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# Multinode Maritime Emergency Communication System for Traditional Fishing Vessels in Indonesia Using Haversine-Based GPS Signaling

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***Abstrak***

Keselamatan maritim pada kapal nelayan tradisional di Indonesia masih terbatas akibat belum tersedianya sistem komunikasi darurat yang andal dan mudah terjangkau. Penelitian ini mengusulkan sistem komunikasi darurat maritim multi-node yang memanfaatkan jaringan LoRa multi-hop serta pendekatan routing berbasis kedekatan berdasarkan data GPS dan kualitas sinyal (RSSI). Sistem ini dirancang untuk mendukung pembangkitan sinyal SOS secara otomatis, pengiriman pesan adaptif, serta pemantauan kondisi secara real-time melalui platform berbasis cloud. Perangkat keras sistem mengintegrasikan berbagai sensor, seperti GPS, giroskop, magnetometer, sensor suhu, dan ketinggian air, serta dikendalikan oleh mikrokontroler ESP32 untuk memungkinkan komunikasi jarak jauh dengan konsumsi daya rendah. Hasil pengujian lapangan pada kondisi perairan pesisir menunjukkan bahwa komunikasi multi-hop tidak mengalami kehilangan paket pada skenario terkontrol dengan jarak antar-node yang relatif dekat. Sistem juga menunjukkan nilai RSSI yang stabil pada kisaran –89 hingga –90 dBm serta delay transmisi sebesar 8-13 detik. Sebaliknya, komunikasi single-hop mengalami kehilangan paket sebesar 10% hingga 40% pada jarak lebih dari 385 meter. Temuan ini menunjukkan bahwa pendekatan multi-hop mampu meningkatkan keandalan komunikasi, meskipun dengan konsekuensi berupa peningkatan delay. Secara keseluruhan, sistem yang diusulkan menawarkan solusi yang praktis dan hemat biaya untuk meningkatkan keselamatan komunikasi darurat pada kapal nelayan skala kecil, dengan potensi pengembangan lebih lanjut melalui pengujian skala besar dan dalam kondisi laut lepas.

***Kata kunci***— LoRa, jaringan multi-hop, sinyal darurat, perikanan skala kecil, penentuan rute berdasarkan kedekatan

***Abstract***

*Maritime safety for traditional fishing vessels in Indonesia remains limited due to the lack of a reliable and affordable emergency communication system. This research proposes a multi-node maritime emergency communication system that leverages a multi-hop LoRa network and a proximity-based routing approach based on GPS data and signal quality (RSSI). This system is designed to support automatic SOS signal generation, adaptive message delivery, and real-time condition monitoring through a cloud-based platform. The system hardware integrates various sensors, such as GPS, gyroscope, magnetometer, temperature, and water level, and is controlled by an ESP32 microcontroller to enable long-range communication with low power consumption. Field testing results in coastal water conditions show that multi-hop communication does not experience packet loss in controlled scenarios with relatively close distances between nodes. The system also demonstrated stable RSSI values in the range of –89 to –90 dBm and a transmission delay of 8-13 seconds. In contrast, single-hop communication experienced 10% to 40% packet loss at distances greater than 385 meters. These findings demonstrate that a multi-hop approach can improve communication reliability, albeit at the*

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*expense of increased delay. Overall, the proposed system offers a practical, cost-effective solution to improve the safety of emergency communications on small-scale fishing vessels, with potential for further development through large-scale testing and in high-seas conditions.*

***Keywords***— *LoRa, multi-hop networking, emergency signaling, small-scale fisheries, proximity-based routing*

## 1. INTRODUCTION

Maritime safety remains a significant issue for small-scale fishing vessels in Indonesia. These vessels often lack adequate automated emergency communication systems. Currently, manual methods like VHF radio and visual signaling prevail. These methods can lead to human error, delays in information delivery, and limited coverage, especially in offshore areas without cellular infrastructure or AIS [1]-[3]. While global systems like GMDSS offer reliable options for larger vessels, their high costs and complexity make them impractical for traditional fishing boats [4], [5]. In this situation, Low Power Wide Area Network (LPWAN) technologies, such as LoRaWAN, have emerged as a viable alternative. These technologies provide low-cost, energy-efficient, and wide-range data communication suitable for maritime environments [6], [7]. Several studies indicate that LoRaWAN is more cost-effective and consumes less power than NB-IoT and AIS for long-distance maritime communication applications [8].

