An Advanced Networking Protocol for VHF Data Exchange System

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Abstract

Since the appearance, AIS has been widely applied in worldwide navigation fields by virtue of outstanding performance. It helps to achieve automatic identification between ships, guarantee ships navigation safety and increase efficiency of maritime traffic management. However, with increasingly higher demands for maritime communication, a lot of problems of AIS are exposed one after another. System upgrade is urgently required due to stress from frequency bands and higher demands for data exchange. As a novel maritime digital communication system, VDES (VHF Data Exchange System) is developed based on AIS and aims to solve the problem that AIS is unqualified for high-speed data transmission. VDES are still under researching, wherein networking protocols play a crucial role in VDES, and an efficient networking protocol is of great importance to the system. At present, networking protocol is also under researching [1], but CSTMDA is the main consideration because of the high performance in AIS. The paper mainly researches and improves the CSTDMA networking access protocols. In comparison with traditional CSTDMA protocols, the improved CSTDMA protocol has a lower slot collision rate and can satisfy requirements of VDES for data transmission performance.

Keywords: VDES, CSTDMA, VHF, e-Navigation

1 Introduction

Reliable maritime communication could satisfy demands for ship navigation safety and healthy development of shipping industry, and play a necessary role in guaranteeing life safety of seafarers and ship property safety. Automatic Identification System (AIS) is a very important maritime communication approach and also a major communication service of maritime Very High Frequency (VHF) bands. With continuous increase of ships, AIS often suffers from continuous congestion states. At large ports all across the world, especially in China, AIS has already occupied over 50% of the VHF bands. According to analysis and research results of International Association of Lighthouse Authorities (IALA) [2], serious problems such as channel congestion or collapse would appear due to information congestion when the data link load rate of AIS exceeds 50%. A basic Chinese research in 2012 [3] indicated that the occupation rates of AIS1 and AIS2 channels exceeded 40% in the water area of Shanghai Port and Bohai Bay at ship traffic low peaks.

The International Maritime Organization (IMO) formulated development strategies of e-Navigation and modernized development strategies of Global Maritime Distress and Safety System (GMDSS) [4] so as to solve the lag problem of current maritime communication technologies. Under this background, the e-NAV Committee of IALA proposed the concept of VDES and researches how to increase utilization rate and communication rate of maritime VHF bands so as to solve problems of network busyness and congestion in current AIS data link.

The concept of VDES has been widely discussed by International Telecommunication Union (ITU), IMO and other international organizations. The concept of VDES was proposed at the 2012 Word Radio Communication (WRC-12) Conference. In October 2015, ITU released the ITU-R M.2092-0 proposal, making detailed introduction to technological features of VDES [5] VDES is still under researching, international organizations such as IMO and ITU fail to form a uniform standard. Hence, it is necessary to research related technologies and development trends of the new generation of VDES. Research and development of VDES are of important significance for theoretical guidance and practice of later development of ship navigation and maritime traffic management, promising broad application prospect.

Research on networking protocols of VDES is a crucial key of system communication performance. At present, a lot of scholars have carried out a lot of researches on VDES networking protocols based on networking protocols of AIS. The NAMA algorithm [6] proposed by Garcia-Luna-Aceves can distribute channels resources averagely, but fails to consider the different loads of different nodes. In addition, certain continuous data collision exists when new nodes are added into a network. The NEBS algorithm [7]

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proposed by Sung and Denh improves the NAMA algorithm. NEBS is highly adaptable to network load rate change. However, slot waste also exists to a certain extent due to the corresponding fixed slot occupied. Scholars such as Li and Chennikara-varghese added a QoS guarantee mechanism [8] on the protocol USAP-MA (Unifying Slot Assignment Protocol-Multiple Access). In this way, resource demands of different services are satisfied, but problems in frame structure of USAP-MA protocols are not solved. Chlamtac et al. [9] proposed a TDMA proposal called as ABROAD algorithm, which overlays the CSMA/CA competition mechanism on the basis of fixed TDMA. The TDMA proposal can be achieved easily, but the dead lock mechanism is not eliminated. Scholars such as Bruhadeshwar et al. [10] proposed a TDMA protocol based clustering mechanism, which has high self-adaptability and self-stability and ensures throughput capacity and certain fairness. Tan et al. [11] introduce the channel access mechanism TDMA into the PH-MAC to save energy and maximize the throughput. Scholars such as Raulefs and Stenbock [12] conducted physical layer design based on VDES.

