LifeBeacon: A Self-Adaptive Network Model for Emergency Communication and User Localization

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***Abstract*—Natural disasters often compromise traditional communication infrastructure, significantly delaying emergency response and coordination efforts. This research presents a novel, disaster-resilient communication system designed to address these challenges through the integration of mobile ad-hoc networking and Wi-Fi-based victim localization. The proposed system comprises of a decentralized, infrastructure-less, self-healing mobile ad-hoc network (MANET) utilizing Bluetooth Low Energy (BLE) and Wi-Fi direct with an encrypted SOS messaging mechanism between end devices and a Wi-Fi probe request-based end device detection mechanism that estimates the location of affected individuals based on their mobile phones. If nodes disconnect, a self-healing algorithm guarantees automatic reconnection and uninterrupted message flow, while the ad-hoc network facilitates low-power, peer-to-peer communication without the need for traditional infrastructure. Both targeted and broadcast notifications are supported by the SOS messaging system, which is encrypted to protect the integrity and security of data. The victim localization system, meantime, makes precise estimates of the population and location of people in the disaster region using trilateration and Received Signal Strength Indicator** (RSSI). **Experimental evaluations conducted under simulated disaster conditions demonstrate the system's scalability, energy efficiency, and effectiveness in maintaining real-time communication and accurate victim tracking.**

Keywords— Emergency communication, Mobile ad-hoc networks, victim localization, Peer-to-Peer Communication, post-disaster Communication

I. Introduction

Natural disasters frequently interrupt traditional communication infrastructure, which impedes emergency response efforts by isolating impacted populations and delaying rescues. During such emergencies, centralized infrastructures, such as the internet and cellular networks, are susceptible to disruption and congestion. Alternative, robust, and infrastructure-independent communication solutions are therefore becoming more and more necessary. Device-to-device communication is made possible by technologies like BLE, Wi-Fi Direct, and MANETs which minimize the need for fixed infrastructure. These decentralized systems are perfect for uncertain, resource-constrained contexts since they are self-organizing, flexible, and energy-efficient. The creation of disaster-resilient communication methods with these technologies is examined in this study, with a focus on intelligent decision-making, secure data transfer, and real-time localization to aid rescue efforts and boost productivity in post-disaster situations.

II. Literature Review

Direct device-to-device communication is made feasible by technologies like BLE, Wi-Fi Direct, and Mobile Ad Hoc Networks (MANETs), which avoid centralized systems that are susceptible to congestion or damage [1]. In disaster areas, MANETs are especially useful for setting up decentralised networks that provide emergency connectivity in situations where traditional networks are unable to function [2]. They do, however, have issues with mobility and interference from the surroundings. BLE and Wi-Fi-based systems have been incorporated into disaster communication plans to improve stability and dependability, offering more resilient and flexible options for post-disaster situations.

BLE has gained attention due to its energy efficiency and widespread support in modern smartphones. Unlike traditional Bluetooth, BLE is optimized for low- power, intermittent communication, making it ideal for disaster scenarios where power availability is limited. Research indicates that BLE-based networks provide significant advantages in terms of energy consumption and network resilience, ensuring continuous communication even in resource-constrained environment [3]. Moreover, self-healing mechanisms have been introduced to improve network stability by allowing automatic reconnection in the event of node failure, thus enhancing the overall reliability of MANETs in disaster recovery [4]. Wi-Fi Direct complements BLE by enabling fast, peer-to-peer connections without requiring an internet connection or access points. This technology supports high- speed data transfer and extended communication ranges compared to BLE, making it particularly useful in disaster scenarios where rapid information exchange is critical. Research has shown that Wi-Fi Direct enhances the efficiency of emergency communication systems by reducing latency and ensuring stable connectivity among rescue teams and victims [5].

Combining the higher data transfer speed of Wi-Fi direct with BLE's power efficiency and continuous connectivity provides a well-rounded approach to disaster communication. To overcome traditional network delays and provide dependable and low-latency emergency communication, ad hoc SOS message systems have been proposed [6]. These systems, which are protected by encryption methods, guarantee the confidentiality of messages and protect sensitive data [7] . Furthermore, by analysing mobile device information and signal strength, Wi-Fi probe request analysis helps rescue teams pinpoint priority zones and enables precise victim localization [8]. For data administration, Apache Cassandra offers scalable and fault-tolerant central storage, while SQLite guarantees quick local access. Disaster response operations can be tracked, routed, and coordinated with the help of a real-time dashboard.