Previous research has shown that LoRa works well for wide-range maritime and coastal monitoring. Applications include buoy-based marine data-collection systems [9], sailing-race tracking [10], coastal observatories [11], and monitoring offshore aquaculture [12]. This technology may also be applicable in underwater acoustic communications [13], [14]. However, most implementations currently rely on a single-hop architecture with a star topology [15], [16]. This setup limits network resilience when a direct connection to the central station is unavailable. In dynamic ship networks, where the distance and position of vessels constantly change, the absence of an adaptive multi-hop routing mechanism can create coverage gaps and reduce communication reliability [7]-[9]. Different multi-hop and mesh-based LoRa protocols, such as MCLORA [7], hybrid LoRa Mesh/LoRaWAN [8], and the cross-layer protocol JMAC [17], have proven effective in extending coverage and improving connection reliability. However, many of these solutions are still tested in static or land-based IoT settings and have not yet been widely applied to dynamic maritime emergency networks [6]-[12]. Other studies have explored adaptive modulation [18], [19], frequency optimization in maritime channels [20], [21], and hybrid routing strategies [22]-[25]. While they provide a strong technical basis, integrating these approaches into a unified maritime safety framework has not been thoroughly investigated.

To tackle these issues, this study proposes a multi-node maritime emergency communication system that combines proximity-aware distance estimation with an RSSI-based adaptive forwarding mechanism in a multi-hop LoRa network. In this implementation, the Haversine method is used as a support tool to calculate distances between vessels, rather than as the main focus of the research. The system can automatically generate SOS signals, use proximity-based routing, and enable cooperative message delivery among fishing vessels operating in a dynamic maritime environment. Beyond communication, the system is equipped with environmental sensors and a cloud-based monitoring dashboard. This provides improved real-time situational awareness for port authorities. The main contribution of this research lies in integrating multi-hop communication, proximity-based routing, and a low-power IoT architecture into a cohesive framework tailored to small-scale fisheries operations.

Field experiments conducted in coastal waters with traditional fishing vessels show that the proposed system can reliably perform multi-hop SOS transmissions. No packet loss occurred during controlled tests with relatively short distances between nodes and a limited number of transmissions. In contrast, single-hop communication resulted in packet loss rates of 10%-40% when the distance exceeded 385 meters. The system maintained relatively stable

RSSI values under moderate signal conditions and achieved end-to-end delays ranging from 8 to 13 seconds. These results suggest a trade-off between reliability and latency; using multiple hops increases data delivery success rates but adds to the delay.

Overall, the findings of this study suggest that the proposed approach is well-suited for emergency communication scenarios in the small-scale fisheries sector, especially for groups of vessels with distances between nodes falling within reliable communication ranges.

## 2. METHODS

This research employs a systems development approach along with field experiments to design, build, and evaluate a multi-node maritime emergency communication system for traditional fishing vessels. The research process consists of three key stages. The first stage involved designing the system architecture, focusing on integrating various sensors, processing units, and communication modules to support both automatic and manual emergency signaling methods. The second stage developed the communication and data processing flow, detailing how information is collected from individual vessels, sent to a central node, and displayed on a monitoring platform. The final stage included field testing to evaluate the system's performance and feasibility under real maritime conditions. Additionally, this research conceptually addressed scalability, examining the potential to expand the network to include more vessels within the effective communication range and the system's ability to implement multi-hop mechanisms.

### *2.1 Hardware Setup*

The communication system developed in this research aims to enhance maritime safety for traditional fishing vessels by offering an emergency signal feature that operates automatically and manually. The system's architecture is divided into three main parts: input, processing, and output. For input, various sensors capture the vessel's and environmental conditions. These include a Ublox NEO-M8N GPS for position tracking, an MPU6050 sensor for movement and tilt detection, an HMC5883L magnetometer for direction, and a DS3231 RTC module for time synchronization. The system also includes a temperature sensor with a specific threshold, a water level sensor to detect leaks, and a manually activated SOS button for emergency situations. All data from these sensors is processed by an ESP32 microcontroller, chosen for its energy efficiency and wireless communication capabilities. This device continuously monitors conditions, analyzes incoming data, and compares it to set thresholds. When the system identifies a potentially dangerous condition, it automatically generates an emergency signal ready for transmission. The processed data is sent via the LoRa module at 915 MHz, displayed on an LCD screen, and accompanied by a buzzer to alert the crew. To ensure stable operation in marine environments, a battery-based power supply with a 3S BMS module effectively manages energy use.

Network-wise, the system employs a star topology. Three ship nodes function as data transmitters, while a central node acts as a coordinator. This topology was selected for its ability to maintain communication efficiency, decrease energy use, and support the effective collection of data from multiple vessels. However, the system does not rely solely on direct communication with the central node. If the connection quality declines, the system allows data to be forwarded through other ship nodes as intermediaries. This ensures communication remains stable even in fluctuating network conditions, enhancing system reliability in a dynamic maritime environment. The overall hardware configuration and system architecture used in this study are shown in Figures 1 and 2, demonstrating how each component connects to support integrated emergency communication. The star topology connects vessel nodes (1-3) to a central node (4) for efficient, low-power communication while minimizing delays. The process includes initializing LoRa and GPS, collecting sensor data, performing local processing, and transmitting the data to the central node.

