Propagation Characteristics of LoRa-Based Wireless Communication in Steel Ship Cabin

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Abstract. The deployment of wireless sensor network in ship application traditionally relies on human experience and lack of theoretical analysis so far. Based on electromagnetic theory calculation (ray-tracing method) and experimental measurement, this paper investigates the propagation of radio signals inside ship cabin for wireless sensor network with LoRa (Long Range) technology. A three-dimensional model of radio wave propagation in typical hull ship cabin with the main diesel engine and central control room is established. The multipath propagation prediction is carried on and the received power of the receiver is calculated. Besides, through comparative analysis with experimental test, the main influence of cabin spatial factors on the characteristics of wireless signal is discussed. The results clearly demonstrate that the wireless network with LoRa band is possible and quite feasible in ship cabin, and the simulated results could give well agreement with experimental data about the rules of influence on wireless signal in different areas of the ship's cabin. Some important guidance is also given for communication link design of actual LoRa network in ship.

Keywords: LoRa technology · Ray-tracing method · Ship cabin · Propagation characteristics

1 Introduction

The main engine room is the power center of a ship. Monitoring the equipment state of the ship cabin during navigation is of great significance to the stability and safety of the ship's operation. With the traditional method, the data transmission in the cabin adopts wired communication using fieldbus technology (such as CAN or Modbus protocol). The cost of marine wired communication cable layout in a ship is relatively high, and it takes very long period for construction. The ship is usually designed as a relatively compact and complex structure. When it is necessary to install new equipment on the

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ship during its service, the cables need to be rearranged, and new holes may need to be cut on the steel plate, which would affect the strength of the hull structure and was strictly controlled. In addition, broken and aging cable is a major hidden risk of fire. The International Maritime Organization (IMO) requires the installation of fire detection sensors in each cabin and major zone on a ship. Therefore, wireless sensor network (WSN) and internet of things (IoT) solution are adopted for ship application [1, 2].

The WSN consists of low power devices, and its sensor module can move easily due to small size as well as lower cost, which makes it potential alternative for traditional ca-bling networks. Some researches employed the WSN system based on 2.4 GHz Zigbee communication technologies to establish real-time monitoring system on board [3–6]. Furthermore, propagation modeling of such frequency band in ship also have been studied [7]. This work group did some researches on 2.4 GHz wireless channel propagation in the ship cabin of a sand carrier, and the simulated results were agreed well with the experimental results, as can be seen in our previous works [8]. However, despite its significant benefits, using WSN-based Zigbee protocol in the engine room also needs to face some problems such as large battery consumption and interference of transmission sig-nals. For the large-scale ship with more complex environment which contains abundance of reflecting and diffracting elements, it need communication technology with longer transmission distance, longer battery life and better pass-through ability.

Low Power-Wide Area Network (LP-WAN) has received much attention and development due to its significant advantages in long-distance transmission and low end-node's power consumption. LoRa (Long Range) is based on Chirp Spread Spectrum (CSS) modulation, where each chirp encodes 2 m symbol values for spreading factor. And LoRa modulation uses cyclic error correction coding for forward error detection and error correction which can make LoRa more robust against the interference and maintain high acceptance sensitivity and anti-jamming ability even in complex environments [9, 10]. Feasibility of LoRa technique applying for indoor environment of ship has also been verified by researchers. Zhang Qin et al. designed a ship-based temperature measurement system based on LoRa technology and proved its stable working performance [11]. On the other hand, so far researches on applications of LoRa technology on ship were mostly focused on experimental test, and the installation location of the access point was mainly based on the experience of designers, which would greatly lengthen the construction cycle and demand lots of resources. It is critical to design a reliable communication link that collects the data from wireless sensors in the harsh channel environments and conveys them to the center node. Thus further analysis about the impact of ship cabin environment on LoRa-based wireless communication technology is still required.

