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ABSTRACT

The growth of digital technology is expected to transform small-scale fishery sectors, where a need for robust, low-cost, long-range communication networks becomes critical. There exist several technologies that are used in the fishery sector but they are never affordable to small scale fisheries. This study evaluates the feasibility of using low cost Long Range Wide Area Network (LoRaWAN) technology specifically tailored for smart fishing environments to small scale fishery sector. Using simulation, we assess the performance of the key performance metrics including probability of success and energy efficiency under varying device densities and time. During evaluation, we considered end devices distributed in a rectangular shape with one gateway and two gateways architectures. We have evaluated the performance of both standard ALOHA and Time Division Multiple Access (TDMA) LoRaWAN in both one and two gateways configuration. The results showed that the probability of delivering packets successfully is high when there are fewer devices in the network for both models. However, there is a significant drop in standard LoRaWAN when the number of devices increases as they contend for the channels unsuccessfully. It was demonstrated that TDMA approach significantly outperforms standard ALOHA in high-density scenarios, maintaining a 1.0 success probability. While the network exhibits high reliability for non-critical data across distances up to 10km, the consistent 20-second latency suggests limitations for time-sensitive emergency alerts.

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Highlights:

- *Affordability gap identified*: Existing fishery technologies are not affordable for small-scale fishers, creating a need for low-cost, long-range communication solutions tailored to this sector.
- *TDMA outperforms standard ALOHA in high-density scenarios*: The TDMA-based LoRaWAN approach maintained a 1.0 probability of successful packet delivery, while standard ALOHA experienced significant performance drops as the number of connected devices increased.
- *Network reliability for non-critical data up to 10 km*: The proposed LoRaWAN system demonstrated high reliability for transmitting non-critical data across distances reaching 10 kilometers.
- *Performance trade-off with two gateway architectures*: The study evaluated both one-gateway and two-gateway configurations, showing that probability of success is higher when fewer devices are in the network regardless of the model used.
- *Latency limitation for emergency applications*: A consistent 20-second latency was observed, suggesting that while the system is suitable for routine data transmission, it has limitations for time-sensitive emergency alerts that require immediate response.

INTRODUCTION

The fishing industry plays a crucial role in feeding millions of people and satisfying global seafood demands (Virdin et al. 2023). However, its sustainability is at risk due to issues like overfishing, bycatch, and inefficient management practices. Traditional management approaches often lack mechanism in acquiring and utilizing real-time data, which facilitate proactive and data-driven decision-making. The lack of timely information may lead to over-exploitation, habitat degradation, and broader ecosystem damage, which can negatively affect fish stocks, local communities, and the economy in general (Han & Chen, 2024). The overfishing, which is caused by insufficient real-time data of fetched fishes over a duration of time, has caused economic losses and threatens the livelihoods of fishing communities (Batool et al., 2025). In addition, the overfishing may result into habitat destruction and ecosystem disruption

posing a serious concern about global food security. These challenges necessitate the need for sustainable technologies in smart fishing.

Artisanal fishers who are small scale are more affected by the challenges due to limited access to essential fishery information and knowledge, which in turn affects their productivity. Information and Communication Technologies (ICTs) could address this gap by delivering valuable information about fishing activities and upcoming events to the fishing community (Calderwood 2022, Haambiya et al., 2020). One promising solution is the Long-Range Wide Area Network (LoRaWAN), which can enhance monitoring and data-driven decision-making in smart fishing. LoRaWAN is a low-power, long-range wireless communication protocol, well-suited for the remote environments encountered in fishing operations (Kumari et al. 2024). By deploying sensors on vessels, buoys, and equipment, real-time data on location, environmental conditions, and fishing activities can be transmitted to offshore stations. This enables informed decisions regarding sustainable practices, resource management, and regulatory compliance. Additionally, LoRaWAN devices are designed to consume minimal power, extending their operational life and reducing the need for frequent battery changes which is a significant benefit in challenging marine environments (Tamang et al. 2022).

