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Enhancing Situational Awareness with LoRa Mesh Networks: Communication in Internet-Deprived Areas

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Abstract

This paper focuses on the implementation of Meshtastic firmware, showcasing its effectiveness in establishing a decentralized mesh network for communication and location tracking in areas where internet connectivity is unreliable. A thorough analysis of the system's features, including real-time device tracking and secure messaging, highlights its significant potential for military and surveillance applications in remote or off-grid settings. The decentralized mesh framework enhances resilience in dynamic environments, providing a versatile communication solution where conventional infrastructure is lacking or compromised. The experiments successfully demonstrate the real-world application of LoRa communication technology in urban settings, achieving dependable communication between sender and receiver boards over distances of up to 2 kilometers, even in the presence of potential urban interference. Additionally, this research highlights security protocols and ethical considerations relevant to the deployment of Meshtastic firmware in military and surveillance scenarios, offering insightful guidance for future studies and practical implementations.

Keywords: LoRaWAN, LoRa, RSSI, Decentralized Mesh networks, Meshtastic Firmware, Wireless Communication, Internet of Things

1 Introduction

In the 21st century, the Internet of Things (IoT) has transformed various sectors by enabling seamless connectivity and automation among billions of devices. IoT relies heavily on wireless communication, which has become indispensable for connecting a vast array of devices, from household appliances[1] to industrial machinery[2], across diverse environments. Wireless communication technologies allow IoT systems to transmit data, operate remotely, and perform real-time monitoring without the constraints of physical connections. This adaptability has enabled the development of smart cities[3], cutting-edge healthcare solutions[4], streamlined supply chains[5], and advanced infrastructure systems[6]. Wireless communication technologies in IoT systems are generally classified into short-range, medium-range, and long-range categories, each offering specific advantages in terms of coverage, data rates, and power consumption[7]. Short-range solutions, like Bluetooth [8], Zigbee[9], Wi-Fi[10], and Bluetooth Low Energy (BLE)[11], operate within a few meters to tens of meters, delivering high data rates but limited coverage, ideal for smart homes, wearables, and industrial automation. Medium-range technologies, including Cellular Networks[12] and Heterogeneous Networks (HetNets)[13], extend connectivity over hundreds of meters to a few kilometers, balancing data rate and coverage for applications like campus networks and building automation. Long-range solutions, such as LoRa[14], NB-IoT[15], and Sigfox[16], provide wide-area coverage and low power consumption, supporting applications with extensive range requirements, emergency response coordination, and secure data transmission for surveillance purposes. Figure 1 illustrates the range-based categorization of IoT wireless communication technologies

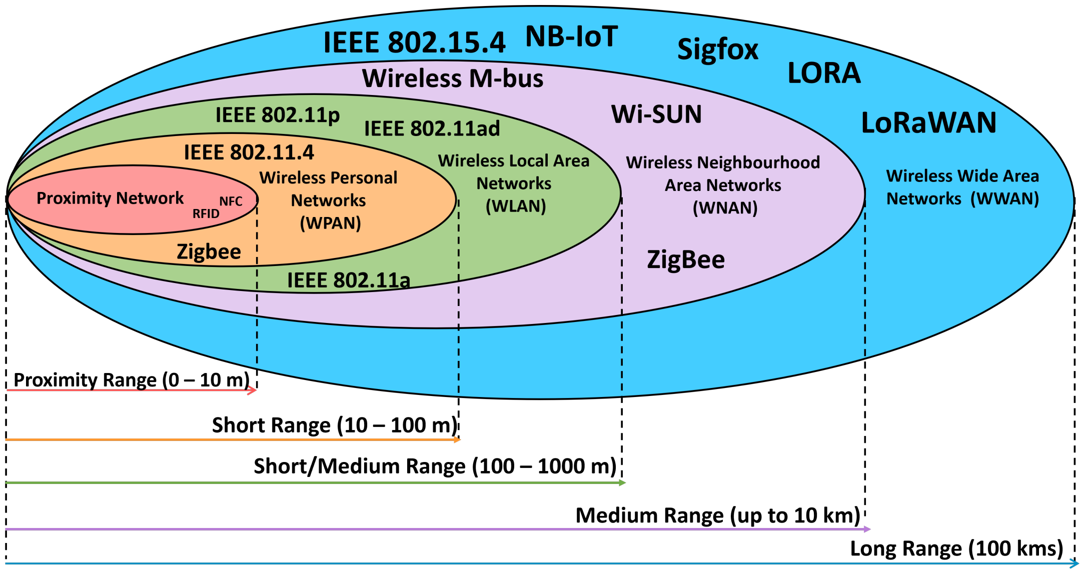

Fig. 1 Classification of Wireless Technologies for IoT Based on Range

Although traditional wireless technologies work well within their specific ranges, they often struggle to provide extended coverage and low power consumption, especially in urban areas filled with dense infrastructure and interference[17, 18]. For example, in disaster management situations[19], standard solutions like Bluetooth, Wi-Fi, and cellular networks may not offer reliable connectivity. This problem is often caused by damaged infrastructure and limited coverage in remote locations. In such cases, LoRa technology[20] stands out as a strong alternative, capable of transmitting data over long distances while using minimal power.