Establishing accurate indoor path loss model and predicting the propagation characteristics of wireless signal according to the propagation environment would greatly re-duce the cost of network construction and would also be of great significance to maintain communication stability [12]. In this work, a ray-tracing based model is established to calculate and analyze the propagation characteristics of wireless signal at 433 MHz frequency band in typical and complex vessel cabin environment. The influence of reflection, transmission and diffraction on wireless signals caused by large obstacles and other factors is taken into account. In addition, the experimental measurement with LoRa module is also carried out in a real ship cabin. The simulated results are compared with the experimental detection results, which could help to learn the propagation characteristics of wireless communication in cabin and is valuable for better application of LoRa technology in steel ship. The analysis could provide important guidance for the rational deployment of wireless sensing systems.

2 First Section Modeling of Radio Wave 433 MHz Propagation in Ship's Engine Room Based on Ray-Tracing Method

2.1 Ray-Tracing Method

Simulation-based studies of wireless networks require simple path loss models that can capture indoor propagation effects such as attenuation, scattering, diffraction, and reflection with enough accuracy. By ray-tracing method, the electromagnetic wave propagation characteristics could be analyzed based on the principle of geometric optics [13]. Figure 1(a) shows the diagram of wave propagation by ray-tracing method, and Fig. 1(b) is the spherical coordinate system. For the diffraction caused by the obstacle, it emits a ray from the transmitting antenna (Tx) and then tracks the ray to see if it collides with the surface of an obstacle and is received by the receiving antenna (Rx), then calculates the power or electric field associated with the ray to contribute to the receiving point.

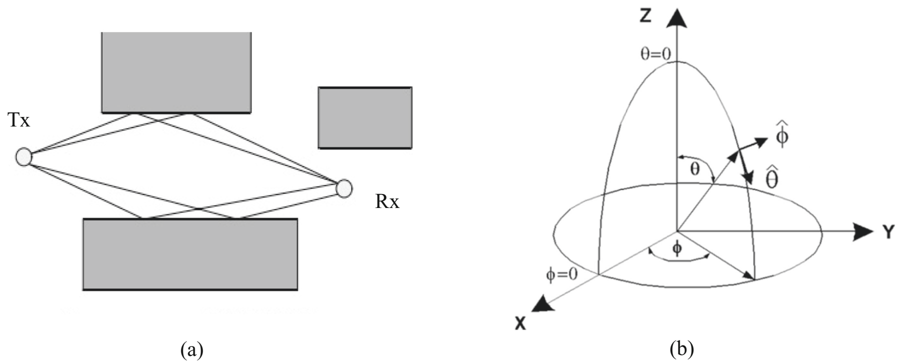


Fig. 1. (a) Diagram of wave propagation by ray-tracing method (b) The spherical coordinate system

According to the geometrical position of the incident and the electrical parameter characteristics of the obstacle, the situation of reflection, transmission, diffraction or some combination of these can be determined so that the next path can be tracked until the ray is received or the exit tracking condition is reached. It was validated as an effective method of solving the problem of radio wave transmission planning and prediction in indoor complex environment. When there is no line of sight for propagation path between the transmitter and receiver, the signal fading in transmission is closely to the Rayleigh distribution. The presence of obstructions along the path may cause the signal more distorted or impaired than it would under free space condition [14]. The received power is an important parameter to evaluate the communication system and characterize the received signal strength, which determines whether the receiving end can receive information well. The average received power of total propagation path P_N is defined by the sum of the average received power of the i-th propagation path P_i, as follows [13, 15]:

$$P_N = \sum_{i=1}^{N_P} \left(\frac{\lambda^2 \beta}{8\pi \eta_0} \left| E_{\theta,i} \sqrt{|G_\theta(\theta_i, \phi_i)|} e^{j\psi_\theta} + E_{\phi,i} \sqrt{|G_\phi(\theta_i, \phi_i)|} e^{j\psi_\phi} \right|^2 \right) \quad (1)$$

where N_P: the number of propagation path; λ: signal wave length; β: parameter related to the center frequency and bandwidth of the transmitter and receiver; η_0: impedance of free space; $E_{\theta,i}$ and $E_{\phi,i}$: electric field intensity of the i-th receiving path in θ and ϕ direction, respectively; θ_i and ϕ_i: arrival direction of the i-th ray; G_θ and G_ϕ: antenna gain of receiver in θ and ϕ direction, respectively; ψ_θ and ψ_ϕ: phase in θ and ϕ direction of the far-zone, respectively. All simulations reported here are performed using the Remcom Wireless InSite commercial software package.

