# Fault-Tolerant Networking Architecture for Smart Street Lighting Systems

Saranya Mukherjee[1] and Sankar Mukherjee[2]

[1] University of Calcutta, Kolkata, India
saranyamukherjee0403@gmail.com,
[2] Bengal College of Engineering and Technology, Durgapur, India
sanmukher@gmail.com,

**Abstract.** This paper presents low-cost, fault-tolerant, street lighting systems designed for scalable deployments. It focuses on 2.4GHz peer-to-peer mesh networks, automatic peer discovery, centralized route optimization, heartbeat-driven fault monitoring, and self-healing. Each node houses a STM32F4 microcontroller, NRF24L01 transceiver, voltage, current, temperature, Light Dependent Resistor(LDR), Passive Infrared(PIR) sensors, enabling adaptive control. It employs hysteresis-based robust ambient switching, with distributed voting mechanisms to minimize faulty LDR readings. Motion-triggered dimming lowers energy consumption also intelligent logic prioritizes safety over aggressive power savings. Heartbeat messages provide real-time node health, enabling failure detection, traffic rerouting, and fault classification for schedule maintenance. Simulation-based studies show that the system can sustain up-to 75% random node failures without significant network partitioning and achieve up-to 35% energy savings over traditional always-on streetlights. Unlike conventional ZigBee or LoRaWAN-based star networks, the proposed design balances fault tolerance, reliability, and deployment cost, making it suitable for smart and intelligent city lighting infrastructure.

**Keywords:** IOT, Street Lighting, Fault Tolerance, Mesh Network, Energy Efficiency

## 1 INTRODUCTION

Rapid growth of Internet of Things (IoT) has enabled seamless, connected, automated, and intelligent city-scale systems. Street lighting is one of the most critical component of such cities in terms of energy usage and basic safety; it needs to undergo significant changes to turn into adaptive and networked systems capable of real-time monitoring and control. By effectively using sensors, communication modules, and network connectivity, smart street lighting has high potential for reducing energy wastage, increasing operational efficiency, and improving public safety.

Currently deployed legacy systems in most urban and sub-urban regions, running on manual operation or timer based control at best, suffer from excessive energy consumption, have no form of fault detection, which aid in inefficient maintenance notifications and processes. Lamp failures staying unnoticed for weeks, lead not only to both energy losses, but also safety risks. In city-wide, large-scale deployments, unified control for thousands of nodes adds network congestion, single points of failure, and significant operational overhead as major issues.

When scaling IoT-enabled street lighting to thousands of nodes, networking challenges become critical. Most existing implementations rely on Wi-Fi, ZigBee, or LoRaWAN-based star or mesh topologies, which not only increase infrastructure costs, but also limit scalability due to restricted communication ranges and available 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, capable of sustaining upto 75% random node failures without network partitioning, and upto 35% energy savings through adaptive dimming. The motivation for choosing NRF modules is driven by their low cost, easy availablity, and ease of development compared to proprietary communication solutions. The proposed network forms automatically through peer discovery, creating self-healing meshs where each node can act, both as a sensor and a relay node. A minimal number of Central Nodes, equipped with internet connectivity, serve as the gateway for cloud integration, while all other nodes can operate autonomously in case of internet failure.

The key contributions of this paper are:

- Design of lightweight, low-cost 2.4 GHz mesh network for smart street lighting using NRF modules.
- Automatic peer discovery and topology formation, enabling scalability without extensive manual configuration.
- Redundant communication paths and fallback mechanisms to maximize network uptime and minimize service disruption in case of node/link failures. (Upto 75% random node failures without network partitioning)
- Separation of hardware architecture between light bulb nodes and central nodes, optimizing both cost and computational requirements.
- Evaluation of the proposed network in terms of fault recovery, scalability, and energy efficiency(Upto 35% energy savings) for large-scale urban deployments.

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], [13] 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 [8] 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 [6], 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 [13], 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 [9], offering redundancy, low cost, and STM32 integration for scalable, adaptive control [9].

