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Multi-hop Wireless Transmission for Maritime Scenarios

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Multi-hop Wireless Transmission for Maritime Scenarios

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Abstract—The collection and processing of maritime information is an essential task that demands extensive analysis to achieve a more profound understanding of coastal regions. Usually, data is gathered through sensors placed on buoys and transmitted to onshore data centres for storage and examination. Nevertheless, the harsh marine environment, including waves, wind, and vessel traffic, creates substantial challenges for effectively managing this task. This paper focuses on two key objectives: firstly, introducing a physical model for electromagnetic propagation in a buoy network that takes into account the unique characteristics of the marine environment, and secondly, evaluating the performance of the physical model in a multi-hop data transmission scenario using a LoRaWAN mesh network. The main aim of the proposed approach is to facilitate efficient communication while optimising the utilisation of reconfigurable devices to reduce power consumption and accelerate data transmission. To gauge the effectiveness of the proposed solution, we explored a multi-hop approach centred on a single relay node that receives packets from other nodes and forwards them to the gateway. We analyse two quality-of-service parameters: throughput and packet losses. Our proposed solution indicates that employing a straightforward one-hop relay can enhance throughput up to three times during the transmission process.

Index Terms—LoRaWAN, multi-hop, simulation, Marine of Things (MoT), mesh network

I. INTRODUCTION

Maritime environments are critical ecosystems that have a significant impact on global economic and social development. The acquisition and processing of maritime information, particularly in coastal zones, is essential for improving maritime safety, environmental monitoring, and resource management. However, this task presents significant challenges due to the complex and dynamic nature of the marine environment. Sensors installed on buoys are typically used to collect maritime information, which is then transmitted to onshore data centres for processing and storage. Nevertheless, the hostile marine environment, characterised by waves, wind, and ship traffic, poses significant challenges in effectively transmitting and processing this information.

Long Range (LoRa) and Long Range Wide Area Networks (LoRaWAN) are Low Power, Wide Area Networks (LPWAN) protocols designed to wirelessly connect battery-operated devices to the internet in regional, national, or global networks. This type of network differs from a wireless WAN, which is intended to connect users or businesses and carries more data using more power. The low power, low bit rate, and Internet of Things (IoT) use distinguish LoRaWAN. LoRaWAN offers long-range communication at data rate ranges from 0.30 kbit/s to 50 kbit/s per channel and is available under a free license, making it ideal for use in maritime environments. However, numerous challenges must be addressed. Although LoRaWAN can achieve a range of several km in optimal conditions, the range may be significantly lower in real-world deployments due to factors such as obstacles, interference, and environmental conditions. The movement of buoys in unpredictable maritime conditions can also impair transmission stability, as the antenna moves with the waves. Furthermore, LoRaWAN currently does not support routing, limiting communication to node-to-gateway communication. Therefore, it is necessary to develop an approach that allows for node-to-node communication to find the optimal path to reach the gateway. See Fig. 1.

In this paper, we present a physical model for electromagnetic propagation in a buoy network that accounts for the unique characteristics of the marine environment. This model aims to test the reliability and efficiency of the data transmission performance of the marine environment. We also evaluate the effectiveness of the proposed physical model in a basic multi-hop data transmission scenario using a LoRaWAN mesh network. Our primary objective is to investigate the challenges associated with wireless transmission in coastal environments due to maritime conditions, which can degrade transmission performance. Our research aims to provide an initial approach to the scientific community for developing new communication protocols for maritime wireless transmission