The growing blue economy sector is driving demand for more sustainable and technologically advanced solutions. Despite its potential, research on LoRaWAN's application in smart fishing remains limited (Shayo 2026, Tassetti et al. 2022a).This study aims to explore the benefits of LoRaWAN in smart fishing, evaluating its performance based on energy efficiency, data delivery and scalability to harsh marine conditions. The findings will assist stakeholders, including regulatory bodies, consumers, and industry leaders, in evaluating LoRaWAN's effectiveness in promoting the blue economy. As the fishing industry works to reconcile resource conservation with the demand for ethically sourced seafood, LoRaWAN's benefits could play a pivotal role in transforming the seafood supply chain.

ARTISANAL FISHERIES AND TECHNOLOGICAL GAPS

Artisanal fisheries, also known as small-scale or subsistence fisheries, are fundamental to the livelihoods of millions of people worldwide. These fisheries are characterized by their reliance on traditional fishing techniques, relatively small-scale operations, and limited technological resources. Artisanal fishers typically use hand tools, small boats, and simple gear to catch fish, often operating in nearshore or inland waters(Lloret and Font 2013, Shrestha et al. 2022) .Their practices are deeply rooted in local knowledge and culture, and they play a critical role in providing food security and economic stability to coastal and rural communities.

Despite their crucial role, artisanal fishers encounter several significant challenges including suffering from limited access to timely and accurate information on fish stocks, weather conditions, and market prices, which impedes their ability to make informed decisions and affects their catch efficiency and economic returns (Idfonce, 2023). Additionally, their reliance on local fish stocks makes them vulnerable to overfishing and resource depletion (Awolumate et al., 2025), exacerbated by a lack of real-time data and effective management, leading to declining fish populations and reduced catches (Tidd et al., 2022). Many artisanal fisheries are governed by informal or inadequate regulatory frameworks, resulting in poor enforcement of sustainable practices and contributing to environmental degradation. Furthermore, economic and market challenges persist, as artisanal fishers often struggle with market inefficiencies and limited bargaining power, which can lead to economic instability and lower incomes (Okafor-Yarwood et al. 2022).

Technological advancements present promising solutions to the challenges faced by artisanal fishers. Information and Communication Technologies (ICTs) can bridge critical information gaps by providing real-time data on weather conditions, fish stock availability, and market trends. Mobile applications and digital platforms facilitate access to this information, allowing fishers to plan their activities more effectively and make better-informed decisions(Ruth et al. 2025). On the other hand, technologies such as remote sensing and electronic monitoring systems can significantly enhance data collection and monitoring within artisanal fisheries (Tassetti et al. 2022b). The ICT tools offer valuable insights into fishing practices, catch rates, and environmental conditions, thereby supporting more effective management and conservation efforts (Ramanathan et al. 2023).

Several initiatives have effectively harnessed technology to address gaps in artisanal fisheries, though each faces its own set of challenges. Mobile fisheries management platforms by Calderwood, (2022) and Krasnikov et al., (2024) provide real-time information on fish prices, weather forecasts, and fishing regulations, enhancing catch efficiency and market access for fishers. However, challenges include limited smartphone penetration and varying levels of digital literacy among fishers, which can hinder the widespread adoption of this system. Electronic monitoring systems, proposed by (Orofino et al., 2023; and Ramanathan et al., 2023) track fishing activities and enforce sustainable practices, improving data collection on fish stocks and management. However, these systems face issues such as high equipment maintenance costs and the need for extensive training to ensure effective use and data interpretation.

Community-based technology solutions, such as smart buoys equipped with sensors for environmental monitoring, have been developed (Dimitrov et al., 2025; Zhang et al., 2025). The smart buoys allow fishers to gather data on water quality and environmental conditions. However, the systems are challenged by high costs of deployment and maintenance and technical difficulties associated with calibrating sensors in variable marine environments.

Other initiatives include the use of Autonomous Underwater Vehicles (AUVs) (Ma et al., 2025) and Satellite (Kamaruzzaman & Ahmad, 2023) used for collecting data on marine ecosystems and fish populations. Satellite data integration projects can create detailed maps of fishing grounds and marine biodiversity(Kamaruzzaman & Ahmad, 2023). High cost of AUVs and the logistical difficulties of operating them in harsh and remote marine conditions remains a challenge. Again, a need for high resolution satellite image and the complexity of installing satellite is a challenge especially to small scale fisheries.