By leveraging a combination of MANETs, BLE, Wi-Fi Direct, Wi-Fi–based localization, and optimized data management, a disaster-resilient telecommunication infrastructure can be established to ensure seamless communication, victim tracking, and effective rescue operations. In this system, Wi-Fi probe requests emitted by victims' smartphones are passively collected by multiple detection nodes, enabling trilateration-based localization without requiring any user interaction. This allows rescuers to estimate victim locations quickly and efficiently, even when individuals are unconscious or immobilized. The integration of self-healing networks, encryption, and efficient messaging mechanism further enhances system reliability, making it a viable and scalable solution for emergency response in infrastructure-deficient environments.

III. Methodology

The approach began with stakeholder consultations involving key organizations such as the Disaster Management Centre (DMC) of Sri Lanka, the Landslide Risk Reduction and Mitigation Division (LRRMD), and the National Building Research Organization (NBRO), as well as emergency responders and disaster management professionals, to identify critical operational needs and system constraints. Based on this analysis, core system requirements were defined, emphasizing decentralization, scalability, and need for victim localization. The communication network is designed using BLE and Wi-Fi Direct to establish a MANET capable of supporting real-time, infrastructure-independent messaging. A self-healing mechanism ensures network continuity in dynamic environments. In parallel, a victim localization system is developed using ESP32 devices to detect Wi-Fi probe requests and estimate distance to detected end devices via RSSI values. Both communication and localization modules are integrated with a centralized dashboard and hybrid data storage architecture for monitoring and coordination. The complete system is evaluated under disaster-simulated conditions to validate performance and reliability.

A. *System Architecture*

The overall structure emphasizes decentralized operation, dynamic network formation, and efficient information flow to facilitate timely and effective emergency response coordination.

The proposed architecture begins with the deployment of RF Signal Detection Nodes surrounding the disaster zone, which operate in promiscuous mode and detect signals from survivors' mobile devices. These nodes detect signal intensity and direction, allowing for victim density assessment and directional mapping to aid in rescue prioritization. The gathered information is sent to a decentralised MANET made up of mobile devices with Wi-Fi Direct and BLE capabilities. Each device can be used as both a transmitter and a receiver, allowing for multi-hop communication without the need for infrastructure. When a node disconnects, a self-healing mechanism keeps track of its associated peers' hash map, enabling dynamic reconfiguration and automatic reconnection. To reduce congestion, the network allows both tailored alerts and broader SOS broadcasts. To protect the confidentiality and integrity of the data, all communications are encrypted. The system contains a centralized administration dashboard that enables disaster response teams to monitor in real time, broadcast messages, follow victims, and modify configurations.

The victim localization system uses ESP32 devices operating in promiscuous mode to detect Wi-Fi probe requests emitted by nearby mobile devices. The system measures RSSI values, which are used to estimate the distance between the victim's device and each sensor node.

B. *Implementation*

1) Mobile application and self-healing feature

A mobile application developed using Flutter establishes a BLE and Wi-Fi Direct-based Mobile Ad-Hoc Network (MANET) for internet-free, device-to-device communication during disasters [9]. It features secure messaging, automatic node discovery, and a user-friendly interface to support effective communication. The app employs encryption for data security and ensures continuous connectivity through a self-healing algorithm [10]. This algorithm operates in three phases failure detection, path reconfiguration, and reintegration using hash maps to track device connections. When a node disconnects, nearby nodes detect the change and reroute communication through alternative paths. The disconnected node rejoins automatically, allowing the network to adapt and maintain functionality without manual intervention.

