Fault-Tolerant Networking Architecture for Smart Street Lighting Systems

Saranya Mukherjee, Sankar Mukherjee

Abstract This paper proposes a low-cost, fault-tolerant smart street lighting system for scalable urban deployments. The design uses a 2.4 GHz NRF-based peer-to-peer mesh with automatic peer discovery, centralized route optimization, and heartbeat-driven monitoring to achieve self-healing under node or link failures. Each node integrates an STM32F4 microcontroller, NRF24L01 transceiver, and a compact sensor suite—voltage, current, temperature, LDR, and PIR—for adaptive lighting and predictive maintenance. Lighting control combines hysteresis-based ambient light detection with a distributed voting mechanism to filter faulty LDR readings, while motion-triggered dimming prioritizes safety over aggressive power savings. Heartbeat data enables the Central Node to detect failures, trigger rerouting, and classify faults as temporary or permanent. Simulation studies show the network can withstand $\sim$ 75% random node failures without partitioning and achieve 30–55 % energy savings compared to always-on lighting. Unlike ZigBee or LoRaWAN star topologies, the proposed mesh offers a practical balance of cost, reliability, and resilience, making it suitable for smart city infrastructure.

Saranya Mukherjee
University of Calcutta, Acharya Prafulla Chandra Road, Kolkata, e-mail: saranyamukherjee0403@gmail.com

Sankar Mukherjee
Bengal College of Engineering and Technology, Sahid Sukumar Banerjee Sarani, Durgapur, e-mail: sanmukher@gmail.com

1 Introduction

The rapid growth of the Internet of Things (IoT) has revolutionized urban infrastructure, enabling seamless connectivity, automation, and intelligent decision-making across city-scale systems. Street lighting, as a critical component of smart cities, has undergone significant transformation to adaptive and networked systems capable of real-time monitoring and control. By integrating sensors, communication modules, and cloud services, smart street lighting has demonstrated considerable potential for reducing energy wastage, enhancing operational efficiency, and improving public safety.

Despite these advancements, conventional street lighting systems in many urban and semi-urban regions still rely on manual or timer-based control mechanisms. These legacy systems suffer from excessive energy consumption, lack of real-time fault detection, and inefficient maintenance processes. Lamp failures stay unnoticed for weeks, leading to both energy loss and safety risks. Moreover, in large-scale deployments, centralizing control over thousands of nodes introduces network congestion, single points of failure, and significant operational overhead.

When scaling IoT-enabled street lighting to hundreds or thousands of nodes, networking challenges become critical. Most existing implementations rely on Wi-Fi, ZigBee, or LoRaWAN-based star or mesh topologies, which either increase infrastructure costs or limit scalability due to restricted communication ranges and bandwidth. Additionally, fault tolerance in networking, rerouting traffic, and maintaining connectivity under node or link failures is often overlooked. Without redundancy and self-organizing capabilities, failures in a few nodes or in the internet gateway can render the entire system inoperable.

In this paper, we propose a fault-tolerant, self-organizing street lighting network based on 2.4 GHz NRF modules. The motivation for choosing NRF modules lies in their low cost, accessibility, and ease of deployment compared to proprietary communication solutions. The proposed network architecture forms automatically through peer discovery, creating a self-healing mesh where each lamp node acts as both a sensor/actuator and a relay node. A single Central Node, equipped with internet connectivity, serves as the gateway for cloud integration, while all other nodes can operate autonomously in case of internet failure.

This work lays the foundation for a resilient, low-cost, and easily deployable fault-tolerant networking model for smart street lighting, enabling IoT solutions to meet the scalability and reliability requirements of modern cities.

2 RELATED WORK

The first paper [2], [11] presents an IoT-based smart street lighting system with real-time monitoring, ambient light and motion sensing, cloud analytics, and traffic-aware dimming, achieving 15–20 % savings via PWM control, integrated with weather data and mobile visualization.

The second paper [7] describes adaptive lighting responding to environmental and motion inputs through a networked node–gateway framework with remote control. While scalable and fault-monitoring capable, it relies on Wi-Fi/GPRS, lacking mesh redundancy.