With its robust signal, LoRa can reach difficult indoor locations where Wi-Fi and Bluetooth struggle without the use of extenders. It ensures efficient data transmission at a lower development cost. According to studies, LoRa is ideal for smart devices that require minimal energy and don't need constant communication. These advantages help LoRa compete well on the Internet of Things (IoT) market against other technologies like Wi-Fi and Bluetooth.

2 OVERVIEW OF LORA AND LORAWAN

This section provides an overview of the LoRa physical layer and relevant MAC protocols for WSNs and LoRa-based LPWANs, with references to detailed surveys for further information. LoRa is a low-power, long-range wireless technology designed to extend battery life, support numerous connected devices, and enhance network capacity. It uses Chirp Spread Spectrum (CSS) modulation, which is patented by Semtech[21] and provides resilience against noise, aided by forward error correction. LoRa operates on open-access ISM bands (433 MHz in Asia, 868 MHz in Europe, and 915 MHz in the USA), and its MAC layer protocol, LoRaWAN, is standardized by the LoRa Alliance[22]. With its pseudo-random signal spreading, LoRa achieves basic security and is well-suited for IoT applications, especially where long-term, low-power communication is essential. The line-of-sight communication range for LoRa may extend up to 10 km, influenced by the specific Spreading Factor (SF). Through its unique modulation technique, LoRa allows users to adjust data rate and range by changing the SF, with the relationship specified in Equation 1[23], where both data and symbol rates depend on SF and bandwidth.

$$R_b = \frac{B * S}{2^s} \tag{1}$$

Where B represents the bandwidth, Rb denotes the data rate, and S signifies the Spreading Factor; increasing the range necessitates a reduction in the data rate, and vice versa. LoRaWAN outlines the communication protocol and system architecture, whereas LoRa focuses on the physical layer. It operates on a long-range star architecture that enables gateways to relay messages from end devices to a central core network, which includes end devices, gateways, and various back-end servers, such as the network server and application server. The network architecture is shown in figure 2.

- End Devices: These are sensors or actuators that send and receive LoRa-modulated wireless messages to and from gateways. They transmit data using the LoRa physical layer.

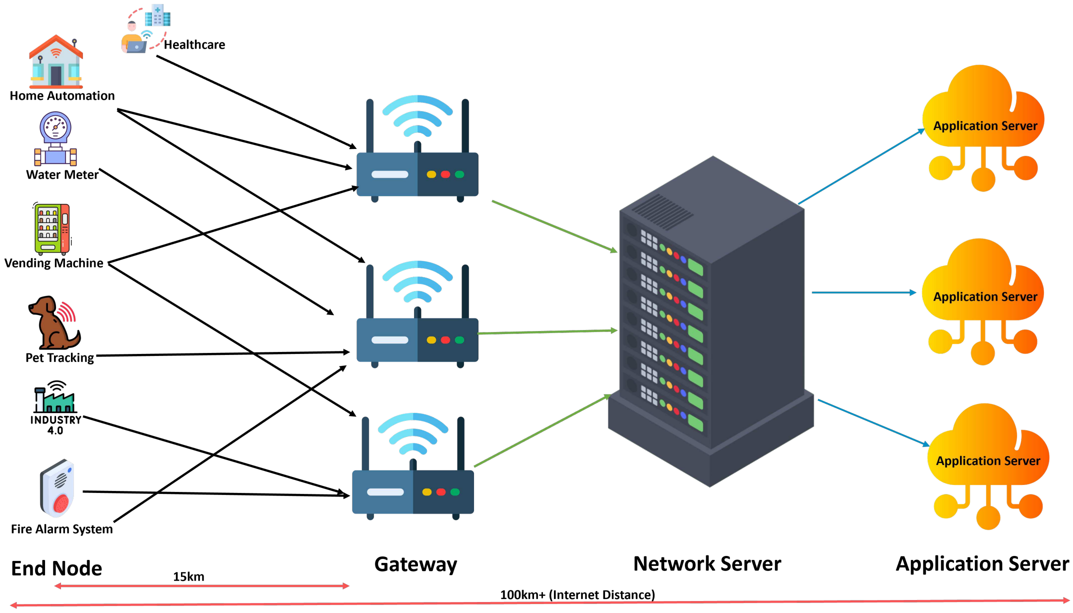

Fig. 2 A Typical LoRaWAN Network Architecture

- Gateway: Serving as intermediaries, it receives data from end devices and forwards it to the network server. They use fast IP backhaul connections, such as Ethernet or cellular networks, to relay messages without needing a prior search for a gateway.
- Network Server: It is software that manages the entire network. It handles tasks like removing duplicate packets, sending confirmations through the right gateway, and adjusting data rates based on current network conditions.
- Application servers: It is responsible for processing data securely and ensuring that the information from the network server is utilized properly by different applications.

LoRaWAN divides its end devices into three classes to address different application requirements[24–26]. Class A devices, which are bidirectional, are designed for energy efficiency and remain in sleep mode until an uplink message needs to be sent. Once activated, they open two reception windows for potential downlink communication and initiate the communication process. Class B devices also support bidirectional communication but can open additional reception windows periodically through beacons, allowing the server to control transmission timing. Class C devices keep their reception windows continuously open, except when they are transmitted, resulting in increased energy consumption. These devices are suitable for applications with a constant power source, as they significantly reduce latency.

