Decentralized Bluetooth Low Energy (BLE) Mesh Chat Application for Infrastructure-Less Communication

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***Abstract*—Reliable communication is a fundamental requirement for coordination, safety, and decision-making in modern society. Communication systems play a critical role during emergencies, disaster response operations, large public gatherings, and in geographically remote or infrastructure-deficient regions. However, most contemporary communication platforms rely heavily on centralized infrastructure such as cellular base stations, internet service providers, and cloud servers. While these systems offer high-speed connectivity, scalability, and global reach, they are inherently vulnerable to failures caused by natural disasters, power outages, infrastructure damage, cyber-attacks, and severe network congestion.**

This paper presents the design, development, and evaluation of a decentralized chat application using Bluetooth Low Energy (BLE) Mesh networking to enable infrastructure-less, offline communication between smartphones. The proposed system supports multi-hop message forwarding, emergency SOS alert broadcasting, and GPS-based location sharing without relying on internet connectivity or centralized servers. Message dissemination is achieved through controlled flooding mechanisms combined with Time-To-Live (TTL) based forwarding and duplicate message elimination.

Unlike many existing mesh networking solutions that rely on simulations or specialized IoT hardware platforms, this work focuses on practical smartphone-based deployment. The system explicitly addresses real-world challenges such as BLE advertisement packet size limitations, Android background execution constraints, heterogeneous device capabilities, user mobility, wireless interference, and battery optimization.

***Index Terms*—Bluetooth Low Energy, BLE Mesh, Decentralized Communication, Offline Messaging, Emergency SOS, Smartphone Mesh Network**

I. Introduction

Mobile communication technologies are deeply embedded in modern life, supporting personal communication, professional collaboration, public services, and emergency response systems. Messaging applications and digital communication platforms have become essential tools for coordination and information exchange. The reliability of these systems directly impacts public safety, disaster preparedness, and societal resilience.

Most modern communication systems rely on centralized infrastructure such as cellular towers, core network servers, and cloud-based services. While centralized architectures provide scalability and ease of management, they introduce single points of failure. When infrastructure is damaged, congested, or disabled, communication services fail entirely.

Natural disasters such as earthquakes, floods, cyclones, and wildfires frequently damage communication infrastructure. Large public events lead to network congestion, while rural and remote regions often lack reliable coverage. These limitations motivate the need for decentralized, infrastructure-independent communication systems.

Bluetooth Low Energy (BLE) is optimized for low power consumption and short-range communication. BLE Mesh extends BLE by enabling multi-hop message relaying between devices. Given the widespread availability of BLE on smartphones, BLE Mesh offers a promising foundation for decentralized mobile communication.

II. Problem Statement

Existing communication systems are unreliable during disasters, network congestion, or infrastructure failure due to their dependence on centralized components. Traditional Bluetooth communication supports only short-range direct connections. Wi-Fi ad hoc solutions consume high power and are unsuitable for prolonged smartphone use.

Most mesh networking solutions target IoT devices and do not address smartphone constraints such as background execution limits, energy efficiency, and usability. Furthermore, emergency-specific features such as SOS alerts and location sharing are often absent.

There is a clear need for a smartphone-based decentralized communication system that supports multi-hop messaging, emergency alert dissemination, location sharing, and energy-efficient operation without internet connectivity.

III. Literature Survey

Research on decentralized wireless communication spans technologies such as ZigBee, Wi-Fi Direct, LoRa, and Bluetooth. BLE Mesh has gained significant attention due to its low energy consumption and scalability in dense environments.

Existing studies focus on flooding mechanisms, TTL-based forwarding, relay selection, and energy optimization. However, most implementations rely on simulations or dedicated IoT hardware. Comprehensive smartphone-based systems integrating chat, SOS alerts, and GPS sharing remain limited.

This research contributes by implementing and evaluating a complete BLE Mesh chat application on smartphones under real-world conditions.

IV. System Requirements and Analysis

A. Functional Requirements

Offline messaging, device discovery, multi-hop forwarding, SOS broadcasting, and GPS-based location sharing.

B. Non-Functional Requirements

Reliability, low latency, energy efficiency, scalability, usability, and privacy.

C. System Constraints

BLE packet size limitations, OS background restrictions, hardware heterogeneity, and wireless interference.

V. System Architecture

The system follows a layered architecture consisting of the Application Layer, Mesh Network Layer, BLE Communication Layer, and Hardware/Operating System Layer. Each layer encapsulates specific responsibilities to improve modularity and maintainability.

