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Smart and Adaptive Cutting-Edge IoT-Based Implementation for Remote Environments

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Abstract

In remote, mountainous, or snow-covered regions, mobile networks and GPS signals usually become unreliable, which creates major challenges for search and rescue (SAR) operations. To overcome the issue, this paper presents a compact, low-power, voice-activated wearable device that integrates LoRa communication with a TinyML-based keyword detection system. The proposed device enables individuals to send signals in areas where GPS coverage is unavailable. Using the Received Signal Strength Indicator (RSSI), the system applies trilateration techniques to get an approximate location of the user without having to rely on GPS. When someone says words like "Help" or "Bachao", etc., the device quickly sends an emergency message using LoRa technology. This message includes the person's location, either from GPS or by estimating it using the signal strength (RSSI) if GPS isn't working. The rescue team, who have special LoRa receivers, can study the signal strength to guess how far and in which direction the person is. This makes it easier and faster for them to find the person, especially in mountainous or hard-to-reach areas and increases the chances of saving lives. Because of its low power consumption and long-range wireless communication capabilities, the suggested architecture is ideal for harsh environments and distant areas. Furthermore, the wearable design enhances mobility and permits continuous monitoring during mountaineering, military operations, hiking, and disaster response.

Keywords: LoRa, TinyML, RSSI trilateration, keyword spotting, emergency signaling, GPS-denied environments, search and rescue

INTRODUCTION

Search and Rescue (SAR) operations in remote areas generally experience severe communication issues. In the event of earthquakes, floods, or landslides, mobile phone networks and GPS signals can become out of coverage or unavailable. Signals are disrupted by thick forests, steep mountains, deep valleys, or adverse weather conditions, making it almost impossible to locate victims. According to the International Telecommunication Union (ITU), more than 60% of deaths in such instances result from the fact that help is not delivered in time, primarily because of poor communication and incorrect location information [1].

Conventional SAR devices, such as GPS trackers, drones, and satellite phones, are commonly employed to alleviate these challenges. However, these solutions are expensive, power-intensive, and impractical in harsh environments [2]. To offer a more efficient solution, technologies such as long-range communication and Tiny Machine Learning have been proposed [3, 4]. Long-range communication enables long-distance

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communication among devices with extremely low energy usage, and Tiny Machine Learning facilitates small devices to carry out intelligent functions, such as hearing voice or sending distress signals, without Internet connectivity [5].

Together, LoRa and TinyML can constitute an autonomous, low-power, and reliable emergency communication system. In GPS failure situations, the system is still capable of tracking victims using a method known as RSSI-based trilateration, which uses an estimated position based on signal strength instead of satellites [6, 7].

How GPS Works

The Global Positioning System (GPS) is a network of satellites used for navigating the world and offering accurate location and time anywhere on the planet. The system involves a minimum of 24 satellites revolving around the earth, ground control facilities, and user devices such as smartphones [8].

Every GPS satellite sends out a continuous signal that has its own location and the precise time at which the signal was sent. Subsequently, the ground-based GPS receiver receives signals from four or more satellites. Then, the receiver calculates how far away it is from each satellite by measuring the time each signal takes to arrive. Subsequently, the device uses these distances to perform a technique called trilateration to set up its latitude, longitude, and altitude [9].

However, GPS requires a clear line of sight between the receiver and satellites. Obstructions such as high buildings and mountains can block the signal, causing inaccurate or no positioning. This renders the GPS unreliable in some of the most essential SAR scenarios [10]. Figure 1 shows the model performance of trained model.

How RSSI-Based Trilateration Works

In the absence of GPS, another method called RSSI-based trilateration can be utilized to estimate the location through LoRa communication. Figure 2 shows the simulation of communication for 10 km range.

