JPTM PUBLICATIONS

Emerging Trends in Science & Technology Vol-I
eISBN : 978-81-999970-1-1 | ISBN : 978-81-999970-0-4
https://doi.org/10.67389/jptm.0626.etstv1.oa3

EchoMesh: A Decentralized Off-Grid LoRa Mesh Communication System for Emergency and Remote Connectivity

Aditya Tripathi[1], Durgesh Tiwari[2]

[1]*Maharishi School of Engineering and Technology, Maharishi University of Information Technology, Noida, Gautam Buddha Nagar, Uttar Pradesh 201304, India*

[1]aditya.tripathi.tech@gmail.com

[2]*Maharishi School of Engineering and Technology, Maharishi University of Information Technology, Noida, Gautam Buddha Nagar, Uttar Pradesh 201304, India*

[2]dtiwari.it@gmail.com

ARTICLE INFO

Article history:
Received 13 May 2026
Received in revised form 09 June 2026
Accepted 12 June 2026
Available online 12 July 2026

Keywords:
LoRa,
Mesh Networking,
Emergency Communication,
ESP32,
IoT,
BLE,
Embedded Systems

ABSTRACT

Modern communication systems rely heavily on centralized infrastructure like cellular towers, internet backbones, and cloud services. During natural disasters, military conflicts, remote expeditions, and large public events, these infrastructures often fail or become congested, causing communication breakdowns. This research introduces EchoMesh, a decentralized LoRa-based mesh communication system designed for off-grid communication using low-power embedded devices. EchoMesh enables text messaging, GPS sharing, emergency SOS signaling, and low-bitrate voice transmission without relying on cellular networks or internet connectivity. The system uses ESP32 microcontrollers, SX1276 LoRa transceivers, Bluetooth Low Energy (BLE), GPS modules, and open-source firmware architecture. It combines mesh routing, AES-128 encryption, and hybrid mobile integration through a Flutter-based smartphone app. This research evaluates how well long-range communication can work with low power consumption while keeping scalability and reliability in disaster-response and rural communication scenarios.

1. Introduction

Communication infrastructure forms the backbone of modern society. Most contemporary communication technologies depend on centralized cellular towers, internet gateways, and cloud servers. While these systems offer high-speed connectivity under normal circumstances, they become vulnerable during disasters and infrastructure failures. Earthquakes, floods, hurricanes, forest fires, and large events can overload or damage communication systems, leaving users disconnected at critical times.

Low-Power Wide Area Network (LPWAN) technologies like LoRa (Long Range) have emerged as promising alternatives for long-distance, low-power communication. LoRa technology allows for communication over several kilometers while using minimal energy, making it suitable for emergency communication systems, wireless sensor networks, and off-grid deployments.

EchoMesh is proposed as a decentralized mesh communication platform that combines LoRa radio communication, ESP32 embedded systems, BLE integration, and GPS-based location sharing. Unlike standard star-topology LoRaWAN systems that rely on gateways, EchoMesh uses a peer-to-peer mesh architecture where every node acts as a sender, receiver, and relay.

The system focuses on:

- Infrastructure-independent communication
- Long-range communication using LoRa
- Emergency SOS broadcasting
- GPS location sharing
- Secure encrypted communication
- Smartphone integration using BLE
- Low power consumption
- Community deployability

This research examines the architecture, implementation, performance characteristics, security considerations, and future potential of the EchoMesh system.

ISBN : 978-81-999970-0-4

2. Problem Statement

Traditional communication systems fail in situations where network infrastructure is missing or damaged. During disasters, communication congestion can prevent timely coordination between emergency responders and affected people. Rural and remote areas often suffer poor network coverage.

Several limitations exist in current communication technologies:

- Cellular communication needs operational towers.
- Internet-based messaging relies on centralized servers.
- Satellite communication systems are costly.
- Traditional walkie-talkies have limited range with no mesh routing.
- Existing mesh systems are often expensive or proprietary.

The inability to maintain communication during emergencies can delay rescue efforts, lower situational awareness, and increase risks to human life.