2.2 Three-Dimensional Model of Ship's Main-Engine Room

'M/V YU DE', a 64000-ton-class cargo training ship, was chosen for this study. It is the largest training vessel in the world and has been used for seafaring education, training and scientific research as well as carrying bulk cargo. The main engine room is located at the rear of the ship. Figure 2 shows the side view of 'M/V YU DE' and Table 1 shows its specifications [16].

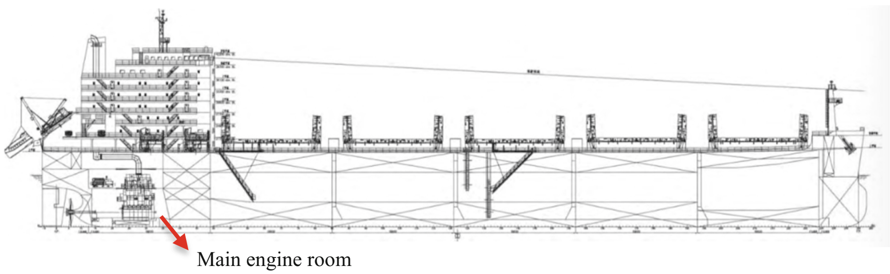
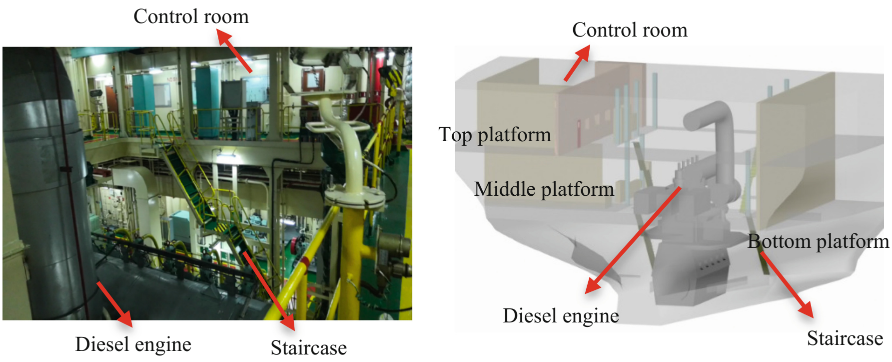


Fig. 2. Side view of 'M/V YU DE'

Table 1. Specifications of 'M/V YU DE'

Length (m)	Width (m)	Height (m)	Tonnage (ton)	Speed (knot)	Main engine
199.90	32.26	18.00	64000	14.0 (max. 15)	MAN-B&W 5S60ME-C8.2(Tier Π)

The wireless communication tests and wave propagation investigation are conducted in the main-engine room which houses the vessel's prime mover, diesel engine. The main engine room accommodates lots of equipment such as motor, diesel engine, water pumps, compressors and so on. To examine how the equipment affects the wireless signal propagation, the diesel engine is selected and modeled in this simulation, as it is the largest equipment obstacle for signals. The diesel engine is located in the middle place of the engine room, and there are three platforms with connecting staircase on the side, which can be seen from Fig. 3(a). The established model is shown in Fig. 3(b). The bottom platform has set-wire cabinets at its rear part, the middle platform has auxiliary machine at its rear part and corridor around the diesel engine, and the control room is located in the top platform with a corridor around the engine and pipes. Some detail interior construction is ignored and simplified.



