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Genetic Algorithm for Ship Robbery Emergency Reporting System

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ABSTRACT: In contemporary maritime navigation, ships in distress primarily rely on satellite systems in conjunction with radio systems within the framework of the Global Maritime Distress and Safety System (GMDSS) to transmit distress signals. However, the insufficient confidentiality of satellite data enables pirates engaged in ship hijacking to intercept these signals, potentially endangering the safety of hostages on board. Additionally, the high communication costs associated with satellite information transmission often discourage fishing ships from incurring these expenses. Given these cost constraints, this study seeks to develop an intelligent emergency distress notification method integrated with the Automatic Identification System (AIS). Specifically, this study introduces an innovative intelligent radio emergency notification system by incorporating the concept of radio relay stations. The proposed system integrates the Genetic Algorithm (GA) with the Maritime Geographic Information System (MGIS) as an alternative rescue method for ships in distress. The system collects all relevant information from the distressed ship through shore stations, enabling it to respond to the ship and verify the receipt of distress messages transmitted via AIS. The proposed method functions as an intermediary for distress signal transmission and confirmation. By gathering ship positions, it establishes a mobile network for message dissemination, thereby enhancing the reliability and efficiency of emergency distress communications at sea.

1 INTRODUCTION

Maritime safety and operational efficiency are critical challenges within the global maritime industry, particularly in regions susceptible to piracy, natural disasters, mechanical failures, and collisions [1-3]. Ship robbery and piracy present significant risks to human life and valuable cargo, underscoring the need for robust emergency reporting systems [4-6]. Traditional systems, such as the Global Maritime Distress and Safety System (GMDSS) and Vessel Management Systems (VMS), primarily rely on satellite communications [7-10]. A major vulnerability of satellite-based systems lies in their potential for signal interception by malicious actors [11,12]. During hijacking incidents, pirates can intercept distress signals, compromising hostage safety and potentially escalating dangerous situations. Additionally, the high communication costs of satellite systems deter many fishing ships, particularly those from economically constrained communities, from adopting these systems.

Numerous fishing ships utilize receive-only AIS Class B systems to maintain the confidentiality of their fishing grounds, inadvertently reducing the efficiency of distress signaling during emergencies such as piracy, fires, collisions, grounding, and sinking incidents [13,14]. Historical events, including the hijacking of fishing ships by pirates, highlight the urgent need for secure and cost-effective emergency communication solutions [15,16]. AIS is widely used in maritime operations for real-time tracking and monitoring of ship movements [17]. It provides essential data such as ship identity, position, speed, and course, contributing to enhanced maritime situational awareness. When integrated with advanced algorithms, AIS data can significantly improve maritime safety by identifying anomalies and predicting potential threats.

Genetic Algorithms (GAs) are search heuristics inspired by the principles of natural selection and genetics [18,19]. These algorithms are particularly effective in solving complex optimization problems where traditional methods may fall short [20]. GAs simulate evolutionary processes by employing operators such as selection, crossover, and mutation to evolve solutions over generations [21]. Through this iterative process, GAs are capable of exploring large search spaces efficiently and finding near-optimal solutions, making them suitable for dynamic and uncertain environments like maritime emergency communication networks.

The main objective of this study is to develop a secure and cost-effective emergency distress notification system by integrating AIS, Genetic Algorithm (GA), and Maritime Geographic Information System (MGIS) to form an Intelligent Radio Emergency Notification system as an alternative to vulnerable and costly satellite-based systems. This system employs a Genetic Algorithm (GA) to identify the most effective distress relay return path by selecting the route with the optimal Ship Escape Time Index (SETI). GAs operate through processes such as selection, crossover, and mutation to evolve solutions over generations, aiming to find the optimal result within a large search space.

In the context of the Intelligent Radio Emergency Notification system, GA helps evaluate numerous potential relay paths. It dynamically adjusts to changing maritime conditions. It also optimizes the route based on SETI. This approach ensures that the shore station verifies whether the distress message was mistakenly sent. Once verified, the system maintains optimal communication timing within the mobile relay communication network. By avoiding repeated communication path searches, the system ensures that acknowledgment messages are accurately delivered to distressed ships. This reduces the risk of lost distress messages.

The rest of this study is organized as follows. Section 2 provides an overview of related research. Section 3 presents research design and system architecture. Section 4 discusses experimental results and analysis. Finally, conclusions are presented in Section 5.