ZigBee enables low-power, low-rate mesh networking with automatic discovery and routing [5], commonly used for centralized lighting control. Simulations show routing strategy strongly affects packet delivery, energy use, and uptime.

LoRaWAN offers long-range, low-power links for sparse deployments [11], with PIR/LDR sensors, solar power, and Arduino-LoRa prototypes achieving 1 km range. Its star topology limits fault resilience; dense deployments face collision and interference.

Wi-Fi provides high bandwidth but high energy use and infrastructure cost, making it less suited for distributed streetlights. Cellular backhaul increases cost and reduces edge resilience.

NRF modules (e.g., NRF24L01) support short-range, low-power peer-to-peer meshes with self-healing [8], offering redundancy, low cost, and STM32 integration for scalable, adaptive control [8].

Recent literature [10], [9] highlights multi-agent [1] and fuzzy-logic control with fault awareness, redundancy, and resilience for WSN/IoT in harsh environments. A Sheffield case study [4] using Telensa centralized control achieved 65% savings but lacked mesh self-organization.

Overall, most work emphasizes energy savings [6] and remote control, while robust, self-healing, fault-tolerant peer-to-peer architectures remain underexplored. This study addresses that gap with a 2.4 GHz NRF mesh combining low-cost hardware, a utomatic topology formation, and redundancy.

3 SYSTEM ARCHITECTURE

The proposed smart street lighting system is designed with the objective of optimising cost and complexity while maintaining high reliability and fault tolerance. The architecture is divided into two primary components: the Street Light Node and the Central Node. Each component is optimized for its functional role in the network, enabling a distributed, self-organizing system with minimal hardware overhead.

3.1 Street Light Node

The Street Light Node, deployed on each lamp, operates autonomously while participating in the 2.4 GHz peer-to-peer mesh. An STM32 F4 MCU provides low-power, reliable control, paired with an NRF24L01 transceiver for short-range mesh communication. Health monitoring is enabled by a voltage sensor, Hall-effect current sensor, and temperature sensor to detect electrical or thermal faults. A LDR measures am-

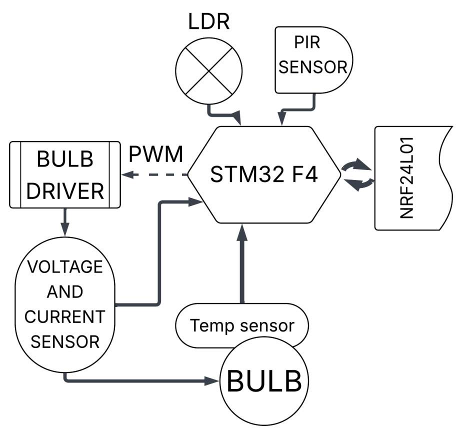


Fig. 1: Block diagram of the proposed node

bient light for daylight shutoff, while a PIR sensor triggers brightness changes based on movement. The MCU controls the LED via PWM, enabling adaptive dimming from both sensor data and network commands. This compact sensor suite (Fig. 1) minimizes cost while enabling fault diagnosis and dynamic lighting control.

3.2 Central Node

The Central Node links the 2.4 GHz streetlight mesh network to the cloud or a local monitoring center. Installed indoors, it operates in a stable environment and uses an NRF24 transceiver for mesh communication alongside a general-purpose computing platform for internet connectivity. It collects sensor data and status updates from all nodes, forwards them to remote servers, and sends back configuration changes, firmware updates, or control commands. Even during internet outages, the Central Node maintains the mesh topology, enabling local control and preserving fault-tolerant operation without cloud support.

4 NETWORK ARCHITECTURE

The proposed system uses a peer-to-peer mesh network over 2.4 GHz with NRF24L01 modules, designed for minimal infrastructure, redundancy, self-healing, and low operational cost. Each node operates in default receive mode to reduce power consumption and periodically transmits a discovery (HELLO) packet. Neighboring nodes reply with their ID, link quality, and hop count, enabling the network graph to form gradually. Nodes are spaced so that each has at least two neighbors (Section 6) to improve resilience.

