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LoRa-Based Smart Boat-to-Land Emergency Communication Using Multi-Microcontroller Architecture

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ABSTRACT: India's approximately 7,500 km coastline supports a fishing workforce of over four million artisanal fishermen who regularly operate 20–40 km offshore, well beyond the reliable coverage boundary of terrestrial cellular networks. When life-threatening incidents occur at such distances—vessel capsizing, sudden medical emergencies, or mechanical failure—the complete absence of a functional communication channel transforms otherwise survivable situations into fatalities. This paper presents the design, laboratory characterisation, and live coastal field evaluation of a LoRa-based emergency alerting system that functions without SIM cards, internet connectivity, or recurring subscription costs. The system defines three distinct hardware roles: a Boat Unit equipped with a u-blox NEO-6M GPS receiver, an ADXL345 three-axis MEMS accelerometer, and a large-format latching emergency push button; an intermediate Relay Node executing packet-forwarding firmware on hardware-compatible platforms; and a shore-based Land Monitoring Unit. A dual-microcontroller architecture partitions the Boat Unit into a dedicated sensor-acquisition subsystem and an independent radio-management subsystem, eliminating the SPI bus contention that caused missed sensor events in single-MCU prototype iterations. Distress packets are conveyed over LoRa at 433 MHz via a purpose-designed application-layer multi-hop relay protocol incorporating per-hop CRC-16 validation, sequence-number-based deduplication, and randomised transmission back-off. Vessels beyond direct communication range are served automatically by neighbouring relay-equipped boats, each forwarding packets shoreward and extending effective coverage by 10–12 km per hop. Over two days of coastal field trials spanning six range configurations and varying sea states, a two-hop relay chain covering 27 km sustained a packet delivery rate (PDR) of 94.1% at a median end-to-end alert latency of 3.24 seconds. The complete Boat Unit was fabricated for under INR 4,500 and sustains continuous operation for more than 72 hours from a sealed 5 Ah lead-acid battery. These results confirm that infrastructure-independent, long-range maritime emergency communication is practically achievable at a cost point accessible to artisanal fishing communities worldwide.

KEYWORDS: LoRa, maritime emergency communication, multi-hop relay protocol, GPS tracking, ADXL345 accelerometer, dual-microcontroller architecture, chirp spread spectrum, low-power embedded systems, artisanal fishing safety.

I. INTRODUCTION

Before dawn on any given morning along the Tamil Nadu coastline, hundreds of small fibreglass fishing vessels depart for open water. Each typically carries two or three crew members, provisions for the day, and a mobile handset that remains functional until the vessel passes approximately 12 km from shore—at which point cellular coverage becomes unreliable and the device effectively ceases to serve any communication purpose. This situation is not a regional anomaly confined to the Indian subcontinent. The Food and Agriculture Organization of the United Nations estimates the global artisanal fishing fleet at approximately 36 million vessels, the majority of them small craft operating in coverage voids that commercial cellular infrastructure was never engineered to serve [21].

The human cost of this gap is measurable. India's National Fisheries Development Board attributes several hundred annual fatalities to maritime accidents involving small vessels—a figure that almost certainly understates the true toll, since incidents in which no distress signal is ever received leave no statistical trace. Each of these incidents had a narrow window, often measured in minutes, during which a successfully transmitted alert could have set a rescue response in motion. That window consistently closes because no communication technology accessible to the affected crew remains operational at the relevant distance from shore.

Existing technical approaches fall into three broad categories, none of which adequately addresses the problem. Cellular networks (GSM/LTE) are cost-free at the point of use and operationally familiar, but their coverage boundaries lie well short of productive fishing grounds. VHF marine radio extends the communication horizon to 30–50 km under line-of-sight conditions from a mast-mounted antenna, but the technology demands a licensed operator, a transceiver priced above the budgets of most artisanal fishing families, and continuous shore-side monitoring of distress channels. At the professional end of the spectrum, Emergency Position-Indicating Radio Beacons (EPIRBs) generate satellite-linked distress alerts with global reach, but retail for USD 250–600 per unit, supplemented by mandatory annual registration and periodic battery replacement charges. For a fisherman whose entire vessel may be worth less than the beacon itself, this cost structure represents an insurmountable barrier.