LoRaWAN primarily operates on star, tree, or the widely used star-of-stars topology, where end devices (nodes) communicate with gateways that relay information to a central network server. This configuration allows thousands of devices to connect to gateways, which then transmit the data[27]. Figure 3 illustrates the star-of-stars

LoRaWAN architecture. However, a drawback is that if a gateway fails, the end devices in that area lose communication since they cannot interact directly with one another.

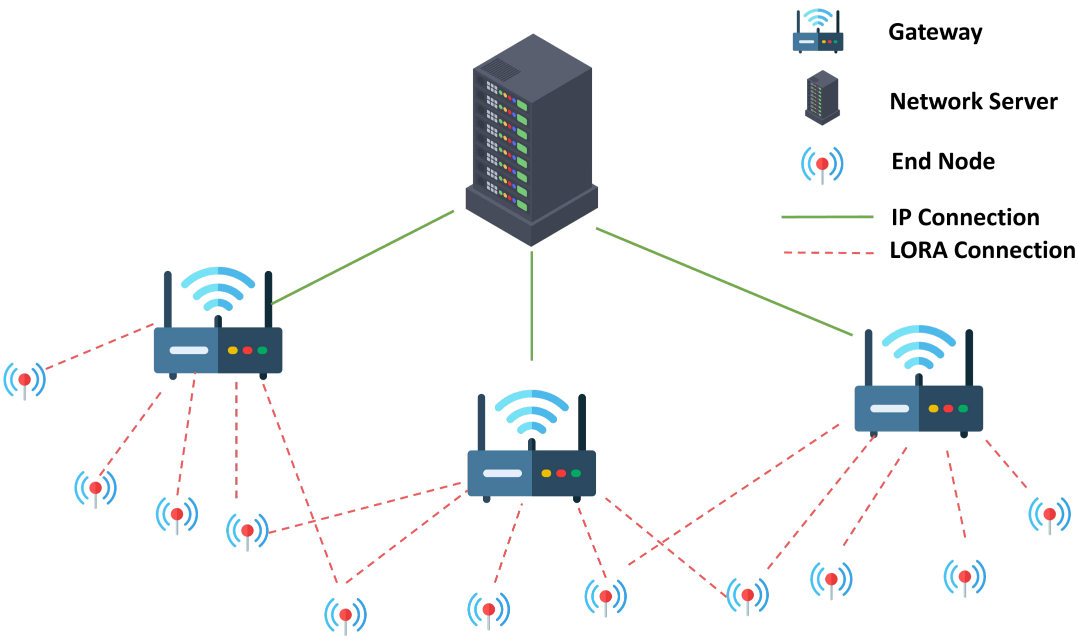

Fig. 3 LoRaWAN Star of Star Network Architecture

To address this limitation, a LoRa Mesh network system has been introduced. In this framework, network nodes are dynamically connected in a non-hierarchical manner, allowing for many-to-many communication. These nodes work together to efficiently route data from any source to any destination. A mesh topology operates as a multi-hop network, where packets traverse multiple hops to reach their destination. This architecture can be easily expanded by adding new devices, enabling any device to communicate with any other within the network[28]. Figure 4 illustrates the LoRaWAN architecture featuring a mesh topology

3 EXPERIMENTAL SETUP

The LILYGO T-Beam LoRa32 board features a powerful ESP32 microcontroller, delivering robust processing capabilities along with various connectivity options. It integrates an SX1276 LoRa module operating at a frequency of 433MHz for long-range, low-power wireless communication and includes a GPS Neo-6M module for accurate location tracking. This board is utilized in our situational awareness experiment, where Figure 5 illustrates the LILYGO T-Beam functioning as a gateway.

A series of experiments were conducted in urban areas of Ahmedabad, India, at an elevation of 53 meters, to study the relationship between distance and RSSI values.