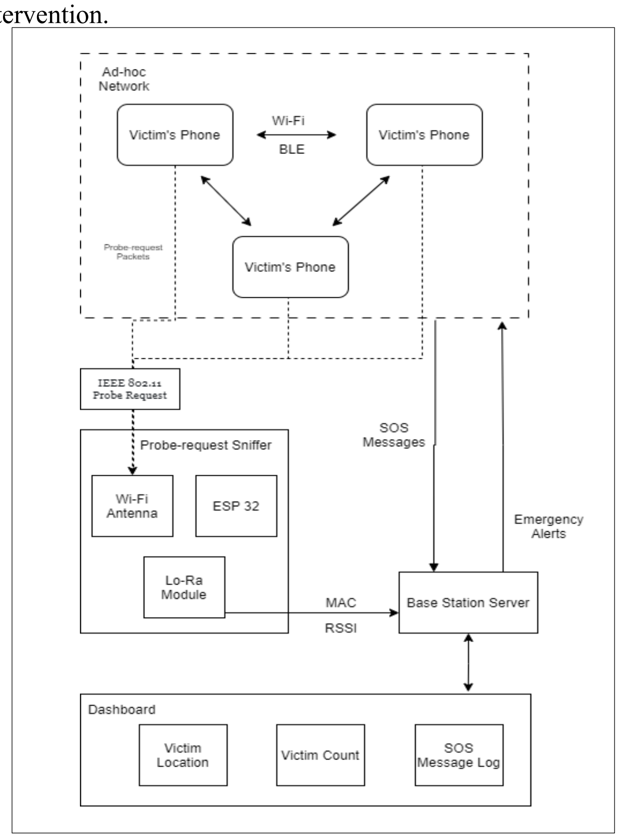

Fig. 1. System Architecture

2) SOS Messaging and Communication Mechanism

The SOS Messaging System integrates Flask-SocketIO, Flutter, and P2P communication to provide secure, reliable disaster communication. It supports targeted and broadcast messaging, allowing responders to send encrypted direct messages to victims and mass notifications for wider alerts. End-to-end encryption (E2EE) ensures secure transmission, while Bluetooth and Wi-Fi Direct enable offline device-to-device communication. The app, built with Flutter, uses the flutter_nearby_connections plugin for P2P messaging and Local Notifications for emergency alerts. It also collects device data (e.g., battery health, location, and message logs) to help prioritize high-risk victims [11].

The system relays messages across nearby devices to extend communication beyond direct range, ensuring offline messaging. It minimizes network congestion by prioritizing emergency messages and reducing redundancy. Switching between Web Sockets, Bluetooth, and Wi-Fi Direct, the system ensures low latency and high reliability. This approach enhances disaster response, and the next phase will focus on evaluating latency, message success rate, and scalability for real-world deployment.

3) Data Management Architecture

A dual-layered database architecture is used in the proposed disaster-resilient telecommunication system to guarantee fault tolerance, synchronization, and data durability. For lightweight, local storage that supports offline access and continues to function even during network disruptions, SQLite is deployed at edge nodes [12]. Cassandra functions as a distributed NoSQL database at the base station, facilitating fault-tolerant, scalable data synchronization and replication. When the network is accessible, data is moved asynchronously from SQLite to Cassandra, minimizing data loss. Timestamp-based reconciliation and versioning are used to manage conflict resolution while preserving data integrity. Both strong, scalable management at the core and resilience at the edge are guaranteed by this integration of local and centralized storage.

4) Victim Localization System

The victim localization system uses Wi-Fi probe request detection and RSSI values to estimate the location of individuals in disaster zones. A module comprising of an ESP32 device equipped with microcontrollers, external Wi-Fi and Lora antennas, a voltage regulator and Lithium-ion batteries, all protected with an enclosure, detect probe requests from nearby mobile devices (Fig. 2). These requests contain the device's MAC address, and the RSSI values are used to estimate the distance between the victim's device and the sensor node.

To improve the reliability of these measurements, an Exponential Moving Average (EMA) filter is applied to the raw RSSI data, smoothing out short-term fluctuations caused by environmental noise and interference. EMA was selected after a comparative evaluation of several filtering techniques, including moving average, median, Gaussian, and exponential moving average filters, due to its ability to provide a balance between responsiveness and noise reduction.

The distance d is then calculated using the path loss equation where $RSSI_0$ is the reference RSSI at 1 meter, RSSI is the captured signal strength, and n is the path loss

Fig. 2. Victim localization device in enclosure

exponent [13]. The RSSI data is transmitted via LoRa and MQTT protocols for real-time processing. Victim location estimates, obtained through trilateration from multiple detection nodes, are visualized on The RSSI data is transmitted via LoRa and MQTT protocols for real-time processing. Victim location estimates, obtained through trilateration from multiple detection nodes, are visualized on a Node-RED dashboard, allowing rescue teams to track victims dynamically. This approach, with its combination of lightweight hardware, adaptive filtering, and real-time visualization, offers a scalable and cost-effective solution ideally suited for disaster scenarios with limited infrastructure.

$$d = 10\ \frac{(RSSI_0 - RSSI)}{10 \times n} \quad (1)$$

The system applies trilateration to estimate the victim's position. Multiple ESP32 sensor nodes are placed in the disaster area, measuring signal strength and calculating approximate distances. These measurements are transmitted in real-time using LoRa for long-range, low-power communication and MQTT for efficient messaging. The data is processed and visualized on a Node-RED dashboard, which displays the victim's location for rescue teams. This non-intrusive system requires no modifications to the mobile devices of the victims, making it scalable and adaptable in emergency situations. The solution is cost- effective, infrastructure-independent, and ideal for scenarios where traditional communication networks are unavailable. By combining RSSI-based trilateration, ESP32, Node-RED, and real-time data transmission, the system enhances situational awareness, helping improve the efficiency and speed of rescue operations.