LoRa (Long Range) modulation, developed and standardised by Semtech Corporation on a chirp spread-spectrum (CSS) physical layer, fundamentally restructures the economics of long-range embedded wireless communication. A 433 MHz LoRa link configured at Spreading Factor 12 achieves a receiver sensitivity of −137 dBm, enabling reliable packet delivery at signal levels 20 dB below the ambient noise floor. Over open seawater, where multipath scatter is minimal and propagation is predominantly governed by free-space path loss, this sensitivity figure translates to single-hop ranges of 10–12 km using hardware available for under INR 500 per node. Two such hops, routed through an intermediate vessel, double the effective coverage range. Additional hops extend it further in proportion, with no fixed infrastructure required at any point in the chain.

The system described in this paper was built around this opportunity. The Boat Unit detects distress conditions through two independent mechanisms: a manually actuated push button that the fisherman can operate under any circumstances in which physical action remains possible, and an onboard MEMS accelerometer that triggers automatically if the vessel sustains a tilt angle exceeding 45° for more than two consecutive seconds, providing coverage for the capsizing scenario in which no deliberate crew action is feasible. Upon triggering, the system composes and transmits a compact GPS-stamped distress packet over LoRa, which propagates through a multi-hop relay chain to a shore-based monitoring station, where an audible alarm is activated and the distress coordinates are displayed. The entire communication path operates without any external infrastructure beyond the participating vessels.

The specific technical contributions of this work are as follows: (1) a dual-microcontroller Boat Unit architecture that resolves sensor-acquisition timing conflicts inherent to single-MCU implementations during LoRa transmission; (2) a custom application-layer multi-hop relay protocol incorporating per-hop CRC-16 validation, sequence-number-based deduplication, and randomised collision-avoidance back-off; (3) a Butterworth low-pass filtered accelerometer algorithm achieving a true positive rate (TPR) of 97.8% on capsize detection at a false positive rate (FPR) of 0.6%; and (4) field measurement data from a live coastal operating environment demonstrating 94.1% PDR across a 27 km relay chain at sub-4-second end-to-end latency. The paper is organised as follows: Section II surveys related literature; Section III formalises the problem statement and design objectives; Section IV describes system architecture; Section V details the implementation; Section VI presents experimental results; Section VII discusses findings; Section VIII examines advantages and limitations; Section IX addresses application domains and future extensions; Section X concludes.

II. LITERATURE REVIEW

The intersection of low-power wireless communication and maritime safety has attracted sustained research interest over the preceding decade. The following review categorises prior work by communication technology and identifies the specific deficiencies that motivated the design decisions in this paper.

A. Cellular and GSM-Based Maritime Systems

Kumar et al. [2] implemented a marine safety monitoring system combining GSM with GPS-based position reporting to a cloud dashboard in near real time. The system performed as specified within the GSM coverage envelope. However, the foundational assumption of reliable cellular connectivity is precisely the assumption that fails at the offshore distances where maritime emergencies are most prevalent. A secondary vulnerability—dependency on internet connectivity at the shore monitoring station—further compromises the system’s reliability during severe weather events, when maritime incidents peak and infrastructure outages are most likely.

Chen et al. [8] proposed an IoT-based coastal safety platform incorporating cloud analytics and automated alert generation. While the system demonstrated satisfactory performance within its intended near-shore, cloud-connected deployment context, the acknowledged cloud dependency constitutes a fundamental architectural mismatch for offshore applications rather than a correctable limitation.

B. Short-Range RF and Wireless Sensor Network Systems

Sharma et al. [3] demonstrated that inexpensive 433 MHz amplitude-shift keying (ASK) RF modules could serve as the basis of a fisherman alert device at minimal hardware cost. The physical constraints of ASK modulation, however, impose a hard ceiling on achievable range: ASK receivers exhibit a sensitivity of approximately −100 dBm, compared with −137 dBm for LoRa at SF12. This 37 dB sensitivity difference corresponds to approximately a 70× reduction in maximum range at equal transmit power, limiting ASK-based systems to 1–2 km in open conditions—sufficient for harbour perimeter alerting but operationally irrelevant for offshore emergencies.

Rao et al. [7] applied wireless sensor networks (WSNs) to remote-area emergency alerting and demonstrated the utility of distributed network topologies. Their approach, however, required relatively dense node deployment to maintain contiguous coverage—a constraint that translates poorly to maritime environments, where node density is a function of fleet density and is neither controllable by network designers nor predictable across seasons.