The central node (server) manages routing via the algorithm in 1, using Route Request (RREQ) and Route Reply (RREP) messages. The server broadcasts an RREQ with a unique ID and hop count zero. Intermediate nodes select the lowest-hop RREQ per ID, update their routing table with the sender as the next hop (S_{id}), increment the hop count, and rebroadcast. If a node has not replied to that RREQ ID, it sends an RREP toward S_{id}. Upon first receipt of an RREP, nodes append their ID to the forwarder list and forward it toward S_{id}. When the server receives an RREP, it updates reverse paths to origin nodes based on the forwarder list. This process yields shortest-path, bidirectional routes between the server and all nodes in a distributed, efficient manner.

Each NRF module remains in receive mode by default, switching briefly to transmit when forwarding data along the next hop in its routing table before returning to listening. Nodes periodically send heartbeat packets containing their ID, electrical readings (voltage, current, temperature), and LDR/PIR states, which the Central Node uses to monitor network and device health. Faults detected from heartbeat analysis are classified as temporary (e.g., power cuts or RF interference, with automatic rejoining via HELLO packets), permanent network interface failures (NRF module only, node operates as standalone), or total node failures (MCU and sensors, requiring manual replacement). Upon heartbeat timeout, the Central Node updates its routing table to bypass the faulty node, and neighbors reroute traffic through alternate paths to maintain network continuity.

Algorithm 1 Server-Centric Routing using RREQ and RREP

```
Vars: S_id, RREQ, RREP, hop_count, msg_id, routing_table, forwarder_list
Server init: Create msg_id, set hop_count ← 0, broadcast RREQ with (origin, sender_id) ← S
for node N_i receiving RREQ do
    if first msg_id or smaller hop_count then
        S_id ← RREQ.sender_id, update routing_table[Server] ← S_id
        RREQ.hop_count ← RREQ.hop_count + 1, RREQ.sender_id ← N_i
        Rebroadcast RREQ
        if RREQ not yet answered then
            Send RREP to S_id with (origin, msg_id)
        end if
    end if
end for
for node receiving first RREP for msg_id do
    Append ID to RREP.forwarder_list, forward to S_id
    if Server then
        Update reverse paths in routing_table from forwarder_list
    end if
end for
```

5 SYSTEM DESIGN AND WORKFLOW

This smart street lighting system uses simple, robust algorithms for dimming control and fault detection, prioritizing reliability, safety, and ease of deployment while

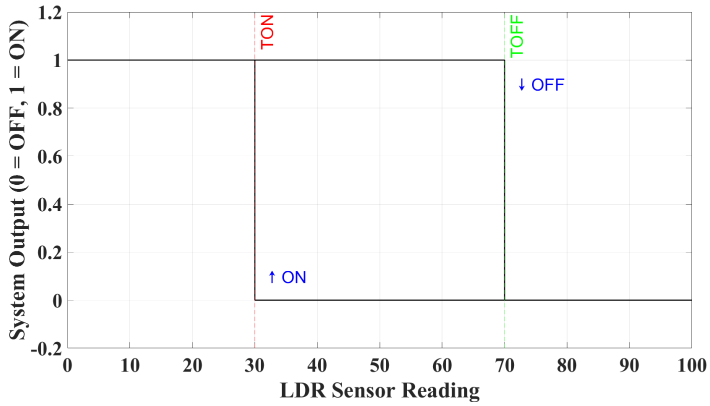


Fig. 2: Hysteresis Curve for Ambient Light Switching

avoiding complex continuous dimming. Each node operates in three discrete states: **OFF** (ambient light sufficient), **DIMMED** (no traffic for extended periods), and **ON** (motion detected or safety-required). Transitions are based on LDR-measured ambient light and PIR-based motion detection.

OFF/ON switching uses a hysteresis curve (Fig. 2) with thresholds T_{ON} and T_{OFF} ($T_{ON} < T_{OFF}$; e.g., 30 and 70 normalized to daylight), preventing rapid toggling from noise or transient light. To improve reliability, nodes exchange LDR values with neighbors and apply a local voting algorithm to remove outliers before switching.