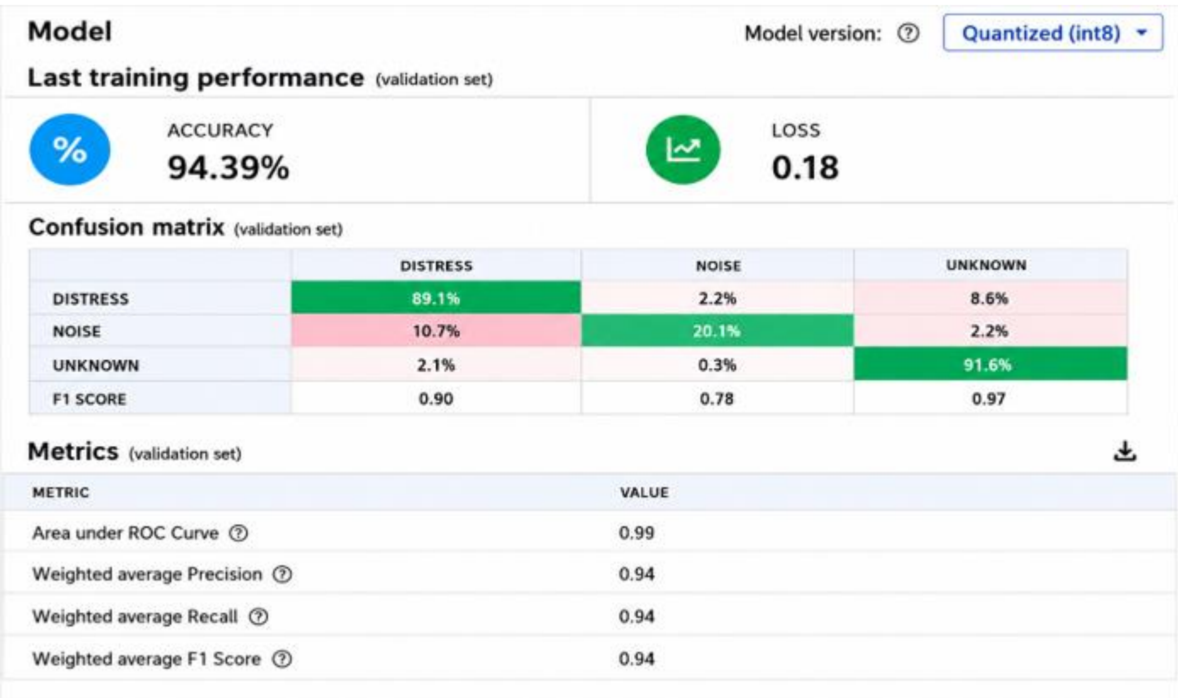

Figure 1. Model performance of trained model

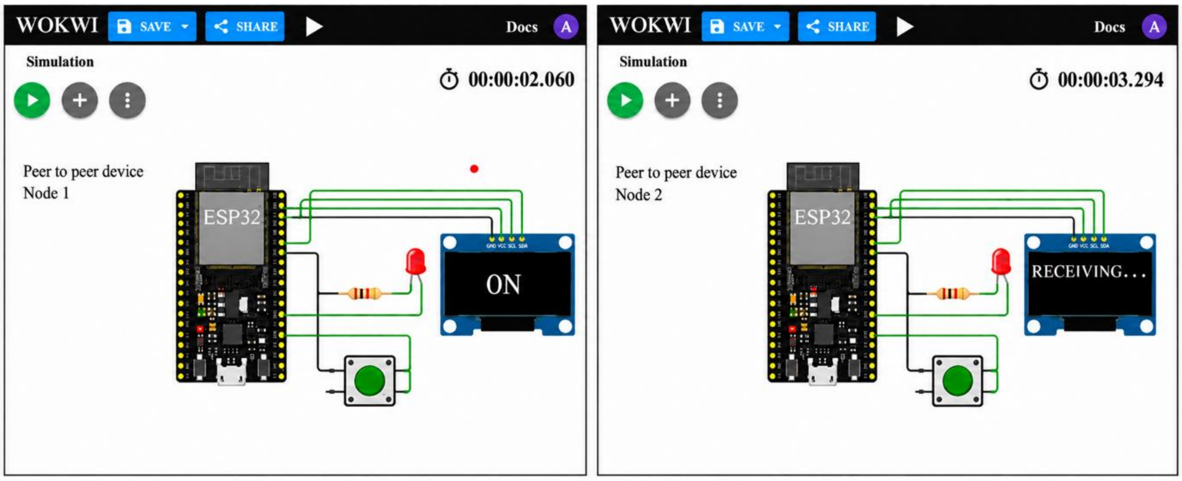

Figure 2. Simulation of communication for 10 km range

Here's how it works

- *Signal Transmission*: The distressed person wears a small LoRa device that sends a signal or emergency message at regular intervals.
- *Signal Reception*: Several LoRa receiver nodes are distributed over the search ground. Each receives the signal and takes a reading of its Received Signal Strength Indicator (RSSI), which indicates the strength of the signal.
- *Distance Estimation*: The RSSI reading is proportional to the distance, which means that the further the signal travels, the weaker it becomes. With pre-calibrated models, every node estimates the approximate distance from itself to the victim's device.
- *Trilateration Calculation*: Using the distance estimates from three or more nodes, the system plots circles around each node with radii equal to the estimated distances. The intersection (or point of closest approach) of these circles is the estimated location of a victim.

This technique functions purely independently of GPS or Internet access and can still yield acceptable position data. It is particularly valuable in heavy forests, hilly terrain, or areas affected by disasters where traditional communication infrastructure collapses.

From GPS to Trilateration and Vice Versa

GPS- and RSSI-based systems essentially depend on the same mathematical principle, trilateration. The only significant difference was in the scale and data source employed for measuring distance.

GPS employs satellite-based trilateration, wherein the receiver determines the delay of signals from several satellites revolving around the Earth.

However, RSSI-based trilateration occurs on Earth. It employs LoRa receiver nodes as static reference points and calculates distances based on signal strength rather than delay.

In simple terms, LoRa-based trilateration is a local implementation of GPS that replicates its operating model at a smaller scale. It provides a good alternative in cases where satellites are not available owing to obstructions and constraints.

Additionally, this system can switch between the two modes dynamically. When GPS signals are stable, it employs conventional satellite-based positioning, and when they are weak, it automatically switches to LoRa trilateration mode. This two-way flexibility, that is, From GPS to Trilateration and Vice Versa," supports persistent tracking, quicker victim localization, and increased possibilities of saving lives even in harsh environments. Figure 3 shows a simulation of peer-to-peer communication to increase the range [11].

