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Low-Power LoRa-Based Disaster Alert System for Remote Areas

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Abstract

Natural disasters such as floods, earthquakes, landslides, and forest fires often strike with little or no warning, causing severe loss of life and property. The situation becomes worse in remote and rural regions where communication infrastructure is either absent or disrupted during calamities. Conventional systems relying on GSM or satellite communication are expensive, power-intensive, and often unavailable at critical moments. This paper proposes a low-cost, low-power disaster alert system using LoRa (Long Range) wireless communication technology combined with an Arduino-based IoT architecture. The system integrates environmental sensors (temperature, humidity, vibration, gas, and water-level) with a LoRa transceiver to provide real-time disaster detection and communication to a central monitoring station. A GSM module is added as a redundant fallback channel, ensuring alerts reach authorities and communities even if the LoRa gateway becomes unavailable. The proposed system ensures energy efficiency, cost-effectiveness, and long-range communication (up to 10–15 km line-of-sight), making it highly suitable for deployment in rural and disaster-prone regions. Experimental analysis demonstrates that the system operates reliably with minimal power, supporting long-term battery operation or integration with solar charging. The architecture can be further scaled to form a mesh network, enabling community-level disaster preparedness and early warning systems.

Introduction

The increasing frequency of natural disasters such as floods, cyclones, landslides, earthquakes, and forest fires pose significant challenges for disaster management authorities. According to the World Risk Index 2022, over 270 million people are affected annually by disasters, with a majority of victims belonging to rural or underdeveloped regions where communication infrastructure is limited. Quick dissemination of alerts and timely response can save lives, but conventional technologies like cellular networks often fail during disasters due to tower collapse, power failure, or network congestion.

In rural India and similar developing regions, communication blackouts during emergencies remain a major bottleneck. There is a growing need for a reliable, low-power, and affordable disaster alert system that can:

- Operate independently of cellular or satellite networks.

- Cover long distances with minimal energy consumption.
- Be scalable and easy to deploy in villages and remote communities.

LoRa (Long Range Radio) technology emerges as a strong candidate due to its ability to transmit small packets of data over 10–15 km range with very low power consumption. When integrated with IoT sensors, LoRa enables real-time monitoring of environmental parameters and immediate alert dissemination. To further enhance reliability, GSM is added as a backup system to ensure redundancy. This research work focuses on designing and developing a LoRa-based disaster alert system, evaluating its performance in terms of communication range, power efficiency, and reliability under disaster-like conditions.

Overall Structure

The architecture (Figure 1) is partitioned into layers:

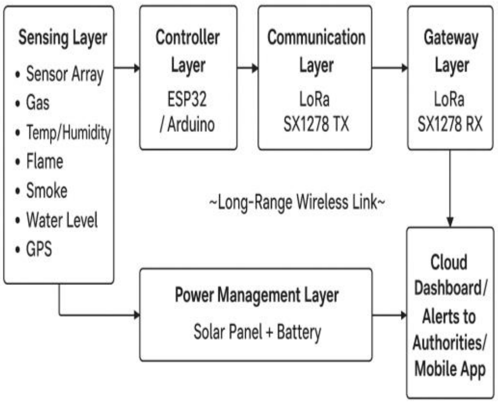

Fig 1: Layered Architecture

- **Sensing Layer**: The sensing layer employs multiple sensors such as temperature, humidity, gas, smoke, water level, and flame sensors to detect early signs of disasters. These sensors provide real-time environmental data for effective monitoring.
- **Controller Layer**: ESP32/Arduino microcontrollers serve as the primary processing units, aggregating sensor data, filtering noise, and preparing the information for communication. They also manage system logic and power-saving operations.
- **Communication Layer**: The LoRa SX1278 transceiver module facilitates long-range, low-power wireless communication in ISM bands (433/868 MHz). This ensures reliable data transmission even in remote and disaster-prone areas where cellular networks may fail.
- **Gateway Layer**: A central gateway node, built using NodeMCU, or a PC with a LoRa receiver, collects data packets from multiple nodes. It forwards the information to cloud platforms, dashboards, or mobile applications for alert dissemination.
- **Power Management Layer**: A solar panel combined with a rechargeable battery powers the system, enabling energy autonomy. Low-power sleep modes are employed to extend battery life, ensuring continuous operation in resource-constrained environments.