Therefore, there is a need for a low-cost, decentralized, energy-efficient communication platform that operates independently of traditional infrastructure.

3. Objectives of the Research

The primary objectives of this research are:

- To design a decentralized off-grid communication system using LoRa technology.
- To implement mesh-based message routing between nodes.
- To enable GPS-based location broadcasting.
- To integrate smartphone connectivity through BLE.
- To evaluate communication range and power efficiency.
- To provide secure communication using AES encryption.
- To develop a scalable architecture for disaster communication.
- To create an affordable communication solution for remote areas.

4. Literature Review

The Internet of Things (IoT) links computing devices, machines, and objects into a shared network, enabling data exchange without direct human involvement (Tiwari, 2026). This framework involves multiple layers, from sensors and data acquisition systems to edge computing and cloud environments, which collectively enable automation, improved efficiency, and smarter decision-making (Tiwari, 2026). As these ecosystems grow, maintaining system scalability and implementing robust security measures, such as strong encryption and regular updates, remains a critical challenge for sustainable development (Tiwari, 2026).

LoRa technology has received significant attention in recent years for its long-range communication abilities and low power needs (Augustin et al., 2016; Raza et al., 2017). Studies highlight its suitability for Internet of Things (IoT) applications and analyze limitations and scalability issues of LoRaWAN systems.

Mesh networking has been widely studied in wireless communication research (Akyildiz et al., 2005). Surveys have provided overviews of wireless mesh networks and their routing mechanisms. Research on LoRa mesh networking approaches has classified multi-hop communication methods.

Disaster communication systems have also seen extensive research (Ranaweera et al., 2018). Surveys of emergency communication technologies emphasize the need for decentralized communication frameworks.

Bluetooth Low Energy (BLE) integration has enabled smartphone-device interaction in embedded systems (Gomez et al., 2012). Studies have evaluated BLE's performance and power efficiency in wireless systems.

Security in wireless sensor networks continues to be a significant challenge (Roman et al., 2013; Perrig et al., 2002). Security protocols for sensor networks and discussions on IoT security and privacy issues are part of ongoing research.

Recent research has addressed these challenges through multi-layer clustering security protocols (Gupta & Kumar, 2022b) and the implementation of lightweight cryptography specifically designed for resource-constrained IoT devices (Gupta & Kumar, 2019). Studies have further introduced lightweight hash functions and pseudo-random number generators, such as DeeR-Hash and DeeR-Gen, to enhance

security within Industry 4.0 environments (Gupta & Kumar, 2023a, 2023b). Additionally, specialized frameworks have been proposed for managing smart healthcare services in IoT (Gupta & Kumar, 2022a), while broader reviews have identified key networking technologies, security threats, and potential countermeasures in IoT (Gupta & Kumar, 2020).
The existing literature confirms that LoRa mesh communication combined with embedded IoT devices can offer a practical solution for decentralized emergency communication.

5. System Architecture

5.1 Overview

EchoMesh consists of multiple handheld LoRa nodes that can form a self-healing mesh network. Each node includes:

- ESP32 microcontroller
- SX1276 LoRa transceiver
- GPS module
- OLED display
- BLE interface
- Rechargeable Li-ion battery
- Embedded firmware

The system supports:

- Text messaging
- GPS beaconing
- SOS transmission
- Private encrypted channels
- Multi-hop message relaying
- Smartphone companion application

5.2 Hardware Components

5.2.1 ESP32 Microcontroller

The ESP32 acts as the main processing unit. It offers dual-core processing, integrated BLE/Wi-Fi, low-power modes, and sufficient capability for routing and encryption.

5.2.2 SX1276 LoRa Module

The SX1276 transceiver allows for long-range communication using Chirp Spread Spectrum modulation. The module supports various ISM frequency bands.

5.2.3 GPS Module

The NEO-M8N GPS module provides latitude, longitude, altitude, and satellite information for location sharing and emergency tracking.

5.2.4 OLED Display

The OLED display provides a low-power interface for viewing messages, battery status, and node information.