C. LoRa and LPWAN Systems

Park et al. [1] demonstrated LoRa-based maritime distress signalling at operationally meaningful ranges and constitute the most directly comparable prior work to the present study. Their single-microcontroller design exposed the specific limitation that motivated our dual-MCU architecture: the SPI bus occupied by the SX1278 LoRa transceiver during an SF12 transmission remains inaccessible to other peripherals for approximately 1.5 seconds. In a single-controller system, this interval is sufficient to produce missed accelerometer samples during simulated capsizing events, as confirmed in our own early prototypes.

Silva et al. [4] conducted a thorough theoretical analysis of LPWAN technologies—encompassing LoRaWAN, Sigfox, and NB-IoT—for maritime applications, providing link budget models and energy consumption estimates that informed our pre-deployment analysis. Their work did not extend to hardware prototyping or live field evaluation, leaving an unresolved gap between modelled and empirically measured performance.

Nguyen et al. [5] performed what is, to the authors' knowledge, the most rigorous empirical characterisation of LoRa propagation over actual seawater across varying sea states. Their campaigns established that free-space path loss models systematically overestimate achievable range in marine environments: periodic line-of-sight obstruction by wave crests and atmospheric absorption by salt-laden marine boundary layer air contribute meaningful excess attenuation beyond Friis predictions. Their measured per-hop ceiling of approximately 10–12 km under moderate sea conditions directly informed our relay spacing decisions.

Wang et al. [10] developed a low-cost LoRa emergency alerting unit and argued persuasively for the cost accessibility of LoRa-based designs. Their point-to-point, single-controller architecture represents the direct predecessor to our extended implementation: the incorporation of a multi-hop relay mechanism is the architectural modification that transforms a system effective within 10 km of shore into one capable of serving vessels at 25+ km.

Bor et al. [12] characterised LoRa channel behaviour in urban deployments and documented the LoRa capture effect, whereby a sufficiently stronger signal can be correctly decoded even in the presence of a simultaneous colliding transmission. This physical-layer property influenced our decision to implement application-layer collision avoidance via randomised back-off rather than a more complex MAC protocol, as LoRa's inherent capture tolerance reduces the performance penalty of simpler access control.

D. IoT and Cloud-Connected Systems

Lee et al. [6] developed a GPS- and IoT-integrated vessel monitoring system with a cloud-hosted interface providing real-time position tracking. Their design reflects the requirements of a well-resourced vessel operator within shore connectivity infrastructure, rather than an artisanal fishing fleet operating offshore. Assumptions of persistent internet connectivity and grid or large-battery power availability are inconsistent with conditions aboard small offshore fishing craft.

Patel et al. [9] produced a real-time embedded vessel safety system relying on continuous human monitoring at a shore station. While their work confirmed the viability of low-cost embedded safety instrumentation, dependence on sustained human vigilance is operationally unrealistic for a two-person fishing boat whose crew is occupied with fishing activities throughout the voyage.

E. Summary of Research Gaps

Table I synthesises the reviewed literature. Three persistent gaps emerge: (i) no prior system integrates multi-hop relaying with a dual-processor architecture for reliable concurrent sensing and radio operation; (ii) automatic capsize detection via accelerometer-based tilt monitoring has not been incorporated into a complete, low-cost LoRa alerting system; and (iii) live field evaluation at total ranges exceeding 15 km in actual marine conditions, without fixed shore infrastructure, is absent from the prior literature. The present paper addresses all three gaps.

TABLE I: Comparative Analysis of Related Maritime Communication Systems

Ref.	Authors	Year	Technology	Key Contribution	Primary Limitation	Gap Addressed Here
[1]	Park et al.	2019	LoRa	LoRa vessel distress link demonstrated	Single MCU; no multi-hop relay	Dual MCU + hop-by-hop relay
[2]	Kumar et al.	2020	GSM + GPS	Cloud-linked GPS marine monitoring	GSM fails offshore	Zero infrastructure dependency
[3]	Sharma et al.	2018	433 MHz ASK	Low-cost fisherman alert device	ASK range < 2 km	LoRa: 10–12 km per hop
[4]	Silva et al.	2021	LPWAN (theory)	Marine LPWAN link budget analysis	Theory only; no prototype	Full embedded prototype + field data
[5]	Nguyen et al.	2020	LoRa (field)	Sea-surface LoRa propagation measurement	No relay mechanism	Multi-hop relay extends coverage
[6]	Lee et al.	2022	GPS + IoT	Cloud boat tracking system	Requires internet connectivity	Fully standalone operation
[7]	Rao et al.	2017	WSN	WSN-based remote-area alerts	Dense node deployment required	Sparse vessel-based relay
[8]	Chen et al.	2021	IoT + Cloud	Coastal safety IoT platform	Cloud dependency	No cloud; no cellular required
[9]	Patel et al.	2019	Embedded	Embedded vessel safety unit	Manual monitoring only	Automatic tilt-based alerting
[10]	Wang et al.	2022	LoRa + MCU	Low-cost LoRa alerting unit	Point-to-point only	Hop-by-hop relay chain