Above research results mainly aim at slot distribution and slot collisions, wherein the slot collisions are mainly reduced by designing and distributing the slot distribution algorithm. The paper will research and improve the CSTDMA protocol in combination with use characteristics of VDES and reduce slot collisions by increasing discreteness of slot selection. In this way, slot collisions can be avoided and reduced during data transmission of the improved CSTDMA protocol in VDES, and better communication performance can be provided for VDES. The paper is specifically divided into the following parts. Section 2 researches slot schemes and protocol theories and puts forward the improved CSTDMA protocol. Section 3 conducts simulation modeling of the improved protocol. Section 4 conducts experimental testing and analysis of the improved protocol. Section 5 gives conclusions of the paper.

2 Key Technologies

2.1 Slot Division Scheme

According to requirements for slot division schemes in the ITU-R M.2092-0 proposal released by ITU and with the frame structure of AIS as the reference, 1 frame was divided into 5 sub-frames, involving 2250 slots; 1 sub-frame was divided into 15 super slots, involving 450 slots; 1 super slot was divided into five 6-slots, involving 30 slots; one 6-slot was divided into 6 slots, each duration lasted for 26.667ms. Specific frame structure is shown in Figure 1.

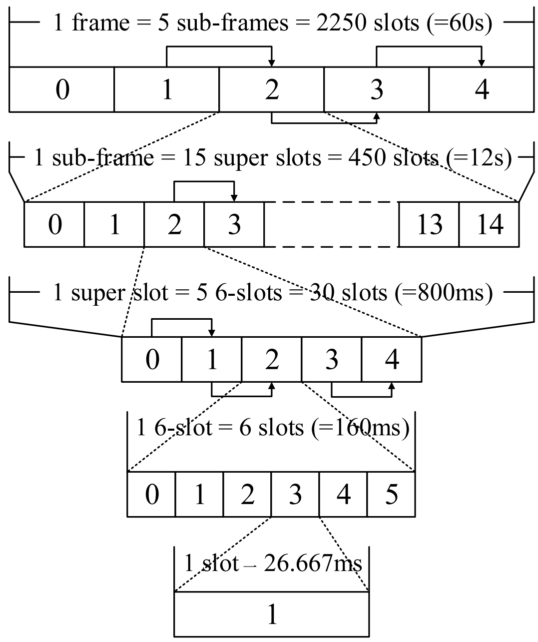

Figure 1. Slot division scheme

2.2 Research on CSTDMA Protocol

2.2.1 Carrier Detection Principles

Detection duration stayed within 2ms before starting of each slot, lasted for 1146μs in total and ranged between 833μs and 1979μs, as shown in Figure 2. When the frame hears that the signal level was higher than the critical value, it would not send information; if it heard that the signal level is lower than the critical value, the slot would send data according to the slot. Data sent by VDES would be sent at the time of 20 bits after arrival of the slot, namely T_A=2083us+T_0. (T_0, start time of slot. T_A, start time of VDES signal sending)

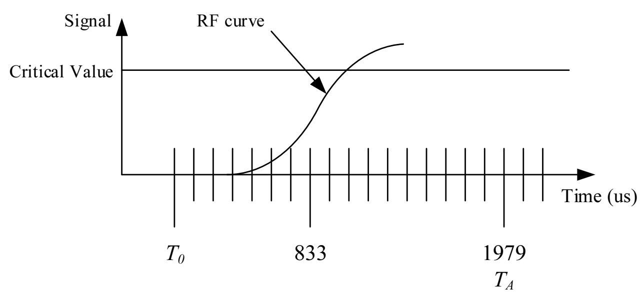

Figure 2. Slot division scheme

2.2.2 Access Scheme of CSTDMA

Access scheme of CSTDMA shall obey the following stipulations:

(1) 10 or 10n candidate slots CP in TI are selected according to a certain CP selection algorithm (Where: n refers to the number of required slots, 1<n<TI/10, CP means candidate slot, TI means transfer interval)

(2) Detection is started from the first slot waiting for carrier monitoring according to the time sequence.