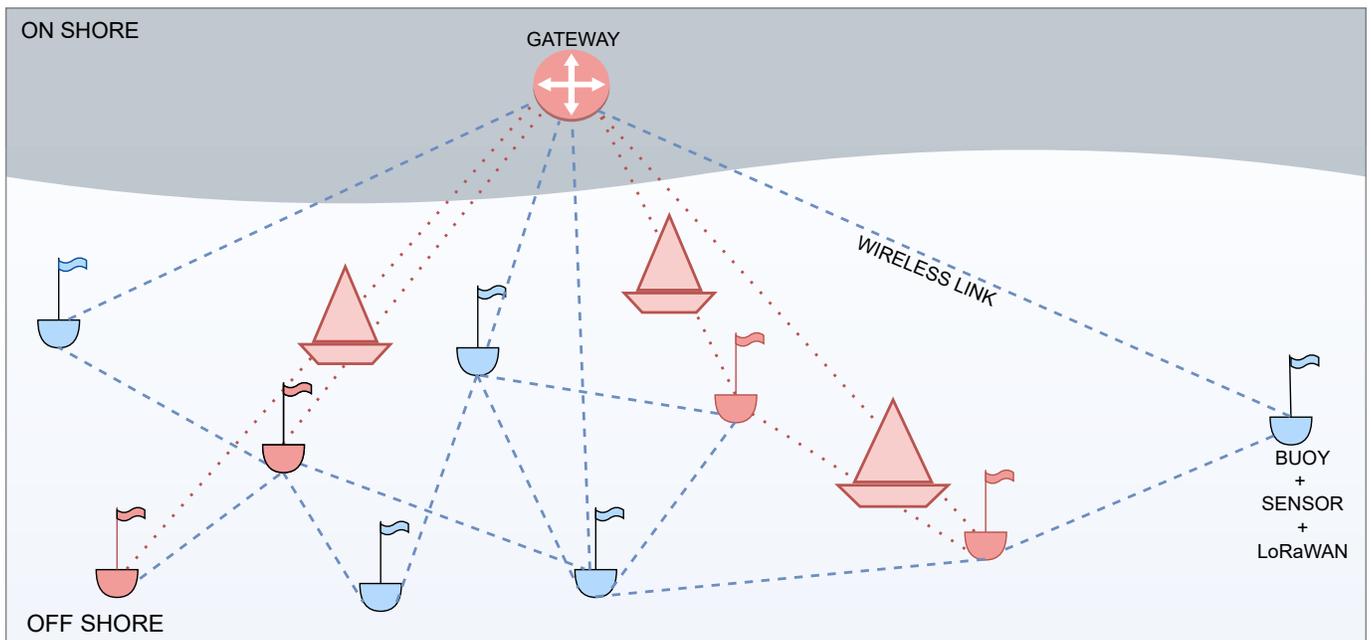


Fig. 1: Each buoy is equipped with a LoRaWAN node. Nodes marked in red cannot transmit directly to the gateway due to ships causing interference between the node and the gateway. Thus, they require relaying on buoys marked in blue to reach the gateway.

that consider the aforementioned physical parameters of sea behaviour.

The remainder of this paper is organised as follows. Section II provides a comprehensive review of the current state-of-the-art research in the field of maritime information acquisition and transmission. In Section III, we present our proposed physical model for electromagnetic propagation in maritime environments, taking into account the unique characteristics of the marine environment. Section IV describes the simulation scenario and network configuration utilised in our experimental evaluation. Section V presents the results of our analysis, including several quality-of-service parameters such as throughput and packet losses. Finally, in Section VI, we summarise our findings and discuss their implications for future research in the field of maritime information acquisition and transmission.

II. PREVIOUS WORKS

Extensive research in recent years has been conducted on the acquisition and transmission of maritime information, motivated by the need to understand and manage coastal environments. A considerable amount of prior work has investigated various aspects of this topic, including the development of wireless communication protocols, the design of sensor networks for marine environments, and the evaluation of existing wireless technologies. Numerous techniques have been proposed to maintain connectivity in Wireless Sensor Networks (WSN) [1]. With regards to wireless communication protocols, earlier studies have examined the use of different technologies such as Wireless Fidelity (Wi-Fi), Zonal Intercommunication

Global-Standard (Zigbee), Fourth-Generation (4G) and Fifth-Generation (5G), as well as more specialised wireless technologies tested and adapted for marine environments.

A solution proposed for surveying coastal maritime zones is based on 4G and 5G networks to achieve high-speed transmission [2]–[5]. However, this solution is limited to terrestrial base stations covering only several kilometres offshore. It may work for ship communications, but the communication of maritime IoT cannot be guaranteed due to the unpredictable sea conditions. Another approach to maritime communications focuses on utilising full satellite communication or hybrid satellite-terrestrial maritime communication networks to achieve high-speed transmission [6]. This solution appears to be technically practical, although it incurs high costs.

In [7], the authors presented a WSN that enabled reliable, long-term hazard monitoring at the Port of Brisbane, Australia. The sensor nodes were capable of measuring a range of hazardous events and capturing their time and location in the maritime environment. Additionally, each sensor node was equipped with a Global Positioning System (GPS) module and a Zigbee module. In [8], the authors proposed a Zigbee mesh network for coastal environmental monitoring. This cost-effective solution utilised small, lightweight buoy mesh networks, each equipped with sensors and a Zigbee hardware module for communication.

Numerous studies have investigated Wi-Fi technology for maritime communications. For instance, in [9], the authors evaluated the performance of IEEE 802.11n networks in the 5.8GHz band in a maritime environment. They established a point-to-point link between a fishing ship and shore, demon-

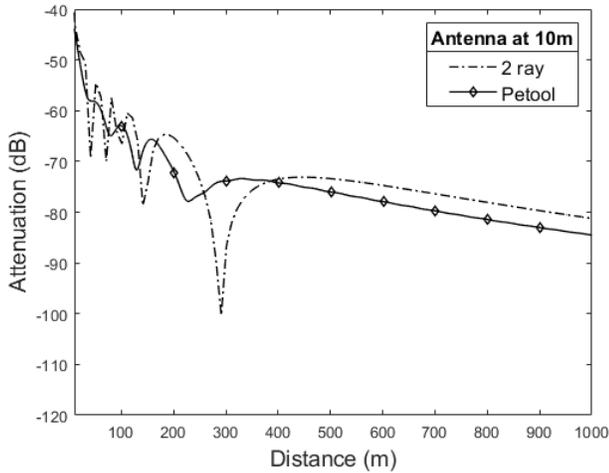


Fig. 3: Attenuation versus distance at 433MHz for antenna height $h_{Ant} = 10m$ using 2-ray and Petool models