A. Hardware Details

Table 1: Hardware Details

Component	**Model/Range**	**Role**
Microcontroller	ESP32, Arduino Uno	Data aggregation, control
LoRa Module	SX1278 (433/868 MHz)	Wireless comm.(>10km)
Gas Sensor	MQ-2, MQ-135	Smoke/gas detection
Temp/Humidity	DHT11, DHT22	Weather sensing
Water Level	Resistive/sonar	Flood/overflow detection
Flame Sensor	IR/UV photodiode	Fire detection
GPS (optional)	NEO-6M	Geotagging alerts
Solar Panel	5–10 W	Energy harvesting
Battery	Li-ion 2600–4000mAh	Storage

The proposed system integrates multiple hardware modules to achieve efficient environmental sensing and reliable communication. The ESP32/Arduino Uno microcontroller serves as the central processing unit, responsible for data acquisition, aggregation, and control of peripheral sensors. The LoRa SX1278 module (433/868 MHz) provides long-range, low-power wireless communication exceeding 10 km, ensuring seamless data transmission even in rural or remote locations.

Environmental monitoring is achieved through a set of calibrated sensors: the MQ-2 and MQ-135 gas sensors detect combustible and toxic gases;

DHT11/DHT22 measure temperature and humidity levels for weather analysis; resistive or sonar-based water level sensors identify flooding or overflow conditions; and an IR/UV flame sensor provides rapid fire detection. An optional NEO-6M GPS module enables geotagging of sensor data for precise localization.

For sustainable operation, the system employs a 5–10 W solar panel for renewable energy harvesting and a Li-ion battery (2600–4000 mAh) for energy storage, ensuring continuous performance under off-grid conditions.

B. Software & Firmware

- **Timer-Based Periodic Sensing & Threshold Detection:** The system uses a timer-driven routine where sensors wake at predefined intervals to capture readings. Each parameter (temperature, humidity, gas, smoke, water level, flame) is compared against safety thresholds. If abnormal conditions are detected (e.g., smoke density above safe limit), an event is triggered.
- **Data Packet Construction**: Once a hazard is detected, the controller prepares a structured data packet.

This packet typically includes:
  - Alert type (fire, flood, gas leak, etc.)
  - Sensor value (e.g., ppm of gas, °C of temperature)
  - Timestamp (real-time occurrence)
  - GPS coordinates (if integrated)
  - Unique Node ID (to identify the reporting device)

- **LoRa Burst Transmission**: Instead of continuous radio use (which drains battery), LoRa operates in burst mode. The transceiver wakes only when needed, transmits the packet over long range, and immediately switches off. This minimizes radio-on time, conserving energy while ensuring reliable delivery.
- **Duty-Cycling & Deep Sleep**: Between transmissions, the microcontroller and sensors enter deep sleep mode. Only essential timers remain active. This reduces overall power consumption drastically, allowing the system to run on solar + battery backup for extended periods (months to years).
- **Gateway-Side Dashboard & Alerts:** The LoRa gateway receives the packets, logs them, and forwards data to a cloud or local dashboard.

The dashboard provides:
  - Real-time alert visualization (graphs, maps, status indicators)
  - Event logs for historical analysis
  - Automated notifications (SMS, email, or mobile app alerts) to authorities, disaster response teams, or local users

C. LoRa Link Budget and Energy Autonomy Analysis

1) Link Budget (LoRa)

The received power (Pr) is given by:

$$Pr = Pt + Gt + Gr - Lp - Lc$$

Where:

Pr = received power (dBm);
Pt = transmit power (dBm);
Gt, Gr = antenna gains (dBi);
Lp = path loss (dB);
Lc = connector/cable loss (dB).

Free-space path loss (FSPL) at 433 MHz:

$$Lp = 32.45 + 20 \log10(f) + 20 \log10(d)$$

with f in MHz and d in km.

Worked Example (Rural LoS)

Frequency f = 433 MHz, Distance d = 5 km.

Lp calculation:

$$20 \log10(433) \approx 52.73$$

$$20 \log10(5) \approx 13.98$$

$$Lp \approx 32.45 + 52.73 + 13.98 \approx 99.16 \text{ dB}$$

Assumptions:

Pt =14 dBm,
Gt = 2 dBi,
Gr =2 dBi,
Lc =1 dB

$$Pr \approx 14 + 2 + 2 - 99.16 - 1 \approx -82.16 \text{ dBm}$$

Interpretation:

Typical LoRa receiver sensitivity ranges from −124 to −137 dBm. Thus, the link margin is ~42–55 dB, which indicates strong connectivity up to 5 km line-of-sight.