5.2.5 BLE Connectivity

The Bluetooth Low Energy (BLE) module allows the EchoMesh device to connect wirelessly to smartphones, enabling users to send messages and view data through a simple app interface.

6. Software Architecture

The software architecture consists of three layers as shown in Figure 1:

- Embedded firmware layer
- Communication layer
- Mobile application layer

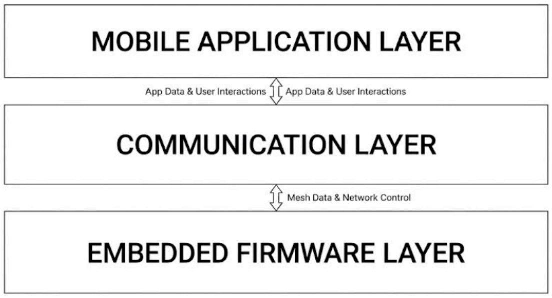

Figure 1: Software Architecture of Echo Mesh

6.1 Embedded Firmware

The firmware is developed using the Arduino framework and PlatformIO environment. Key firmware modules include:

- **Radio management:** Controls LoRa signal transmission and reception to ensure reliable data exchange between devices.
- **Mesh routing:** Determines the optimal path for data to travel across multiple devices to reach its final destination.
- **GPS parsing:** Decodes raw location data from the GPS module into readable coordinates for the user.

ISBN : 978-81-999970-0-4

- **Display management:** Updates the device screen to show battery levels, incoming messages, and current node status.
- **BLE communication:** Facilitates wireless data transfer between the LoRa hardware and a user's smartphone.
- **Encryption handling:** Secures all outgoing data using AES-128, ensuring the privacy of messages sent over the network.

6.2 Mesh Routing

The routing mechanism includes:

- **Packet ID generation:** Assigns a unique tag to every message to track its delivery status and avoid confusion.
- **Hop count tracking:** Monitors how many nodes a packet has passed through to prevent network congestion and infinite loops.
- **Relay forwarding:** Automatically passes received information along to other nodes to extend the total range of the network.
- **Packet deduplication:** Recognizes and discards redundant copies of the same message that may arrive via different network paths.

6.3 Mobile Application

A Flutter-based mobile application provides:

- **Chat interface:** Provides a familiar screen for users to type and read text messages sent through the mesh network.
- **Offline maps:** Displays local geographic data directly in the app without requiring an internet connection.
- **Node radar visualization:** Shows the relative position and signal status of nearby active nodes to help maintain connection.
- **BLE connectivity:** Manages the pairing and continuous data stream between the user's phone and the LoRa hardware device.
- **SOS controls:** Offers a dedicated, easy-to-access feature for broadcasting emergency distress alerts to all nearby users.
- **Channel management:** Allows users to create, join, or switch between private communication groups.

7. Communication Protocol

The EchoMesh protocol utilizes a custom packet structure that includes:

- **Packet header:** Contains essential control information used to route the message correctly through the network.
- **Sender information:** Identifies the unique ID of the device that originally sent the message.
- **Receiver information:** Specifies the intended target node ID to ensure the message reaches the correct destination.
- **Packet type:** Indicates the nature of the data being sent, such as text, location updates, or emergency signals.
- **Hop count:** Tracks how many times a message has been forwarded, preventing infinite routing loops.
- **Payload data:** Carries the actual message content, including text characters or GPS coordinates.

Supported packet types include:

- **Text messages:** Carries user-generated text content for direct communication between nodes.
- **GPS beacons:** Transmits geographical coordinates periodically to maintain location awareness within the network.
- **SOS packets:** Broadcasts high-priority emergency distress signals to alert nearby nodes of a critical situation.
- **Acknowledgment packets:** Confirms the successful receipt of a message to ensure reliable data delivery and network integrity.
- **Presence beacons:** Broadcasts node status to signal availability and assist in network discovery and topology maintenance.

AES-128 encryption protects private communication channels according to modern IoT security practices.