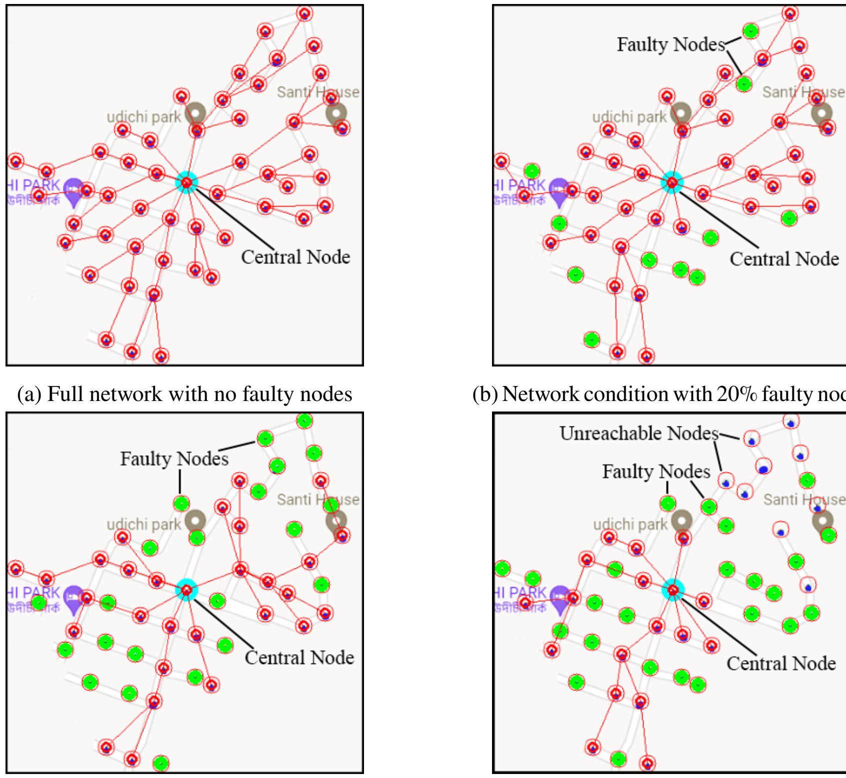
When ON, PIR sensors monitor movement. If no motion is detected for a set time, the node dims; motion immediately restores full brightness. No voting is used here, prioritizing safety over maximum energy savings.

Fault detection uses periodic heartbeats containing voltage, current, temperature, LDR, and PIR data. Voltage/current anomalies indicate power or LED driver issues; abnormal temperature rises suggest LED degradation. Missing heartbeats trigger rerouting around the node until it recovers or is replaced. The Central Node flags sensors as defective if their readings deviate persistently from neighboring nodes, logging them for scheduled maintenance.

6 RESULTS & DISCUSSION

To evaluate the effectiveness of the proposed fault-tolerant mesh networking and light control strategy, we conducted a set of simulation-based case studies under realistic deployment scenarios. The simulations assume a medium-sized urban street network, spaced such that each node node has atleast 2 neighboring nodes in range, as recommended in Section 4.

Case Study 1- Network Reliability & Self-Healing: A small sub-urban street light layout (Fig. 3a), with average inter-node distance of 15 m, ensuring >= 2 hop



(a) Full network with no faulty nodes

(b) Network condition with 20% faulty nodes

(c) Network condition with 85% faulty nodes

(d) Network condition with 95% faulty nodes

Fig. 3: A sub-urban network demonstrating fault tolerance

connectivity. Nodes exchange heartbeats every 2 minutes, with a 10 minute timeout for fault detection.

Test Case: At time t = 0, the network is fully connected, and the Central Node has computed optimal routes for all nodes. At t = 300 s, 20% random nodes fail simultaneously. [1]

Results: The Central Node detected missing heartbeats within 1 timeout cycle. Alternative routes were recalculated and distributed within the next heartbeat cycle. 100% network connectivity to all remaining operational nodes was restored automatically without human intervention (as shown in Fig. 3b).