Sending will be conducted when the slot idleness is detected; next detection will be waited if the slot is occupied.

(3) When all the selected slots to be detected are occupied, the emission will be deemed to be failing. Next emission will be waited.

2.3 Improvement of CSTDMA Protocol

2.3.1 Problems in Traditional CSTDMA Protocol

Theoretically, the data rate of VDES could reach 307.2 kbit/s. When the slot division of AIS is adopted, each slot can send 767.8 bytes (4915bits) according to the standard of 75% valid data. More emission slots are needed when the transmitted data increases continuously and the data packets get larger, while the occupation rate of information channels will be increased.

Traditional CSTDMA is mainly used in AIS of small and middle-sized ships and will not affect other ships in the channels, while only one slot is used each time. Increase of data packets in VDES requires occupation of multiple slots and shall satisfy certain requirements for timeliness. In random selection of slots, relatively rear slots might be selected, so that requirements for data transmission timeliness would be affected.

During carrier monitoring of the traditional CSTDMA protocol, the probability of collisions is low when there are only a few of ships; where there are a lot of ships, the same idle slot may be selected by multiple ships at the same time, so that slot collisions would be generated and affect complete data transmission.

2.3.2 Improved CSTDMA Protocol

A proper slot shall be subject to shipping states of a ship, such as speed and location. Various parameters related to the slot are determined by shipping states of the ships. Hence, a proper slot would be selected within a complete frame period to send data. VDES has brand new VHF channels and does not have presetting of slots, so that all the arriving slots are empty. VDES mainly takes into account the occupation capacity of idle slots and the ability to avoid slot collisions. The improved CSDTMA protocol scheme is as follows (Figure 3):

(1) As for the original CSTDMA protocol, the detection slot is selected from candidate detection slots within the future 10s. As an improvement, the slots coming soon will be detected in succession when the ship station needs to conduct data transmission. The beneficial effect is that timeliness of data transmission of the ship station is guaranteed. However, probability in slot collisions is also increased.

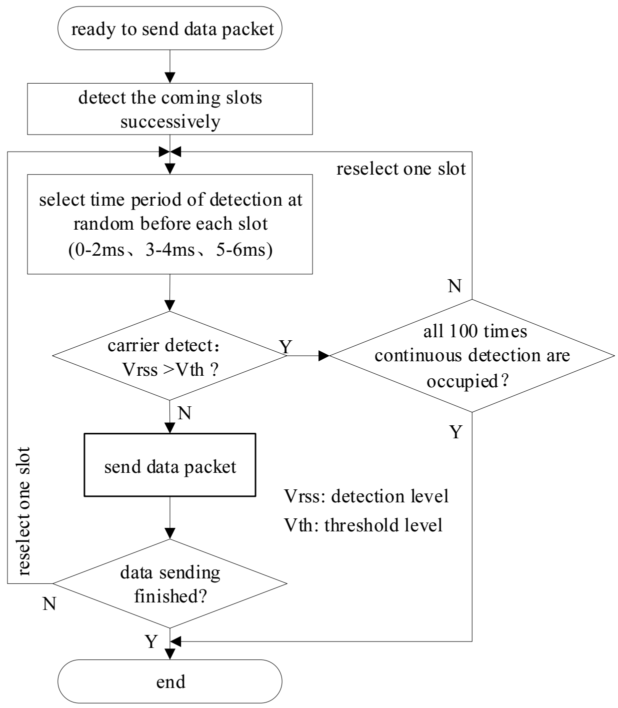

Figure 3. Slot division scheme

(2) As for the original CSTDMA protocol, whether a slot is occupied is detected within 2ms of the slot. Emission will be conducted if the idle slot is detected. Then, detection of randomly selected periods will be conducted. In view of data transmission duration, detection of randomly selected periods within first 2ms will be changed to that within 6ms. Transmission delay and slope time of other modules occupy 0.8ms. Time of carrier monitoring lasts for 1.2ms. Specific time periods are as follows: 0-2ms, 3-4ms and 5-6ms.

(3) When a base station is used to broadcast big message data, a slot preservation mechanism is adopted rather than the ship station carrier monitoring mode based on randomly selected periods. According to the amount of slots occupied by the broadcasted message data, slots of the same amount will be preserved for the base station. Continuous slots are directly occupied till all the broadcasted message data is sent.