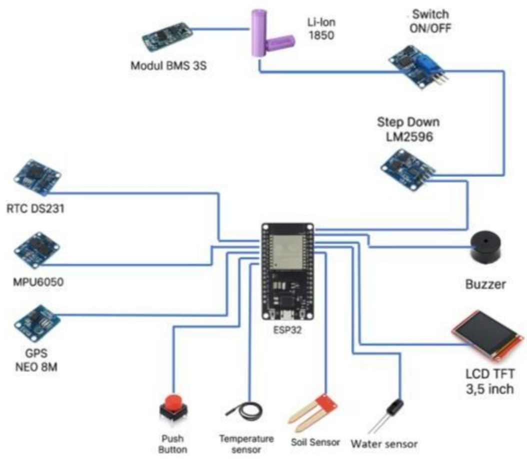



Figure 1 Hardware Connectivity

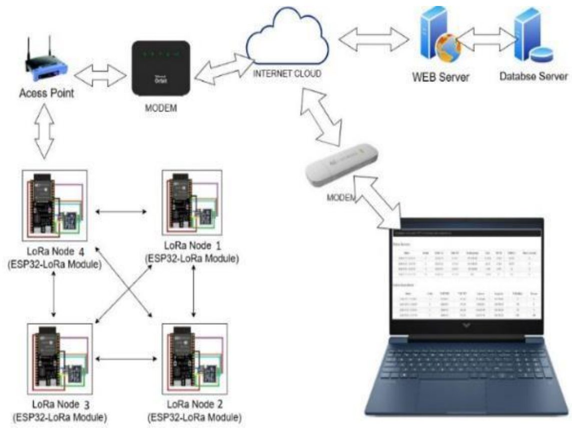



Figure 2 System Architecture and Data Communication Flow

This node then forwards data to a web server and uses the Haversine formula (Equation 1) to calculate the distance between vessels for determining the nearest ones. In its implementation, the Haversine formula serves as a method for estimating distances between nodes and supporting decision-making in proximity-based routing. This method is not the main focus but rather an additional feature that improves the performance of the proposed communication system.

$$d = 2r \cdot arc\sin\left(\sqrt{\sin^2\left(\frac{\Delta\phi}{2}\right) + \cos(\phi_1)\cdot\cos(\phi_2)\cdot\sin^2\left(\frac{\Delta\lambda}{2}\right)}\right) \quad (1)$$

where:
d = distance between two points (in meters or kilometers, depending on r)
r = radius of the Earth (mean radius ≈ 6,371 km)
$\varphi_1$ , $\varphi_2$ = latitudes of point 1 and point 2 (in radians)
$\lambda 1$, $\lambda 2$ =longitudes of point 1 and point 2 (in radians)
$\Delta\phi = \phi 2 - \phi 1$ = difference in latitude

*2.2 Communication and Data Processing Workflow*

The system's workflow begins with initializing LoRa and GPS modules, followed by continuous sensor data collection. Each vessel operates as a node, gathering essential information like position, tilt, water level, and ambient temperature. The ESP32 microcontroller processes this data locally and compares it against predetermined thresholds. If the system detects an abnormal condition, such as elevated temperature, water ingress, or dangerous tilt, it automatically activates an emergency signal. The system also calculates distances between vessels using GPS coordinates, allowing it to identify the nearest vessel to the emergency signal. This information aids decision-making in the proximity-based routing mechanism. Signal quality, indicated by RSSI, is a crucial factor; nodes with stronger signals and closer proximity are prioritized as paths for data transmission.

This approach allows the system to transmit emergency information and improve coordination between vessels in critical situations. Figure 3 illustrates the communication process, showing how data is captured on the ship, processed locally, transmitted via LoRa, and presented on a cloud-based monitoring platform. Additionally, this design allows for future development. By adding more ship nodes, we can extend the communication range through relay paths. This allows the system to meet broader network needs without major changes to the current setup. Overall, the strategy strikes a balance among reliable communication, energy efficiency, and flexibility in the constantly changing maritime environment.

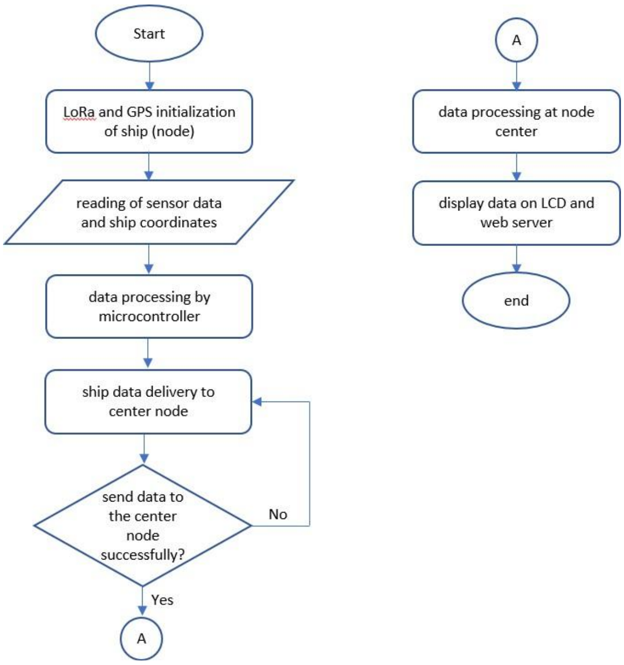



Figure 3 System Flowchart

To further analyze the relationship between signal strength and transmission distance, a logarithmic path loss model is adopted. This model describes the attenuation of received signal strength with distance in wireless communication systems, including LoRa-based networks operating in maritime environments. The RSSI value at a given distance can be expressed as follows:

$$RSSI(d) = RSSI(d_0) + 10nlog_{10}\left(\frac{d}{d_0}\right) \quad (2)$$

where:
RSSI (d) = the received signal strength at distance *d*
RSSI ($d_0$) = the reference RSSI measured at a close reference distance $d_0$
n = path loss exponent that characterizes signal attenuation under specific environmental conditions

In maritime scenarios, the value of *n* is influenced by factors such as sea surface reflection, multipath propagation, and vessel mobility. This model provides a theoretical basis for interpreting the observed RSSI variations and supports the analysis of communication performance in the proposed system.

## 3. RESULTS AND DISCUSSION

The experimental validation includes three main areas: assessing sensor performance, verifying the reliability of long-range wireless communication, and integrating the system under field conditions. Each component was evaluated individually and in combination to assess the feasibility, accuracy, and robustness of the proposed design.

### *3.1 Sensor Calibration and Accuracy Assessment*

To ensure that the maritime monitoring system operates reliably, each sensor module undergoes quantitative testing. This testing evaluates performance under conditions that closely mimic real-world scenarios. The NEO M8N GPS module showed excellent accuracy, with position deviations of 0.00% to 0.09% compared to reference coordinates from Google Maps. These results confirm that the GPS module delivers real-time vessel positioning with high reliability, essential for navigation, fleet monitoring, and emergency reporting. The MPU6050 gyroscope sensor was also tested to evaluate its ability to detect vessel movement. The results showed an average deviation of 1.28% for roll and 0.51% for pitch. These low error rates indicate that the sensor can accurately detect angular changes, enabling early identification of abnormal vessel tilt before serious issues, such as instability or capsizing, arise. Other sensors in the system were also tested.

The HMC5883L magnetometer achieved 0.96% heading measurement accuracy, supporting accurate vessel orientation in marine environments with low magnetic interference. The DS18B20 temperature sensor showed a very low error rate of about 0.46%, making it suitable for continuous monitoring of environmental and device temperatures. The water ingress sensor had an error rate of 0.80%, proving its ability to detect potential leaks early. Finally, the DS3231 Real-Time Clock (RTC) module displayed very stable timekeeping, with an error rate of only 0.02%. Overall, the test results suggest that the sensors used have low enough error rates to be practical for maritime applications. However, it's important to note that these tests were conducted in controlled conditions, so performance may vary in a dynamic marine environment.

Table 1 Sensor Accuracy Based on Experimental Measurements under Controlled Conditions

| **Sensor Module** | **Measured Parameter** | **Average Error (%)** |
|---|---|---|
| GPS NEO-M8N | Latitude/Longitude | 0.00–0.09 |
| MPU6050 Gyroscope | Roll | 1.28 |
| | Pitch | 0.51 |
| HMC5883L Magnetometer | Heading | 0.96 |
| DS18B20 Temperature | Temperature | 0.46 |
| Water Level Sensor | Water Intrusion Detection | 0.80 |
| DS3231 RTC | Timekeeping | 0.02 |

*3.2 Long-Range (LoRa) Communication and Multinode Reliability*

The logarithmic trendline in Figure 4 shows the general characteristics of LoRa signal propagation.

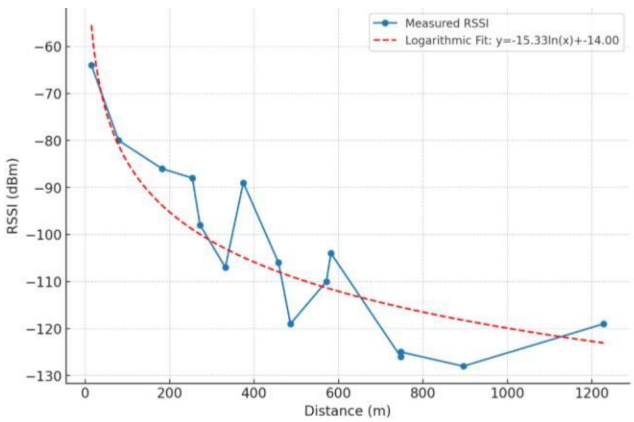
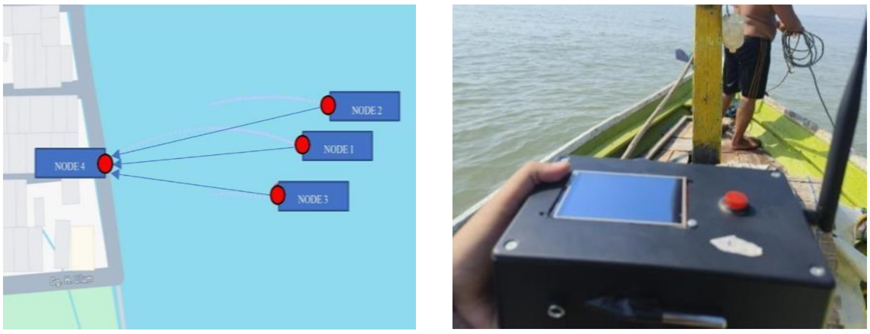