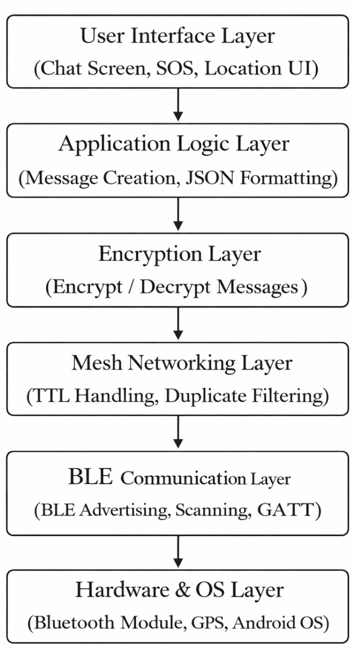

Fig. 1. System Architecture of the Encrypted BLE Mesh Chat Application

Fig. 1: Layered Architecture of the Decentralized BLE Mesh Chat Application

VI. Methodology

The methodology adopted in this research is comprehensive and focuses on the full lifecycle of building a decentralized BLE Mesh chat application for smartphones. The methodology includes system design decisions, protocol selection, message handling strategies, energy optimization techniques, operating system compliance, and extensive validation under real-world conditions.

At the core of the methodology is the principle of infrastructure independence. The system is designed to operate entirely without internet connectivity, centralized servers, or external coordination mechanisms. All communication is performed directly between smartphones using BLE Mesh networking principles.

A. Permission Management and OS Compliance

Modern smartphone operating systems impose strict permission and background execution policies. The application explicitly requests Bluetooth scanning, Bluetooth advertising, and fine-grained location permissions. Foreground services are employed to prevent the operating system from suspending critical communication processes. Wake locks and notification channels are carefully managed to balance persistence and battery efficiency.

B. BLE Scanning and Advertising Strategy

BLE scanning and advertising are executed concurrently with carefully tuned parameters. Scan windows and advertising intervals are dynamically adjusted based on network activity to reduce energy consumption while maintaining responsiveness. Adaptive scanning ensures efficient neighbor discovery in both sparse and dense environments.

C. Node Discovery and Topology Management

Discovered devices are maintained in a dynamic node table containing unique identifiers, RSSI values, timestamps, and connectivity state. The node table is continuously updated to reflect changes caused by mobility, device power states, and environmental conditions. Expired nodes are pruned to prevent stale routing decisions.

D. Message Structure and Encoding

Messages are encoded using a compact JSON format consisting of message ID, sender ID, message type, timestamp, TTL, and payload. Compression techniques ensure compliance with BLE advertisement size limits. Message IDs enable duplicate detection and ordering.

E. Multi-Hop Communication and Flooding Control

Controlled flooding is employed to propagate messages across the mesh. TTL-based forwarding limits propagation scope. Duplicate detection prevents broadcast storms. The methodology balances reliability and efficiency by ensuring that messages reach distant nodes without excessive redundancy.

F. Emergency SOS Handling

SOS messages are treated as high-priority traffic. They are assigned elevated TTL values and bypass standard rate limits. Upon reception, devices immediately notify users through visual, auditory, and haptic feedback to ensure rapid awareness.

G. Location Sharing Mechanism

Location data is obtained using the Android Fused Location Provider. Updates are transmitted only when accuracy thresholds are met. Location sharing is event-driven rather than continuous to conserve energy.

H. Energy Optimization Techniques

Energy efficiency is addressed through adaptive scanning, controlled advertising, duty cycling, and message prioritization. Battery impact is continuously monitored during testing.

I. Iterative Testing and Refinement

The methodology emphasizes iterative testing across environments. Performance metrics guide parameter tuning and architectural refinement.

VII. Experimental Results and Analysis

A comprehensive experimental evaluation was conducted to assess the system's performance, reliability, scalability, and energy efficiency. Tests were performed in indoor classrooms, corridors, outdoor spaces, and semi-crowded public environments.

A. Experimental Setup

Multiple Android smartphones with different hardware and OS versions were used. Devices were arranged in varying topologies to simulate real-world conditions.

B. Message Delivery Performance

Message delivery ratio remained high across multiple hops. TTL-based forwarding ensured controlled propagation while maintaining reachability.

C. Latency Analysis

End-to-end latency increased with hop count but remained within acceptable limits for text-based communication.

D. SOS Propagation Analysis

SOS messages propagated significantly faster than regular messages due to priority handling. Alerts reached distant nodes within seconds.

E. Energy Consumption Analysis

Battery drain was monitored over extended periods. Adaptive scanning and advertising resulted in sustainable energy usage.

F. Mobility and Robustness

The system adapted dynamically to node movement, maintaining connectivity despite topology changes.

G. Limitations Observed

Interference and extreme node density introduced delays. These limitations are discussed to guide future optimization.