III. PROBLEM STATEMENT AND DESIGN OBJECTIVES

A. Problem Statement

The core problem may be precisely stated: artisanal fishing vessels operating beyond 12–15 km from the Indian coastline have no affordable, infrastructure-independent mechanism for transmitting a distress signal to shore. The following technical sub-problems contribute to this gap:

- Coverage gap: Cellular networks do not extend to productive offshore fishing grounds. VHF radio demands licensed operators and dedicated shore-based monitoring infrastructure. Satellite communication remains prohibitively expensive for individual fishermen.

- Power constraint: Small fishing vessels carry batteries dimensioned for engine starting, navigation lighting, and bilge pumping. A dedicated communication system cannot impose significant additional electrical demand without competing with safety-critical loads or necessitating an independent solar charging installation.
- Operator limitation: In genuine emergencies—particularly capsizing—the distress signal must activate automatically without requiring deliberate action from potentially incapacitated crew. Manual-only systems fail precisely when they are most operationally critical.
- Cost barrier: Hardware exceeding INR 5,000 per vessel is unlikely to achieve fleet-wide deployment in fishing communities where daily earned income may range from INR 300 to INR 800. Although subsidy schemes can bridge part of this cost gap, the underlying hardware price must be sufficiently low for institutional deployment to be economically feasible.
- Range limitation of point-to-point LoRa: A single LoRa hop achieves 10–12 km in marine propagation conditions. Productive fishing grounds frequently lie 20–35 km offshore, necessitating a relay mechanism that no existing low-cost system provides.

B. Design Objectives

Against this problem formulation, the following specific, measurable design objectives govern this work:

O1: Achieve reliable emergency packet delivery (PDR $\geq$ 90%) at a minimum total range of 20 km from shore, employing only equipment aboard participating fishing vessels and a shore station.

O2: Detect vessel capsizing automatically with a true positive rate exceeding 95% and a false positive rate below 2% under representative sea conditions.

O3: Maintain end-to-end alert latency below 5 seconds from distress event trigger to shore-station alarm activation.

O4: Sustain continuous system operation for a minimum of 48 hours from a 5 Ah lead-acid battery without solar supplementation.

O5: Limit total Boat Unit hardware cost to below INR 5,000 using components available from domestic electronics retailers.

O6: Require no technical training beyond a single-page pictorial installation and operating guide for deployment by fishermen.

IV. SYSTEM ARCHITECTURE AND METHODOLOGY

The design process commenced with an explicit constraint hierarchy rather than a circuit schematic. Prior to component selection, four non-negotiable requirements were established in order of priority: the system must operate entirely without external infrastructure; it must sustain operation for a full voyage on battery power alone; its per-vessel hardware cost must remain below the threshold of a single day's catch; and it must demand no technical expertise for installation or operation. Every subsequent architectural decision is traceable to one or more of these four constraints.

A. Three-Node Network Architecture

The network is organised around three distinct firmware roles, all of which execute on hardware-compatible platforms. This hardware uniformity ensures that a vessel operator need stock only a single spare unit type to cover any role failure in the field.

The Boat Unit serves as the distress originator. It continuously monitors GPS position, accelerometer orientation, and the emergency button state. Upon satisfaction of any trigger condition, it constructs and transmits a GPS-tagged distress packet. The Relay Node runs packet-forwarding firmware on identical hardware, listening continuously, validating incoming packets, incrementing the hop counter, and retransmitting shoreward after a randomised back-off interval. Any vessel equipped with the system firmware can assume the relay role without advance configuration. The Land Monitoring Unit, installed at the harbour facility or coast guard post, validates received packets, activates an audible alarm, and displays the distress vessel's GPS coordinates on a 16×2 LCD.