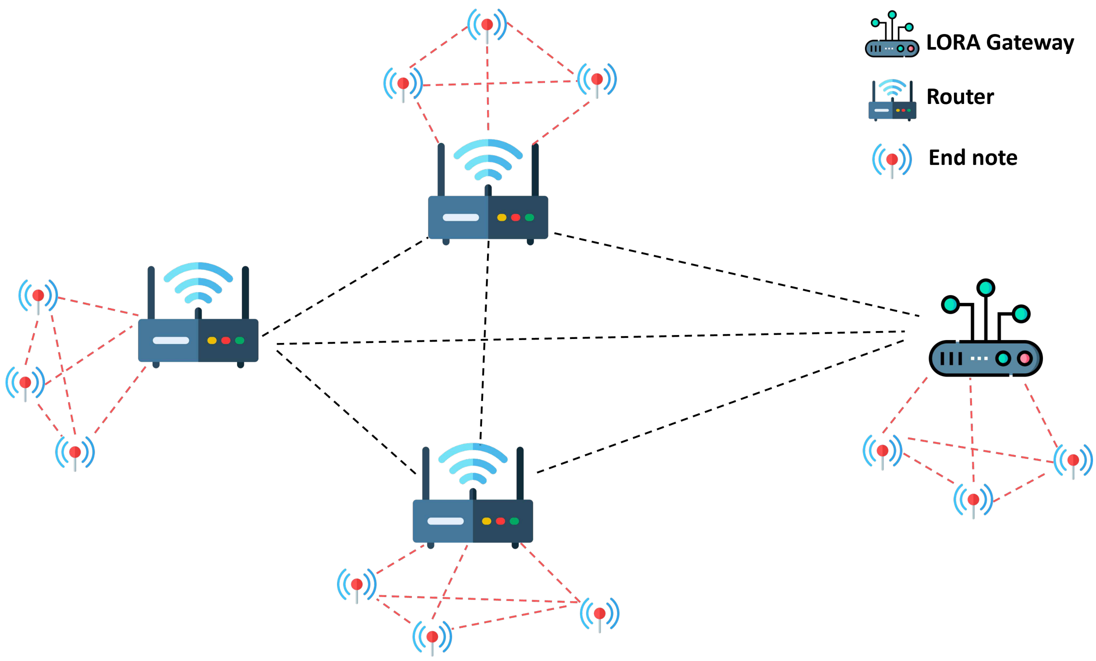

Fig. 4 LoRaWAN Mesh Architecture

Two experiments were carried out using LoRa modules, focusing on different aspects of long-range wireless communication. In the first experiment, a LoRa module tuned to 433 MHz was utilized as the sender. It transmitted data packets containing a counter and the phrase "HELLO WORLD" at one-second intervals. The receiver module was responsible for receiving and displaying this data in real-time. The experiment was conducted in an open outdoor space with few obstructions, ensuring a direct line of sight between the sender and receiver. Communication was established at a baud rate of 115200 bps.

The sender was fixed at a specific location known as Point A (coordinates: 22° 59' 45.6" N, 72° 33' 57.2" E), serving as a reference point for distance measurement. The receiver module, connected via USB to a mobile device for monitoring, was systematically moved away from Point A in a straight line. The received signal strength indicator (RSSI) was observed and recorded at each distance increment. This setup facilitated a comprehensive assessment of how distance influenced RSSI values, providing insights into the impact of environmental factors on signal quality. The figure 6 illustrates the selected location for conducting LoRa mesh network experiments.

In Experiment 2, the focus shifted toward enhancing the communication range of LoRa modules while investigating the mesh networking capabilities enabled by Meshtastic firmware. Utilizing LilyGO T-Beam LoRa modules, three devices were strategically positioned at specific locations: Point A (the reference point at 22°59'45.6"N, 72°33'57.2"E), Point B (1.5 km from Point A), and Point C (3 km from

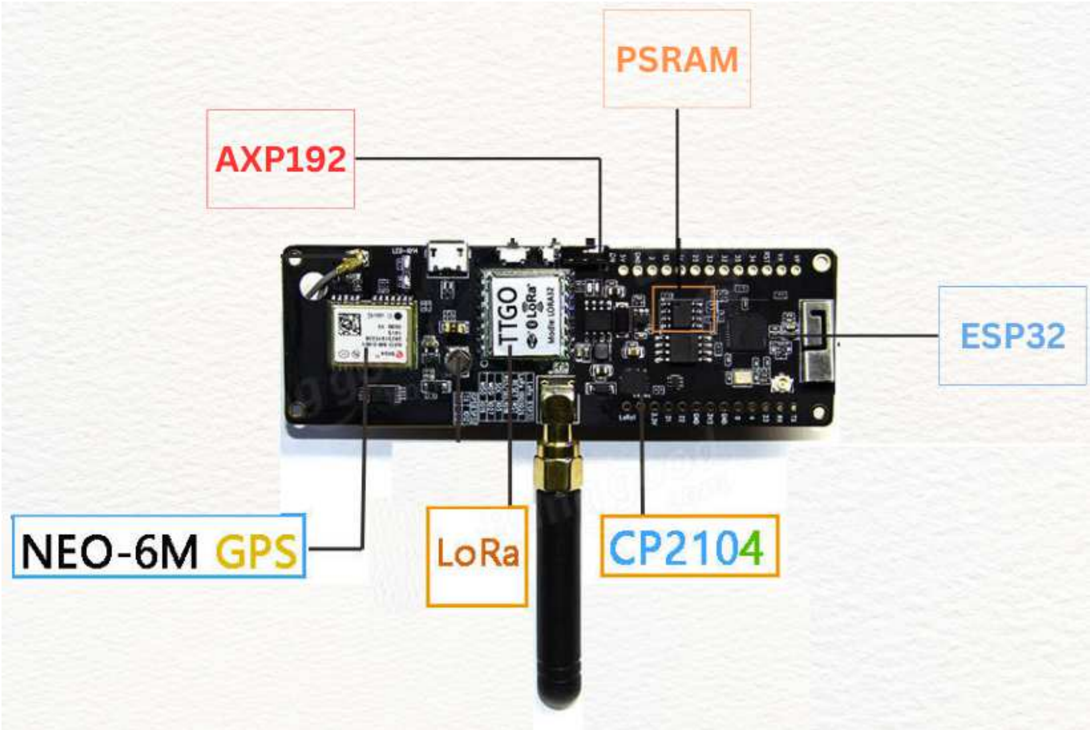

Fig. 5 TTGO T-Beam Board Use for a LoRa Gateway

Point A). This configuration established a decentralized mesh network, allowing for long-distance data relaying.