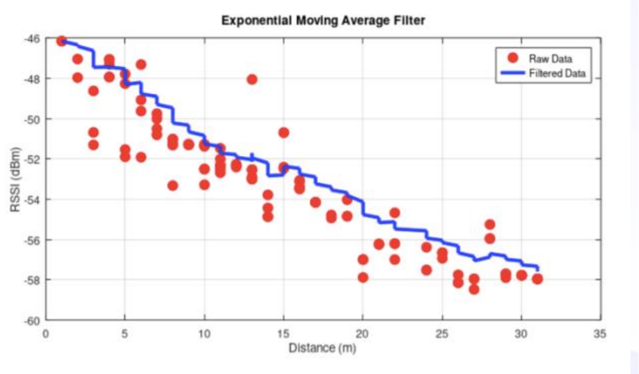

Fig. 3. Exponential moving average filter analysis

C. Testing and validation

Testing is conducted in both controlled and real-world disaster simulation environments.

1) Test case 01: Network Stability and healing

During the test, response time, reconnection rate, and message accuracy were measured. The network immediately reconnected to patch the disconnected nodes, with a response time of less than 5 seconds. SOS messages were successfully delivered to the reconnected nodes as well. The updated node status was clearly reflected on the centralized dashboard (Fig. 4) and a test message sent after the deliberate disconnection was successfully received by all nodes connected at that time. Message accuracy remained at 100% throughout all test cases. These basic tests were conducted in controlled environments with minimal to no interference, allowing for a clear evaluation of the network's self-healing capabilities and reliable communication performance.

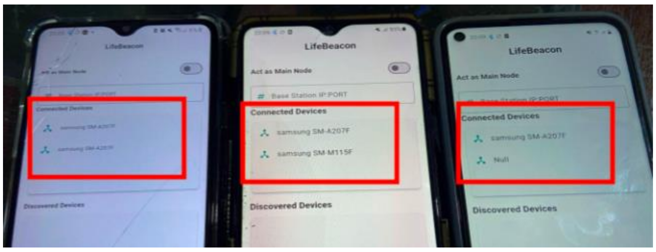

Fig. 4. Network healing test

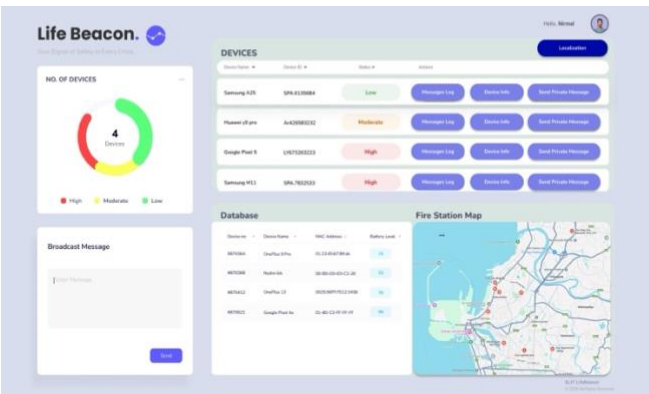

Fig. 5. Centralized Dashboard

2) Test case 02: Encrypted Targeted Message Transmission within the MANET

Three devices within the MANET were configured for this test (devices A, B, C): one (A) as the sender and another (B) as the recipient. The sender prepared a message and encrypted it using the designated encryption algorithm before transmitting it to the recipient via the MANET. Upon receipt at the specific device (B), the recipient decrypted the message using the correct decryption key. It was verified that the decrypted message matched the original message and remained unreadable by any other devices in the network. Throughout the multi-hop transmission across the three nodes, the message remained securely encrypted. Only the intended recipient was able to access its contents, confirming the confidentiality and integrity of targeted communications in a disaster setting.

