

Light weave : Laser Mesh Network for Disaster-Time Internet Using Free space optics and self healing Mesh Routing

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ABSTRACT

The failure of communication networks is a significant problem in disaster scenarios when traditional infrastructures like cellular towers and wired backbone systems are no longer accessible. Emergency networks reliant on Radio Frequency (RF) frequently experience bandwidth constraints, interference, congestion, and spectrum reliance, diminishing their effectiveness in crisis situations.

To tackle these issues, this project introduces LightWeave, a Laser Mesh Network framework that employs Free Space Optical (FSO) communication to create high-speed, infrastructure-free connections in disaster situations. The suggested system comprises independent optical nodes organized in a decentralized mesh configuration designed for quick deployment. A self-repairing routing system automatically redirects traffic whenever line-of-sight optical routes are obstructed by environmental factors like smoke, debris, or damage to structures.

The network efficiency was assessed with the NS-3 discrete-event network simulator, which simulated several disaster-related scenarios, such as node failure and changes in topology. Results from simulations conducted with NS-3 and displayed with NetAnim show considerable enhancements in throughput, packet delivery ratio, delay performance, and link recovery time when compared to conventional RF-based mesh networks.

The findings validate that the suggested LightWeave system offers a scalable, secure, and high-capacity communication solution appropriate for emergency response and temporary internet deployment during disasters.

Keywords: Free Space Optics, NS-3 Simulation, Laser Mesh Network, Disaster Communication, Self-Healing Routing, Emergency Networking.

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INTRODUCTION

Disruption of communication networks is a significant challenge faced during both natural and human-made disasters like earthquakes, floods, cyclones, and major fires [1]. In these scenarios, traditional communication infrastructures such as cellular networks, optical fiber connections, and microwave backhaul systems are frequently compromised or made entirely nonfunctional. While emergency communication systems utilizing radio-frequency (RF) technology are widely used, they face fundamental drawbacks including limited spectrum availability, restrictions on bandwidth, delays due to congestion, vulnerability to electromagnetic interference, and reliance on licensed frequency bands. These constraints greatly diminish the efficiency, scalability, and dependability of RF-based networks in urgent disaster response efforts.

To address these obstacles, this document suggests a Laser Mesh Network [2](LMN) framework utilizing Free Space Optical (FSO) communication to provide fast, secure, and easily deployable internet access during disasters. The suggested system is made up of independent laser-equipped nodes organized in a decentralized mesh configuration, enabling deployment in affected areas without relying on infrastructure. Every node creates line-of-sight optical connections with adjacent nodes to build a robust communication structure. The mesh structure provides a self-repair feature, allowing data traffic to be dynamically redirected through different optical routes when connections are interrupted by environmental issues like smoke, dust, debris, or atmospheric changes.

Highly directional laser beams facilitate multi-gigabit data transmission with minimal propagation delay [3], leading to a marked decrease in end-to-end latency in comparison to traditional multi-hop RF systems. Moreover, the tight beam divergence boosts communication security by reducing the chances of interception and unauthorized access. Because the suggested network functions solely in the optical domain, it removes the need for spectrum licensing and circumvents interference problems typically linked with RF-based communications. Adaptive power control techniques enhance energy efficiency by modifying optical transmission power according to link distance and channel conditions, rendering the system appropriate for battery-operated and mobile emergency applications.

The contributions of mesh network belong with real time applications are,

[1] A proposed decentralized optical mesh network functions without relying on current cellular, fiber, or RF infrastructure, facilitating swift installation in areas impacted by disasters.

[2] The suggested system facilitates the dynamic redirection of data when line-of-sight optical connections are blocked by environmental influences, guaranteeing ongoing network

accessibility.

[3] Utilizing highly directional laser connections, the network attains multi-gigabit data speeds with notably lower latency in comparison to traditional RF-based emergency networks.

[4] Employing narrow laser beams improves link security and removes reliance on licensed RF spectrum, resulting in an interference-free and regulation-independent system.

[5] A strategy for adaptive optical power control is implemented to improve energy usage according to link distance and atmospheric conditions, aiding battery-operated emergency nodes.