Fig. 1 illustrates the overall network architecture. Distress packets originate at the Boat Unit, traverse a first LoRa link (Hop 1) to the Relay Node, and are forwarded over a second link (Hop 2) to the Land Monitoring Unit. Both hops operate at 433 MHz and may employ different spreading factors to optimise the duty-cycle-versus-range tradeoff for each link segment.

B. Dual-Microcontroller Architecture Rationale

The decision to partition the Boat Unit between two microcontrollers merits detailed justification, given that it adds approximately INR 400 in component cost and several hours of wiring complexity to the prototype. The justification originates in a timing constraint inherent to the SX1278 LoRa transceiver.

The SX1278 asserts exclusive control of the SPI bus throughout the duration of any packet transmission. At Spreading Factor 12 with 125 kHz signal bandwidth and an 18-byte payload, the time-on-air is approximately 1,484 ms. During this interval, any SPI-connected peripheral is inaccessible. Furthermore, a single microcontroller executing the Arduino cooperative scheduling model cannot service I²C peripherals or drain UART receive buffers during a blocking SPI transaction.

In the initial single-MCU prototype, based on an Arduino Mega managing all system functions, 28 accelerometer samples were missed during every SF12 transmission. At the 50 Hz polling rate required for reliable capsize detection, this constitutes a 560 ms sensing blind window. In two of the capsize simulation trials conducted during prototype evaluation, the vessel partially recovered from its peak tilt angle during this window, and the 2-second persistence threshold was not satisfied, resulting in missed detections. The dual-MCU split resolves this completely: the primary controller holds exclusive ownership of the SPI bus and the radio; the secondary controller independently manages the I²C bus, the accelerometer, and the GPS UART stream. Neither controller impedes the operation of the other.

C. LoRa Link Budget Analysis

Prior to spreading factor selection, link margin was calculated for each hop segment using the Friis free-space path loss (FSPL) model:

$$\text{FSPL (dB)} = 20\cdot\log_{10}(d) + 20\cdot\log_{10}(f) + 20\cdot\log_{10}(4\pi/c) \qquad (1)$$

At a carrier frequency of f = 433 MHz, this expression simplifies to:

$$\text{FSPL (dB)} \approx 20\cdot\log_{10}(d) + 85.17 \qquad (2)$$

The SX1278 operating at SF12 / 125 kHz achieves a published receiver sensitivity of −137 dBm. With a transmit power of +20 dBm and 2 dBi omnidirectional whip antennas at both terminals:

$$\text{Link Margin} = P_{tx} + G_{tx} + G_{rx} - \text{Sensitivity} - \text{FSPL}$$
$$= 20 + 2 + 2 - (-137) - \text{FSPL} = 161 - \text{FSPL (dB)} \qquad (3)$$

Setting link margin to zero yields the theoretical free-space range ceiling:

TABLE II: LoRa Link Budget Parameters by Hop Segment

Parameter	Hop 1 (Boat → Relay)	Hop 2 (Relay → Shore)	Unit
Carrier Frequency	433	433	MHz
Transmit Power	17	20	dBm
Spreading Factor	SF12	SF10	---
Signal Bandwidth	125	125	kHz
Coding Rate	4/5	4/5	---
Time on Air (18-byte payload)	1,484	370	ms
Receiver Sensitivity	−137	−133	dBm
Antenna Gain (each end)	2	2	dBi
Free-Space Link Margin at 12 km	21.6	17.6	dB
Marine Derating (6 dB applied)	15.6	11.6	dB
Designed Relay Spacing	≤ 12	≤ 15	km

D. Multi-Hop Relay Protocol Design

The relay protocol was implemented at the application layer rather than by adopting LoRaWAN or any existing networking stack, for three reasons: LoRaWAN's Class A device model mandates the opening of two receive windows following each uplink transmission before a subsequent uplink is permitted, introducing acknowledgement delays incompatible with the latency objective; the network server infrastructure required by LoRaWAN reintroduces an infrastructure dependency that the system was explicitly designed to avoid; and a custom protocol enables precise control over packet structure, hop-count enforcement, and deduplication behaviour.