(a) (b)

Fig. 3. Layout of main engine room (a) Main engine room of the real ship (b) Three-dimensional model of main engine room

2.3 Simulation Parameter Setting

Arrangement of the initial transmitter (Tx) and the receiver (Rx) is shown in Fig. 4. Figure 4(a) is the wireframe rendering view, and Fig. 4(b) is the solid rendering view, where the roof and surrounding walls are set invisible for observation convenience. Tx is placed at a height of 1.7 m above floor level on the bottom platform of cabin, and Rx is moving away from the Tx and is set at various route around the diesel engine. The transmission of wireless signals is still possible due to the open three-storey structure of the cabin with staircase connection and the glass windows of control room. Vertical polarization mode leads to lower path loss than horizontal polarization mode and has the best coverage in indoor environment. Therefore, an omnidirectional monopole antenna working in vertical polarization mode is chosen in this investigation. The performance is investigated in the center frequency of 433 MHz, with the bandwidth 250 kHz, the transmitting power 17 dBm, the path gains 15 dBi, and the transmitting signal adopts sinusoid wave shape. Set up radio waves to undergo 5 reflections, 2 refractions and 2 diffractions during propagation. Further, in all simulations, the factors such as atmospheric propagation losses, and the non-uniformities of the surface materials are not considered for simplicity. Different from the propagation in traditional building space, the ship cabin structure is mainly made of metal material which would made all energy reflected. Besides, absorption loss of electromagnetic waves propagation in the atmosphere is negligible for the humidity in the ship cabin is not high and is relatively stable, which would hardly affect the spread of narrow band signals [14]. The simulated results of received power is obtained for further analysis.

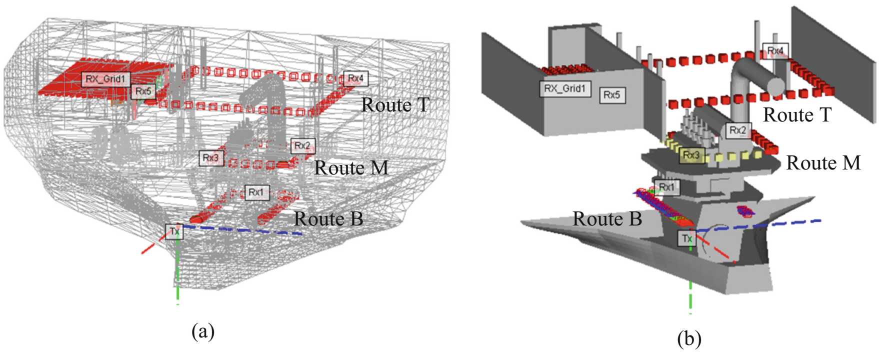


Fig. 4. Arrangement of the transmitter (Tx) and receivers (Rx) (a) wireframe rendering view (b) solid rendering view

3 Experiment Measurement

The experiment measurement is taken at the main engine room of 'M/V YU DE'. The experimental equipment includes LoRa communication nodes, a small computer with Uart Assist serial port program, as well as a tripod used for adjusting measuring receiver. The layout is shown in Fig. 5. The omnidirectional and monopole copper rod antennas working with vertically polarized mode are used as the stationary transmitter and roaming receiver. The overall height is 205 mm with effective length 175 mm, thus the monitoring is done with 433 MHz frequency at the measuring points which are selected alongside the same path in simulation. The average received power over fifty measurement results for each measurement point is adopted to ensure stabilization.