In this setup, mobile devices communicated with the LoRa modules via Bluetooth, transmitting data or commands that were subsequently broadcast using the LoRa radio. Each module served as a relay within the mesh network, allowing data packets to hop from one module to another until reaching their intended destination. This configuration enabled extensive data exchange without relying on conventional internet infrastructure, making it suitable for various applications, including remote communication during outdoor activities and reliable IoT data transmission. Figure 8 (a) demonstrates this configuration.

The experiment also included a situational awareness test involving three modules named Alpha, Charlie, and Dhvl. The Charlie module employed a pinning technique to identify an "enemy" position and relayed this information to the other modules in the network. The Alpha and Dhvl modules successfully accessed this precise location data through the Meshtastic app, illustrating the practical utility of situational awareness within the mesh network. This experiment showcased the robustness and flexibility of the dynamic routing mechanism, where modules could automatically reroute data

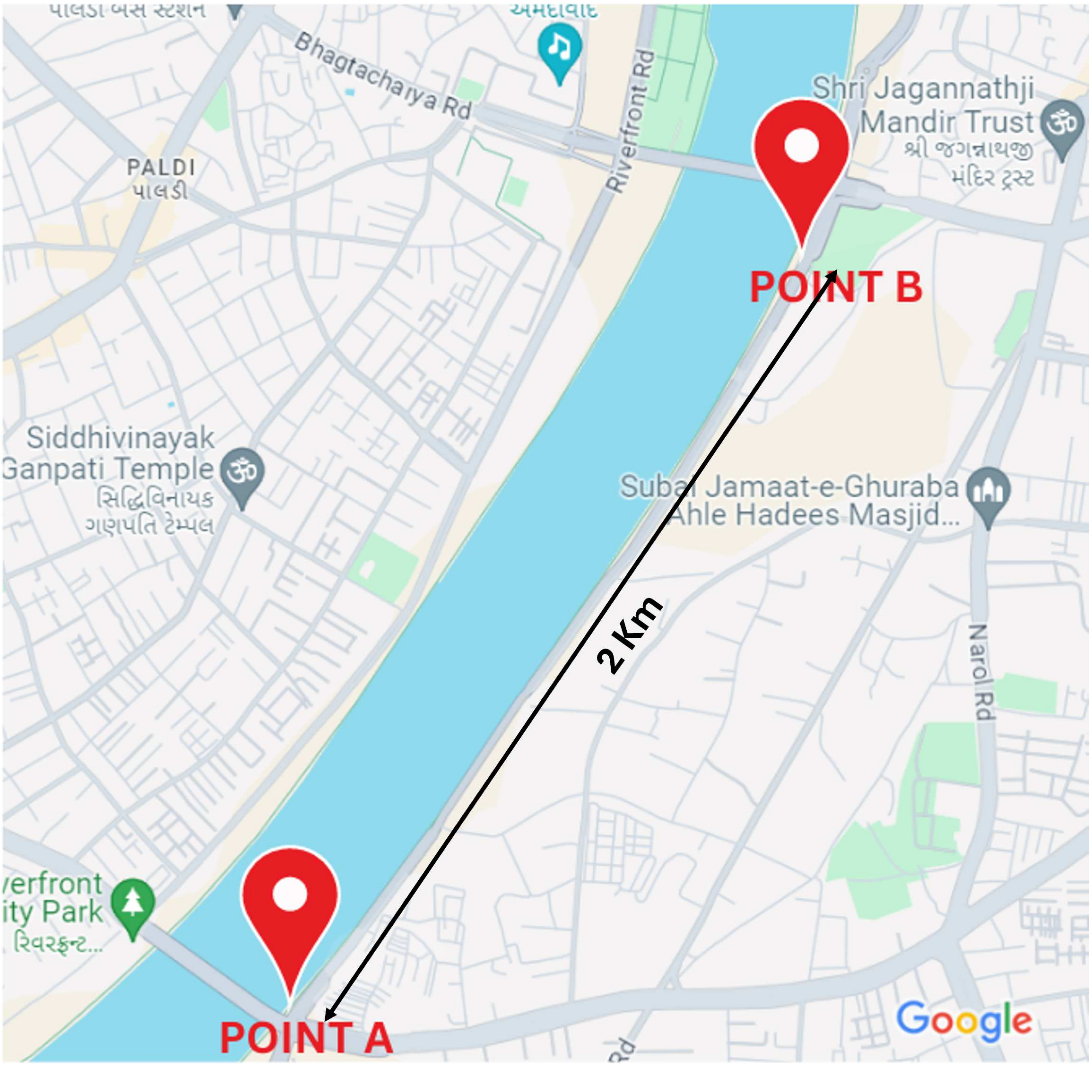

Fig. 6 LoRa Mesh Network Test field for Experiment

if one module went offline, ensuring efficient communication even in changing network conditions. Figure 8(b) shows the three LoRa modules equipped with Meshtastic firmware.

3.1 Role of RSSI in Communication

The Received Signal Strength Indicator (RSSI) is an essential parameter that measures the strength of signals from end devices, thereby indicating communication reliability.