The LoRaWAN offers significant advantages in addressing the challenges faced by the various technological initiatives in artisanal fisheries. Its long-range, low-power communication capabilities provide an effective solution for remote and isolated fishing areas where traditional connectivity options are limited. By enabling reliable, real-time data transmission over vast distances, LoRaWAN addresses issues such as intermittent network access and connectivity problems. Its low energy consumption supports the extended operational life of devices, reducing the need for frequent maintenance and battery replacements, which can be costly and cumbersome. Additionally, LoRaWAN's as a cost-effective infrastructure can lower the overall expenses associated with deploying and maintaining monitoring systems, making advanced technologies more accessible to artisanal fishers.

LoRaWAN APPLICATIONS IN SMART FISHING

One of the primary advantages of LoRaWAN in smart fishing is its capacity for low-cost, real-time data collection and transmission. LoRaWAN sensors can be deployed on fishing vessels, buoys, and monitoring stations to continuously collect data. The data can then be transmitted in real time to central servers for analysis and actionable insights. Moreover, LoRaWAN enables the transmission of data from remote locations where traditional cellular networks are unavailable, providing critical information that can enhance decision-making and resource management in the sector.

Proposed LoRaWAN Model for Smart fishing

The proposed LoRaWAN model for smart fishing represents a comprehensive architecture designed to enhance data collection and communication in marine environments. This model integrates sensors, gateways, network servers, and application servers into three main subsystems: the finder, fishing gear, and fishing vessel, as illustrated in Figure 1.

Sensors are deployed strategically both underwater and on the boards of fishing vessels. These sensors are equipped to gather a range of data from the underwater sensors, and operational data such as location and movement from those on the fishing vessels. Additionally, sensors integrated with fish finders and smart fishing gear collect data on fish presence and behavior, providing a comprehensive view of fishing conditions.

Gateways play a crucial role in the system by transmitting the sensor data to the network. Utilizing the LoRa communication protocol, these gateways enable long-range communication with minimal power consumption, making them well-suited for the expansive and often remote marine environments. The gateways ensure that data from sensors is reliably relayed over significant distances to network servers, even in areas where traditional communication methods are limited or non-existent.

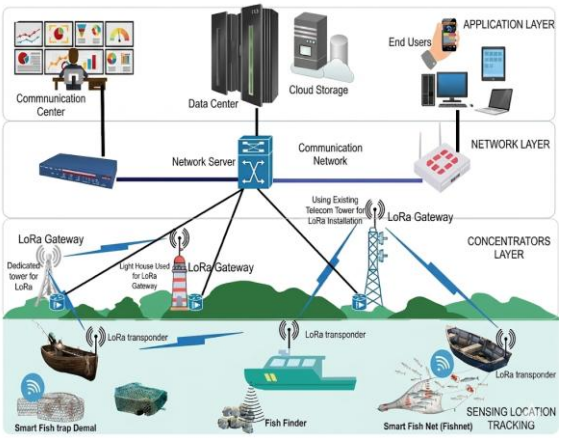

Figure 1: LoRaWAN model for the smart fishing.

Network servers manage several critical tasks, including authentication of data sources, routing of data packets, and handling roaming as vessels navigate through different areas. This functionality ensures that data is accurately processed and directed to the appropriate destination, maintaining data integrity and connectivity across varying geographic locations.

Application servers provide the interface through which users can access and interact with the data collected by the sensors. These servers aggregate and process the data from the three subsystems; finder, fishing gear, and fishing vessel to enable users to visualize real-time information and make informed decisions. The application server also facilitates data analysis, reporting, and user access management, as detailed in Figure 1. This architecture, through its integration of advanced technologies and communication protocols, addresses the specific needs of smart fishing, enhancing operational efficiency,

environmental monitoring, and resource management in marine settings.