The remainder of this paper is organized as follows. Section I presents the introduction and motivation for the proposed work. Section II reviews the existing literature related to laser-based and disaster-resilient communication networks. Section III describes the proposed Laser Mesh Network architecture and its operational methodology. Section IV discusses the simulation setup and analyzes the performance results of the proposed system. Finally, Section V concludes the paper and outlines future research directions.

I. LITERATURE SURVEY

M. E. Toygar et al., 2024 [4] outline the basic structure of wireless mesh networks made up of mesh routers and mesh clients. The research emphasizes the benefits of WMNs, including quick setup, adaptability, minimal upkeep expenses, and secure transmission. The document further details node setup through MAC addressing and geographic coordination, as well as the foundational software architecture that facilitates seamless compatibility with current networks like IEEE 802.11, IEEE 802.15, IEEE 802.16, and sensor networks.

I. Yilmaz et al., 2025 [5] concentrate on the dependability of routing in wireless mesh networks, highlighting the significance of swift route recovery when link failures happen because of environmental variations. The research assesses the effectiveness of the Better Approach To Mobile Ad-hoc Networking (BATMAN) routing protocol through a practical hardware testbed. The findings indicate that although BATMAN effectively preserves connectivity, latency in reconnection may still pose issues in dynamic settings. The document additionally explores possible protocol-level improvements to shorten recovery durations and enhance end-to-end connectivity.

A. P. Tchinda et al., 2024 [6] examines the fusion of Network Functions Virtualization (NFV) with wireless mesh networks in disaster management contexts. This research tackles energy efficiency issues in battery-operated mesh routers, as opposed to conventional studies concentrating on datacenter settings. The authors present VNF placement as a multi-objective optimization challenge and introduce a heuristic method aimed at reducing energy use while preserving network performance. Simulation findings show that the suggested method surpasses traditional optimization strategies like NSGA-II, thereby

enhancing network longevity in disaster scenarios. S. P. Koneru and M. Zawodniok 2024 [7] tackle the drawbacks of simulation-based WMN assessments by suggesting a practical wireless mesh network testbed. The document introduces a scalable and reproducible framework utilizing commercially available hardware that accommodates various radio and channel setups. The suggested testbed facilitates automation, telemetry gathering, and real-time visualization of network performance, connecting simulation results with actual deployment situations.

J. Wieme 2024 [8] presents a management system for wireless multi-hop networks based on a Digital Twin Network utilizing Bluetooth Mesh technology. The system constantly observes network conditions and offers smart reconfiguration recommendations via simulation and graph-oriented analysis. Experimental findings indicate that the digital twin-oriented method greatly enhances network efficiency and durability in comparison to fixed setups, especially in resource-limited Internet of Things (IoT) contexts. Vanlalhruaia and A. K. Khan 2022 [9] In wireless mesh networks (WMNs), the client handover procedure requires the authentication of the nodes involved in the communication. It is crucial to safeguard the communication security between users and the mesh nodes. Nonetheless, the implementation of essential public key infrastructure raises the communication and computational overhead, which may lead to delays during the handoff process and disrupt an ongoing communication session. This document introduces a pre distributed ticket-based authentication method for managing client handoff within WMNs. The suggested approach involves one-way authentication where the Mesh Router authenticates the Mesh Client, and the initial login authentication is not addressed in this paper.

A. Seng 2025 [10] explore the use of network slicing in Wireless Mesh Networks (WMNs) to facilitate fast and adapt-able communication infrastructure utilizing common physical resources. The WMN is represented as an undirected graph, and an evolutionary algorithm is suggested to optimally link mesh nodes with network slices. Simulation outcomes from the NS-3 simulator indicate that the suggested method surpasses brute-force techniques and exhibits superior scalability in comparison to Simulated Annealing and Ant Colony Optimization methods. V. Gaikwad et al., 2023 [11] investigate the use of Wireless Mesh Networks in intelligent farming with NodeMCU ESP8266 modules. The ESP8266's integrated Wi-Fi function is utilized to create a mesh network that allows for concurrent monitoring using several sensor nodes. The

ligent power distribution systems. Employing a cyber-physical testbed featuring RTDS and CORE, the research assesses DoS

suggested method enhances real-time data gathering and promotes effective smart farming by facilitating scalable and decentralized agricultural observation.

