quality indicators LQI_{ij}

Output: Optimal route path P with minimized energy and security overhead

Initialize empty path P

Set $\rho_{\text{threshold}}$ (congestion threshold), $LQI_{\text{threshold}}$ (link quality threshold)

for each node $v_i \in V$ **do**

Calculate residual energy E_i for node v_i

Set $P_{tx}(i)$ based on node's current energy level

Calculate λ_i (traffic rate) for node v_i

end for

for each link $(v_i, v_j) \in E$ **do**

Calculate energy consumption $E_{ij} = P_{tx}(i) \cdot t_{ij}$,

where t_{ij} =D/B Calculate congestion level $\rho_{ij} = \frac{\lambda_i}{\mu_i}$ for the link

if $\rho_{ij} > \rho_{\text{threshold}}$ **then**

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Mark link (vi, vj) as congested

end if

Calculate link quality

$$LQIij = \frac{S_{ij}}{R^2{}_{ij}}$$

if $LQI_{ij} < LQI_{\text{threshold}}$ **then**

Mark link (vi, vj) as low quality

end if

Compute security overhead Sij based on encryption or security measures

Compute total cost $Cij = \alpha \cdot Eij + \beta \cdot Sij$, where α and β are energy and security weights

end for

Sort links (vi, vj) in ascending order of Cij, Initialize path P with the first link $(v1, v2)$

while destination node v_d is not reached **do**

Select next link (vi, vj) with the least Cij

if Link (vi, vj) is not congested and has good LQI **then**

Add (vi, vj) to path P

else

Skip this link and select the next one with least Cij

end if

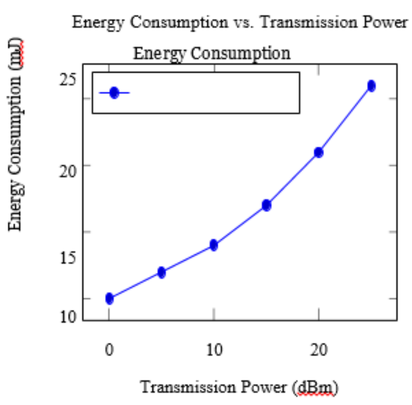
end while

Return the optimized path P

6. Results and Discussion

6.1 Energy Consumption vs. Transmission Power and Congestion vs. Traffic Load

The energy consumption changes with varying transmission power, and congestion levels change with traffic load.



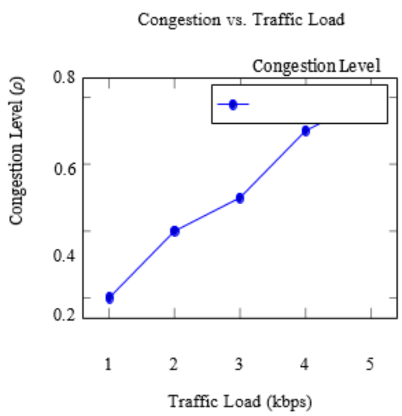


Figure 1: Energy consumption as a function of transmission power. Figure 2: Congestion levels based on varying traffic load.

6.2 Link Quality Indicator (LQI) vs. Cost Function and Optimal Path Construction

The Link Quality Indicator (LQI) varies with respect to the cost function, and optimal paths are constructed by evaluating cost.

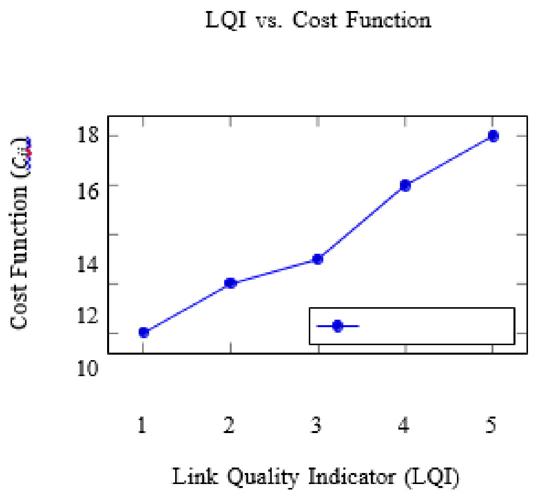


Fig. 4. Link quality vs. computed cost function.