Simulation Model and Parameters

We have modeled the LoRaWAN communication network in the smart fishing architecture and evaluated the performance of the network using simulations. The simulations were carried using ns3 to determine the performance of the communication network in carrying out data from the different end devices to the main office. We have considered both standard and TDMA *LoRaWAN where devices transmit randomly or in the* scheduled time whenever they have data to transmit.
We have distributed 1000 devices in a rectangular architecture with one gateway placed inshore and added one gateway offshore as shown in Figure 2. The amount of data to be transmitted from the end devices to the gateway is 32-bit float that can be transmitted using LoRaWAN.

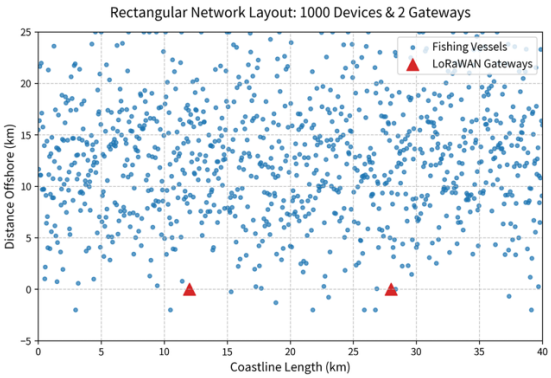

Figure 2: Ends devices distribution in the smart fishing network architecture.

We modelled the maritime propagation environment and the proposed relay architectures to validate performance against the 20 km range requirement. To accurately simulate the communication link over the ocean surface, we implement a Log-Distance Path Loss Model in equation (1) specifically calibrated for the maritime Fresnel zone within ns-3. The path loss L is calculated as:

$$L = L_0 + 10nlog_{10}\left(\frac{d}{d_0}\right) + X_\delta \quad (1)$$

where L_0 represents the path loss at the reference distance d_0 usually 1 km while n is the path loss exponent typically between 2.0 and 2.5 for open-sea Line-of-Sight and d stands for distance between the vessel node and the gateway (targeting 15–20 km).

X_δ: A Gaussian random variable representing shadowing effects caused by wave height and sea state.

The simulation environment includes N fishing vessels as nodes randomly distributed within a rectangular coastal sector. Two architectures with single and two gateways were considered. In a single gateway architecture, the gateway is positioned at a coastal height of $H = 30m$ to maximize the radio horizon in the network. The Signal-to-Interference Noise Ratio (SINR) for a successful packet reception is modelled by equation (2).

$$SINR = \frac{P_{rx}}{N_{power}+\sum I} \quad (2)$$

where P_{rx} is the received power, N_{power} is the thermal noise floor, and $\sum I$ is the cumulative interference from other vessels (collisions) within the same Spreading Factor (SF). The Packet Delivery Rate (PDR) is defined as the ratio of successfully received packets as presented in equation (3).

$$PDR = \frac{\sum P_{rec}}{\sum P_{gen}} \times 100\% \quad (3)$$

The energy efficiency was evaluated by considering the number of successfully transmitted bits per joule of energy consumed. Based on real-world measurements of the typical LoRaWAN devices SX1272 transceiver, we assumed each transmission attempt consumes approximately 0.05 J which accounts for transmit power at +14 dBm, airtime for a small packet and brief receive windows in Class A mode for packet carrying 32 bits of data.
Therefore, the energy efficiency is thus calculated as using equation (4).

$$Enery\ Efficiency = \frac{32\times Probability\ of\ Sucess}{0.05} \quad (4)$$

The projection of battery life after ten years is calculated using equation (5)

$$L = \frac{C_{bat}\times V\times(1-S_d)}{E_{avg}} \quad (5)$$

where: C_{bat}-battery capacity, V-operating voltage, S_d-Self battery discharge rate, E_{avg}- average energy consumption.

PERFORMANCE EVALUATION OF LoRaWAN IN SMART FISHING

We evaluated the performance of LoRaWAN in facilitating the data transmission in the smart fishing architecture using probability of success and energy efficiency as the performance parameters.