Recent literature [12], [10] highlights multi-agent [1] and fuzzy-logic control with fault awareness, redundancy, and resilience for WSN/IoT in harsh environments. A Sheffield case study [5] using Telensa centralized control achieved 65% savings but lacked mesh self-organization.

Overall, most work emphasizes energy savings [7] 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, automatic topology formation, and redundancy [3].

## 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 Microcontroller Unit(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 ambient 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.

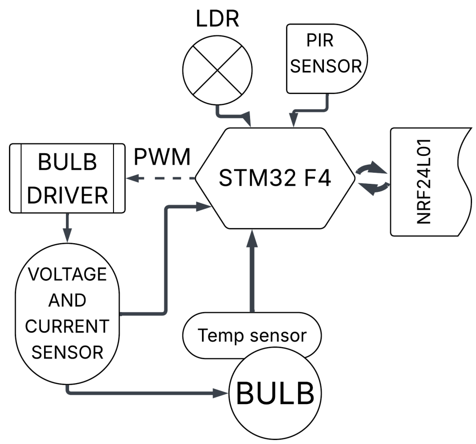



Fig. 1: Block diagram of the proposed node

### 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 gathers sensor data and status from all of its associated nodes, forwards them to remote servers, and sends back configuration changes, firmware updates, or control commands, or anything else that might need central communication. Even during internet outages, the Central Node sustains the mesh topology, enabling local mesh based decision control and preserving fault-tolerant operation without cloud support.

## 4 SYSTEM DESIGN AND WORKFLOW

This smart street lighting system uses simple, robust algorithms for dimming control, which place reliability and safety at the top; it also avoids complex continuous dimming to minimize hardware costs. 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 is based on a hysteresis curve (Fig. 2) with thresholds $T_{ON}$ and $T_{OFF}$ ($T_{ON} < T_{OFF}$; e.g., 0.3 and 0.7 respectively, normalized with respect to average daylight), preventing race conditions due to noise or transient lights. To utilize the mesh and improove reliability, nodes congregate LDR values with its neighbors and apply a local voting algorithm to remove outliers before switching.

After switching to the ON state, PIR sensors monitor movement. If no motion is detected for certain periods of time, the node dims, assuming that no traffic is coming;

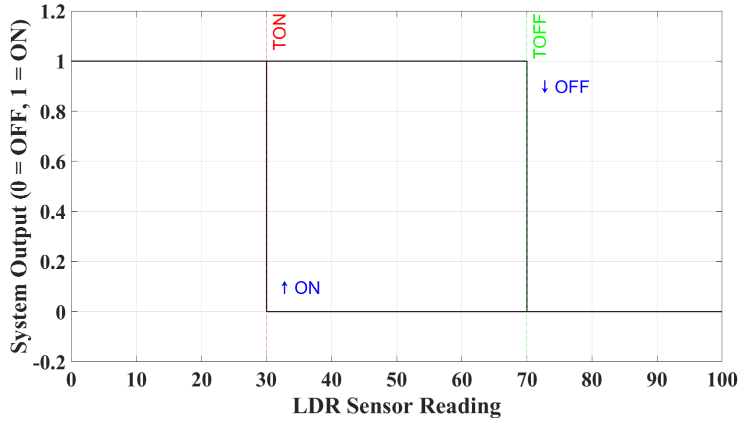



Fig. 2: Hysteresis Curve for Ambient Light Switching

any motion immediately restores full brightness. No voting is used here, prioritizing safety over maximum energy savings.

Fault detection is based on periodic heartbeat messages from each node, which contains voltage, current, temperature, LDR, and PIR data. Consistent voltage/current outliers indicate power or LED driver issues; abnormal temperature rises suggest LED degradation or driver thermal run-away tendencies. Multiple missing heartbeats points to node/link failure, triggering rerouting around the node until it recovers(temporary faults) or is replaced(permanent faults). The Central Node flags sensors as defective if their readings deviate persistently from neighboring nodes, logging them for scheduled maintenance.