2.4 Access Rate Analysis and Slot Collision Analysis

Transmission intervals are small values in general according to actual situation. Transmission interval of 30 min or 30s appears occasionally. Within other periods of ship sailing, the transmission interval TI is basically set as 10s.

It is assumed that P is the load rate of VHF information channel; N denotes the amount of ship stations within the communication sea area; N_{TI} denotes the total number of slots within the TI; N_Y denotes the total number of slots which are not occupied within TI; N_N denotes the total number of slots occupied within TI:

$$N_N = N_{TI} \times P \tag{1}$$

$$N_Y = N_{TI} \times (1-P) \tag{2}$$

Emission is completed in only one information channel each time. Hence, aiming at one VHF information channel only, the probability P_N of selecting the occupied slot and the probability P_Y of selecting an idle slot are as follows:

$$P_N = \frac{N_N}{N_{TI}} = \frac{N_{TI} \times P}{N_{TI}} = P \tag{3}$$

$$P_Y = 1 - P \tag{4}$$

It is set that all the idle slots are distributed averagely within a frame period, and slots for data sending required by all the ship stations are also distributed averagely. A slot could hardly be selected by multiple ships, so this case is neglected. It is set that two ship stations have the same probability to acquire idle slots, namely 1/2. In view of the slots within the whole TI, the probability P_S for the ship station to acquire the idle slot is:

$$P_S = P_Y \times \left(1 - \frac{p_n}{2}\right) \tag{5}$$

All the slots of TI are independent. Each slot is occupied or stays idle, satisfying N tests of Bernoulli experiment. N is 10. It is assumed that each ship station selects X idle slots, so X~b (10, P_S). The access rate is as follows:

$$\begin{aligned} P1_{Y1} &= \sum_{X=1}^{10} \binom{10}{X} P_S^X (1-P_S)^{10-X} \\ &= 1 - \binom{10}{0} (1-P_S)^{10} \end{aligned} \tag{6}$$

When multiple ship stations detect the same slot at the same time, the ship stations will conduct emission at the same time, leading to collision and failure of normal data transmission. It is set that the slots selected by ship stations for planned emission are distributed averagely in the whole frame. Hence, the total number n of ship stations within TI is equal to 1/6 of N.

2 ship stations. When only two ship stations α and β exist within the TI and size of the packet needing to be sent is equal to that of one slot, the probability in slot collisions between α and β would be:

$$P_{\alpha\beta} = P_\alpha \times P_\beta \times N_{TI} \tag{7}$$

When the size of data packet to be sent is equal to that of m slots (m< N_{TI}, one slot collision would lead to the failure of data sending. The probability of non-repeatability of m slots could be computed according to the formula $C_{N_{TI-m}}^m \big/ C_{N_{TI}}^m$. Hence, the probability in occurrence of slot collisions is $Pm_{\alpha\beta} = 1 - C_{N_{TI-m}}^m \big/ C_{N_{TI}}^m$. In the agreed protocol, the probability for two ships to select 0-2ms, 3-4ms and 5-6ms at the same time is P_S, wherein P_S=1/3. Hence, the slot collision rate is $P = Pm_{\alpha\beta} \times P_S$.

N ship stations. It is assumed that there are N ship stations, so other N-1 ship stations would generate slot collisions with one of the ship stations. If there are 3 ship stations *α*, *β* and *γ*, the probability for ship station *α* to generate slot collisions is the sum of following two aspects:

(1) The probability of ship station *α*, when slot collisions is generated between ship station *α* and ship station *β*;

(2) The probability of ship station *α*, when no slot collisions is generated between ship station *α* and ship station *β*;

It is set that the probability of slot collisions between *α* and *β*, *β* and *γ*, *α* and *γ* are $P_{\alpha\beta}$, $P_{\beta\gamma}$ and $P_{\alpha\gamma}$, also $P_{\alpha\beta}$=$P_{\beta\gamma}$=$P_{\alpha\lambda}$=$P(A_2)$, so:

$$P(A_3) = [1 - P(A_2)][P(A_2)(1 - P(A_2))] + P(A_2) \tag{8}$$

Hence, when N ship stations exist, the probability for ship station *α* to generate slot collisions during first time of data packet emission is:

$$P(A_N) = [1 - P(A_{N-1})]\left[P(A_2)(1 - P(A_2))^{N-2}\right] + P(A_{N-1}) \tag{9}$$

3 Simulation Model of CSTDMA Protocol

3.1 Simulation Processes of Protocol

Understand system. The paper aims at simulation of a protocol under the VDES system network. Different protocol algorithms are adopted for base stations and ship stations. The whole system undergoes simulation under the VHF wireless communication environment.