(a) (b)

Fig. 5. Experimental test for LoRa wireless communication (a) The stationary transmitter antenna (b) The roaming receiver antenna on a tripod

4 Results and Discussion

The influence of large device such as the diesel engine on the signal transmission couldn't be ignored and should be analyzed. As can be seen from Fig. 4, there are three receiver routes for investigating signal transmission characteristics around the diesel engine. R $\times$ 1 is set at the bottom platform of engine room which is named Route B here. R $\times$ 2 and R $\times$ 3 are set at the middle platform which is 5.0 m height distance from the bottom one and it is named Route M. R $\times$ 4 is set at the top platform which is 9.8 m height distance from the middle one and it is named Route T. Obviously, due to the irregular structure of diesel engine, there is significant difference between the measurement paths. Thus, the receiver points set at each route are various, where Route B has 25 points, Route M has 22 points and Route T has 50 points. The received power values are measured every 1 m from the starting point to the end point of each route by the receiver.

Figure 6(a) is the comparison of experimental and simulated results of the Route B, where normalization is done in order to facilitate the comparison. The vertical axis represents received power value, and the horizontal axis is the receiver point of the corresponding path. The #8 receiver point which is 7 m distance from #1 receiver point has large received power, both in simulation or in experiment. It is located between the staircase and engine within this environment, where the reflection and the diffraction paths of the transmitter signal are superimposed and make a larger received power. The similar situation also happens on the #21 receiver point. The minimum received power of simulation occurs at #15 receiver point which is 20 dBm less than the adjacent point #16. Figure 6(b) shows their three most strong wave propagation paths obtained by simulation, where the two receiver point are arranged in the diagonal position of the Tx. Here, dBm is an abbreviation for the power ratio in decibel (dB) of the measured power referenced to one milliwatt (mW). Zero dBm equals one milliwatt. Obviously, the received power strength of #16's propagation paths is larger than that of #15's, which subsequently makes the significance difference of their received power. In experiment, the minimum received power of Route B is −25.14 dBm. It should be pointed out that in simulation the receiver point with minimum value is not in the same place with that in experimental test. It is mainly because the model couldn't fully represent the actual complicated ship structure. Even so, the simulation could still provide effective guidance for excluding the bad receiving region ahead, and the best node location can be determined with relatively few experimental test. Compared to the traditional method which is mainly depended on the experience of designers or amount of on-site test, it is better targeted and more efficient for wireless node deployment.

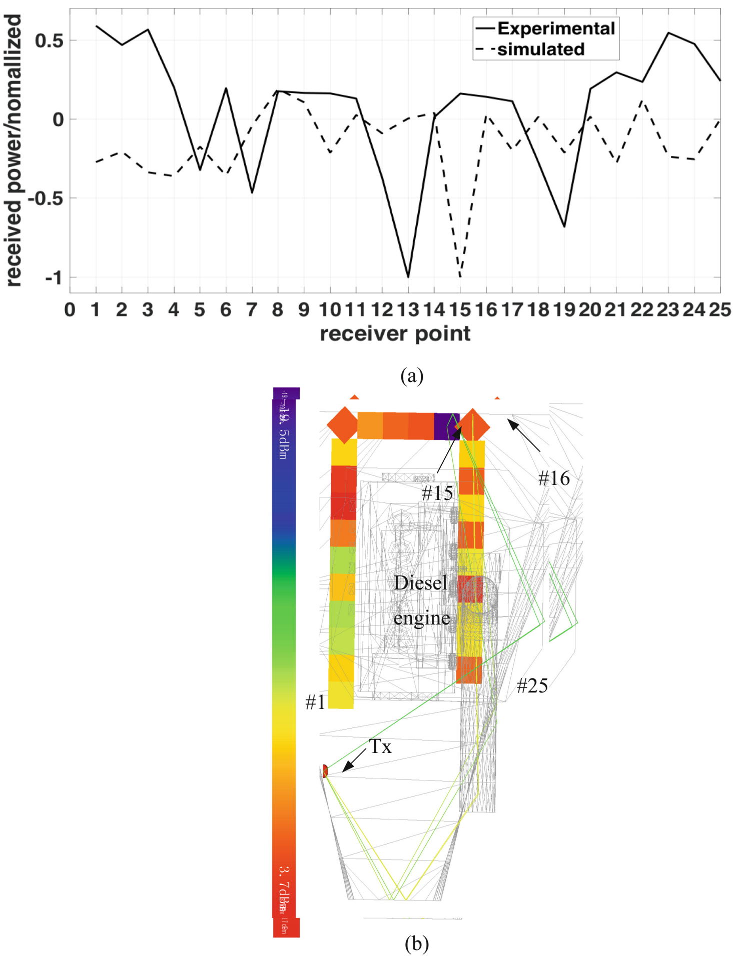
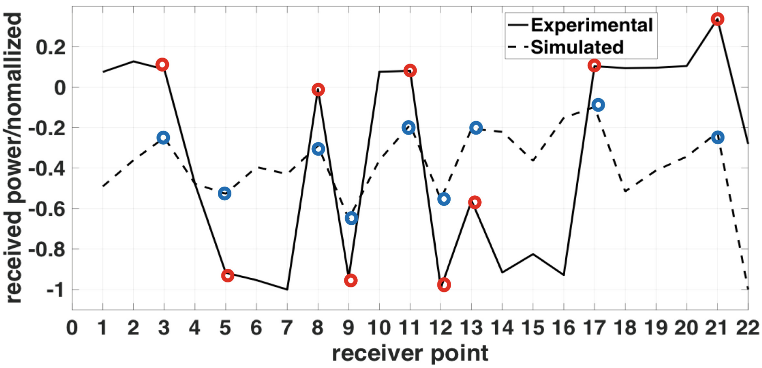
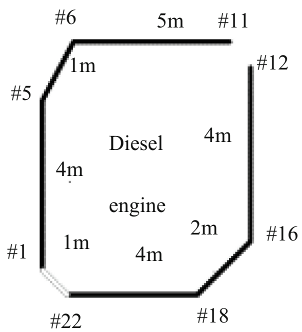