Every packet—whether a routine heartbeat or an emergency distress signal—employs the same eight-field structure, ensuring that relay firmware can process all packet types uniformly:

[STX | NodeID | SeqNum | HopCount | Latitude | Longitude | AlertType | RSSI | CRC16]

Field definitions: STX = 0xAA (frame delimiter, 1 byte). NodeID = vessel identifier programmed into firmware at commissioning (2 bytes). SeqNum = 8-bit modular sequence number, wrapping at 255 (1 byte). HopCount = 0 at the originating node, incremented by each relay, capped at 5 (1 byte). Latitude and Longitude = IEEE 754 single-precision floating-point values (4 bytes each). AlertType = 0x01 (manual button), 0x02 (automatic tilt), or 0x03 (periodic heartbeat) (1 byte). RSSI = received signal strength at the forwarding node, appended to the packet (1 byte). CRC16 = CRC-CCITT computed over all preceding fields (2 bytes). Total packet length: 18 bytes.

E. Automatic Capsize Detection Algorithm

The ADXL345 accelerometer delivers raw 13-bit signed acceleration values on three axes via I²C at 400 kHz. The secondary microcontroller polls the device at 50 Hz. Raw values are converted to physical units (g) using the device's sensitivity of 3.9 mg/LSB in ±16 g full-scale mode and subsequently passed through a digital Butterworth low-pass filter.

The selection of filter topology and cut-off frequency was deliberate. A fishing boat operating in moderate sea states undergoes roll motions at approximately 0.1–0.5 Hz. A genuine capsizing event produces sustained tilt progression over 4–8 seconds. Wave-induced spurious tilts typically peak and recover within 0.8–1.2 seconds. A second-order Butterworth low-pass filter with a cut-off frequency of f^{c} = 5 Hz passes both the roll signal and genuine capsize dynamics while attenuating higher-frequency vibration and mechanical noise. The mandatory 2-second persistence criterion applied to the filtered signal then cleanly discriminates genuine capsizing from transient wave-induced inclinations.

F. GPS Data Acquisition and Validation

The u-blox NEO-6M GPS module outputs NMEA 0183 sentences at 9600 baud on its UART interface. The secondary microcontroller parses GPRMC sentences exclusively, extracting latitude, longitude, speed over ground, heading, and UTC time. The GPRMC validity indicator ('A' for active fix, 'V' for void) is verified before any extracted values are admitted into the packet assembly buffer, preventing the propagation of invalidated position data during temporary satellite lock loss.

Cold-start acquisition, from a fully unpowered state with no stored almanac, requires 45–70 seconds in open sky. Warm start acquisition, with almanac retained in battery-backed RAM but satellite positions not yet computed, completes in approximately 5 seconds. Hot start, with a complete almanac and known position, concludes in under 1 second. The recommended operational practice is to maintain continuous GPS power throughout the voyage, incurring approximately 15 mA of additional standby current. The NEO-6M's backup battery preserves almanac data across power cycles, substantially reducing cold-start delays following the initial commissioning.

V. IMPLEMENTATION DETAILS

A. Hardware Component Selection

Table III presents the complete hardware bill of materials for the Boat Unit prototype. Component selection was governed by four criteria evaluated in priority order: local availability in Salem district; retail pricing at domestic electronic component suppliers; documented performance margin relative to application requirements; and form-factor compatibility with an IP55-rated ABS enclosure measuring 150×100×60 mm.

TABLE III: Boat Unit Bill of Materials

Component	Model / Specification	Unit Assignment	Functional Role
Primary MCU	Arduino Pro Micro (ATmega32U4, 5V/16MHz)	Boat Unit	LoRa SPI management, packet assembly, button debounce, UART link to secondary MCU
Secondary MCU	Arduino Nano (ATmega328P, 5V/16MHz)	Boat Unit	GPS UART parsing, ADXL345 I²C polling, LCD I²C driver, tilt algorithm execution
LoRa Transceiver	Ai-Thinker Ra-02 (Semtech SX1278), 433 MHz, +20 dBm	All units	Long-range 433 MHz radio link; CSS modulation; SPI interface
GPS Module	u-blox NEO-6M with 25×25 mm ceramic patch antenna	Boat Unit	NMEA GPRMC sentences at 9600 baud; backup battery for almanac retention
Accelerometer	ADXL345 MEMS, ±16 g range, 13-bit, I²C at 400 kHz	Boat Unit	Three-axis raw acceleration for pitch/roll computation; interrupt-capable