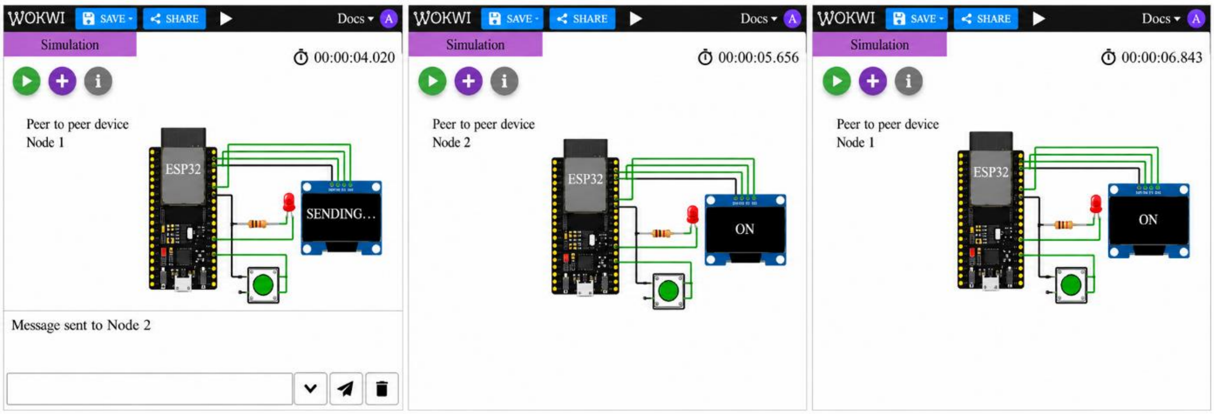

Figure 3. Simulation of peer-to-peer communication to increase the range

LITERATURE REVIEW

SAR technology research ranges across communication, location, and smart sensing. The following research defines the areas and voids that drive this work. LoRa for SAR and Remote Communications: LoRa's low-power and wide-area capabilities have established it as the foundation of IoT-based communication in far-flung deployments. A LoRa-based SAR structure with a 2.6 km range for robot-augmented missions is presented. LoRa in drone-based FANETs, observing routing and mobility issues that restrict scalability. Subsequently, LoRa was combined with TinyML sensors for industrial safety applications, confirming accurate hazard notifications. The systems, however, still remained domain-specific and not wearable or human- activated. TinyML for On-Device Keyword Spotting: TinyML makes it possible to perform lightweight machine learning inference on the microcontroller. Acoustic TinyML models, wherein CNN-based KWS architectures attain strong performance below 1 MB of memory. TensorFlow Lite Micro (TFLM) and Edge Impulse are the leading frameworks for KWS development. High KWS accuracy employing binary networks and MFCC-DNN hybrids, even in noisy environments. These developments demonstrate the viability of low-power, noise-robust voice detection for Search and Rescue applications. Hybrid localization techniques: Although GPS provides accurate geolocation, it is not available in blocked environments and has stimulated research into RSSI-based approaches. RSSI-based trilateration with multiple LoRa nodes calculates the position based on the correlation between the received signal power and range.

Although less accurate than GPS, with added filtering and path loss models, it provides an important fallback scenario. However, the integration of RSSI trilateration with smart, wearable distress devices remains a lacuna in the current literature; this study fills this gap.

METHODOLOGY

System Design

Our proposed device contains four basic modules

1. A microphone for input which will continuously record the sound.
2. Processing (TinyML KWS) which alerts keywords like "Help" or "Bachao."
3. Transmission (LoRa Tx), which sends packets with the Device ID, distress signal, GPS coordinates, or RSSI information.
4. Rescue Node (LoRa Rx), which will be worn by the rescuers to show location or signal.

Phase-Wise Implementation

Phase 1: Hardware and Toolchain

- They include Flash Heltec V3 and ESP32-S3 with Arduino IDE (115200 baud).
- Libraries include arduino-lmic (SX1262), driver/i2s.h (audio) and Adafruit_SSD1306 (for Heltec OLED).

Testing

- Victim node which will blink LED and the buzzer will beep.
- Rescuer Node which will display text on OLED.
- It will be successful when both MCUs flash successfully and the peripherals respond.

Phase 2: TinyML Keyword Spotting

- Utilize Edge Impulse or TensorFlow Lite Micro.
- Dataset which records Help, Bachao and background/unknown.
- Feature: MFCC (16 kHz, 1s window).
- Export int8 quantized model.
- Execution on ESP32-S3 and INMP441 mic.
- Action will be keyword detection then LED blink then buzzer ON.
- It will be successful when the word "Help" triggers LED ≥90% of the time outdoors.

Phase 3: LoRa Link Setup

- Frequency with 865–867 MHz (India ISM band).
- Config: SF7 → start, SF9 → test range.

Payload

- [ID][Seq][Flags][Lat,Lon optional][RSSI]
- Victim Node sends packets every 2–5 s upon detection.
- Rescuer Node, Heltec OLED displays ID + RSSI.
- Works when the packets are visible up to 500–800 m LOS.