Figure 4 RSSI Values Based on Distance

RSSI values tend to drop as transmission distance increases, from about -64 dBm at 15 meters to nearly -128 dBm at 900 meters. However, there are fluctuations at intermediate distances (around 300 to 600 meters), likely due to multipath effects, environmental interference, and vessel movement during testing. Field testing took place in the Kenjeran coastal area using traditional fishing vessels as test platforms. The experiments were conducted under near-shore maritime conditions with moderate environmental disturbances.




(a) (b)

Figure 5 The testing configuration (a) Communication Testing Between Ship Nodes and the Node Center (b) Placement of nodes on the ship

The configuration included three transmitting nodes and one central node, simulating small-scale conditions common in clustered deployments of fishing vessels. Specifically, Node 1 was about 74.4 meters from the central node, Node 2 was 86.2 meters away, and Node 3 was 64.3 meters away. The measured RSSI values ranged from -97 dBm to -83 dBm, with averages of -81 dBm for Node 1, -89 dBm for Node 2, and -88 dBm for Node 3. These variations reflect differences in transmission distance and the vessels' movement conditions, as shown by changes in heading, roll, and pitch during testing. These findings indicate that LoRa communication remains stable over short to medium distances (approximately 150 meters), consistent with the observed conditions. However, signal quality decreases beyond this range, as shown by dropping RSSI values and increased signal variability due to environmental and movement factors. The average distance between Node 3 and Node 4 during trials was 64.3 meters, the shortest of all node pairs tested (compared to 74.4 meters between Node 1 and Node 4 and 86.2 meters between Node 2 and Node 4). Even with the shorter range, RSSI values showed the greatest fluctuation, from -77 dBm to -105 dBm, with an average of -88 dBm. The heading values ranged from 95.3° to 112.9°, indicating some directional differences between transmitter and receiver. Figure 5 illustrates the deployment of communication nodes in the maritime environment alongside the real-world implementation of the developed hardware system on a traditional fishing vessel

*3.3 Data Transmission with Varying Distances*

Field testing was done to see how transmission distance affects successful data delivery between three ship nodes (Node 1, Node 2, and Node 3) and a central node (Node 4). Each node sent structured data packets containing GPS coordinates, RTC timestamps, orientation data, environmental parameters, and RSSI values. We measured system performance using packet loss percentage and RSSI at distances ranging from very short (under 20 meters) to longer (over 300 meters). As shown in Figure 6, signal strength generally decreased with increasing transmission distance, resulting in greater packet loss across all nodes. Node 1 maintained reliable communication up to about 65 meters before performance began to drop. Packet loss reached around 30% at distances between 272 and 341 meters when the RSSI value fell below –100 dBm. Node 2 performed better, with stable communication up to about 150 meters, gradually decreasing beyond 400 meters. Node 3 performed optimally only at short distances, around 80 meters. These observations indicate that the system performs reliably within short to medium communication ranges. Using multiple nodes with overlapping coverage offers redundancy and improves communication security, especially in emergencies.

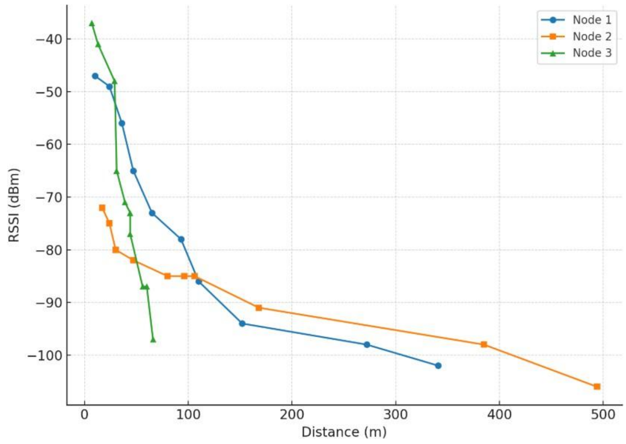



Figure 6. Measurement of RSSI as a Function of Distance for Each Node

Additionally, a proximity-based approach using the Haversine distance metric allows the system to adaptively adjust communication based on node distance and signal quality. Overall, these results show that even though signal quality and data transmission performance decline with distance, the system can maintain reliable performance within realistic operational limits. This makes the proposed approach relevant for maritime emergency communication systems, particularly for groups of fishing vessels that need reliable communication over short- to medium-distance routes.