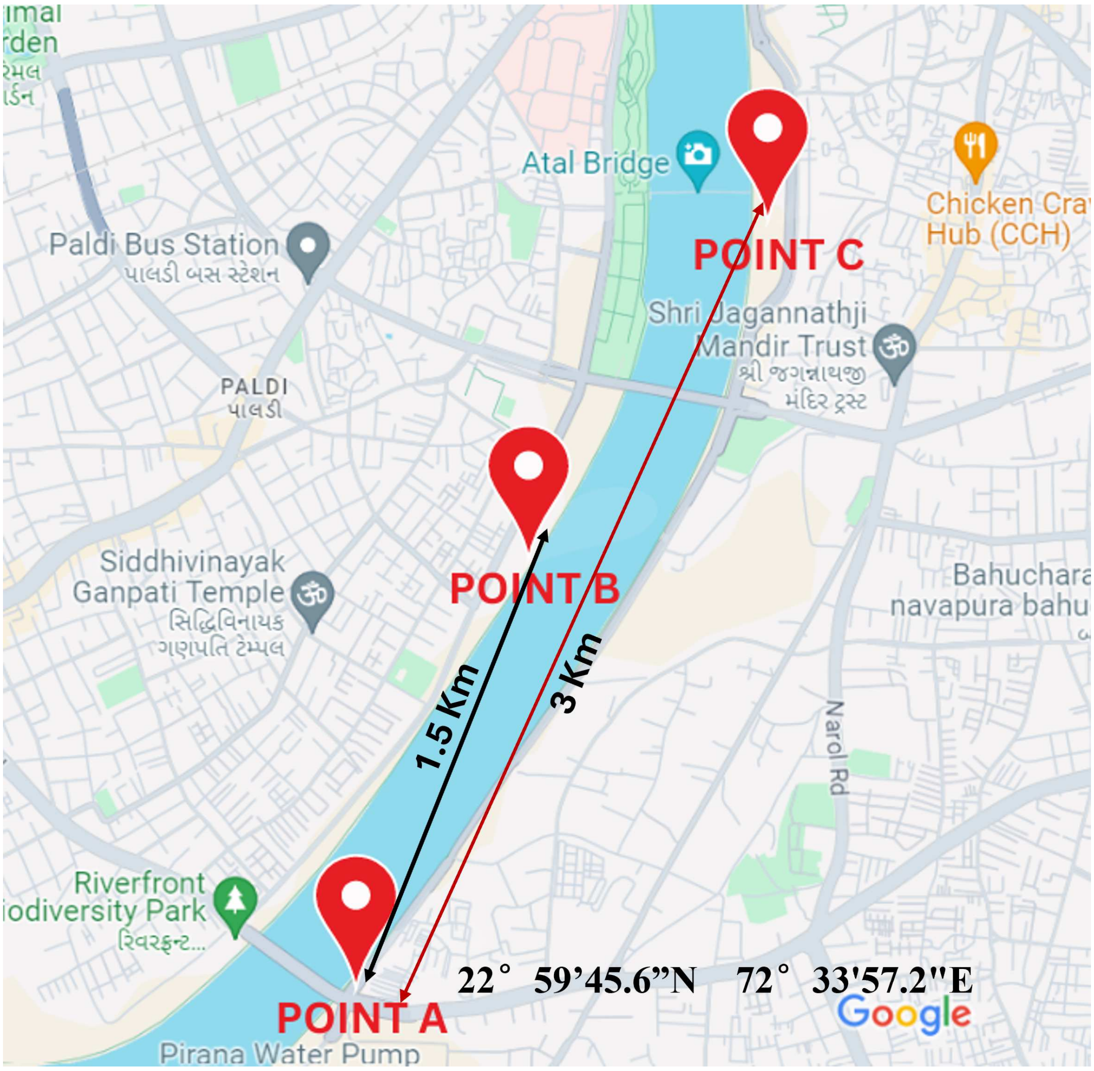

Fig. 7 Map Showing analyzing area with LoRa Mesh Gateway

A value closer to 0 dBm signifies a stronger signal. Environmental factors, including distance (d) and obstacles, can lower RSSI as the distance from the transmitter increases. Typically, RSSI values range from 0 dBm (indicating the strongest signal) to -120 dBm (indicating the weakest signal). In a LoRa mesh network, RSSI can be calculated as follows