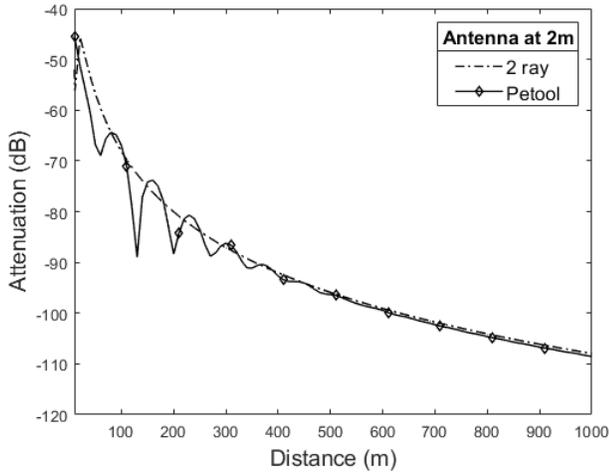


Fig. 4: Attenuation versus distance at 433MHz for antenna height $h_{Ant} = 2m$ using 2-ray and Petool models

Petool model are compared to those obtained with the two-ray model. In Fig. 3, where $h_{Ant} = 10m$, classical interferences predicted by the two-ray model are found, where the last oscillation is given by the relation $d_{break} = 2h_{Ant}^2/\lambda = 288m$ (where λ is the wavelength). However, for $h_{Ant} = 2m$ (Fig. 4), a large number of interferences are observed, well beyond the distance $d_{break} = 11.5m$ (on the chosen distance scale, the last oscillation predicted by the two-ray model cannot be observed in Fig. 4). The Petool model clearly shows interferences that cannot be predicted by a two-ray model. These fading phenomena are related to the reflection on the water, and the level and number of these interferences are directly related to the radiation pattern of the antenna and the surface impedance of the water. Fig. 5 shows the attenuation of the communication channel for an antenna with an aperture angle of 20° and 1° and in the case of transmission on the sea

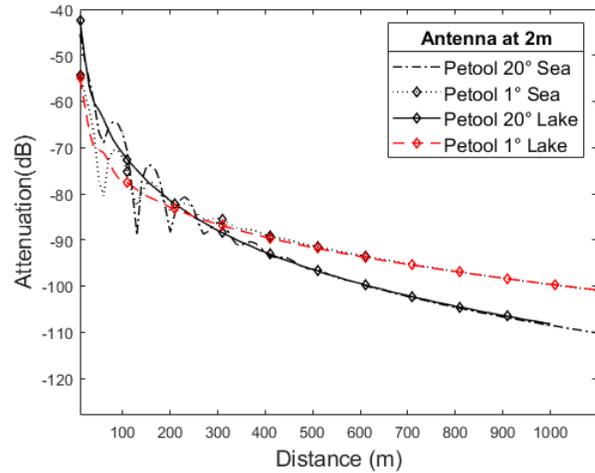


Fig. 5: Attenuation versus distance at 433MHz using a Petool model in the case of transmission over the sea or over a lake, for an antenna height $h_{Ant} = 2m$ with an aperture angle of 20° or 1°

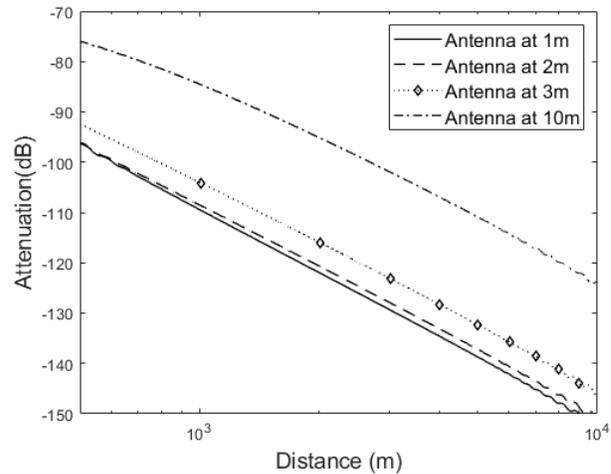


Fig. 6: Attenuation versus distance at 433MHz for different antenna heights using a Petool model

($\epsilon_r = 80$, $\sigma = 5S/m$) or on a lake ($\epsilon_r = 70$, $\sigma = 0.01S/m$).

The height of the antennas is a significant factor in signal attenuation. As depicted in Fig. 6, when the antenna is positioned too close to the water, the transmitted signal undergoes significant attenuation due to diffraction. When the antenna is situated near the water, the Fresnel ellipsoid is not clear [21]. To minimise the effects of reflections and attenuation by the sea, the antenna must be raised to a certain height. Increasing the antenna height by 1 to 2m has little impact on signal attenuation. An antenna height of at least 3m above the sea is required to begin to see a decrease in attenuation with antenna height. While an antenna height of 10m would decrease attenuation by over 20dB, it is challenging to place antennas at such a height on a reasonably sized buoy.