Understand simulation purpose. It aims to research effects of ship station amount and data size sent by each ship station within one frame on the slot collision rate of whole system, so as to determine relations of them.

Select modeling objects. Modeling shall be conducted on the network layer, node layer and process layer. The protocol algorithm is mainly achieved through programming during each node process.

Define input and output. It is mainly necessary to define the amount of input ships, the amount of data packets to be sent by each ship station within a frame, simulation time, and size of unit data packet. Total amount of sent packets, total amount of received packets, amount of packet collisions and slot collision rate will be output.

Confirm system model. Various steps mentioned above are completed. A protocol algorithm is designed to determine the final system model.

Confirm input and run simulation. Different results are obtained after running by changing the ship station amount and the amount of data packets sent by ship stations within each frame. Relations between the ship station amount, amount of data packets sent by ship stations within each frame and the slot collision rate are determined according to results.

Statistics and analysis. check the simulation results data if they are valid, exclude the unusual phenomenon, then an valid result of the simulation will be obtained (Figure 4).

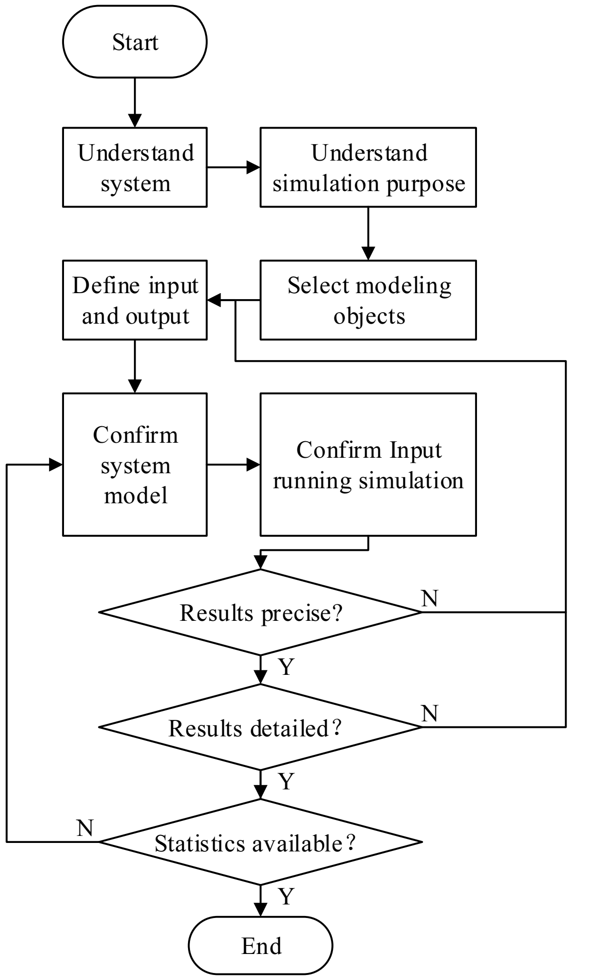

Figure 4. Simulation model of protocol

3.2 Modeling of Protocol Simulation

The simulation system is composed of a base station, ship stations and a counter node. The network adopts a broadcast protocol. The ship stations are dynamic nodes. The base station is a fixed node. The ship stations and base station transmitted packets to the bus. The counter recorded occupation of slots within the continuous simulation duration by all the ships and worked out the system slot collision rate through processing. The simulation experiment researched the relations between the amount of ship stations, the amount of data packets sent by each ship station per min and the slot collision rate. Hence, networks with different amounts of ship stations should be simulated. The model achieved network systems under many cases. There was one base station and one counter. The amount of ship stations could be increased or decreased according to experimental demands. Figure 5 shows a system network diagram with 100 ship stations.