Probability of Success

We have evaluated the suitability of both standard LoRaWAN that uses ALOHA as the medium access control and the TDMA LoRaWAN that uses TDMA to access the medium in the smart fishing applications. We considered both single gateway architecture and multigateway architecture with 1000 devices distributed in a rectangular sector.
In a single gateway architecture, even with TDMA, which eliminates network collisions, the probability of success at 20 km is slightly lower than that achieved by the multi-gateway setup due to environmental attenuation at extreme range (See Figure 3). In the same arrangement, the Standard LoRaWAN performance collapses much faster due to the combination of weak signals and high contention as

seen in Figure 3. However, the data are successfully delivered using the TDMA LoRaWAN regardless of the number of devices in the network because the devices will transmit at their scheduled time without any collision in both scenarios.

It is worth noting that while TDMA solves the scalability issue, a single gateway architecture remains physically limited by the radio horizon and path loss at the 20 km range. The performance of both models is expected to be improved with the increase in number of gateways in the network due to the increase in the spatial diversity. In a multi-gateway configuration, we noted that the probability of success is influenced by increased macro-diversity where the probability of a packet being captured despite shadowing from sea states in two gateways is lower than with more than two gateways.

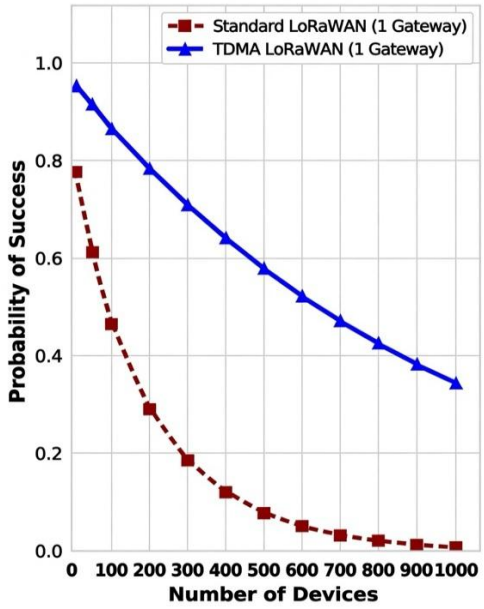

Figure 3: Probability of success for single-gateway architecture.

In Mult-gateways architecture the performance of the standard LoRaWAN is better than in a single gateway architecture as shown in Figure 4. The high contention from up to 1,000 devices causes significant packet loss, with the success rate falling below 0.5 before reaching 200 devices. On the other end, TDMA LoRaWAN in two gateways architecture maintains a stable performance near 0.95 (Figure 4). This is a slight decrease compared to the performance of more than two-gateway setup which is attributed by the increased likelihood of signal blockage and attenuation at the 20 km edge where fewer gateways are available to provide alternative reception paths.

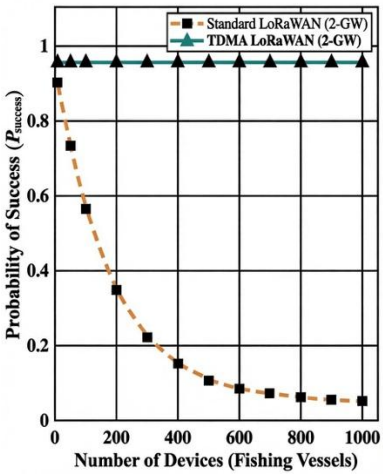

Figure 4: Probability of success for two-gateway architecture.

In general, the results showed that the probability of success is high when there are fewer devices in the network for both models. However, there is a significant drop in standard LoRaWAN when the number of devices increases as they contend for the channels unsuccessfully. In addition, standard LoRaWAN exhibits a decline in reliability as device density increases, in both architectures emphasizing the necessity of scheduled access (TDMA) for large-scale maritime deployments. Increasing the number of gateways is costly but the performance is superior for maintaining the high probability of success required for consistent fishery monitoring and safety.

Energy Efficiency

The energy efficiency was projected over a 10-year time span to reveal the critical difference between the two protocols for long-term viability in smart fishery infrastructure. The results for the two protocols in a harsh marine environment at a 20 km range, demonstrate a clear breaking point for standard LoRaWAN. The scheduled approach continues to conserve energy by avoiding collisions and minimizing retransmissions as described in Figure 5. After 10 years of continuous operation, TDMA LoRaWAN will still retains approximately 56% of its original battery capacity. This provides a massive buffer for unforeseen events, such as extended periods of rough weather that might require higher power or more frequent updates.