Swell or waves also play an important role in attenuation. Firstly, they change the orientation of the antenna due to the oscillating movement of the buoy (see Fig. 7a). We simulated the effects of swells by varying the orientation of the antenna by an angle of $\pm 20^\circ$ from the vertical, resulting in an excess attenuation of 6dB. We also attempted to simulate the influence of the position of one antenna in relation to the other, as shown in Figs. 7b-7d (buoy located in the trough of the wave, on the top, or a combination of these two possibilities). However, the spatial calculation step of the Petool software does not allow consistent results to be obtained.

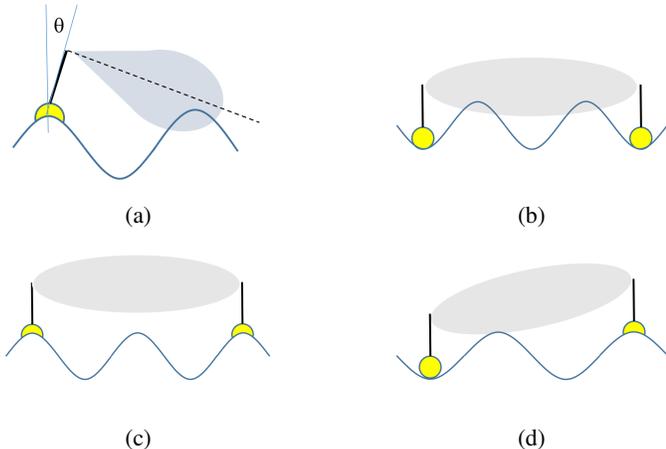


Fig. 7: Influence of the waves: a) On the signal propagation direction; b-d) Interaction between the Fresnel zone and waves vs buoy position

B. Experimental Results and Analysis

A radio link was established between two buoys, each equipped with a LORA radio module (based on the SX1276 component), a Diamond NR770H antenna, an Intel NUC PC, and a GPS. Additionally, the receiving buoy was equipped with a 4G modem to transmit the Received Signal Strength Indication (RSSI) and Signal-to-Noise Ratio (SNR) data in real-time. Table II describes the configuration parameters of the radio module. The measurements were conducted in calm weather conditions with a swell not exceeding 30cm, as seen in Photography Fig. 8. The experimental results of SNR and RSSI measurements as a function of distance are displayed in Fig. 9.

TABLE II: Configuration parameters of the radio module

Parameters	Value
Transmit Power	14dBm
Spreading Factor	12
Bandwidth	125kHz
Coding Rate	4/5
Frequency	433MHz
Gain Antenna	5dBi

We observed a link loss for an inter-buoy distance of 3.5km, resulting in an SNR of -20dB and an RSSI of -130dBm. The



Fig. 8: Physical appearance of the buoy

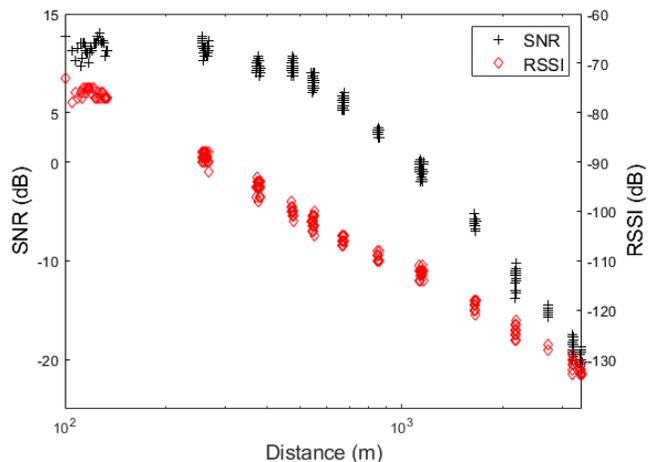


Fig. 9: Measured RSSI and SNR versus distance at 433MHz

theoretical minimum sensitivity for a LORA receiver is given by Eq. 1

$$S = -174\text{dBm} + 10\text{Log}(\text{Bw}) + \text{NF} + \text{SNR}_{Lim} \quad (1)$$

where $\text{Bw} = 125\text{kHz}$ and the SX1276 manufacturer's data ($\text{NF}=6$ and $\text{SNR}_{lim} = -20\text{dB}$ when $\text{SF}=12$) give a minimum theoretical sensitivity of -137dBm . Our experimental measurements reveal that the receiver drops out for an RSSI of -130dBm and an SNR of -20dB (as shown in Fig. 9). This indicates that the link is limited by the noise level, but there is potentially a 7dB margin over the sensitivity. With a

more careful Electromagnetic Compatibility (EMC) design, we could possibly reach the theoretical value of -137dBm , and thereby increase the communication distance. The experimental attenuation, as shown in Fig. 10, is derived from the RSSI measurement using the detailed link budget (See Equation 2).

$$\text{Att} = P_{\text{Tx}} + 2 \times G_{\text{Ant}} - 2 \times \text{Losses}_{\text{Connector \& Cable}} - \text{RSSI} \quad (2)$$

where the cable and connector losses are estimated at 1.5dB per buoy, the antenna gain is 5dBi , and the transmitted power is 14dBm .