*3.4 The SOS Signal Testing Using the Hopping Method*

To evaluate the reliability of the proposed multi-hop communication method, we conducted tests with a limited number of transmission attempts in controlled conditions. The SOS signal testing using this hopping method aimed to check how well the system could send emergency messages across multiple nodes in a dynamic maritime setting. The results in Table 9 show that no packet loss occurred during the transmission trials, indicating that emergency message delivery worked successfully under these conditions. The recorded RSSI values ranged from –89 dBm to –90 dBm, showing stable signal strength within the communication range. Transmission delays ranged from 8 to 13 seconds, depending on the number of hops and network conditions during the test. It is important to note that these results were obtained under controlled conditions, with limited transmission attempts and relatively short distances between nodes. Therefore, they may not represent absolute performance in all real-world conditions.

The transmission scenarios in Figure 7 correspond to the multi-hop communication paths shown in Table 2, in which SOS messages are relayed through intermediate nodes to reach their destinations. Table 3 shows the performance of SOS transmission in terms of delivery success rate and delay time. All packets sent in the test scenario were successfully received, with no data loss. The resulting delay was strongly influenced by the number of intermediate nodes along the communication path, demonstrating a trade-off between communication reliability and delay. A similar trend appears in Table 4, which lists test results using different node configurations. The results were consistent: all messages were successfully received, confirming that the multi-hop mechanism maintains communication reliability. In contrast, the single-hop communication tests showed significant packet loss, ranging from 10% to 40%, particularly at distances greater than 385 meters.

Table 2 Multi-Hop SOS Transmission Performance (Controlled Conditions, N = 5 Trials)

| Trial | Number of Hops | RSSI (dBm) | Delay (s) | Packet Loss (%) |
|---|---|---|---|---|
| 1 | 2 | -89 | 8 | 0 |
| 2 | 2 | -90 | 9 | 0 |
| 3 | 3 | -90 | 11 | 0 |
| 4 | 3 | -89 | 12 | 0 |
| 5 | 3 | -90 | 13 | 0 |


(a) (b) (c)

Figure 7. Multi-hop SOS transmission scenarios corresponding to the experimental results in Table 2: (a) Node 1 to Node 2, (b) Node 2 to Node 3, (c) Node 3 to Node 2 via the central node

This illustrates that the multi-hop approach improves communication reliability when direct transmission is not feasible. The results of this study show that the hopping method can enhance the reliability of SOS signal delivery in maritime environments. However, this improved reliability comes at the cost of increased delays due to the relay process between nodes. With this in mind, the proposed system is still relevant for emergency communication, where successful message delivery is more important than transmission speed.

Table 3. Summary of Multi-Hop SOS Transmission Performance

| Parameter | Value |
|---|---|
| Number of Trials | 5 |
| Packet Loss | 0% (observed) |
| RSSI Range | -89 to -90 dBm |
| Average Delay | 8–13 s |

Table 4 Comparison Between Single-Hop and Multi-Hop Communication

| Parameter | Single-Hop | Multi-Hop |
|---|---|---|
| Packet Loss | 10% – 40% | 0% (observed) |
| Reliable Range | <150 m | Extended via relay |
| RSSI | Down to -106 dBm | Stable (-89 to -90 dBm) |
| Delay | Lower | 8–13 s |
| Reliability | Low (long distance) | High |

*3.5 Energy Consumption Analysis*

Energy consumption is crucial in LPWAN-based communication systems, especially in maritime applications. In this study, we did not measure direct power consumption during field testing. Instead, we estimated energy use based on device specifications and the system's general operating conditions. The ESP32 microcontroller, which serves as the main processing unit, draws about 160–240 mA during active operation, depending on the workload and any additional modules used. The LoRa transceiver module, the main communication component, draws about 120 mA during transmission and about 10–15 mA during reception. Details on estimated power consumption for each system component are provided in Table 5. According to these estimates, power consumption during active transmission is mostly driven by the ESP32 microcontroller and the LoRa module in data transmission mode. Conversely, when the system is in standby or only receiving signals, power use is lower due to reduced communication activity. With a 3S Li-ion battery in the hardware system, the system can generally sustain a long operational time, especially when used in an intermittent communication pattern. In practical applications, the system often stays in standby mode and transmits only during emergencies, helping lower overall energy usage. It’s important to recognize that the power consumption estimates are based on ideal conditions, so actual usage may vary in a dynamic maritime environment. Factors such as weather, transmission frequency, and hardware setup can influence true power consumption. Therefore, future research should include direct power measurements and the development of energy optimization strategies.