# 5 NETWORK ARCHITECTURE

The proposed system shows a peer-to-peer mesh networking model using the 2.4 GHz band, implemented by NRF24L01 modules. The design aims to minimize deployment costs while ensuring redundancy, self-healing, and low operational cost, making it extremely scalable in both dense urban and sparse sub-urban environments.

## 5.1 Peer-to-Peer Mesh Discovery

Each node in the network has a NRF24 module, which operates by default, in receive mode to minimize energy consumption. Upon initialization and/or due to periodic network maintenance cycles, each node transmits a discovery message (HELLO packet). Neighboring nodes within RF range respond with their own unique identifiers (Node ID), link quality(calculated from RSSI), and hop count to the original sender.

Through this discovery process, the entire network graph is built, with each node aware of its neighbors and their capabilities. To ensure network robustness, it is recommended to space nodes such that each node has at least two neighbours in range(as found in section 6). This thumb rule increases network resilience against single-node failures and maximises redundant paths.

### 5.2 Central Node Routing & Optimization

Here the central node act as server thus central node are mentioned as server in this algorithm. The proposed algorithm 1 establishes a server-centric routing mechanism in a wireless network using Route Request (RREQ) and Route Reply (RREP) messages. The process begins with the server node broadcasting an RREQ packet that contains a unique message ID, a hop count initialized to zero, and identifies both the origin and sender as the server. As intermediate nodes receive the RREQ, each node selects the message with the lowest hop count among those with the same message ID. It then updates its routing table by setting the $S_{id}$(the next hop toward the server) to the sender ID of the selected RREQ. For all RREQ packet, hop count is incremented, the sender ID is updated to the current node, and the modified RREQ is rebroadcast. If the node has not already responded to this RREQ ID, it also sends an RREP back to the recorded $S_{id}$ . When nodes receive an RREP for the first time corresponding to a given RREQ ID, they append their ID to the forwarder list and forward the RREP to their $S_{id}$. Once the server receives the RREP, it reads the forwarder list and updates its routing table to store reverse paths to the origin nodes, setting the next hop for each listed node as the one from which the RREP was received. This mechanism ensures the establishment of shortest-path, bidirectional routes between the server and all participating nodes in a distributed, efficient manner.

### 5.3 Node Operation & Data Flow

Each NRF module remains in listening mode by default. When a node needs to forward its own data or relay a packet:

- It temporarily switches to transmission mode, forwards the data to the next hop as specified in its routing table, and then reverts to receive mode.
- Every node periodically transmits heartbeat messages; the message contains:
  - Node ID
  - Voltage, current, and temperature sensor readings
  - Ambient light and PIR sensor states
- The Central Node congregates these heartbeats to monitor:
  - Node health
  - Network condition

### 5.4 Fault Detection & Network Self-Healing

The Central Node classifies faults based on the received heartbeats:

- Temporary Faults
  - Caused by short lived issues (e.g., power cuts or RF interference).

  - When the failed node/link recovers, it automatically rejoins the network by broadcasting a HELLO packet, triggering local re-discovery and reintegration into the network.
- Permanent Faults, which can be put into two major groups
  - Network interface failure: Only the NRF module fails, but the main bulb can still continue operating as a standalone smart bulb, switching on/off based on local LDR and PIR readings.
  - Total node failure: Either the MCU along with or without the network interface fails or the MCU detects critical hardware faults (e.g., power supply or LED driver issues), requiring manual inspection and replacement.

When a heartbeat timeout occurs, the Central Node assumes the link to have failed and triggers rerouting:

- The central routing table is updated to exclude the faulty node.
- Neighboring nodes dynamically relay data through alternative paths, ensuring 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 $hop\_count \leftarrow 0$, broadcast $RREQ$ with $(origin, sender\_id) \leftarrow S$
**for** node $N_i$ receiving $RREQ$ **do**
    **if** first $msg\_id$ or smaller $hop\_count$ **then**
        $S\_id \leftarrow RREQ.sender\_id$, update $routing\_table[\text{Server}] \leftarrow S\_id$
    **end if**
    $RREQ.hop\_count \leftarrow RREQ.hop\_count + 1$, $RREQ.sender\_id \leftarrow N_i$
    Rebroadcast $RREQ$
    **if** $RREQ$ not yet answered **then**
        Send $RREP$ to $S\_id$ with $(origin, msg\_id)$
    **end if**
**end for**
**for** node receiving first $RREP$ for each ($msg\_id$,RREP sender) **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**