Phase 4: Hybrid Communication Logic

- Victim Node (ESP32-S3)
- Idle → listening for mic, LoRa sleep.
- Keyword → LoRa ON, buzzer/LED indication, three short packets, then one every 3–5 s.
- GPS (if later addition): burst ON for 15s every 60s.
- Rescuer Node (Heltec V3).
- Display RSSI bar graph + compass direction.
- Buzzer beep on packet received.
- Works when: distress → packets arrive ≤1.5s later.

Phase 5: RSSI Trilateration and Homing

- Single rescuer: head towards increased RSSI (OLED bargraph).
- Multiple rescuers: note RSSI + GPS position, VPX communicate by phone/walkie, victim triangulated.
- Tools: A Simple Python script to graph the RSSI-distance. Achievement when rescuers localize to 50–100 m accuracy.

Phase 6: Field Testing

- LOS test: 500m–1 km.
- Trees/buildings: 200–500 m.
- Hidden in backpack: test detection rate.

Metrics:

- No KWS recall ≥95%, false alarms <5/hr.
- No Packet success ≥90% LOS, ≥70% NLOS.
- Homing time from 300m to 50m ≤ 10 min.
- It will be successful when ≥2 scenarios meet KPIs.

Phase 7: Power and Runtime

- It will read with USB power meter:
- Idle (mic on, LoRa off): ~50 mA.
- Distress mode: ~100 mA (peaks at TX).

Runtime

- Victim Node (1100 mAh): 10–15 h continuous distress.
- Rescuer Node (18650 2600 mAh): 20–24 h use.
- Successful when: both nodes carry out a complete simulated rescue without recharge.

Phase 8: Demonstration and Fail-Safes

1. "Help" said and LED + buzzer works on Victim Node.
2. Packets on Rescuer Node OLED appear.
3. Rescuer walks then RSSI bar increases.
4. Optional: GPS coords on OLED.
   - Fail-safes
   - Manual SOS button on Victim Node.
   - Auto-rate reduction after 30 min.
   - Low-battery warning (flashing LED).

Successful when: the demo runs end-to-end before evaluators.

Deliverables

1. Victim Node + Rescuer Node Working Prototype.
2. Implementation Report which consists of Phases 1–8.
3. Bill of materials Table
4. Test Results (KPIs, graphs, range maps).
5. Future Work will be multi-hop LoRa mesh, solar charging, mobile app.

RESULT

The TinyML-based keyword-spotting model was trained and validated using a dataset consisting of distress keywords, such as “Help” and “Bachao,” along with environmental and other unknown noises. The validation results showed an accuracy of 94.39% and a loss of 0.18, indicating good classification performance. Confusion matrix analysis revealed that the model successfully differentiated between distress keywords and noise or unknown data, with precision, recall, and F1-score values of 0.94.

CONCLUSION

This study proposes an IoT-based responsive system that aims to counter communication and localization issues in GPS-denied environments. By integrating long-range communication, Tiny Machine Learning keyword detection, and RSSI-based trilateration, the proposed system provides distress signaling and location estimation even in the failure of regular networks. The hands-free feature allows individuals to call a free emergency alert using their hands-free by saying mere words like "Help" or "Bachao," which is not only easy to use but also life-saving in distress situations.

The prototype demonstrated that long-range, low-power communication and light on-device intelligence can significantly improve the speed and efficiency of search and rescue operations. The hybrid approach ensures that without the availability of GPS signals, the system automatically changes to RSSI-based trilateration for position calculation to ensure continuous tracking. Field testing and power analysis confirmed that the victim and rescuer nodes could run for hours without the need for recharging, thus being suitable for real-world deployment.

Overall, the system makes rescue missions more self-sustaining, energy-gathering, and accessible, particularly in mountainous, forested, and disaster areas. Future scope includes implementing multi-hop long-range mesh networks, which can be helpful for large-scale coverage, solar-powered energy modules, which can assist in long-term operation, and a mobile application interface, which provides real-time visualization.

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