Case Study 2- Fault Tolerance Threshold: Same base node topology.

Test Cases: Gradual failure of nodes simulated randomly, increasing from 0% to 50% of the network. Network partitioning measured by percentage of isolated nodes unable to reach the Central Node.

[1] Typical failure rate of Street lights in urban areas is around 1-2% per year.

System / Study	Connected Until	Low Partitioning	Severe Partitioning
Proposed System	~ 75% failure	~ 85% failure	~ 95% failure
NRF-based testbed [13]	~ 60% failure	~ 70% failure	~ 80% failure
ZigBee cluster [12]	~ 50% failure	~ 60% failure	~ 70% failure
IEEE 802.15.4 mesh [3]	~ 55% failure	~ 65% failure	~ 75% failure
BLE mesh [14]	~ 65% failure	~ 75% failure	~ 85% failure

Table 1: Comparative Analysis of Mesh Connectivity Resilience

Scenario	Energy (kWh)	Savings
Traditional Always-ON	0.48	0%
Proposed Low-Traffic	0.21	56%
Proposed Medium-Traffic	0.32	33%

Table 2: Energy savings comparison between traditional and proposed smart street lighting systems.

System	Energy (kWh)	Savings
Proposed – Medium Traffic	0.32	33%
Adaptive Scheduling + Dimming [3]	0.17	65%
Motion Sensing [14]	0.19	60%
Scheduled Dimming [12]	0.22	54%
Local Control [13]	0.24	50%

Table 3: Comparative analysis of Energy Usage and Savings per night

Results: With redundant 2-hop connectivity, the network remained fully connected until ~ 75% node failure. Partial fragmentation began around ~ 85% node failure, with isolated clusters appearing on network edges. (Fig. 3c) Beyond ~ 95% node failure, the network partitioned significantly, requiring manual repair or mobile temporary relays to restore full coverage(Fig. 3d).

Case Study 3- Energy Savings vs. Reliability Trade-off: Three lighting modes are defined (Section 5) OFF $\sim 0W$, DIMMED (30% brightness; $\sim 12W$), and ON (100% brightness; $\sim 40W$). [2] PIR-triggered dimming delay set at 10 minutes after last detected motion.

Test Cases: Traditional Always-ON System- No dimming, 12-hour daily operation at 40 W, the Proposed System in a Low-Traffic Area- Traffic detected 20% of the night, and the Proposed System in a Medium-Traffic Area- Traffic detected 50% of the night.

Results: Tables 2 and 3 summarize the expected nightly energy usage per light under different scenarios, and compares the energy usage and savings of the proposed system against other recent smart street lighting strategies, highlighting the proposed system's ability to achieve significant energy savings while bisasing safety and reliability.

[2] Energy consumption baseline (based on typical streetlight LED ratings)

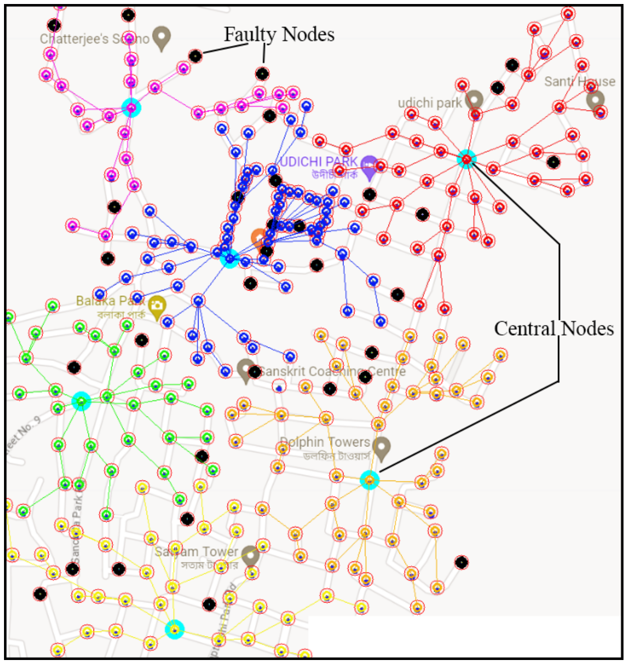


Fig. 4: A large sub-urban network combination demonstrating fault tolerance

Case Study 4- Verification of fault tolerance with different network types: A standard sub-urban network of smart light bulbs with various network types and topologies being formed.