8. Security Mechanisms

Security is crucial in decentralized communication systems.
EchoMesh implements:

- **AES-128 encryption:** Scrambles message data using a secure key to prevent unauthorized access and protect user privacy.
- **Unique packet identifiers:** Assigns a distinct code to every data packet, ensuring messages are not processed or counted twice.
- **Channel-based communication:** Restricts data exchange to specific logical channels, isolating group conversations from others.
- **BLE pairing protection:** Secures the wireless connection between the LoRa hardware and the smartphone to prevent unauthorized access.
- **Packet authentication mechanisms:** Verifies that a received message truly originated from a trusted source, preventing data spoofing.

The encryption process uses CTR mode to ensure low computational load while maintaining confidentiality.

9. Experimental Setup

9.1 Hardware Setup

The prototype nodes were built from:

- **TTGO T-Beam ESP32 boards:** Serves as the primary microcontroller node, integrating the LoRa transceiver, GPS, and power management on a single compact board.
- **SX1276 LoRa radios:** Handles long-range, low-power data transmission over sub-GHz ISM frequency bands.
- **OLED displays:** Provide a visual interface on each node to show real-time network status, messages, and battery levels.
- **18650 Li-ion batteries:** Powers the portable nodes, offering sufficient capacity for prolonged field operation.
- **GPS modules:** Capture accurate location coordinates for tracking nodes and enabling location-based services in the mesh network.

9.2 Test Environment

Experiments were conducted in:

- **Urban environments:** Test signal propagation and interference resilience in densely built-up areas with high signal reflection.
- **Open rural fields:** Evaluates maximum communication range and link reliability in unobstructed, low-noise environments.
- **Indoor settings with obstacles:** Assesses signal penetration and multi-hop stability through walls and various physical barriers.

9.3 Metrics Evaluated

The following metrics were measured:

- **Communication range:** Measures the maximum distance over which nodes can successfully exchange data packets under different environmental conditions.
- **Packet delivery ratio:** Calculates the percentage of successfully received packets compared to the total sent to evaluate network reliability.
- **Battery consumption:** Monitors the power usage of nodes over time to optimize energy efficiency and operational lifespan.
- **Message latency:** Determines the time delay required for a packet to travel from the source to the destination node.
- **Multi-hop reliability:** Assesses the network's ability to maintain stable connections when data must pass through several intermediate relay nodes.
- GPS update success

10. Results and Discussion

10.1 Communication Range

The LoRa mesh network achieved:

- 1–2 km in dense urban areas
- 5–10 km in rural areas with line-of-sight

The communication range varied depending on antenna orientation, terrain, and environmental interference.

10.2 Power Consumption

The average battery life ranged between:

- 10–14 hours with active communication
- Several days under low-duty-cycle operation

Power optimization methods like sleep modes significantly enhanced efficiency.

 ISBN : 978-81-999970-0-4

10.3 Mesh Routing Performance

The mesh routing mechanism successfully relayed packets across multiple nodes with high delivery rates. Preventing packet duplication improved network stability.

10.4 BLE Integration

The BLE communication system enabled reliable smartphone integration for:

- Real-time messaging
- Device configuration
- GPS visualization
- Emergency control

11. Applications of EchoMesh

EchoMesh can be applied in various areas:

11.1 Disaster Response

Emergency responders can maintain communication even when cellular infrastructure fails.

11.2 Rural Connectivity

Remote villages without network coverage can establish community communication systems.

11.3 Military and Tactical Communication

Military units can use this system to coordinate movements and share secure, real-time location data during operations in remote areas without relying on vulnerable public networks.

11.4 Adventure and Expedition Use

Trekkers, hikers, and mountaineers can keep in touch in remote locations.

11.5 Event Management

Event organizers can use the system to keep staff and security teams connected at large festivals or sports events, especially where cellular networks become overcrowded or fail.