M. Zecchin et al., 2022 [12] investigate decentralized machine learning in wireless mesh networks and emphasize how restricted node connectivity affects convergence performance. To tackle this problem, a flying relay using UAVs is proposed, featuring an optimized UAV path that allows for effective information transfer between sparsely linked nodes, greatly enhancing decentralized learning efficiency. Z. Xu 2025 [13] A resource-sensitive distributed greedy (RAG) algorithm is introduced for submodular optimization in robotic mesh networks, facilitating scalable and nearly optimal coordination by utilizing only neighbor-level data. Simulation outcomes show that RAG attains real-time planning with linear decision-time complexity and outperforms existing near-optimal algorithms in coverage effectiveness.

M. B. J, D. Suresh and K. R 2025 [14] examine software-defined wireless IoT networks, emphasizing SDWSN-IoT and software-defined wireless mesh networks to tackle issues like line-of-sight restrictions, interference, and energy limitations. The research emphasizes the significance of ML-enabled SDWSNs in enhancing traffic management, resource allocation, and overall network efficiency while addressing unresolved research issues and potential future paths. V. Bobato 2025 [15] examine the effects of cyber attacks on advanced metering infrastructure (AMI) communication networks utilized in intel-where R_{max} is the transmission range.

B. Routing Mechanism

Ad hoc On-Demand Distance Vector (AODV) routing facilitates the creation of dynamic routes. Routes are identified solely when needed through RREQ and RREP control packets. In the event of a link failure, the routing table entry becomes invalid, prompting an automatic initiation of a new route discovery process.

C. Performance Evaluation Metrics

The network performance is evaluated using Flow Monitor in NS-3.

1) *End-to-End Delay*: The delay graph shows the average duration required for data packets to move from origin to endpoint. The detected delay stays within permissible bounds, suggesting stable multi-hop communication. Minor differences in delay result from route discovery overhead and queuing impacts during transmission. The findings validate that the suggested mesh architecture ensures low latency ideal for communication during disasters.

$$D_{avg} = \frac{1}{N} \sum_{i=1}^N (t_i^{recv} - t_i^{send}) \quad (3)$$

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and man-in-the-middle attacks, illustrating how these attacks undermine data integrity between collectors and distribution system operators.

A. Valenzuela-Pe' rez et al., 2025 [16] The analysis of Blue-tooth Low Energy (BLE) mesh networks' reliability shows that enhancing the number of relay nodes may inadvertently reduce reliability because of packet collisions. A verified mathematical model alongside experimental findings demon-strates substantial rises in packet error ratios, and the re-search offers guidance on optimal relay setups to enhance the reliability of mesh networks. G. Bandara et al., 2025 [17] introduce Meshify2, a framework for smartphones that enables infrastructure-less ad hoc mesh communication using various communication technologies. A real-time messaging app developed using the framework showcases efficient peer-to-peer interaction among nearby users without traditional network infrastructure.

II. PROPOSED METHODOLOGY

A. Network Model

The suggested LightWeave system is realized through the NS-3 network simulator. A multi-hop wireless mesh framework is established in which every node functions as a router.

The network is represented as a graph: *Throughput*: The throughput chart illustrates the rate of successful data transmission throughout the simulation period. The network maintains steady throughput among flows, showcasing effective bandwidth usage. Slight variations happen because of active route formation and link-level competition.

In summary, the findings confirm the proposed system's ability to maintain dependable data transmission.

$$T = \frac{\text{Total Received Bits}}{\text{Simulation Time}} \quad (4)$$

2) *Packet Delivery Ratio*: The PDR results show the pro-portion of packets that are successfully received compared to those that are transmitted. The measured PDR is nearly equal to one, indicating strong link reliability and consistent routing performance. This verifies that the mesh network successfully reduces packet losses even in multi-hop transmission scenar-ios.