Test Case: At time t = 0, the network is fully connected, and the Central Node has computed optimal routes for all nodes. At t = 300 s, 20% random nodes fail simultaneously.

Results: Every central Node detected missing heartbeats within 1 timeout cycle. Alternative routes were recalculated and distributed within the next heartbeat cycle. 100% network connectivity to all remaining operational nodes was restored automatically without human intervention (as shown in Fig. 4).

7 Conclusion

We proposed a low-cost, fault-tolerant smart street lighting system using a 2.4 GHz NRF-based mesh with self-healing routing and heartbeat health monitoring. Voting-based LDR control and PIR-triggered dimming balance energy savings (30–55 %) with public safety, while telemetry enables predictive maintenance. Simulations confirm resilience up to 75 % node failures, making the design a scalable and reliable option for urban deployments.

References

1. Attia, H.A., Omar, A., Takruri, M.: Design of decentralized street led light dimming system. In: 2016 5th international conference on electronic devices, systems and applications (ICEDSA), pp. 1–4. IEEE (2016)
2. Chowdhury, A.T., Sultana, J., Sourav, M.S.U.: Iot-based efficient streetlight controlling, monitoring and real-time error detection system in major bangladeshi cities. arXiv preprint arXiv:2211.00074 (2022)
3. Di Pippo, V., et al.: Comprehensive assessment of context-adaptive street lighting: Technical aspects and sustainability. Sensors **24**(18), 5942 (2024)
4. Dizon, E., Pranggono, B.: Smart streetlights in smart city: A case study of sheffield. Journal of Ambient Intelligence and Humanized Computing **13**(4), 2045–2060 (2022)
5. Dymora, P., Mazurek, M., Smalara, K.: Modeling and fault tolerance analysis of zigbee protocol in iot networks. Energies **14**(24), 8264 (2021)
6. Escolar, S., Carretero, J., Marinescu, M.C., Chessa, S.: Estimating energy savings in smart street lighting by using an adaptive control system. International Journal of Distributed Sensor Networks **10**(5), 971587 (2014)
7. Garg, S., Ahuja, S., Randhawa, S.: Real time adaptive street lighting system. In: International Conference on Computational Intelligence, Security and Internet of Things, pp. 223–239. Springer (2019)
8. Gheorghiu, R.A., Minea, M., Iordache, V., Buretea, L.D.: Field testing of nrf24 communications as a support for smart city applications. In: 2023 46th International Conference on Telecommunications and Signal Processing (TSP), pp. 74–77. IEEE (2023)
9. Gupta, A., Gupta, S.: Design of automatic intensity varying smart street lighting system. In: IOP Conference Series: Materials Science and Engineering, vol. 225, p. 012126. IOP Publishing (2017)
10. Hudda, S., Haribabu, K.: A review on wsn-based resource-constrained smart iot systems. Discover Internet of Things **5**(1), 56 (2025)
11. Jabbar, W.A., Keat, T.K., Dael, F.A., Hong, L.C., Yussof, Y.F.M., Nasir, A.: Optimising urban lighting efficiency with iot and lorawan integration in smart street lighting systems. Discover Internet of Things **5**(1), 64 (2025)
12. Mahoor, M.: State-of-the-art in smart streetlight systems: a review. IET Smart Cities **2**(1), 1–12 (2020)
13. Ramos, W., et al.: Smart streetlight system using mobile applications: secured fault detection and diagnosis with optimal powers. Wireless Networks (2023)
14. Villa, D., et al.: Bluetooth low energy mesh network for power-limited, robust and reliable iot services. arXiv preprint arXiv:2208.04050 (2022)