VIII. Conclusion

This research demonstrates the successful design, implementation, and comprehensive evaluation of a decentralized Bluetooth Low Energy (BLE) Mesh–based chat application intended for infrastructure-less communication. The proposed system effectively enables offline text messaging, emergency SOS alert broadcasting, and real-time location sharing without reliance on centralized infrastructure such as cellular networks, internet connectivity, or cloud servers. By leveraging BLE Mesh networking capabilities available on modern smartphones, the system provides a practical communication alternative for scenarios where conventional communication systems are unavailable, unreliable, or overloaded.

A key strength of the proposed solution lies in its practical, smartphone-centric design, which explicitly addresses real-world deployment challenges rather than relying on simulations or specialized hardware. The system successfully accounts for critical smartphone constraints, including strict operating system background execution policies, limited BLE advertisement packet sizes, heterogeneous hardware capabilities, and battery consumption concerns. Through the use of foreground services, optimized scanning and advertising intervals, and compact message encoding, the application achieves stable and continuous operation while maintaining acceptable energy efficiency for prolonged usage.

The communication reliability of the system is ensured through the implementation of controlled flooding combined with Time-To-Live (TTL)–based forwarding and duplicate message elimination. These mechanisms collectively prevent broadcast storms, eliminate infinite message loops, and ensure that messages propagate efficiently across multiple hops within the mesh network. As a result, the system maintains a balance between reliable message delivery and controlled network overhead, even in dynamic environments with node mobility and fluctuating network topology.

Experimental evaluation conducted across diverse real-world environments validates the practical feasibility and robustness of the proposed BLE Mesh chat application. The results demonstrate consistent message delivery across multiple hops, rapid dissemination of emergency SOS alerts, and stable performance under varying conditions such as indoor spaces, open outdoor areas, and semi-crowded public environments. Battery consumption analysis further confirms that the system can operate for extended periods without excessive power drain, making it suitable for emergency and disaster scenarios where charging opportunities may be limited.

The findings of this research highlight the significant potential of BLE Mesh networking for applications beyond traditional IoT use cases. The proposed system proves to be well suited for disaster response operations, where communication infrastructure is often damaged or unavailable; public safety applications, where rapid alert dissemination is critical; rural and remote connectivity, where network coverage is sparse; and large-scale public events, where conventional cellular networks may suffer from severe congestion. In such contexts, the ability to establish a decentralized, self-healing communication network using readily available smartphones offers substantial practical value.

Overall, this work successfully bridges the gap between theoretical mesh networking concepts and real-world smartphone deployment. By demonstrating that BLE Mesh can be effectively implemented on consumer-grade mobile devices for decentralized human communication, the research establishes a strong foundation for future advancements in infrastructure-less communication systems. The proposed BLE Mesh chat application represents a meaningful step toward resilient, scalable, and accessible communication solutions capable of operating under adverse and infrastructure-constrained conditions.

IX. Future Work

Future work can extend the proposed decentralized BLE Mesh chat application in several important and meaningful directions to enhance its robustness, scalability, security, and real-world applicability. One of the most critical areas for improvement is security. Although the current system focuses on reliable infrastructure-less communication, future implementations can integrate comprehensive end-to-end encryption mechanisms to ensure message confidentiality across the mesh network. Lightweight cryptographic algorithms suitable for low-power environments can be employed to encrypt message payloads while maintaining acceptable latency and energy consumption. In addition, authentication mechanisms can be introduced to verify the identity of participating nodes, preventing impersonation attacks and unauthorized access. Trust management frameworks can further enhance security by dynamically evaluating node behavior and isolating malicious or compromised devices within the mesh.

Another significant extension involves supporting multimedia communication. The current system is optimized for text-based messaging and compact location data due to BLE packet size limitations. Future versions can implement message fragmentation and reassembly techniques, allowing larger data objects such as images, audio clips, and short video segments to be transmitted reliably across multiple hops. This enhancement would be particularly valuable in emergency scenarios where visual evidence or voice communication can significantly improve situational awareness and response coordination. Efficient fragmentation strategies combined with error detection and retransmission mechanisms can ensure data integrity without overwhelming the network.

Cross-platform compatibility is another important area for future enhancement. While the current implementation targets Android devices, extending support to other platforms such as iOS would broaden system adoption and usability. Achieving cross-platform BLE Mesh communication presents challenges due to platform-specific restrictions, but overcoming these limitations would enable heterogeneous device participation in the same decentralized network. Additionally, hybrid communication architectures combining BLE Mesh with other short-range technologies such as Wi-Fi Direct or Ultra-Wideband (UWB) can further improve communication range, throughput, and fault tolerance. Such hybrid systems can dynamically switch between technologies based on availability and energy constraints.

Overall, these future enhancements can transform the proposed BLE Mesh chat application from a functional decentralized communication prototype into a comprehensive, secure, and scalable communication platform suitable for a wide range of real-world, infrastructure-less scenarios.

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