### 5.5 Network Scalability Considerations

The proposed NRF-based mesh architecture is inherently scalable due to its distributed peer discovery and routing. This section formally analyzes the scalability of the proposed low-cost, fault-tolerant smart street lighting system, which employs a 2.4 GHz

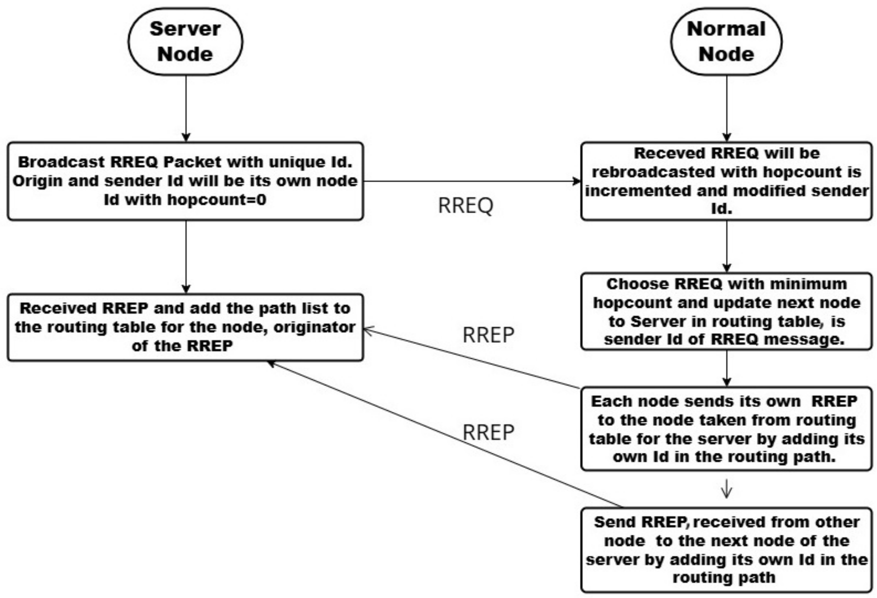



Fig. 3: Flowchart of Server routing

NRF-based peer-to-peer mesh network. Scalability is assessed through key performance indicators (KPIs) critical for dense urban deployments.

Scalability in dense mesh topologies is constrained by network capacity and hop count. The centralized architecture introduces dependency on the Central Node (CN) for control functions. We analyze the following KPIs as functions of the number of nodes ($N$):

- **Latency ($\mathcal{L}$):** The end-to-end latency for a command propagating over $H$ hops is:

$$\mathcal{L} \approx \mathcal{L}_{\text{CN}} + \sum_{i=1}^{H} (\delta_{q,i} + \delta_{p,i} + \delta_{t,i})$$

where $\delta_q$, $\delta_p$, and $\delta_t$ are per-hop queuing, processing, and transmission delays, respectively, and $\mathcal{L}_{\text{CN}}$ is the CN processing latency. In a centralized system, if the CN processes or logs responses from all $N$ nodes, the CN processing component grows with $N$:

$$\mathcal{L}_{\text{CN}} \propto O(N)$$

This factor imposes a critical bottleneck, increasing the worst-case latency and challenging the low latency requirement for motion-triggered dimming. These however are overcome by local control at each node and careful placement of CNs and limiting CN interactions to periodic health monitoring and configuration updates.

- **Throughput ($\mathcal{T}$):** The per-node throughput $\mathcal{T}_{\text{node}}$ degrades significantly due to interference and link-sharing. Following scaling law models for a network with $N$ nodes, the achievable per-node throughput scales sub-linearly [11, 15]:

$$\mathcal{T}_{\text{node}} \propto \frac{1}{\sqrt{N}}$$

  This scaling confirms that the bandwidth available for real-time node health status and remote control messages is inversely proportional to the square root of the number of nodes, constraining the system's data rate as it scales.