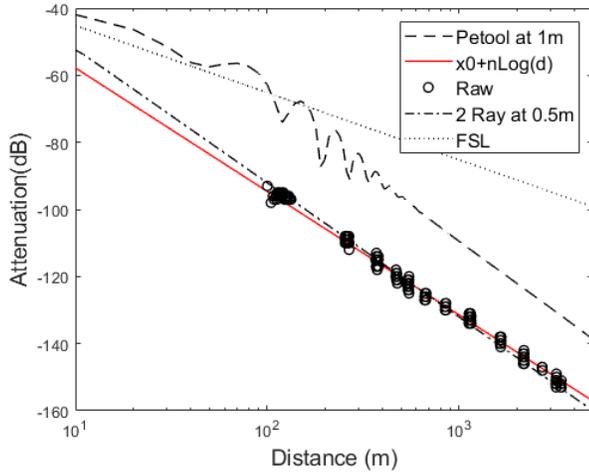


Fig. 10: Comparison between our measurements and four models : Free space loss, 2-ray, Petool and log-distance path loss

We attempted to compare our experimental measurements with various attenuation models. However, the Petool software used for our modelling does not allow for simulation of antenna heights lower than 1 meter. Thus, our inter-buoy link with $h_{\text{Ant}} = 0.5\text{m}$ (which corresponds to the radiation centre of the antenna) could not be modelled. Nevertheless, we observed that for antenna heights below 2m and distances greater than 400m , the two-ray model was comparable to the Petool model (see Fig. 4). Therefore, we used a two-ray model to simulate our inter-buoy link with an antenna height of 0.5m . The model closely matched our experimental data (see Fig. 10).

We also modelled the attenuation using a log-distance power law, which is commonly used in LORA transmissions and implemented in the ns-3 simulator. The log-distance path loss model in dB is expressed as:

$$\text{Att} = -X(d_0) - 10n \times \log\left(\frac{d}{d_0}\right) \quad (3)$$

where d_0 is the distance between receiver and transmitter in meters, n is the path loss exponent, and $X(d_0)$ is the path loss at a reference distance of d_0 . We considered a reference distance d_0 of 1m for the modelling experiments. $X(d_0)$ and n were estimated using a fitting method on the measured data and were found to be 21 and 3.6 , respectively. The n value is similar to that of ref [22].

To achieve inter-buoy links on the order of 10km , the antenna must be placed at a height of approximately 3m above the sea (see Fig. 6). This necessitates the installation of a mast on the buoy to support the antenna. To maintain buoy stability (even with a mast of several meters) and avoid additional transmission losses, the buoy must be equipped with a weighted keel. We designed such a buoy (see Fig. 11).

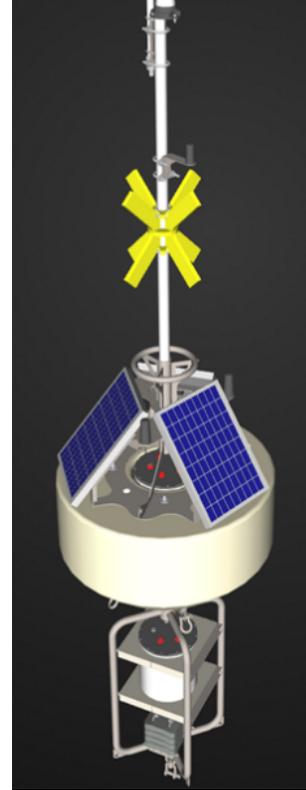


Fig. 11: Schematic diagram of the buoy with mast. The keel is weighted to balance the buoyancy

IV. PERFORMANCE ANALYSIS

A. QoS parameters

1) *Throughput*: The throughput of the transmission between Node A and the gateway is a metric that evaluates the amount of data that can be successfully transmitted over the network. It is determined through the following calculation:

$$\text{Throughput} = \frac{B}{t_2 - t_1} \quad (4)$$

where B is the number of bytes received, t_2 is the time stamp of the last transmitted packet from the Node to the gateway and t_1 is the time stamp of the first transmitted packet from the Node to the gateway.

2) *Packet Loss Ratio*: The Packet Loss Ratio (PLR) measures the proportion of transmitted packets that were not received by the gateway. It is calculated by dividing the number of lost packets by the total number of transmitted packets.

$$PLR = \frac{\delta - \gamma}{\delta} \quad (5)$$

where δ represents the number of packets sent during transmission, and γ represents the total number of packets received.