2 METHOD

2.1 *Automatic Identification System (AIS) relay communication*

The Automated Mutual-Assistance Vessel Rescue System (AMVER) operates through the voluntary participation of ships worldwide. Its primary purpose is to provide rescue support during distress situations. Ship position reporting systems are generally classified into satellite-based and radio-based position reporting systems. Currently, two primary satellite systems serve as data transmission devices for ship monitoring. These systems include the Advanced Research and Global Observation Satellite (ARGOS) and the International Maritime Satellite Organization (INMARSAT) systems. Additionally, radio systems such as AIS and Digital Selective Calling (DSC) provide real-time reporting of ship identity codes and positions.

AIS has been a mandatory navigation device since 2002. The International Maritime Organization (IMO) established this requirement under the International Convention for the Safety of Life at Sea (SOLAS) [22]. All newly constructed ships must be equipped with AIS. This equipment assists watchkeepers and enhances safety by effectively managing emergency situations. The integration of the Global Positioning System (GPS) with Very High Frequency (VHF) radio technologies forms the foundation of AIS technology. Both Class A and Class B systems are included. The system employs Self-Organized Time Division Multiple Access (SOTDMA) and Carrier Sense Time Division Multiple Access (CSTDMA) technologies, as shown in Table 1. The transmission frequency of navigational information is dynamically adjusted based on ship speed. It transmits both dynamic and static data, including the Maritime Mobile Service Identity (MMSI), call sign, ship name, coordinates, course, and speed.

In this study, AIS is proposed as a relay station for distress and acknowledgment messages. By collecting the positions of various ships, the system forms a mobile network for distress message transmission. This approach expands the communication range of radio systems. The system broadcasts radio signals through base stations to ships within the effective reception range. These ships can then forward previously received data, creating a maritime mobile communication relay network. When ship positions meet specific spatial and temporal conditions, the AIS relay function supports long-distance communication. This capability ensures that ships in distress can quickly send distress signals to shore-based command centres or other ships. The relay network significantly enhances rescue response speed and efficiency, improving the safety of personnel at sea.

Table 1. SOTDMA and CSTDMA technologies in AIS systems

Feature	SOTDMA	CSTDMA
Access Method	Time-slot reservation	Listen-before-talk
Synchronization	Requires GPS synchronization	Does not require GPS synchronization
Collision Avoidance	High, due to pre-assigned time slots	Medium, relies on carrier sensing before transmission
Application	Primarily used in Class A AIS systems	Primarily used in Class B AIS systems
Transmission Frequency Adaptation	Automatic based on speed	Manually configurable

2.2 *Genetic Algorithm (GA)*

This study employs a GA to optimize emergency reporting routes. By analyzing AIS distress messages collected from shore stations, the locations of relay ships along different transmission routes can be determined, facilitating the construction of a relay network. The GA is then applied to identify the optimal emergency reporting route based on the SETI. Since GA mitigates the risk of local optima, it demonstrates superior performance compared to other algorithms within the communication range.

The GA operates through an encoding scheme, where each chromosome represents a potential solution, and its genes correspond to problem-specific parameters. Given that the raw data in this study primarily consist of real numbers, real-number encoding is employed. Tournament selection is utilized to randomly select two or more chromosomes from the previous generation, comparing their fitness values and incorporating the fittest chromosome into the next generation.

Considering the constraints of radio transmission distance, each crossover operation must ensure that the resulting chromosome remains within the communication range. To enhance computational efficiency, single-point crossover is adopted. In this method, a random crossover point is selected in two chromosomes of equal length, and genes beyond that point are exchanged. Additionally, to prevent premature convergence to local optima, mutation is introduced. This enables the exploration of a broader solution space by generating individuals with distinct characteristics. The flowchart of the genetic algorithm is illustrated in Figure 1.

In real-life operational scenarios, the GA computations would be performed by shore-based rescue centers or command stations, rather than onboard ships at sea. The hyperparameters, including population size, crossover rate, and mutation rate, are determined through empirical testing. In practical applications, these parameters can be dynamically adjusted based on factors such as ship density and the urgency level of emergency situations.