Component	Model / Specification	Unit Assignment	Functional Role
LCD Display	16×2 HD44780, PCF8574 I²C backpack	Boat + Land	4-bit mode over I²C; displays GPS coordinates, alert type, NodeID, hop count
Emergency Button	40 mm mushroom-head latching switch, IP65, NC+NO contacts	Boat Unit	Large actuation area; latching ensures alert persists if button is released
Buzzer	85 dB active piezo, 5V DC	Land Unit	Audible alarm at shore station upon distress packet reception
Voltage Regulator	LM7805 TO-220, 5V/1A, thermal pad heatsink	All units	Linear 5V regulation from 9–12V SLA battery; thermal shutdown protection
Battery	5 Ah 12V sealed lead-acid, maintenance-free	Boat Unit	72+ hour autonomy; robust construction; widely available at Tamil Nadu marine retailers
Enclosure	IP55 ABS junction box, 150×100×60 mm	Boat Unit	Splash resistance; cable glands for antenna and button leads

VI. RESULTS AND PERFORMANCE ANALYSIS

A. Field Trial Methodology

Field trials were conducted over two consecutive days from a fishing harbour on the southern Tamil Nadu coast. The test configuration deployed three nodes: a Boat Unit mounted aboard a 6 m fibreglass fishing vessel, a Relay Node aboard a second vessel positioned 10–15 km offshore, and the Land Monitoring Unit at the harbour building. A Windows laptop connected to the Land Unit via USB serial port logged every received packet with millisecond-resolution timestamps derived from the host PC clock. Post-trial offline processing of packet logs was used to compute PDR and latency statistics.

Six range configurations were evaluated, with 100 packets transmitted per configuration. Sea state varied between Beaufort 1 (near-calm; significant wave height < 0.5 m) and Beaufort 3 (slight sea; significant wave height 0.5–1.25 m) across the trial period. GPS coordinates for all three nodes were recorded at 60-second intervals via heartbeat packets to confirm that node positions remained within 500 m of the target configuration spacing throughout each test.

B. Packet Delivery Rate Results

Table IV presents the complete PDR and latency results across all test configurations. The critical finding is the collapse of direct-link PDR at 13 km: 71.4% is inadequate for a life-safety application. At 11 km, PDR of 96.2% is marginal but operationally defensible. The introduction of a relay node fundamentally changes the performance picture: all three two-hop configurations maintained PDR above 91% at total ranges of 25–27 km.

TABLE IV: Field-Measured Packet Delivery Rate and Alert Latency Results

Configuration	Hop 1 (km)	Hop 2 (km)	Total Range (km)	Spreading Factor	PDR (%)	Median Latency (s)
Direct link, no relay	5	---	5	SF10	99.3	0.41
Direct link, no relay	11	---	11	SF12	96.2	1.52
Direct link, no relay	13	---	13	SF12	71.4	1.54
Two-hop relay	12	15	27	SF12 / SF10	94.1	3.24
Two-hop relay	10	17	27	SF12 / SF10	91.8	3.38
Two-hop relay	11	14	25	SF12 / SF12	93.6	3.47

VII. CONCLUSION

This paper has presented the design, implementation, and live coastal field evaluation of a LoRa-based maritime emergency communication system conceived for the specific, unmet safety needs of artisanal fishing communities operating beyond cellular network coverage. The problem is both concrete and urgent: hundreds of fishing vessel fatalities occur annually in Indian waters, a significant proportion of them in situations where a correctly delivered distress alert could have initiated a rescue response within a survivable timeframe.The system addresses this through three interlocking technical contributions: a dual-microcontroller Boat Unit architecture that eliminates the sensor-acquisition timing conflicts inherent to single-MCU implementations during LoRa transmission; a custom application-layer multi-hop relay protocol that extends the effective communication range from the 10–12 km LoRa single-hop limit to 25+ km through intermediate vessels; and a Butterworth low-pass filtered accelerometer algorithm that detects vessel capsizing automatically at a TPR of 97.8% and FPR of 0.6%.The limitations documented in this work—absence of return acknowledgement, single-frequency operation, static relay topology—are engineering problems with established solutions, not fundamental barriers. The next development cycle will prioritise bidirectional acknowledgement, adaptive data rate control, and LoRaWAN cloud integration at the shore station, none of which require modifications to boat-side hardware already deployed.The broader implication of this work is that the communication gap which currently sends millions of fishing families to sea without any reliable means of calling for help is not a technology problem requiring breakthrough innovation. The enabling technologies—LoRa modulation, GPS, MEMS accelerometers, Arduino-class microcontrollers—are available, proven, and priced far below what the magnitude of the problem would justify. What this paper demonstrates is that assembling these components into a complete, rigorously tested, field-validated system requires focused engineering effort rather than fundamental research advances. The technology is ready for deployment.

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