The system's energy performance is governed by two distinct components: the energy saved from light dimming and the energy overhead required for communication. The system's net efficiency depends on the balance between these two factors.

- **Energy Savings ($\mathcal{S}$) from LED Dimming:** The targeted **30 − 55**% energy savings is achieved by modulating the light output. This is quantified by the average LED Duty Cycle ($\mathcal{D}_{\text{LED, avg}}$), which is derived from the hysteresis-based ambient detection (Section 4) and motion-triggered dimming. If $P_{\max}$ is the maximum power draw of the streetlight, the total energy consumed by the LED over a time period $T$ is $E_{\text{LED}} = P_{\max} \cdot \mathcal{D}_{\text{LED, avg}} \cdot T$. The long-term energy savings ($\mathcal{S}$) achieved by the control algorithm are directly related to this average duty cycle:

$$\mathcal{S} = 1 - \mathcal{D}_{\text{LED, avg}}$$

  where $\mathcal{D}_{\text{LED, avg}}$ is the time-averaged light output ratio, considering the entire operational cycle (i.e., when the hysteresis-based ambient light detection has switched the light ON). It determines the total energy consumption relative to full brightness.

$$\mathcal{D}_{\text{LED, avg}} \approx D_{\text{base}} + \alpha \cdot (1 - D_{\text{base}})$$

  Here, $D_{\text{base}}$ is the baseline duty cycle considering no motion events, and $\alpha$ is the motion activity ratio, denoting the fraction of time motion is detected during the night.
- **Communication Energy Overhead ($E_{\text{comm}}$):** The energy consumed by the communication module (NRF24L01 transceiver and STM32F4 microcontroller) acts as an overhead. This consumption is determined by the radio's Activity Cycle ($\mathcal{A}_{\text{radio}}$), which represents the fraction of time the radio is in an active state (transmitting or receiving). The communication energy consumed over time $T$ is:

$$E_{\text{comm}} = T \cdot [\mathcal{A}_{\text{radio}} \cdot P_{\text{active}} + (1 - \mathcal{A}_{\text{radio}}) \cdot P_{\text{sleep}}]$$

  For heartbeat-driven fault monitoring, $\mathcal{A}_{\text{radio}}$ is primarily a function of the transmission time ($\tau_{\text{comm}}$) and the heartbeat interval ($\Delta t_{\text{heartbeat}}$):

$$\mathcal{A}_{\text{radio}} \propto \frac{\tau_{\text{comm}}}{\Delta t_{\text{heartbeat}}}$$

  Scalability requires low $E_{\text{comm}}$, imposing a large $\Delta t_{\text{heartbeat}}$. This creates a fundamental trade-off between energy conservation (requiring a low $\mathcal{A}_{\text{radio}}$) and the speed of fault detection (requiring a short $\Delta t_{\text{heartbeat}}$).

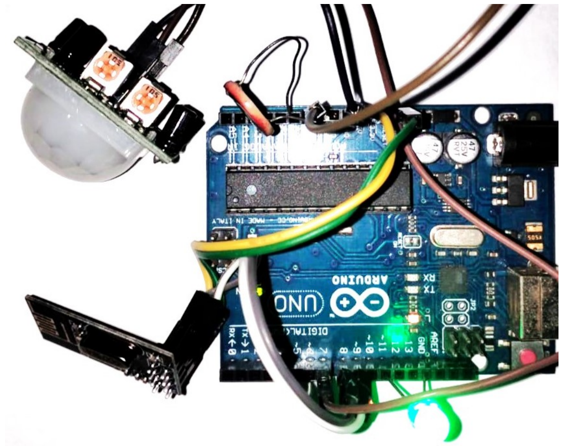



Fig. 4: Hardware prototype of the proposed street light node

Network convergence time ($T_{\text{conv}}$) measures the system's self-healing speed in establishing a new stable topology following a fault.