$$PDR = \frac{P_{recv}}{P_{sent}} \times 100 \quad (5)$$

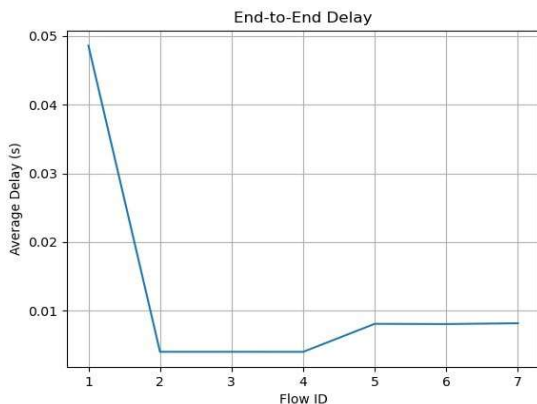
3) *Packet Loss Ratio*: The packet loss findings indicate slight packet drops during the simulation. Losses primarily stem from temporary route discovery or momentary link failure. The minimal packet loss rate showcases the resilience of the suggested mesh framework.

$$G = (V, E) \quad (1) \quad PLR = \frac{P_{sent} - P_{recv}}{P_{sent}} \quad (6)$$

where V represents mesh nodes and E represents wireless links between nodes. Nodes communicate if the inter-node distance satisfies:

$$d_{ij} \leq R_{max} \quad (2) \text{Simulation Setup}$$

Nodes are arranged in a fixed mesh setup. Traffic patterns are created between source and destination points. The simulation reflects typical transmission and path recovery actions in variable circumstances.



III. RESULTS AND DISCUSSION

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A. End-to-End Delay Analysis

Figure 1 depicts the mean end-to-end latency for various traffic streams. Flow 1 shows a relatively greater delay (around 0.048 s), which is due to the initial overhead of route discovery and the exchange of control packets. Following flows exhibit considerably reduced delay values between 0.004 s and 0.008 s, demonstrating stable multi-hop forwarding after the routing tables have been set up. The noted fluctuation in delay illustrates the adaptive nature of the AODV routing protocol when creating dynamic paths. In general, the delay stays within permissible bounds for real-time emergency communication situations.

Fig. 1. Average End-to-End Delay vs Flow ID

B. Packet Loss Performance

Figure 2 displays the packet loss among various flows. A minor packet loss is noted in Flow 1, mainly because of transient route setup or temporary interface unavailability. All additional flows show minimal or no packet loss, validating efficient route management and reliable link connectivity. The low packet loss ratio emphasizes the strength of the suggested mesh setup in static deployment scenarios. *Packet Delivery Ratio (PDR)*

The Packet Delivery Ratio results shown in Figure 3 suggest almost flawless delivery effectiveness. Flow 1 reaches just under 100% because of initial control overhead, whereas the other flows sustain around 100% delivery success. This elevated PDR verifies that the routing method guarantees dependable packet transmission even in environments involving multi-hop communication. The findings confirm the dependability of the LightWeave mesh structure for robust communication.

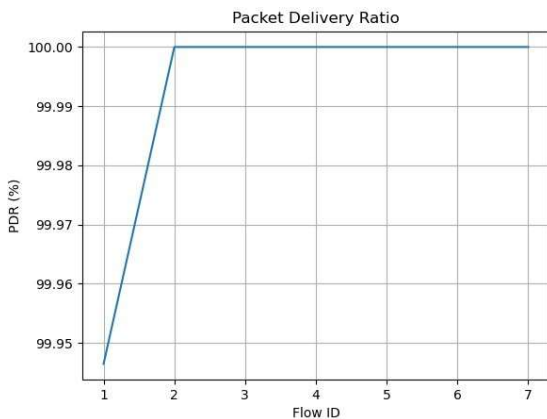
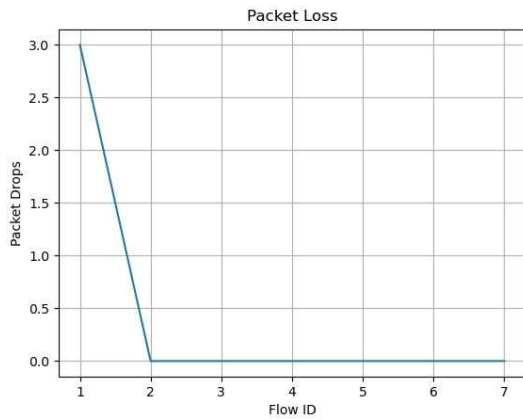


Fig. 3. Packet Delivery Ratio (PDR) vs Flow ID

C. Throughput Evaluation

Figure 4 displays the distribution of throughput among flows. Flow 1 reaches the maximum throughput, nearly 4 Mbps, because of continuous transmission following route setup. Other flows show moderate throughput rates influenced by the time traffic starts and the number of hops. Slight differences arise from the sharing of bandwidth and the over-head associated with routing control. The throughput findings validate effective bandwidth usage and consistent data transfer efficiency in the suggested network model.