B. Simulation environment

For conducting our experimental evaluation, we employed version 3 of the Network Simulator (ns-3) [23], which is a discrete-event network simulator that is designed to simulate Internet systems. The simulator incorporates a LoRaWAN module that is intended for both research and educational purposes. The LoRaWAN module includes support for Class A devices, network server implementation, Adaptive Data Rate (ADR), confirmed messages, multi-gateway support, urban propagation models, a realistic gateway chip model, and energy model integration.

We modified the LoRaWAN module to implement a multi-hop relay architecture scenario. To enable a precise analysis of the scenario under consideration, we simulated the encapsulation and decapsulation mechanisms in full. The simulation scenario featured two offshore nodes and one onshore gateway, all of which were configured to use LoRaWAN technology, as illustrated in Fig. 12. Node A and Node B were initially positioned 2km away from the gateway for SF7 and 4Km away from the gateway for SF12, with a distance of 500m between. Both nodes transmissions are based on the proposed physical model that was detailed in Section III, which takes into account the unique characteristics of the marine environment, such as waves and wind conditions. Only the uplink system was simulated.

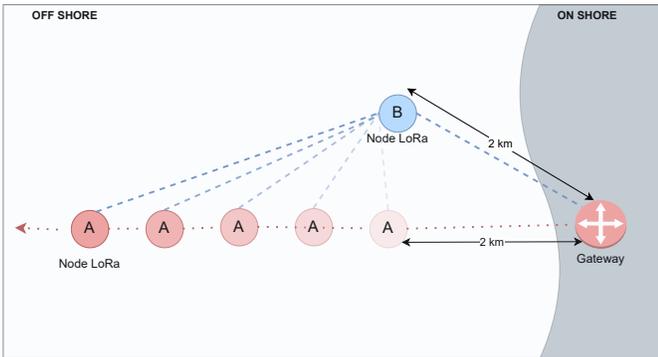


Fig. 12: Node A transmits data at varying distances from the gateway, gradually increasing the distance between them in order to evaluate the impact of distance on the strength and quality of the wireless signal.

In the scenario depicted in Fig. 12, Node A gradually experiences low-performance communication with the gateway as it progressively moves further away from it. The gateway is constantly located on the shore, while Node A moves away from the gateway up to 14km at a speed of 1m/s. Node B and the gateway remain static. To establish communication

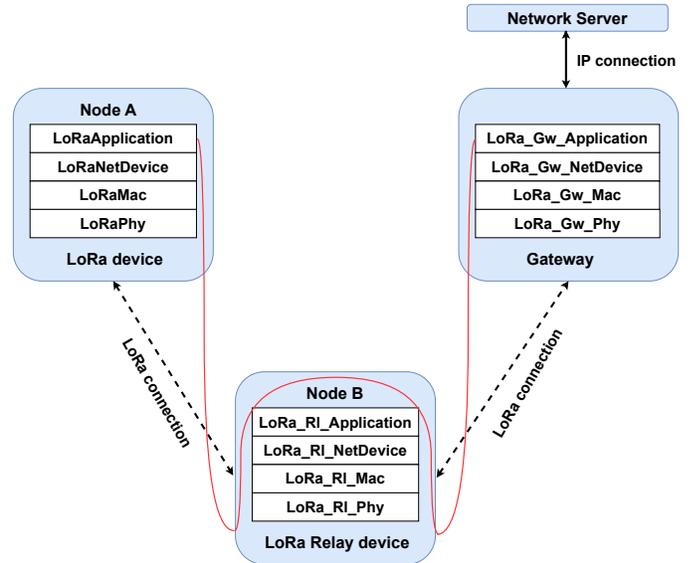


Fig. 13: LoRaWAN relay node process for forwarding packets

with the gateway, Node A sends packets to Node B, which then forwards the packets to the gateway. The simulation only transmits User Datagram Protocol (UDP) flows. The simulation parameters are presented in detail in Table III, with no signalling being simulated.

TABLE III: Simulation Parameters

Parameters	Value
Spreading Factor	7 - 12
Bandwidth	125kHz
Coding Rate	4/5
Frequency	433MHz
Path loss exponent	3.6
Path loss at a reference distance	21
Number of nodes	2
Number of gateways	1
Tx Power	14dBm
Packet payload size -SF7	Max 200bytes
Packet payload size -SF12	Max 51bytes
Simulation time	3h
Position Mobility Model (Gateway & Relay)	Constant
Position Mobility Model (Sender)	Mobile

We transmit a single packet every second, taking into account the 1% duty cycle limitations, channel availability, the maximum number of transmissions for all LoRa nodes, and the Spreading Factor (SF) employed. Fig. 13, illustrates the process for forwarding the packet as it is sent from the end device (nodes) to the gateway. Although packets adhere to the standard, they can also be dispatched to other nodes. Every node has the capacity to receive and forward packets to the gateway.