Fig. 6. (a) Comparison of experimental and simulated results of the Route B (b) Propagation path of some receiver points

Figure 7(a) is the comparison of experimental and simulated results of the Route M, where place of receiver points is shown in Fig. 7(b). In experiment, the minimum received power of Route M is −48.58 dBm. As can be seen from the results, although the Route M is 5.0 m height distance from the Tx, the receiving situation of this floor is still good. The receiver point #9 has small received power, similar to the #15 point in Route B, because it is arranged in the diagonal position of the Tx. The receiver points #2, #3, #17 and #18 have larger value, similar to #22 point in Route B, mainly because the metal staircase helps to improve the propagation path. Besides, in this floor, the simulated results are well consistent with the experimental measured results, especially the distribution of strengths and weakness of received power. Due to the idealization and simplification of the model, certainly there is difference exist between the simulated results and actual measurement values, but the similar changing trends could provide good reference for node deployment.



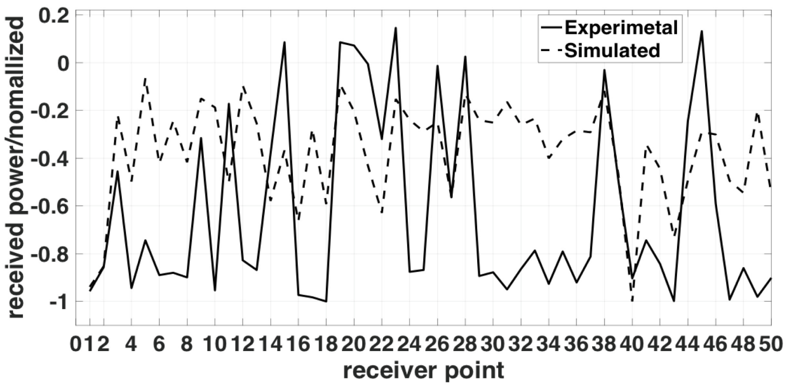
(a)