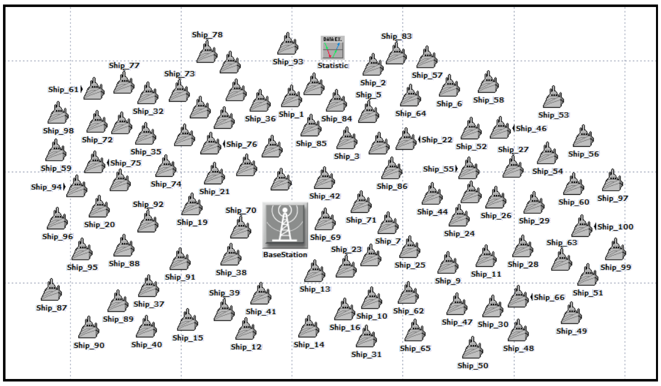

Figure 5. Network model of VDES

4 Simulation Testing of Improved CSTDMA Protocol

The sea area simulated this time is a simulation scene of 10km×10km. 10-100 ship stations were distributed randomly in the simulation sea area. The communication scope of VDES reached 25 sea miles, so all the ship stations were located within mutual communication scopes. By changing the amount of ship stations and the amount of data packets set by each ship station within each frame, the whole network system was set up. Communication performance of the traditional CSTDMA protocol and the improved CSTDMA protocol was analyzed. Simulation was conducted in a single information channel with frequency of 157.2375MHz. The amount of ship stations increased progressively from 10 to 100. When 10 ship stations were added each time, the base station still set 10 data packets. Each data packet occupied one slot. The unit size of data packet was 4048bits. Specific parameter settings are shown in Table 1.

In VDES, system capacity and slot collision rate are taken as important performance indexes. System capacity is defined as the amount of ship stations which could be accepted by the whole system within a specific scope; slot collision rate P refers to the ratio of total amount of slot collisions within each frame and the total amount of data packet slots sent within the whole frame. The higher slot collision rate indicates the lower reliability and poorer performance of the whole network.

Table 1. Simulation parameters

Parameter name (unit)	Parameter value
Frame length (s)	60
Total amount of slots within each frame (a)	2250
Amount of data packets sent within one frame (a)	5, 6, 8, 10, 12, 15
Amount of ship stations (a)	10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Amount of base station (a)	1
Network coverage scope (km×km)	10×10
Simulation time (S)	1800

Under two simulation scenes, including traditional CSTDMA protocol and improved CSTDMA protocol, the amount of ship stations was changed. The amount of data packet sent by ship stations within one frame was 5, 6, 8, 10 and 15. The amount of data packets sent by the base station was always 10. In other words, 50 experiments were conducted under each scheme. There were 100 experiments in total.

Experimental results of each simulation were recorded, as shown in Table 2 and Table 3. Table 2 shows slot collision rates of traditional CSTDMA protocol in each experiment. Table 3 shows slot collision rates of the improved CSTDMA protocol in each experiment. Results of comparative analysis are shown in Figure 6 to Figure 9.

Table 2. Slot collision rates of traditional CSTDMA

Ship Stations	Slot Collision Rate				
N	Packet 5	Packet 6	Packet 8	Packet 10	Packet 15
10	0.0108	0.0095	0.0201	0.0158	0.0309
20	0.0177	0.0196	0.0292	0.0392	0.0589
30	0.0294	0.0353	0.0476	0.0597	0.0866
40	0.0421	0.0517	0.0621	0.0838	0.1196
50	0.0524	0.0631	0.0796	0.0971	0.1406
60	0.0627	0.0741	0.0956	0.1151	0.1651
70	0.0731	0.0862	0.1106	0.1335	0.1831
80	0.0813	0.1003	0.1266	0.1480	0.2053
90	0.0879	0.1081	0.1341	0.1644	0.2208
100	0.0981	0.1149	0.1498	0.1761	0.2381

Table 3. Slot collision rates of improved CSTDMA

Ship Stations	Slot Collision Rate				
N	Packet 5	Packet 6	Packet 8	Packet 10	Packet 15
10	0.0022	0.0057	0.0108	0.0098	0.0148
20	0.0089	0.0111	0.0145	0.0212	0.0301
30	0.0137	0.0161	0.0204	0.0251	0.0393
40	0.0159	0.0181	0.0249	0.0312	0.0476
50	0.0191	0.0251	0.0329	0.0399	0.0598
60	0.0233	0.0276	0.0369	0.0489	0.0701
70	0.0269	0.0343	0.0484	0.0556	0.0827
80	0.0338	0.0391	0.0492	0.0633	0.0939
90	0.0343	0.0433	0.0557	0.0715	0.1088
100	0.0413	0.0464	0.0648	0.0791	0.1194