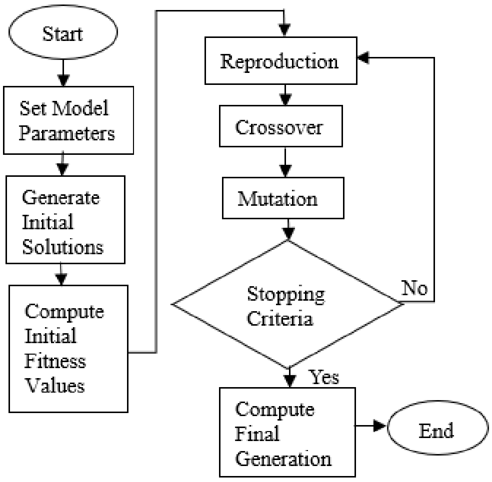

Figure 1. Genetic algorithm process flowchart

2.3 *Maritime Geographic Information System (MGIS)*

This study employs genetic algorithms to determine the optimal relay transmission path. It uses AIS to obtain relevant information such as the location of relay ships. However, if only the latitude and longitude of relay ships are known and additional data is not integrated, more time is required to search for and organize information. In emergency situations, this delay could result in missing critical rescue opportunities. Therefore, this study utilizes MGIS for its robust visualization and data integration capabilities. It is incorporated into a ship emergency response path system. This approach enhances algorithmic efficiency by addressing deficiencies in visualization and information display.

MGIS is a specialized system designed to collect, store, analyze, and visualize marine spatial data. Based on data representation methods, MGIS data can be categorized into vector data—represented by points, lines, and polygons to describe geographical features—and raster data, which partitions marine spatial data into a fixed grid, making it suitable for representing continuous numerical information. Due to the unique characteristics of the marine environment, including hydrological variations and tidal influences, MGIS requires the integration of more complex spatial data and dynamic analysis compared to traditional Geographic Information Systems (GIS). The system development process includes digitizing traditional nautical charts, transforming spatial data, and constructing attribute databases, as shown in Figure 2. This study employs ESRI's ArcGIS 10.0 as the system's demonstration platform due to its widespread application in geographic monitoring and its extensive tool library for data analysis and visualization.

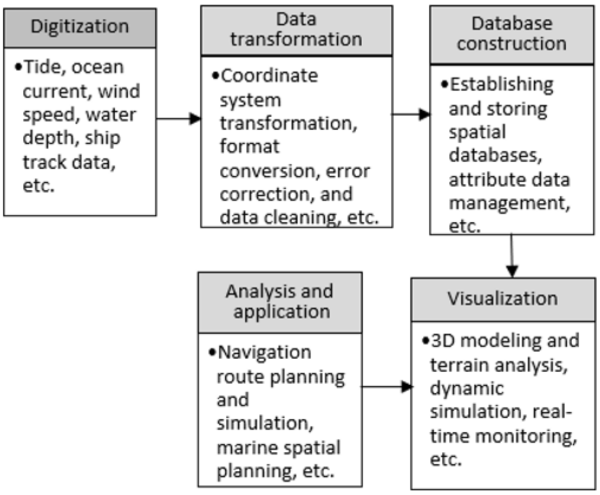

Figure 2. MGIS development process

3 RESEARCH DESIGN

3.1 *Encoding*

The first step in the genetic algorithm is encoding the imported data to facilitate subsequent computations. Ship data is imported into the genetic algorithm system and assigned numerical encoding. Since ships can receive and decrypt AIS messages within a 20-nautical-mile range, precautions are necessary to prevent crossover-generated chromosomes from aligning at grid boundaries. This misalignment could cause some genetic points to fall outside the AIS communication range. To address this issue, the study divides the area surrounding the distressed ship and shore station into 10-nautical-mile intervals. This ensures that scattered ship positions are assigned to distinct grid cells. Each ship is then given a spatial position encoding based on its grid location. This method ensures that data remains within the AIS communication range during the crossover process while maintaining a consistent chromosome length. It also prevents chromosomes from drifting beyond the communication range after crossover, as shown in Figure 3.