2) Energy Autonomy (Average Current)

Average current is computed as:

$$Iavg = (Tactive \times Iactive + Tsleep \times Isleep) / (Tactive + Tsleep)$$

3) Worked Example (1-minute cycle)

Active phase:

Tactive = 2 s at Iactive = 130 mA (LoRa TX burst)

Sleep phase:

Tsleep = 58 s at Isleep = 1 mA (deep sleep)

Computation:

Numerator = (2 × 130) + (58 × 1) = 318 mA·s

Denominator = 60 s Iavg = 318 / 60 ≈ 5.3 mA

4) Battery life with 2600 mAh cell:

$2600 / 5.3 \approx 490.6$ hours ≈ 20.4 days (without solar).
With solar charging, operational autonomy extends significantly.

D. Power & Energy Optimizations

Energy efficiency is a critical factor for autonomous wireless sensor networks, particularly in disaster monitoring systems where grid power may be unavailable. The proposed system incorporates multiple optimization strategies:

- **Solar Panel and Battery Sizing**: The energy sub system is designed to ensure long-term autonomy. A compact solar panel, coupled with a rechargeable lithium-ion battery, is dimensioned to provide more than five days of continuous operation even under low-light conditions. With only 25% of average daily sunlight availability, the system can still harvest enough energy to recharge the battery and maintain uninterrupted operation.
- **Ultra-Low Power Consumption of Controllers**: The NodeMCU/ESP32 microcontrollers are configured in deep-sleep mode during idle periods, consuming only 0.5–2 mA. During active operation particularly when transmitting data, the LoRa transceiver draws 120–130 mA for less than 2 seconds per burst. This short duty period ensures that high current draw does not significantly impact overall energy reserves.
- **Duty Cycling for Energy Savings:** The system implements a duty-cycling mechanism, where sensors are activated only at periodic intervals (every 15–60 seconds depending on application). Between cycles, the microcontroller and sensors remain in low-power sleep states. This approach reduces the average current consumption to below 20 mA per hour, which is practical for long-term deployments powered solely by solar energy and batteries.
- **Energy-Autonomous Design**: By combining solar harvesting, energy storage, deep sleep modes, and optimized duty cycles, the system achieves true energy autonomy. This eliminates frequent battery replacement, making it suitable for remote, disaster-prone areas where maintenance is challenging.

E. Transmitter and Receiver Node Design

The proposed disaster alert system is composed of two primary components: the transmitter node (TX), which functions as the sensing and alerting unit, and the receiver node (RX), which serves as the gateway and decision-making hub. Together, they form a resilient, long-range, low-power communication system for remote disaster monitoring.

1) ***Transmitter Node (TX Section)***

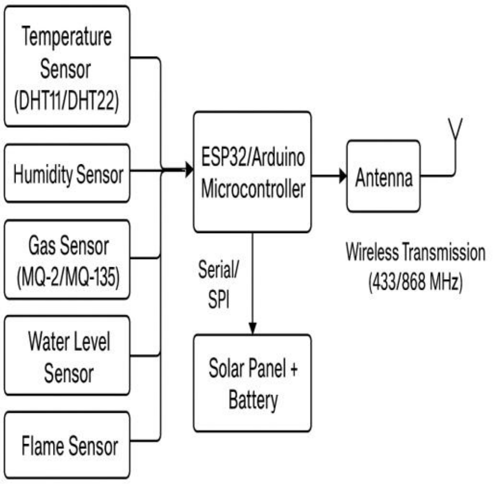

Fig 2: Transmitter Section

The transmitter node integrates a variety of environmental sensors, including temperature, humidity, water level, gas, smoke, and flame sensors, connected to a microcontroller (ESP32/Arduino). The microcontroller collects and processes sensor readings, performs threshold-based event detection, and packages the data into structured alert packets. These packets include information such as node ID, sensor values, event type, timestamp, and optional GPS coordinates.

Communication is handled by the LoRa SX1278 module, operating in the license-free ISM band (433/868 MHz), which ensures reliable long-distance transmission (>8 km in open terrain) with minimal power consumption. The node is powered by a compact solar panel and rechargeable battery, enabling autonomous, off-grid deployment. Energy efficiency is further enhanced by duty cycling and deep sleep modes, reducing average current consumption to less than 20 mA/hr. The TX node's primary role is to detect hazards locally and transmit alerts reliably to the RX node.