For the Standard LoRaWAN, the compounding effect of low probability of success and the resulting need for multiple retransmissions leads to complete battery depletion after 10 years' time. In this model, the standard LoRaWAN reaches 0% capacity at approximately 9.9 years (See Figure 5). This means that a standard LoRaWAN network would require a complete, expensive battery replacement for the entire fleet before the 10-years mark.

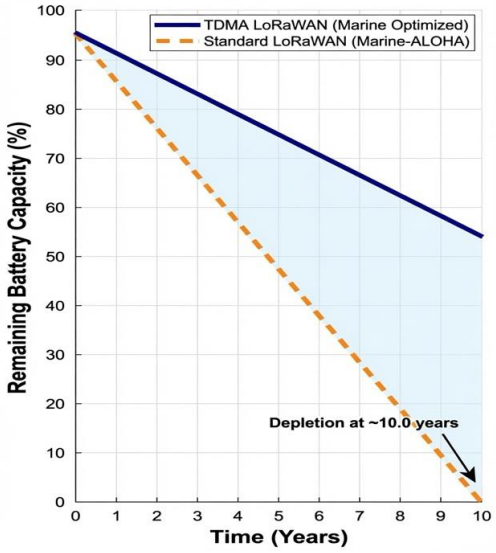

Figure 5: Energy Efficiency for Single gateway architecture.

By adding a second gateway in the network the system benefits from spatial diversity, which improves signal capture and reduces the number of retransmissions required compared to the single-gateway model. With 2 gateways, the probability of success reaches approximately 99% and interference and shadowing risks are significantly mitigated. Therefore, over 10 years, the battery depletion is very gradual, ending at approximately 58% battery capacity remaining.

The 2-gateways architecture also improves the standard LoRaWAN energy efficiency. While this extends the lifespan compared to a single-gateway system, the cumulative energy cost of frequent retransmissions still depletes the battery significantly, leaving only 18% capacity after 10 years. The gap between the two lines in Figure 6, illustrates that while 2 gateways help ALOHA survive the 10-year window, the TDMA protocol still offers nearly double the remaining energy, providing a much higher safety margin for sensor reliability in deep-sea conditions.

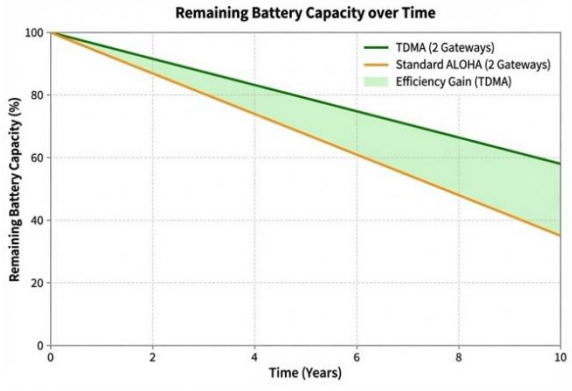

Figure 6: Energy efficiency for multi-gateways architecture.

The results highlight TDMA LoRaWAN's superior scalability and efficiency for dense deployments in smart fishing scenarios, where up to 100 devices may operate in a single network with the projected battery capacity presented in Table 1. In that case, the standard LoRaWAN will require a completely replacement of a battery after 10 years.

Table 1: Performance Comparison of Standard and TDMA LoRaWAN

Metric	Standard LoRaWAN	TDMA LoRaWAN
Projected life span	~ 9.9	> 10
Battery Status at 10 years' time	0% remaining	56% remaining

CONCLUSION

In conclusion, the simulation results demonstrate that TDMA LoRaWAN outperforms standard LoRaWAN in both probability of success and energy efficiency, making it a more suitable choice for smart fishing applications in the blue economy sector. The consistent high performance of TDMA, even with increasing device numbers, supports its adoption for sustainable, real-time monitoring in remote marine environments. Recommendations include further field testing in actual fishing operations, integration with machine learning for adaptive scheduling, and exploration of hybrid models combining LoRaWAN with other ICTs to address connectivity gaps in developing regions.

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