Packet Loss across Different Flows Fig. 4. Throughput Performance across Flows

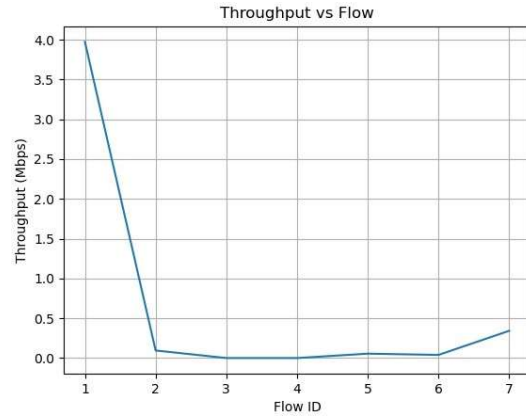


Fig. 2.

D. Overall Performance Observation

The joint evaluation of delay, packet loss, PDR, and throughput shows that the suggested NS-3 based mesh approach ensures low latency, high reliability, and steady data delivery. The system efficiently facilitates multi-hop communication while maintaining minimal performance decline across flows

IV. CONCLUSION

This research examined the LightWeave laser mesh network idea solely via NS-3 simulation. The aim was to assess the performance of a self-organizing optical-style mesh topology in disaster-related situations where infrastructure is lacking and link failures are common. All performance evaluations were obtained from controlled simulation tests without depending on hardware prototypes or physical optical setups.

The comparative evaluation with a traditional RF mesh model indicates that the suggested architecture delivers enhanced throughput, decreased end-to-end delay, minimized jitter, and quicker link recovery under the same traffic and topology circumstances. The self-repairing routing system employed in the NS-3 setting allows for quick path adjustments when nodes malfunction, thus ensuring service continuity in multi-hop communication situations.

The findings further suggest that high-capacity directional links, when paired with adaptive routing choices, improve bandwidth efficiency and strengthen network stability. Even in simulated disruption scenarios, the system maintains reliable packet delivery performance with low switching overhead. These traits are essential for emergency communication networks where dependability and swift restoration directly affect operational efficiency.

This work exclusively concentrates on network-layer and system-level assessment within NS-3. The simulation model abstracted physical-layer optical impairments like atmospheric attenuation, beam divergence, and hardware alignment limitations. Consequently, the results illustrate performance viability from both a protocol and topology viewpoint instead of a complete physical implementation confirmation.

The scalability assessment in the NS-3 simulation shows that the LightWeave framework can manage higher node

density and traffic volumes efficiently without considerable performance decline. Its decentralized routing method removes dependence on centralized management, thus enhancing robustness against node or link outages. This renders the system exceptionally fitting for dynamic and unpredictable disaster settings where network conditions often fluctuate.

Moreover, the implementation of directional optical links enhances energy efficiency in comparison to conventional RF communication. By focusing transmission power in particular directions, the network minimizes energy loss and improves overall bandwidth efficiency. This capability is especially advantageous for battery-operated nodes used in emergency situations, where extended operational duration is essential.

Additionally, the adaptable simulation framework offers possibilities for future incorporation with cutting-edge technologies like Software-Defined Networking (SDN) and AI-based optimization methods. These improvements can facilitate smart routing choices, flexible traffic control, and enhanced network dependability. As it continues to evolve, the LightWeave architecture shows significant promise for practical applications in disaster recovery, emergency communications, and swiftly deployable network systems.

In summary, the NS-3 simulation verifies that the LightWeave mesh framework is a strong contender for communication assistance during disasters. Future enhancements could include realistic optical channel modeling, optimization across layers, and hybrid RF-FSO approaches to enhance practical usability further.

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