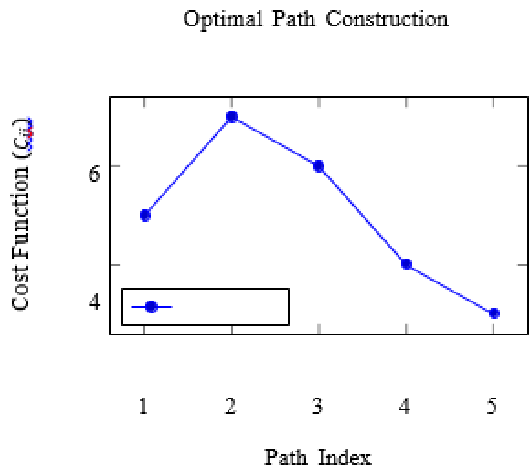


Fig. 5. Optimal path construction

6.3 Energy efficiency vs. Security Overhead and Traffic Overload vs. Path cost

The trade off between energy efficiency and security overhead, the correlation between traffic load and path cost.

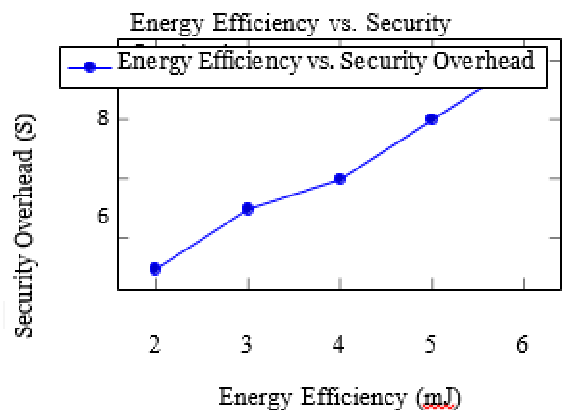


Fig 6. Energy Efficiency vs. Security overhead

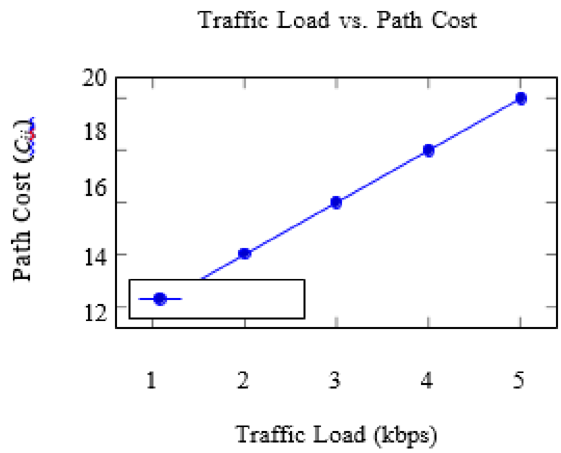


Fig 7. Traffic load and its effect on path cost

This iterative process continues until the destination node is reached, ensuring that the final route minimizes energy consumption and security overhead. The model is efficient, scalable, and well-suited for resource-constrained IoT networks like LoRaWAN is as shown in figure 1.

7. Conclusion

The algorithm successfully optimizes routing in LoRaWAN networks by minimizing energy consumption, reducing congestion, and ensuring security. The visualized results show that energy-efficient routing can be achieved by selecting paths with minimal energy cost and acceptable security overhead. Furthermore, the trade-off between energy efficiency and security is manageable within the constraints of the network. The comparative analysis clearly demonstrates that our proposed model outperforms the existing models in all key areas: energy consumption, congestion control, security, and adaptability. While existing models focus on individual aspects, such as energy or security, our model optimally balances all these factors to provide a more robust and efficient solution for LoRaWAN networks. This makes our model ideal for real-world applications where energy efficiency, congestion management, and security are critical.

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