3) Test case 03: Distance approximation for victim localization

This test case aimed to assess the accuracy of victim localization through distance approximation using RSSI measurements from multiple nodes. Three ESP32 nodes were deployed at known, fixed positions within a defined coverage area ranging from 10 – 100m. Then, a mobile device, simulating a victim, was placed at various coordinates. Using RSSI data collected from the ESP32 nodes and applying the path loss equation, the system estimated the distance from each node to the mobile device to triangulate its location using trilateration mechanism. The outcome showed that, in open environments, the system achieved localization accuracy within a range of 5 to 10 meters. (Fig. 6)

4) Test case 04: Network Stability and healing

The mobile device, simulating a victim was placed in outdoor settings where obstacles such as trees, buildings, rubble, and vehicles were introduced to simulate real disaster conditions. Distance approximation was performed in environments with minimal obstructions using RSSI data and the path loss equation in test case 03. Subsequently, obstacles were introduced at varying distances to observe their effect on signal behavior. RSSI fluctuations were measured, and the variance in estimated distances with and without obstructions was analyzed. The results indicated that RSSI-based distance approximation became less reliable in the presence of obstacles due to issues such as multipath propagation, signal absorption, and reflection, particularly from materials like metal or rubble. These effects led to significant variations in RSSI values, ultimately reducing localization accuracy in obstructed environments.

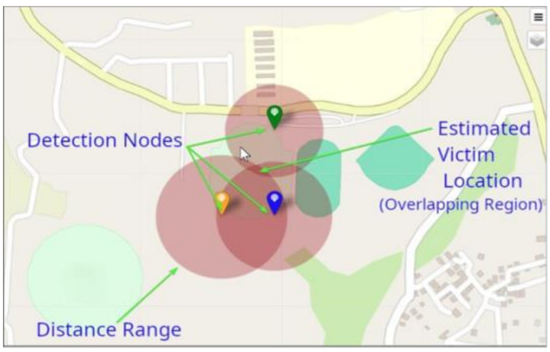

Fig. 6. Three signal capturing devices triangulating the mobile device

IV. Results & Discussion

This study focuses on building a dependable communication system for disaster situations using BLE and Wi-Fi Direct, with added support for locating affected individuals. The system was tested in real- life scenarios to assess its network reliability, accuracy in location detection, and message delivery efficiency. It consistently maintained stable connections in challenging environments, aided by a self-healing mechanism that re-established links when devices became disconnected. Even in areas with physical obstacles, the system minimizes service interruptions by dynamically rerouting data.

The SOS messaging system proved effective in ensuring reliable, real-time communication in emergencies. The encrypted messages were delivered securely and reached the intended recipients within seconds. The average message delivery time was consistent, with a response time of less than 2 seconds, which is critical in disaster communication where every second counts. The targeted messaging capability, which allows sending messages to specific nodes, helped avoid unnecessary network congestion. The system's scalability was also tested, and it showed potential for handling large-scale deployments in extensive disaster areas.

The Wi-Fi-based localization system demonstrated a reasonable ability to estimate the location of individuals within a 5 to 10-meter radius in outdoor environments with minimal obstructions. The system's use of RSSI-based distance approximation provided effective results in open spaces; however, accuracy was impacted in more complex environments. When obstacles such as rubble, vehicles, and buildings were present, significant and unpredictable fluctuations in RSSI readings were observed due to factors like signal attenuation, reflection, and multipath propagation. While the system maintained stable communication even under network congestion and overlapping Wi-Fi signals, the accuracy declined noticeably in high-density and interference-heavy environments. These results indicate that although the approach is promising for real-world disaster scenarios, further enhancements are necessary to increase its reliability under challenging conditions. Future research should focus on integrating more advanced signal filtering techniques, such as adaptive filters or machine learning-based models, to better compensate for environmental disturbances. Additionally, incorporating AI-driven methods for dynamic environment adaptation and cross-verification with supplementary sensors like GPS or inertial measurement units (IMUs) could further improve the accuracy and robustness of victim localization in disaster zones.

V. Conclusion

This research successfully presents a comprehensive solution that comprises of a decentralized, infrastructure-less, self-healing mobile ad-hoc network (MANET) utilizing Bluetooth Low Energy (BLE) and Wi-Fi direct with an encrypted SOS messaging mechanism between end devices and a Wi-Fi probe request based end device detection mechanism that estimates the location of affected individuals based on their mobile phones. Despite the system's success, several challenges were identified based on environmental factors such as physical obstructions and signal interference impacted the accuracy of the RSSI-based localization and the stability of communication links. Moreover, the scalability of the system, while promising in controlled scenarios, requires further validation in large-scale disaster environments with dense device deployments. Future improvements will focus on optimizing BLE range and performance, integrating additional technologies such as GPS or ultrasonic sensors to enhance localization accuracy, and refining the self-healing algorithm for better adaptability. Enhancing system scalability and energy efficiency will also be a key priority to ensure deployment feasibility in expansive and resource-constrained disaster zones.

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