Table 5 Estimated Power Consumption of System Components

| **Component** | **Mode** | **Current Consumption** |
|---|---|---|
| ESP32 | Active | 160–240 mA |
| LoRa Transceiver | Transmission | ~120 mA |
| LoRa Transceiver | Reception | 10–15 mA |

*3.6 System Limitations*

Although the results show promising performance, several areas need more investigation. System performance tends to drop at distances beyond approximately 385 meters, particularly in single-hop scenarios where packet loss rates rise significantly. Additionally, transmission delays of 8 to 13 seconds highlight the trade-offs in multi-hop communication. This delay is acceptable for emergency signals but not suitable for real-time response applications. The test setup, using four nodes, reflects a typical small-scale implementation for fishing boat clusters. Testing on a larger network scale is needed to understand how the system performs in more complex situations. Furthermore, the tests were conducted in coastal waters with moderate interference, so further evaluation in challenging open-sea conditions is necessary to better understand the system's resilience. Overall, these findings open up opportunities for further development, especially to increase communication range, reduce delays, and test system performance in wider and more challenging maritime scenarios.

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## 4. CONCLUSIONS

This study introduces a multi-node maritime emergency communication system designed for traditional fishing vessels. It uses LoRa-based multi-hop communication and adaptive routing that rely on proximity and RSSI. The system can automatically generate SOS signals and reliably deliver messages in changing maritime conditions. Test results indicate that in the multi-hop scenario, there was no packet loss under controlled conditions with nodes placed relatively close together. The RSSI values ranged from 89 to –90 dBm, and end-to-end delays ranged from 8 to 13 seconds. In contrast, single-hop communication experienced 10% to 40% packet loss at distances greater than 385 meters. This confirms that the multi-hop method can greatly improve communication reliability, even at the cost of longer transmission delays. The key contribution of this research is the integration of multi-hop communication, proximity-based routing, and a low-power IoT architecture into a single system for small-scale fisheries. Future development can focus on scaling the network, integrating more sensors, and testing in open sea conditions to prepare for wider use.

## REFERENCES

[1] W. Xu, W. Luo, Y. Sun, Z. Gao, B. Wu, and L. Lai, "MADRL-Based Edge Computing: Joint Energy-Latency Optimization for Marine Internet of Things," *IEEE Internet of Things Journal*, vol. 12, no. 15, pp. 30228–30241, 2025.

[2] Z. Song, W. Xu, L. Lai, W. Luo, and Y. Chen, "Delay-Aware Communication Service Strategy in USV-assisted Maritime MEC Environment," in *Proc. 4th Asia-Pacific Conf. Commun. Technol. Comput. Sci. (ACCTCS)*, 2024, pp. 241–246.

[3] X. Yao, R. Gao, Y. Hu, and J. Wang, "Online Learning Based Beam Allocation for Maritime Communications with Fairness Constraints," in *Proc. IEEE 23rd Int. Conf. Commun. Technol. (ICCT)*, 2023, pp. 1030–1035.

[4] I. Durlik, T. Miller, D. Cembrowska-Lech, A. Krzeminska, E. Zloczowska, and A. Nowak, "Navigating the Sea of Data: A Comprehensive Review on Data Analysis in Maritime IoT Applications," *Appl. Sci.*, vol. 13, no. 9742, pp. 1–26, 2023.

[5] M. Korb, Q. Huang, P. Stockel, G. C. Kappen, B. Weber, and M. Garcia, "A Cellular-Modem-Hosted Low-Cost Single-Shot Dual-Mode Assisted-GNSS Receiver for the Internet of Things," in *Proc. IEEE/ION Position, Location and Navigation Symp. (PLANS)*, Portland, OR, USA, 2020, pp. 1273–1279, doi: 10.1109/PLANS46316.2020.9110212.

[6] T. Janssen, A. Koppert, R. Berkvens, and M. Weyn, "A Survey on IoT Positioning Leveraging LPWAN, GNSS, and LEO-PNT," *IEEE Internet of Things Journal*, vol. 10, no. 13, pp. 11135–11159, Jul. 2023, doi: 10.1109/JIOT.2023.3243207.

[7] N. Hashim, F. Idris, T. N. A. T. Ab Aziz, S. H. Johari, R. Mohd Nor, and N. Ab Wahab, "Location tracking using LoRa," *Int. J. Electr. Comput. Eng.*, vol. 11, no. 4, Aug. 2021. doi: 10.11591/ijece.v11i4.pp3123-3128.

[8] S. E. Elgharbi, M. Iturralde, Y. Dupuis, and A. Gaugue, "OSR: Advancing Multi-Hop Routing for LoRaWAN Mesh Networks in Maritime Scenarios," in *Proc. 20th Int. Conf. Netw. Service Manag. (CNSM)*, 2024, pp. 1–7.

[9] I. McLeod and J. V. Ringwood, "Powering data buoys using wave energy: a review of possibilities," *J. Ocean Eng. Mar. Energy*, vol. 8, no. 3, pp. 417–432, 2022, doi: 10.1007/s40722-022-00240-3.

[10] R. Sanchez-Iborra, G. Liaño, I. Simoes, C. Couñago, and A. F. Skarmeta, "Tracking and Monitoring System Based on LoRa Technology for Lightweight Boats," *Electronics*, vol. 8, no. 1, p. 15, 2019, doi: 10.3390/electronics8010015.