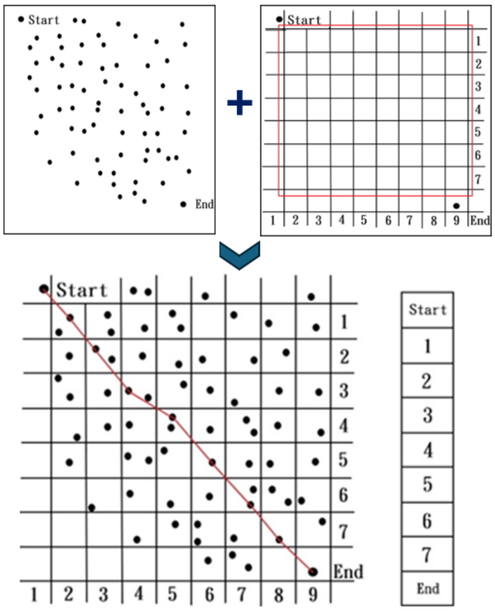

Figure 3. A chromosome with a Length of 7

3.2 *Ship Escape Time Index (SETI)*

SETI represents the duration a chromosome remains within the AIS communication range (20 nautical miles). Specifically, the chromosome maintains communication for the time specified by SETI. This ensures uninterrupted signal transmission and enables wireless message exchange. This study employs SETI as the fitness value in the genetic algorithm. The communication loss time function *f(t)* and the communication range are used to determine the time t at which adjacent genes in a chromosome lose communication. The ship's position coordinates after t seconds provide the basis for constructing the communication loss time function, as expressed in equation (1).

$$f(t)=\sqrt{\left[\left(x_1+s_1\cdot t\cdot\sin\theta_1\right)-\left(x_2+s_2\cdot t\cdot\sin\theta_2\right)\right]^2+\left[\left(y_1+s_1\cdot t\cdot\cos\theta_1\right)-\left(y_2+s_2\cdot t\cdot\cos\theta_2\right)\right]^2} \quad (1)$$

where x represents longitude, y represents latitude, θ denotes course, and s represents speed. The subscripts 1 and 2 respectively indicate two different ships.

The communication range constraint is given by *f(t)*=20 nautical miles. This function determines the time t at which two ships, each following their respective courses and speeds, reach the AIS communication boundary of 20 nautical miles.

A chromosome consists of i genes, where the separation time between adjacent genes is determined using equation (1). This calculation yields the separation times $t_1, t_2, t_3, \ldots, t_{i-1}$. The smallest separation time among them is selected as the SETI for the chromosome, as expressed in equation (2).

$$\mathrm{SETI}=\mathrm{Min}\left\{t_1,t_2,t_3,\cdots,t_{i-1}\right\} \quad (2)$$

In this study, the fitness value of each chromosome is determined by first computing the separation times between its genes. The shortest separation time among them is then selected as the fitness value of that chromosome. The separation time is calculated based on the known latitude and longitude coordinates of two ship positions, along with their respective course and speed.

3.3 *Constraints and algorithm mechanism*

A radio communication system is employed in this study for distress message transmission. To ensure effective message delivery, specific constraints are introduced. These constraints also mitigate the risk of transmission failures caused by radio communication limitations. The key constraints are as follows:

1. The length of all chromosomes in the gene pool is uniform.
2. The transmission distance between any two points must not exceed the AIS communication range of 20 nautical miles.
3. Given the fixed chromosome length, the search for the next relay ship does not consider movement away from the final destination. The final destination is the distressed ship.
4. All relay points must be among the ships detected via AIS within the defined geographic area.

This formalization enhances the rigor of the algorithmic approach and ensures that the optimization process aligns with real-world AIS communication limitations.

In the genetic algorithm, the fitness value determines whether a chromosome is selected for the next-generation gene pool. Chromosomes with higher fitness values have a greater probability of being included in the new gene pool. This study employs a tournament selection method, in which two chromosomes are randomly selected from the current generation, and the one with the higher fitness value is retained in the next-generation gene pool. This approach ensures that the genetic algorithm not only performs extensive searches but also progressively improves the quality of solutions over successive generations.

A single-point random mutation approach is employed. Each chromosome undergoes mutation based on a predefined mutation probability. If a mutation occurs, a gene is randomly selected for modification, as illustrated in Figure 4. Since the encoded genes represent the spatial positions of relay ships in the transmission route, altering the spatial encoding during mutation may cause the transmission path to exceed the radio communication limit of 20 nautical miles, resulting in communication failure. To address this issue, this study retains the original spatial encoding while randomly selecting an alternative ship within the same spatial encoding region as the new relay ship. This approach ensures that although the spatial encoding remains unchanged, the actual relay ship for message transmission is modified.