$$RSSI = -10p \log_{10} d + A \tag{2}$$

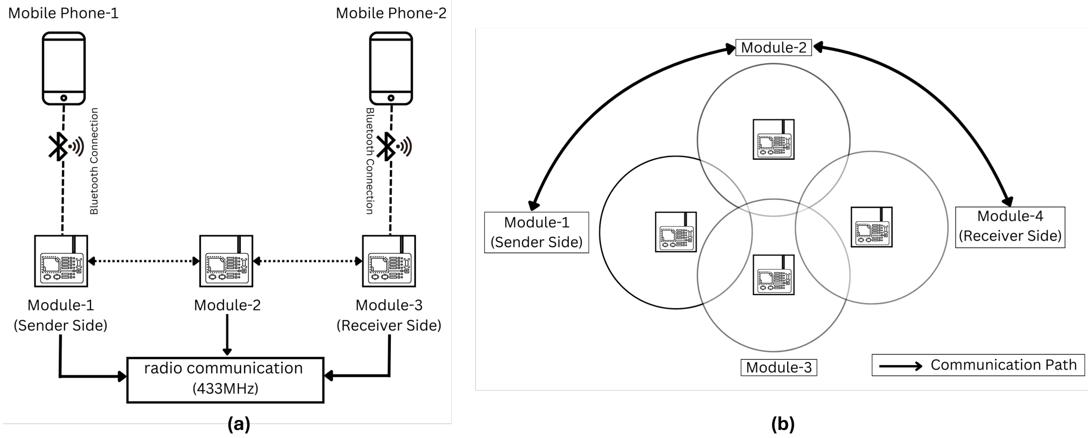

Fig. 8 Mobile to Module Communication setup

Where p is defined as the propagation constant, ddd denotes the distance between the transmitter and receiver in meters, while A represents the received signal strength in dBm at one meter.

4 RESULTS AND DISCUSSION

An analysis of the Received Signal Strength Indicator (RSSI) values provided key insights into the effective communication range between the sender and receiver modules. Experiment 1 demonstrated that the messaging range extended to approximately 2 kilometers. When the modules were co-located, RSSI values were observed to be between -20 dBm and -30 dBm. However, at the maximum distance of 2 kilometers, RSSI values dropped significantly, falling within the range of -110 dBm to -120 dBm. Figure 9 illustrates the relationship between RSSI and distance graphically.

The Received Signal Strength Indicator (RSSI) was significantly affected by environmental elements, including terrain features and the proximity of water bodies. RSSI variations were particularly evident under varying environmental conditions; for instance, when trees or walls obstructed the line of sight between modules, signal degradation occurred. Conversely, proximity to water bodies such as riverbanks appeared to enhance RSSI strength, indicating a potential boost in signal quality in those areas.

In Experiment 2, the mesh network effectively enhanced communication range among the modules, enabling seamless messaging across distances of up to 3 kilometers. With the modules strategically placed at points A, B, and C (0 km, 1.5 km, and 3 km), strong connectivity was demonstrated, ensuring successful data transmission even at maximum node separation. Additionally, the situational awareness experiment showcased the mesh network's ability to improve coordination and information sharing among nodes, including the sharing of the location of a suspicious person. The precise location data from the Charlie module was seamlessly accessed by the Alpha and Dhvl

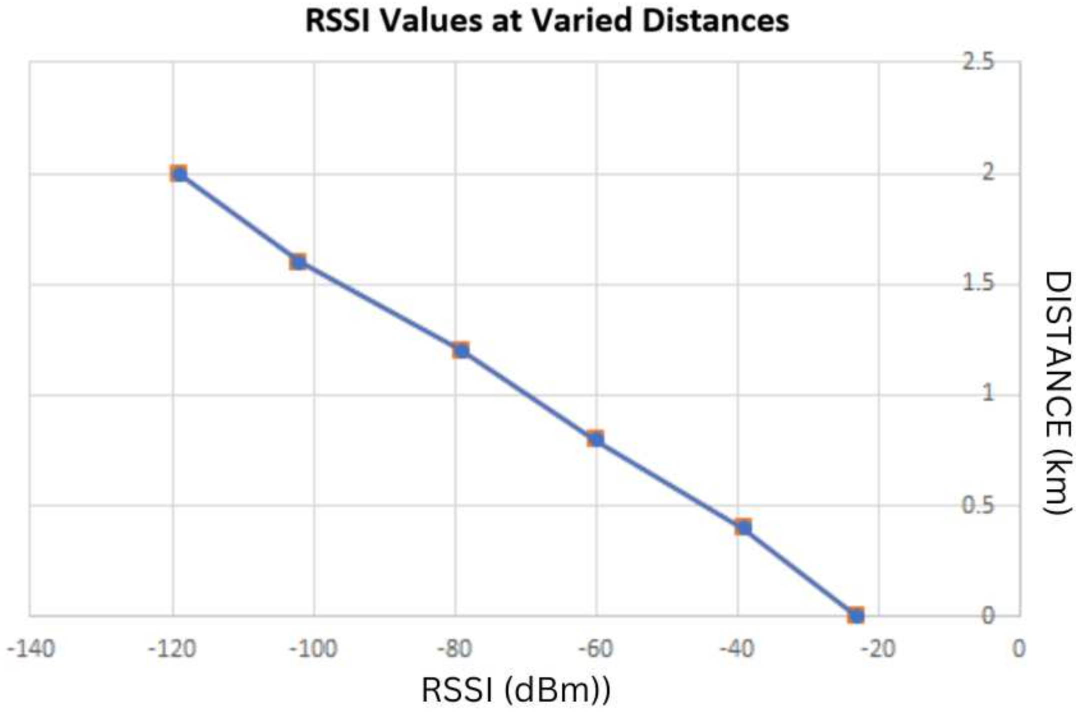

Fig. 9 RSSI Value at Different Experiment Locations

modules through the Meshtastic app, facilitating real-time tracking and collaboration in dynamic environments.

In Figure. 10, it is shown that the module 'Dhvl' successfully transmitted messages to the module 'Alpha' via a dedicated communication channel. Furthermore, the figure illustrates that the messages sent by 'Dhvl' were also visible to all modules within the general channel, demonstrating the effective dissemination of information across the mesh network.