- **Components:** $T_{\text{conv}}$ is the sum of fault detection time ($T_{\text{detect}}$) and route repair time ($T_{\text{repair}}$):
$$T_{\text{conv}} = T_{\text{detect}} + T_{\text{repair}}$$
- **Scalability:** $T_{\text{detect}} \approx \Delta t_{\text{heartbeat}}$. $T_{\text{repair}}$ is dominated by the computational complexity of the Central Node's centralized route optimization algorithm. For a network graph $G = (N, E)$, the minimum time complexity for route recalculation is at least [16]:
$$T_{\text{repair}} \propto O(|E| + |N| \log |N|)$$
Since the number of edges $|E|$ grows faster than linearly with $N$ in a mesh, $T_{\text{repair}}$ grows super-linearly with $N$. This implies that $T_{\text{conv}}$ increases rapidly as $N$ scales, posing a critical limit to how large the network can be while retaining the ability to quickly recover from up to 25% random node failures. Again this turns out to be a optimization problem at the central node, which can be solved by deploying multiple central nodes to handle sub-regions of the network.

## 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 5.

| System / Study | Connected Until | Low Partitioning | Severe Partitioning |
|---|---|---|---|
| **Proposed System** | ~ 75% failure | ~ 85% failure | ~ 95% failure |
| NRF-based testbed [17] | ~ 60% failure | ~ 70% failure | ~ 80% failure |
| ZigBee cluster [14] | ~ 50% failure | ~ 60% failure | ~ 70% failure |
| IEEE 802.15.4 mesh [4] | ~ 55% failure | ~ 65% failure | ~ 75% failure |
| BLE mesh [18] | ~ 65% failure | ~ 75% failure | ~ 85% failure |

Table 1: Comparative Analysis of Mesh Connectivity Resilience

**Case Study 1- Network Reliability & Self-Healing**: A small sub-urban street light layout (Fig. 5a), with average inter-node distance of 15 m, ensuring >= 2 hop connectivity. Network Parameters:

– Total Nodes: 52
– Central Node with internet connectivity: 1
– Average distance between nodes: 15 m
– Communication range per node > 30 m
– Relatively flat and uniform topology ensuring near line of sight between nodes.
– Redundant 2-hop connectivity ensured
– Initial routing tables computed by Central Node

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. [3]

Results: A python based discrete event simulator was developed to model the NRF-based mesh network, incorporating probability based realistic link qualities, interference, and node failures. 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. 5b).

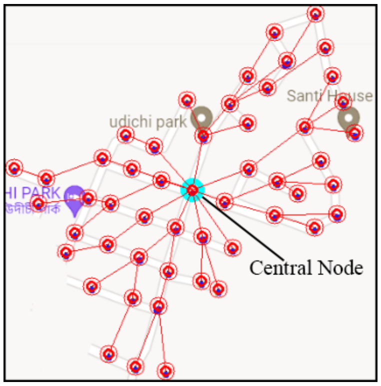
**Case Study 2- Fault Tolerance Threshold**: Same base node topology.

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.

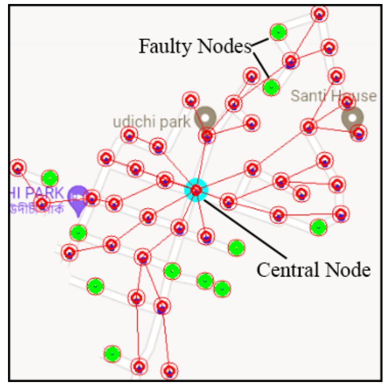
Results: With redundant 2-hop connectivity, the network remained fully connected until ~ 75% node failure. Partial fragmentation began around ~ 85% node failure, with isolated clusters appearing on network edges. (Fig. 5c) Beyond ~ 95% node failure, the network partitioned significantly, requiring manual repair or mobile temporary relays to restore full coverage(Fig. 5d).