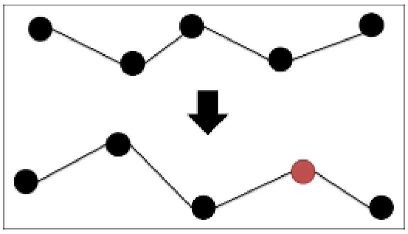

Figure 4. Mutation mechanism diagram

4 EXPERIMENTAL RESULTS

4.1 *Research scope and data sources*

The analysis focuses on the South China Sea and the Philippine Sea. It examines the overlapping exclusive economic zones of Taiwan and the Philippines. The scope extends to the territorial waters of both Taiwan and the Philippines. The main subjects of analysis are ships equipped with AIS that navigate within Taiwan's territorial waters, Taiwan's exclusive economic zone, the Philippine exclusive economic zone, and the territorial waters of the Philippines. Some fishing ships in the territorial waters and exclusive economic zones between Taiwan and the Philippines lack AIS transponders. This absence prevents the acquisition of real ship data for simulation purposes. As a result, the simulation data relies on assumed values derived from international sources such as MarineTraffic. Key assumptions include ship course and speed. Ships included in the model navigate between Taiwan and the Philippines within the geographical range of 19°N to 22°N latitude and 120°E to 122°E longitude. In this study, the GA used for emergency response routing follows specific parameter settings. The algorithm maintains a chromosome population of 20 per generation. It runs for a total of 1500 iterations to ensure sufficient optimization. The crossover probability is set to 1.0, enabling full crossover operations in each generation. The mutation probability is defined as 0.01 to introduce genetic diversity while minimizing disruption. Selection is performed using the tournament selection method, which enhances competitive survival among chromosomes. Mutation is applied using a single-point random mutation technique, and crossover is executed through a single-point crossover mechanism.

4.2 *Results*

The numerical analysis is shown in Table 2.

Table 2. Numerical results

Parameter	Value
Distressed ship location	Lat: 19.5326° N, Long: 121.3760° E
Shore station location	Lat: 21.7996° N, Long: 120.7890° E
Initial generation fitness value	0 seconds
Final generation fitness value	56.8468 seconds
Computation time	48.1658 seconds

The initial ship relay transmission route is shown in Figure 5. After 1500 generations of computation using the GA, the fitness value of the final-generation chromosome, known as the SETI, reaches 56.8468 seconds. This represents a significant improvement compared to the initial-generation chromosome. The relay transmission process of the final-generation ship distress message is depicted in Figure 6. This figure illustrates the optimized communication path and intermediary nodes after computational processing. The trend of the best fitness value across generations is shown in Figure 7. The simulation results indicate that when the distress signal from the distressed ship is received, an appropriate parameter configuration with GA computation determines the SETI. This index remains within a reasonable and acceptable time frame. The SETI is derived from the GA solution. Completing the verification process within this timeframe ensures that the acknowledgment signal from the shore station reliably reaches the distressed ship. This process is illustrated in Figures 8 and 9.