In Figure. 11, the module known as Charlie (Char) used a pinning technique to pinpoint the enemy's position and broadcast this information to the other modules in the mesh network. The Alpha (Alfa) and Dhaval (Dhvl) modules successfully accessed the precise location data provided by the Charlie (Char) module.

5 CONCLUSION

The experiments successfully quantified the messaging range between two LoRa modules in an outdoor environment, demonstrating a maximum effective distance of approximately 2 kilometers. The significant fluctuations in the Received Signal Strength Indicator (RSSI) values highlight the impact of environmental factors on wireless communication performance, specifically concerning terrain features and

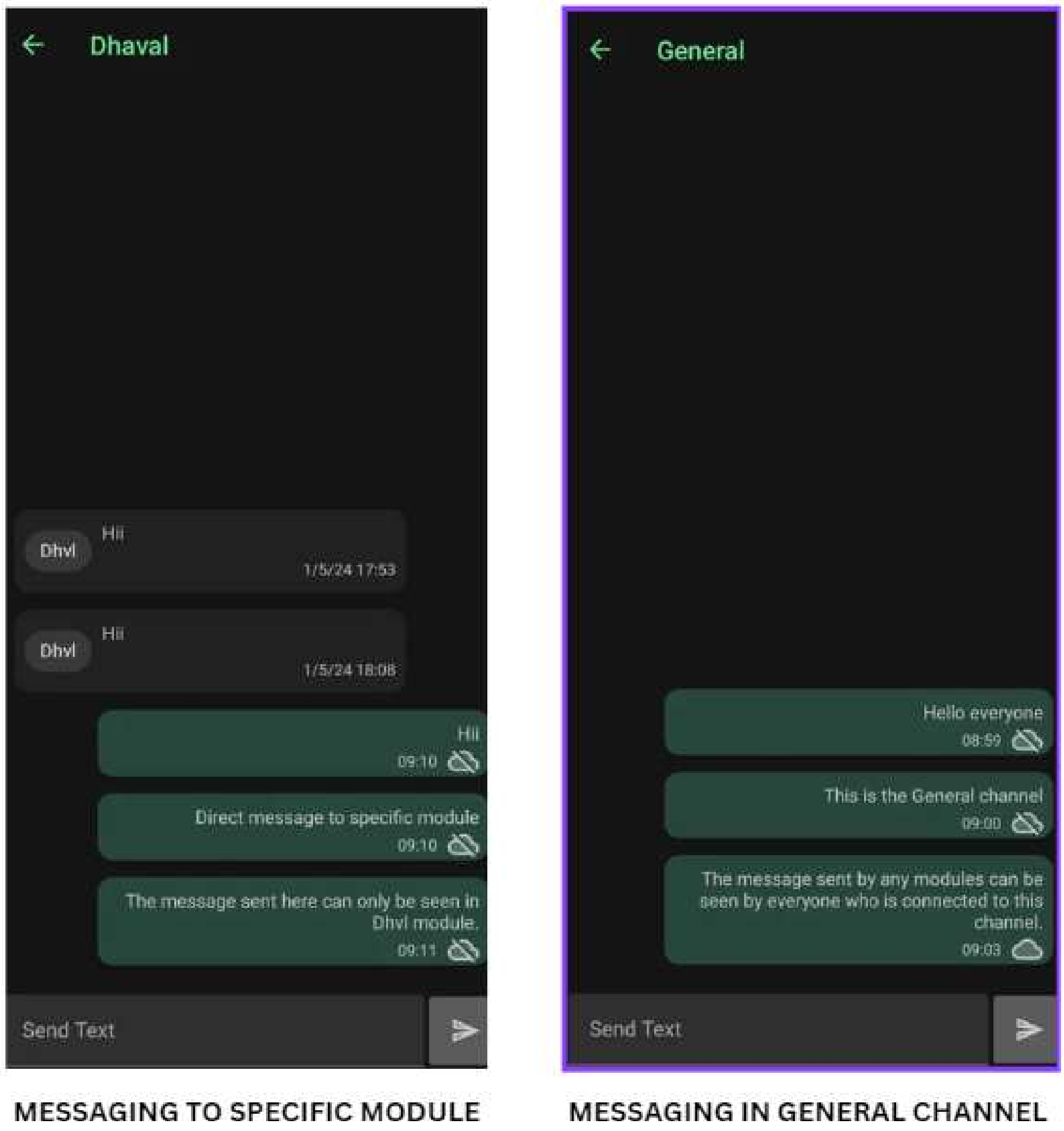

Fig. 10 Comparative Analysis of Messaging in Individual and General Channels

obstacles. This underscores the importance of meticulous planning for LoRa-based deployments. The second experiment effectively expanded communication capabilities by utilizing a mesh network through Meshtastic firmware, extending the communication range to 3 kilometers. This mesh network not only facilitated seamless messaging between modules but also demonstrated situational awareness techniques, showcasing

The module named charlie (Char) marking enemy

The Alpha and Dhvl modules are able to access the enemy position

Fig. 11 Comparative Analysis of Messaging in Individual and General Channels

its ability to enhance communication and coordination in scenarios requiring real-time location tracking and information sharing. Overall, these results illustrate the adaptability and effectiveness of LoRa technology in diverse environments.

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