Within the LoRaWAN MAC header, we find a 3-bit Message Type (MType), a 3-bit section Reserved for the Future (RFU), and a 2-bit Major version. The MType used is “UNCONFIRMED DATA UP”, which is based on the previously mentioned UDP communication. The default Major version 1 is in use; however, the RFU is updated for each process and

stage. These adjustments are essential for the encapsulation and decapsulation processes of each node in the network and for the processing of the LoRa channel. Furthermore, this traceability will be applied in the future to enhance routing and ensure dependable Transmission Control Protocol (TCP) flows.

V. RESULTS AND ANALYSIS

In this section, we present the findings and analysis of the experiments conducted to assess the performance of the transmission.

Based on the parameters outlined in Table III, we examine various cases: SF7 for payload sizes of 23, 128, and 200 bytes, and SF12 for payload sizes 15, 23, and 51 bytes. To evaluate our results, we compare the transmission passing through a relay node to a direct transmission to the gateway, which is the standard current case. The choice of SF and payload size depends on the use case for the transmitted data and, in another sense, is related to the type of application to be used. SF12 is utilised to reach gateways with lower bit rates to avoid connection failure for isolated nodes, while SF7 is employed to maintain high bit rates for shorter distances. Considering the drawbacks of MoT, we investigate each case and numerous scenarios to improve high bit rates for greater distances.

Fig. 14 depicts the comparison between direct transmission and a one-hop relay transmission. We observe that the throughput achieved with direct transmission diminishes rapidly when increasing the distance from approximately 2.6km compared with the transmission achieved through a relay that remains relatively constant up to 5km. Beyond the aforementioned distances, we observe a decrease in throughput. This decline can be attributed to the fact that the SNR goes out of range. An intriguing outcome we have observed is that, in some instances, using a relay node results in a throughput gain that is three times greater than direct transmission. For example, at 6km, direct transmission exhibits a throughput of 4bps, while the transmission passing through a relay node shows a throughput of 16bps.

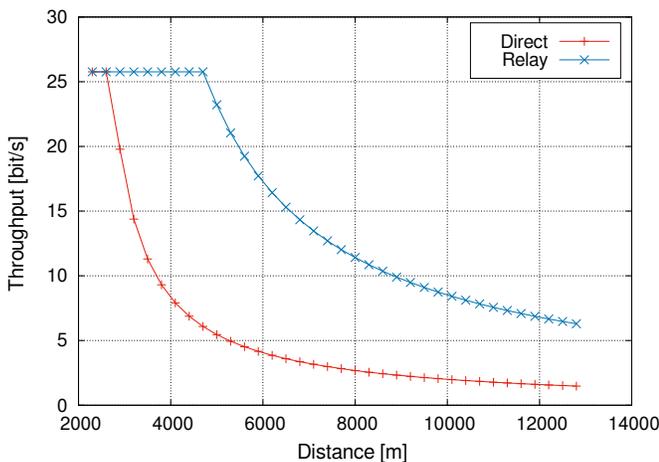


Fig. 14: Throughput of transmitted packets with a 23-byte payload in SF7.

Fig. 15 displays the packet loss ratio of transmission on SF7. As expected, transmission via a relay results in a significantly lower packet loss ratio compared to direct transmission beyond a certain distance. We observe that the packet loss ratio increases as the distance between the node and gateway expands for both direct and relayed transmissions. However, the packet loss ratio for relay transmissions is consistently lower than that of direct transmissions across all distances. When using a relay node, there are fewer packet losses—about 0% up to 5km—while 78% of losses are observed when transmitting directly to the gateway without a relay-hop. Conversely, there is a PLR of approximately 50% for 10km when transmitting with a relay compared to 92% when transmitting without a relay node. This suggests that using relays can enhance the reliability of LoRaWAN communications, especially for longer distances. In this situation, our contribution provides greater reliability in reaching the destination, which reduces the PLR.

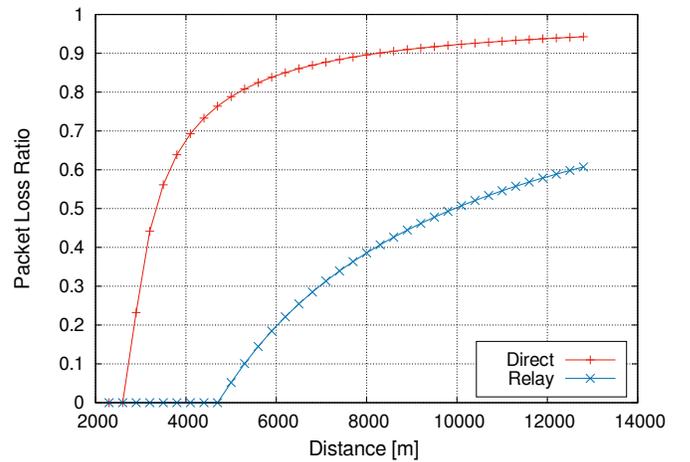


Fig. 15: Packet loss ratio of transmitted packets with a 23-byte payload in SF7.