[11] S. F. Hagh *et al.*, "LoRa Pore Pressure Probe for Real-Time Coastal Environment Monitoring," *IEEE Sensors Journal*, vol. 24, no. 23, pp. 39751–39758, Dec. 2024, doi: 10.1109/JSEN.2024.3479195.

[12] L. Cordova *et al.*, "Energy-Efficient LoRaWan Communication: Real-Time Applications in Aquaculture," in *Proc. IEEE 22nd Int. Conf. Ind. Informat. (INDIN)*, Beijing, China, 2024, pp. 1–6, doi: 10.1109/INDIN58382.2024.10774297.

[13] Y. Widiarti, Wirawan, and Suwadi, "Image Transmission with Joint Time Reversal and OFDM in Underwater Acoustic Environment," *J. Phys.: Conf. Ser.*, vol. 1179, no. 1, pp. 1–6, 2018.

[14] Y. Widiarti, W. Wirawan, and S. Suwadi, "Joint time-reversal precoding and spatial diversity technique for acoustic communication in a shallow water environment," *Int. J. Intell. Eng. Syst.*, vol. 13, no. 1, pp. 237–247, 2020.

[15] S. Paria, D. R. Choudhury, S. Pramanik, and I. S. Misra, "Experimental Characterization of LoRa Point-to-Point Communication Link for Real Time IoT Health Data Transmission,"

in *Proc. IEEE Calcutta Conf. (CALCON)*, Kolkata, India, 2024, pp. 1–5, doi: 10.1109/CALCON63337.2024.10914294.

[16] S. Deepak, H. Anandakumar, S. Pavithra, V. Keerthika, and K. Nandhini, "Performance Analysis of Star Topology for Small Networks Using Riverbed," in *Proc. 8th Int. Conf. Adv. Comput. Commun. Syst. (ICACCS)*, Coimbatore, India, 2022, pp. 2108–2111, doi: 10.1109/ICACCS54159.2022.9785012.

[17] J. J. López Escobar, F. Gil-Castiñeira, and R. P. Díaz Redondo, "JMAC Protocol: A Cross-Layer Multi-Hop Protocol for LoRa," *Sensors*, vol. 20, no. 23, p. 6893, 2020, doi: 10.3390/s20236893.

[18] S. Sampei and H. Harada, "System Design Issues and Performance Evaluations for Adaptive Modulation in New Wireless Access Systems," *Proc. IEEE*, vol. 95, no. 12, pp. 2456–2471, Dec. 2007, doi: 10.1109/JPROC.2007.904440.

[19] A. Svensson, "An Introduction to Adaptive QAM Modulation Schemes for Known and Predicted Channels," *Proc. IEEE*, vol. 95, no. 12, pp. 2322–2336, Dec. 2007, doi: 10.1109/JPROC.2007.904442.

[20] J. Zhang, G. Wang, H. Yang, B. Liu, and B. Li, "Multiuser Maritime Integrated Sensing and Communication Shipboard Base Station Deployment Optimization," *IEEE Internet of Things Journal*, vol. 11, no. 18, pp. 29375–29386, Sept. 2024, doi: 10.1109/JIOT.2024.3411643.

[21] X. Cui, Y. Liu, Y. Li, and G. Rong, "Operating Frequency Optimization Design of Multiple-Relay Wireless Power Transfer System Based on PSO Algorithm," in *Proc. IEEE 17th Conf. Ind. Electron. Appl. (ICIEA)*, Chengdu, China, 2022, pp. 452–457, doi: 10.1109/ICIEA54703.2022.10006069.

[22] H. Xu, D. Li, M. Liu, G. Han, W. Huang, and C. Xu, "A Hybrid Routing Algorithm in Terrestrial-Satellite Integrated Network," in *Proc. IEEE/CIC Int. Conf. Commun. China (ICCC)*, Chongqing, China, 2020, pp. 90–95, doi: 10.1109/ICCC49849.2020.9238984.

[23] X. Wang, H. Wu, Y. Miao, and H. Zhu, "A Hybrid Routing Protocol Based on Naïve Bayes and Improved Particle Swarm Optimization Algorithms," *Electronics*, vol. 11, no. 6, p. 869, 2022, doi: 10.3390/electronics11060869.

[24] A. M. Soomro *et al.*, "In MANET: An Improved Hybrid Routing Approach for Disaster Management," in *Proc. IEEE Int. Conf. Emerg. Trends Eng., Sci. Technol. (ICES&T)*, Bahawalpur, Pakistan, 2023, pp. 1–6, doi: 10.1109/ICEST56843.2023.10138831.

[25] H. Wang, H. Wang, and Y. Xiang, "Intelligent Adaptive Routing Based on Multi-attribute QoS in Hybrid SDNs," in *Proc. IEEE 4th Int. Conf. Inf. Technol., Big Data Artif. Intell. (ICIBA)*, Chongqing, China, 2024, pp. 386–390, doi: 10.1109/ICIBA62489.2024.10868903.