12. Advantages of EchoMesh

- **Infrastructure-independent communication:** Allows users to connect without relying on cell towers or internet services.
- **Low power consumption:** Enables devices to operate for long periods on small battery supplies.
- **Long-range capability:** Supports communication over several kilometers, making it ideal for wide-area coverage.
- **Low deployment cost:** Uses affordable components, making it accessible for communities and budget-constrained projects.
- **Open-source flexibility:** Provides open design files and code, allowing users to modify or improve the system as needed.
- **Smartphone integration:** Connects easily to mobile devices via Bluetooth, providing a user-friendly interface.
- **GPS tracking support:** Allows users to share and view precise location coordinates for navigation or rescue purposes.
- **Multi-hop scalability:** Extends the network reach by automatically relaying messages through intermediate nodes.
- **Secure encrypted channels:** Protects privacy by scrambling message data so only authorized recipients can read it.
- **Quick deployment in disasters:** Sets up rapidly to provide essential communication links when standard networks fail.

13. Limitations

Despite its benefits, EchoMesh has several limitations:

- **Low data transmission rates:** Data moves slowly, making it unsuitable for sending large files.
- **Limited bandwidth for multimedia communication:** The network cannot handle heavy media like high-quality video or large image files effectively.
- **Regulatory restrictions on ISM frequencies:** Local government rules on radio usage may restrict operation in certain regions.

ISBN : 978-81-999970-0-4

- **Possible interference in crowded radio environments:** Many devices sharing the same radio band can create signal noise.
- **Voice communication constraints over LoRa:** Transmitting clear audio is challenging due to the technology's low data capacity.
- **Increased latency with additional hops:** Every relay step adds a slight delay to the message's total travel time.

14. Future Scope

Future enhancements to the EchoMesh system will focus on integrating AI-assisted routing, satellite and UAV gateway connectivity, solar charging, advanced mesh synchronization, dynamic frequency adaptation, improved voice codecs, edge AI for disaster analytics, blockchain-based decentralized identity, secure over-the-air firmware updates, and hybrid communication capabilities using LoRa, Wi-Fi Direct, and satellite uplinks.

15. Conclusion

This research presented EchoMesh, a decentralized off-grid communication system based on LoRa mesh networking technology. The proposed architecture demonstrates that low-cost embedded systems can provide reliable long-range communication without dependence on traditional infrastructure. The integration of LoRa, ESP32, BLE, GPS, and mesh routing creates a scalable communication framework suitable for emergency response, rural communication, and disaster management. Experimental analysis confirms that EchoMesh achieves long communication ranges with low power consumption while maintaining acceptable reliability in multi-hop scenarios. The research highlights the growing importance of decentralized communication systems in modern society, particularly in environments where infrastructure-based communication fails (Shah et al., 2019; Ranaweera et al., 2018). EchoMesh demonstrates the feasibility of creating affordable, scalable, and resilient communication networks capable of supporting emergency coordination and community resilience.

REFERENCES

Adelantado, F., Vilajosana, X., Tuset-Peiro, P., Martinez, B., Melia-Segui, J., & Watteyne, T. (2017). Understanding the limits of LoRaWAN. IEEE Communications Magazine, 55(9), 34–40.

Akyildiz, I. F., Wang, X., & Wang, W. (2005). Wireless mesh networks: A survey. Computer Networks, 47(4), 445–487.

Al-Fuqaha, A., Guizani, M., Mohammadi, M., Aledhari, M., & Ayyash, M. (2015). Internet of Things: A survey on enabling technologies, protocols, and applications. IEEE Communications Surveys & Tutorials, 17(4), 2347–2376.

Augustin, A., Yi, J., Clausen, T., & Townsley, W. (2016). A study of LoRa: Long range & low power networks for the Internet of Things. Sensors, 16(9), 1466.

Bor, M., Vidler, J., & Roedig, U. (2016). LoRa for the Internet of Things. Proceedings of the International Conference on Embedded Wireless Systems and Networks.

Centenaro, M., Vangelista, L., Zanella, A., & Zorzi, M. (2016). Long-range communications in unlicensed bands: The rising stars in the IoT and smart city scenarios. IEEE Wireless Communications, 23(5), 60–67.