The packet loss results are nearly identical when transmitting different payload sizes (23, 128, and 200 bytes) in SF7 and SF12. Therefore, we focus on analysing the throughput values in SF7 for payload sizes of 23, 128, and 200 bytes, as shown in Fig. 16, and for SF12 with payload sizes of 15, 23, and 51 bytes, as displayed in Fig. 17.

According to the results for SF12 (Fig. 17), a transmission can reach up to 10km with stable throughput when using the relay for all three tested payload sizes (15, 23, and 51 bytes). For direct transmission, the throughput begins to decrease after 6km. For SF7 (Fig. 16), a higher throughput is achieved for all three payload sizes. When transmitting directly without a relay-hop, the throughput starts to decrease significantly after 2.5km. On the other hand, when using a relay, the throughput starts to decline after 5km.

In summary, our research findings reveal the notable influence of implementing relay nodes in LoRaWAN transmissions in maritime environments. By evaluating different payload sizes and spreading factors, we identified that utilising a relay node can increase the throughput of the communication,

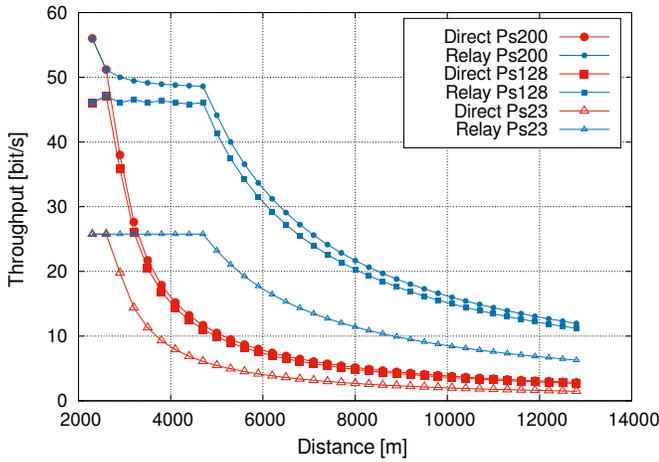


Fig. 16: Throughput of different packet size payloads in SF7, with the relay node placed 2km away from the gateway to consider the sensitivity of SF7.

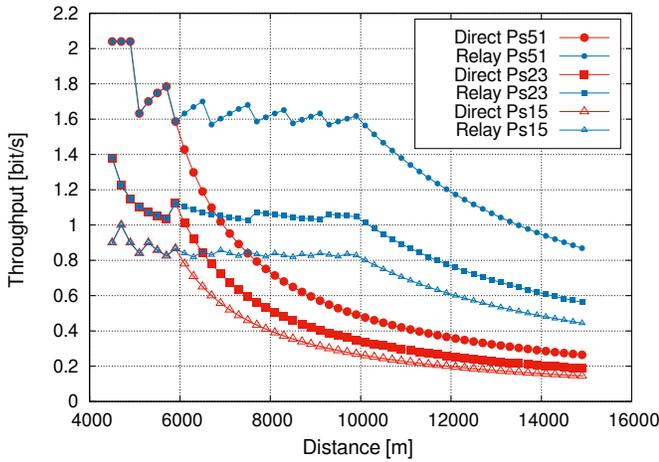


Fig. 17: Throughput of different packet size payloads in SF12, with the relay node placed 4km away from the gateway to consider the sensitivity of SF12.

particularly at extended distances. In certain instances, the throughput gain achieved by employing a relay node was discovered to be three times greater than a direct transmission. Furthermore, the packet loss ratio was persistently lower for relayed transmissions in comparison to direct ones. Importantly, by adopting a multi-hop network, and thus avoiding being out of range on the SNR, the throughput and PLR can consistently maintain good performance. Our results emphasise the significance of relay nodes in LoRaWAN communications and propose that their usage can result in more efficient and reliable transmission of data across various maritime scenarios.

VI. CONCLUSIONS AND FUTURE WORKS

In this paper, we have introduced a physical model for electromagnetic propagation in maritime settings, taking into account the unique attributes of the marine environment. We

appraised the efficacy of the suggested model in a multi-hop data transmission setting, using a multi-hop LoRaWAN mesh network. For our experiments, we initially applied a single-hop approach. Our outcomes indicate that the assessed one-hop transmission protocol bolsters the reliability and effectiveness of marine information collection and transmission. Furthermore, we demonstrated the potential distances that a LoRaWAN transmission can achieve under our presented physical model, accounting for maritime conditions. Our results suggest that by employing a one-hop relay node, the transmission can attain a throughput increase up to three times that of direct transmission. Our investigation contributes to the creation of more effective and dependable techniques for acquiring and analysing maritime data, thereby enabling better decision-making and resource management within marine environments. Subsequent research might focus on the development of a sophisticated routing mechanisms for LoRaWAN transmission in marine contexts, enabling node-to-node communication to ascertain the optimal path towards the gateway. Furthermore, the evaluation of other Quality of Service (QoS) factors, such as end-to-end latency, is essential. Those mechanisms would bolster the effectiveness of multi-hop data transmission in LoRaWAN networks, especially in extensive deployments.

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