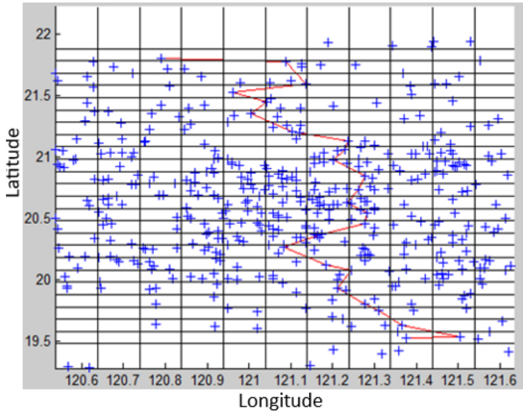

Figure 5. Initial distress message relay route

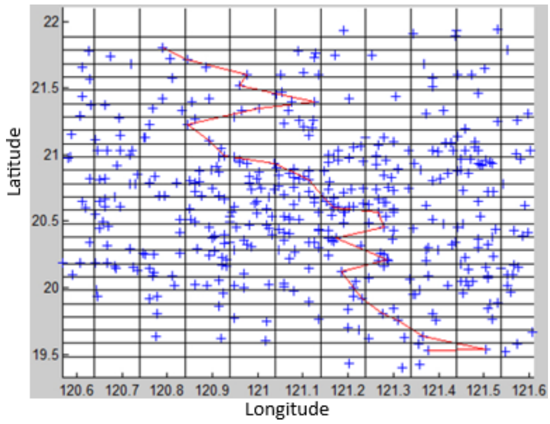

Figure 6. Final distress message relay route

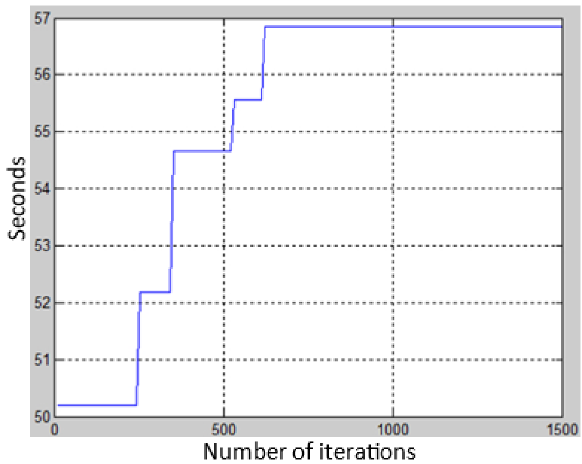

Figure 7. Best fitness value trend per generation

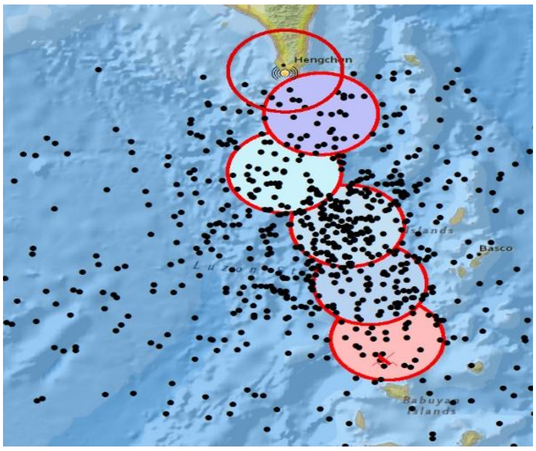

Figure 8. Distress signal transmission

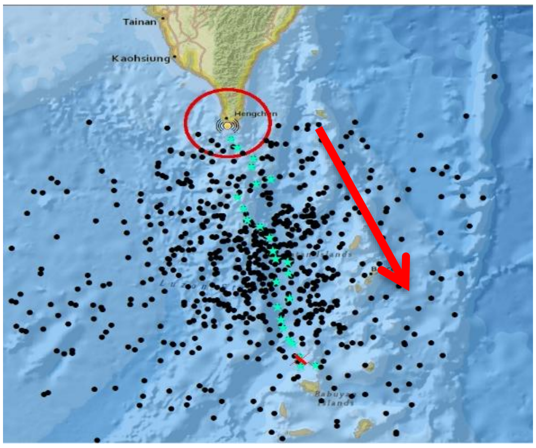

Figure 9. Acknowledgment signal transmission

5 CONCLUSIONS

Based on the concept of relay stations in wireless communication systems, this study proposes an innovative intelligent radio emergency notification system as an alternative mechanism for maritime distress signals. Traditional emergency positioning systems primarily rely on satellite systems for distress message transmission. The proposed approach integrates AIS with genetic algorithms and MGIS. This integration allows ships encountering force majeure incidents in offshore waters to utilize this distress notification mechanism effectively and securely. The system operates without concerns of information leakage or high costs. Moreover, it ensures that the distress message received by coastal stations is acknowledged and confirmed.

The system uses AIS as the transmission medium for distress messages and confirmation signals. The system constructs a network for distress message relay by collecting ship positions and integrating GA. It determines the optimal relay route. Coastal stations send confirmation messages via the AIS network and notify nearby ships of the distress situation. This process ensures that the distressed ship receives the confirmation message and activates the rescue mechanism. The distressed ship sends distress messages and receives acknowledgment signals from relay stations. This system reduces uncertainty in distress message transmission. This approach is particularly suitable for fishing ships as it enhances data security and improves operational safety in international fishing grounds.

This study assumes a moderately dense maritime environment in which nearby ships are equipped with operational AIS transponders, enabling effective maritime communication networks. However, in real-world scenarios, particularly in regions with sparse ship density or among fleets operating inactive or receive-only AIS transponders, the effectiveness of the system could be significantly impacted. Such constraints may limit the capability of maintaining stable and continuous communication.

Additionally, due to limited access to real-time maritime ship data, this study relies on hypothetical AIS data for simulations. Consequently, the actual system performance may differ according to genuine maritime traffic conditions.

The communication network established by this system serves as a general communication network under normal conditions. It provides nearshore ship communication services and extends the wireless radio communication network. This enhances the accessibility and effectiveness of maritime communication, making information transmission more convenient and efficient.

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