Gupta, D. N., & Kumar, R. (2019). Lightweight cryptography: An IoT perspective. International Journal of Innovative Technology and Exploring Engineering, 8(8), 700-706.

Gupta, D. N., & Kumar, R. (2020). Networking in IoT: Technologies used, security threats and possible countermeasures. International Journal of Sensors, Wireless Communications and Control, 10(1).

Cotrim, J. R., & Kleinschmidt, J. H. (2020). LoRaWAN mesh networks: A review and classification of multihop communication. Sensors, 20(15), 4273.

Diffie, W., & Hellman, M. (1976). New directions in cryptography. IEEE Transactions on Information Theory, 22(6), 644–654.

Georgiou, O., & Raza, U. (2017). Low power wide area network analysis: Can LoRa scale? IEEE Wireless Communications Letters, 6(2), 162–165.

Gupta, D. N., & Kumar, R. (2022a). An IoT approach of managing smart healthcare services. In Networking Technologies in Smart Healthcare: Innovations and Analytical Approaches (pp. 398). CRC Press.

Gupta, D. N., & Kumar, R. (2022b). Multi-layer and clustering-based security implementation for an IoT environment. International Journal of System Dynamics Applications, 11(2), 1-21.

Gupta, D. N., & Kumar, R. (2023a). DeeR-Hash: A lightweight hash construction for Industry 4.0 / IoT. Journal of Scientific & Industrial Research, 82(1), 142-150.

Gupta, D. N., & Kumar, R. (2023b). DeeR-Gen: A pseudo random number generator for Industry 4.0 / IoT. Journal of Scientific & Industrial Research, 82(3), 316-321.

Gomez, C., Oller, J., & Paradells, J. (2012). Overview and evaluation of Bluetooth low energy. Sensors, 12(9), 11734–11753.

Mekki, K., Bajic, E., Chaxel, F., & Meyer, F. (2019). A comparative study of LPWAN technologies for large-scale IoT deployment. ICT Express, 5(1), 1–7.

Perrig, A., Szewczyk, R., Wen, V., Culler, D., & Tygar, J. D. (2002). SPINS: Security protocols for sensor networks. Wireless Networks, 8(5), 521–534.

Ranaweera, P., Agrawal, D. P., & Jayalath, D. (2018). Emergency communication networks: A contemporary survey. IEEE Communications Surveys & Tutorials, 20(4), 2486–2529.

Roman, R., Zhou, J., & Lopez, J. (2013). On the features and challenges of security and privacy in distributed Internet of Things. Computer Networks, 57(10), 2266–2279.

Raza, U., Kulkarni, P., & Sooriyabandara, M. (2017). Low power wide area networks: An overview. IEEE Communications Surveys & Tutorials, 19(2), 855–873.

Sanchez-Iborra, R., & Cano, M. D. (2016). State of the art in LP-WAN solutions for industrial IoT services. Sensors, 16(5), 708.

Shah, S. A., Seker, D. Z., Hameed, S., & Draheim, D. (2019). The rising role of big data analytics and IoT in disaster management. International Journal of Information Management, 45, 195–207.

Siekkinen, M., Hiienkari, M., Nurminen, J. K., & Nieminen, J. (2012). How low energy is Bluetooth low energy? Comparative measurements with ZigBee/802.15.4. Proceedings of IEEE WCNC.

Tiwari, D., & Sharma, V. (2020). A Review on Conventional and Lightweight Security Techniques in Mobile and IoT Devices. Journal of Information and Computational Science, 12(12).

Voigt, T., Bor, M., Roedig, U., Alonso, J., & Montavont, J. (2017). Mitigating inter-network interference in LoRa networks. Proceedings of EWSN.

Vangelista, L. (2017). Frequency shift chirp modulation: The LoRa modulation. IEEE Signal Processing Letters, 24(12), 1818–1821.

Zanella, A., Bui, N., Castellani, A., Vangelista, L., & Zorzi, M. (2014). Internet of Things for smart cities. IEEE Internet of Things Journal, 1(1), 22–32.