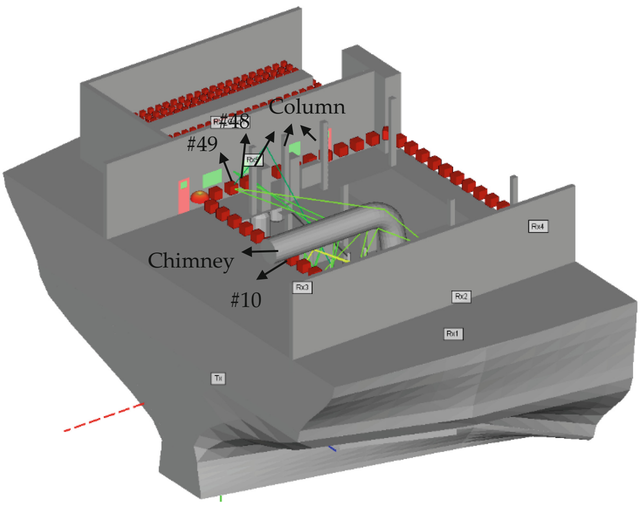
(b)

Fig. 7. (a) Comparison of experimental and simulated results of the Route M (b) Distribution of receiver points in the measurement path

Figure 8(a) is the comparison of experimental and simulated results of the Route T. In experiment, the minimum received power of Route T is −51.6 dBm. Figure 8(b) shows a few propagation paths of some receiver points obtained by simulation. As can be seen from the figure, the receiver point #10 has small received power because it is located directly beneath the main chimney of the diesel engine and close to the chimney, where the impact of the multipath Rayleigh fading results in great loss of transmission wave. On the other hand, #31, #31, #40 and #47–#49 receiver points have relatively low value, mostly because of their locations behind the columns.



(a)



(b)

Fig. 8. (a) Comparison of experimental and simulated results of the Route T (b) Propagation path of some receiver points

The received power gets stronger change with the increase of the platform height relative to the position of transmitter. And the amplitude variation of experimental test is much bigger than the simulated results. That is mainly because of the complexity of the real cabin environment with a lot of machinery equipment as well as metal racks, pipes and grooves. Nonetheless, it shows similarities in signal transmission trends along the measurement path, given the relative roughness of the ship cabin models. The special cabin environment is much more different from the common building interior space; hence some special phenomenon is appeared in the signal transmission characteristics. It's worth noting that even the Tx is set at the bottom platform when Rx is located at the top platform, the received power could still meet the requirement of the transmission system, which ensures the implementation of wireless transmission network in cabin. The receivers are suggested to located near the staircase which would be helpful for the transmission, but avoid the region beneath the chimney of diesel engine or in the diagonal position of transmitter which would reduce the received power.

5 Conclusions

For the welded steel ship, the cabin environment would cause the wireless signal to fade through complex phenomena such as reflection, transmission and scattering and so on. A three-dimensional (3D) ray-tracing model is developed here to simulate the radio wave propagation in the ship environment and a LoRa band communication system is employed to evaluate the LoRa wireless system effectively. It investigates the influence of large equipment on wireless signal transmission. Either the simulation or experimental analysis indicates that the signal propagation in the steel ship cabin is very different from the propagation in ordinary buildings, which is strongly affected by multipath effect. Although large obstacles exist in cabin environment, the wireless signal transmission system using LoRa technology can still meet the requirements with suitable deployment. Deploying a base station near the glass window and avoiding being near the back of the main switchboard in the control room could help to establish good communication link even from the bottom platform of the diesel engine in cabin. The analysis validated that simulation research based on ray-tracing method could help to provide guidance for designing wireless sensor networks with LoRa band. It could clearly show the areas which are prone to produce impact of multipath fading on signal propagation and need to be avoided, as well as the suitable location which would enhance the signal strength. Therefore, LoRa-based wireless communication could be recommended for ship cabin applications, and using the ray-tracing model combined with few on-site measurements to evaluate the signal propagation will be less time-intensive and less costly.

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Conflicts of Interest. The authors declare no conflict of interest.

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