2) ***Receiver Node (RX Section)***

The receiver node, or gateway, is equipped with a LoRa SX1278 receiver interfaced with a processing unit such as a NodeMCU, or PC. Its function is to continuously listen for incoming packets from multiple transmitter nodes distributed across high-risk locations. Upon successful reception, the gateway validates and decodes the alert packets, then forwards the information to a centralized dashboard or server application.

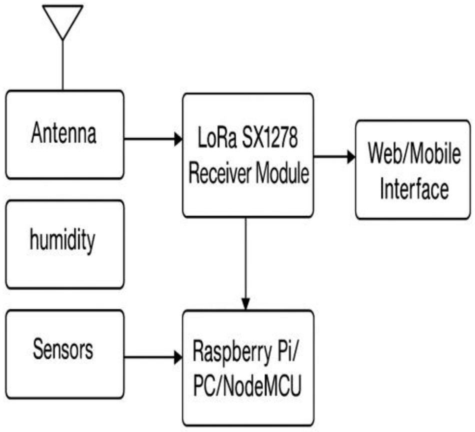

Fig 3: Receiver Section

The dashboard enables real-time visualization of alerts, historical logging, and automated dissemination of notifications to relevant stakeholders via SMS, email, or mobile applications. The RX node thus ensures timely delivery of critical alerts, supports multi-node scalability, and provides the intelligence layer for coordinated disaster response.

F. Integration of TX and RX Nodes

In operation, the TX and RX nodes work in tandem to provide a seamless disaster alerting pipeline. The TX node autonomously senses hazards and transmits minimal but critical alert data, while the RX node aggregates inputs from multiple sources and disseminates actionable intelligence to authorities and communities. This division of roles ensures a scalable, resilient, and low-power IoT-based disaster management framework, capable of operating effectively even in infrastructure-poor rural and remote environments.

Conclusions

The proposed LoRa-based Multi-Sensor Disaster Management System demonstrates a practical and efficient approach to disaster monitoring in rural and remote environments. By integrating temperature, humidity, gas, smoke, flame, and water-level sensors into a low-power IoT framework, the system enables real-time hazard detection and timely alerts. The use of LoRa SX1278 transceivers ensures long-range and energy-efficient communication, making the solution suitable for geographically dispersed areas where traditional communication networks are unreliable.

The system architecture leverages ESP32/Arduino microcontrollers for local data aggregation, LoRa transmission for energy-efficient long-distance communication, and a gateway (NodeMCU) for central monitoring and alert dissemination. The adoption of solar energy with battery backup guarantees autonomous operation, while duty cycling and deep sleep techniques significantly reduce power consumption.

Experimental calculations show that the system can maintain energy autonomy for more than five days with limited solar exposure. Link budget and path loss analysis confirm the viability of LoRa communication over several kilometers in open rural terrain. Overall, the system provides a cost-effective, scalable, and reliable framework for rural disaster management.

Future Scopes

While the current system establishes a strong foundation, there are several opportunities for future improvement and expansion:

- Integration of AI and Machine Learning:
  - Use predictive analytics to identify disaster trends (e.g., flood forecasting, wildfire risk prediction).
  - Implement anomaly detection algorithms for early warning.
- Enhanced Communication Reliability:
  - Incorporate LoRaWAN for multi-node networking, enabling better scalability and interoperability with existing IoT infrastructures.
  - Add satellite or cellular fallback for extreme situations where LoRa coverage is obstructed.
- Mobile and Cloud-Based Dashboards:
  - Develop Android/iOS apps for real-time monitoring by local authorities and citizens.
  - Integrate with cloud IoT platforms (AWS IoT, Google Firebase, Azure IoT Hub) for analytics, storage, and visualization.
- Expanded Sensor Integration:
  - Add rainfall sensors, seismic sensors, and wind-speed detectors to cover a broader range of natural disasters.
  - Include image-based surveillance (camera + AI) for fire/smoke confirmation.
- Mesh Networking for Reliability:
  - Enable multi-hop LoRa communication where nodes act as repeaters, extending coverage in challenging terrains.
- Energy Optimization Enhancements:
  - Apply Maximum Power Point Tracking (MPPT) for solar panels.
  - Investigate supercapacitor-based energy storage for higher lifecycle durability.
- Deployment at Scale:
  - Pilot testing in multiple rural villages and disaster-prone zones.

   - Collaboration with government disaster management authorities for large-scale adoption.

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