**Case Study 3- Energy Savings vs. Reliability Trade-off**: Three lighting modes are defined (Section 4) OFF ~ $0W$, DIMMED (30% brightness; ~ $12W$; $D_{\text{base}}$ in Section

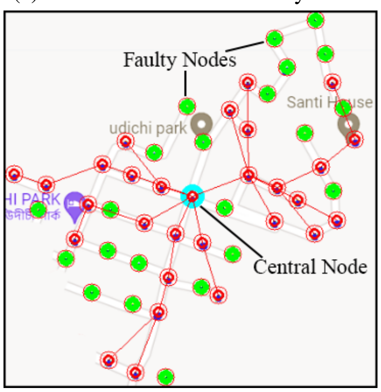
[3] Typical failure rate of Street lights in urban areas is around 1-2% per year.



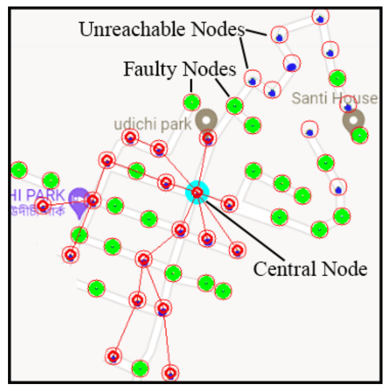

(a) Full network with no faulty nodes




(b) Network condition with 20% faulty nodes




(c) Network condition with 85% faulty nodes




(d) Network condition with 95% faulty nodes

Fig. 5: A sub-urban network demonstrating fault tolerance

5.5), and ON (100% brightness; $\sim 40W$; $P_{\max}$ in Section 5.5). [4] 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. ($\alpha$ = 0.2 and 0.5 respectively in Section 5.5)

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 biasing safety and reliability.

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

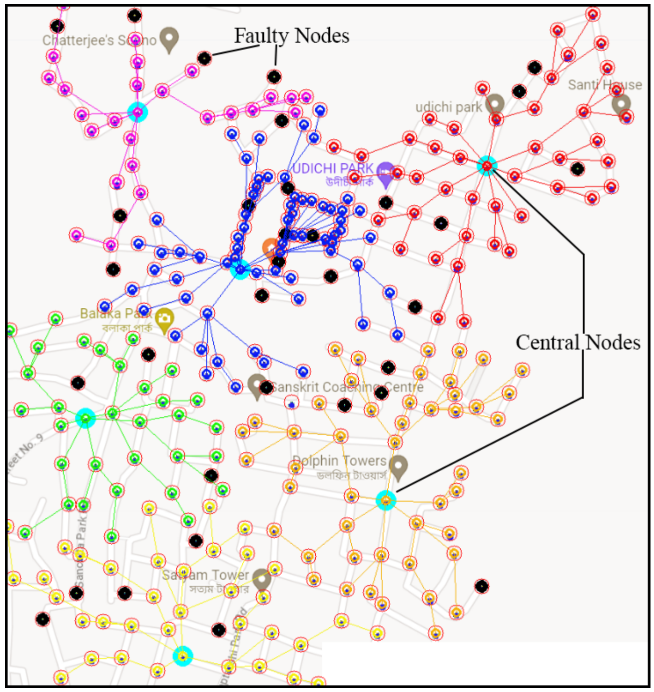



Fig. 6: A large sub-urban network combination demonstrating fault tolerance

**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. Network Parameters:

- Total Nodes: 40(yellow) + 33(green) + 52(orange) + 52(red) + 31(pink) + 71(blue) = 279.
- Central Node with internet connectivity: 6
- Average distance between nodes: 13 m
- Communication range per node > 30 m
- Relatively flat and uniform topology ensuring near line of sight between nodes.
- Redundant 2-hop connectivity ensured
- Initial routing tables computed by internet server

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. 6).

| 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 [4] | 0.17 | 65% |
| Motion Sensing [18] | 0.19 | 60% |
| Scheduled Dimming [14] | 0.22 | 54% |
| Local Control [17] | 0.24 | 50% |

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

## 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.

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