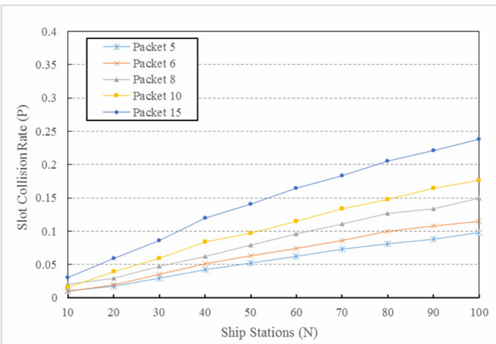

Figure 6. Slot collision rates of traditional CSTDMA protocol

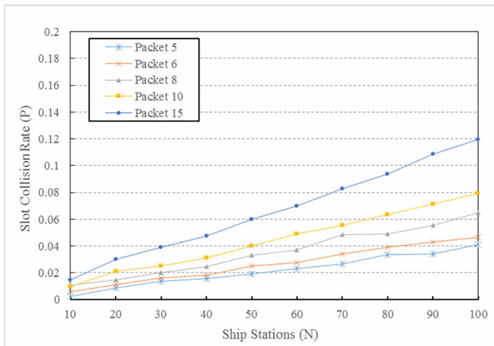

Figure 7. Slot collision rates of improved CSTDMA protocol

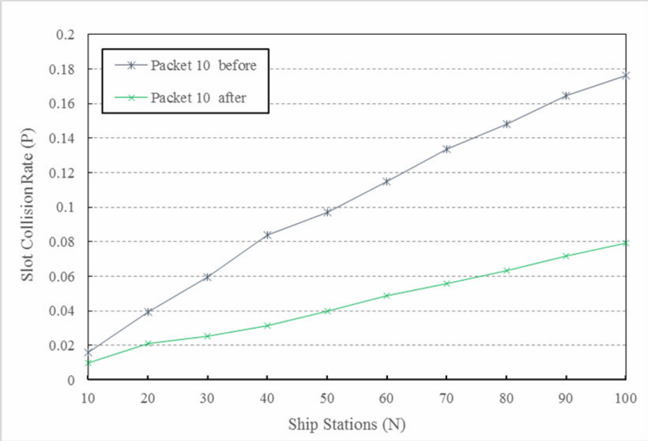

Figure 8. Comparison of slot collision rates of two protocols of data packet 10

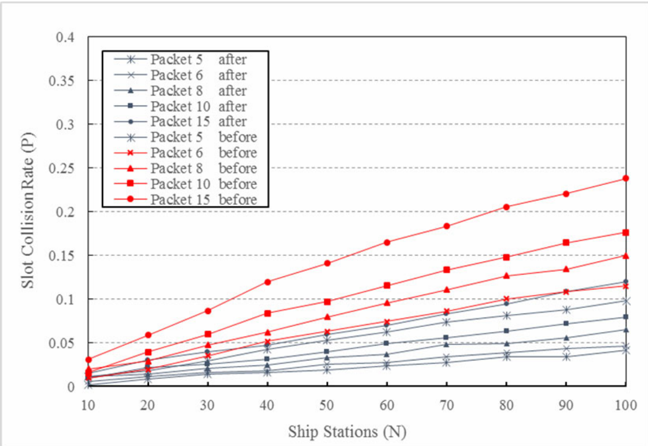

Figure 9. Comparison of slot collision rates of two CSTDMA protocols

Result analysis of experiments indicates:

(1) Under the same amount of ship stations, the slot collision rates of both the traditional CSTDMA and the improved CSTDMA increased when each ship station sent more data packets within each frame. The slot collision rate under 10 sent data packets was about twice the slot collision rate under 5 sent data packets. The slot collision rate under 15 sent data packets was about three times that under 5 sent data packets.

(2) When each ship station sent the same amount of data packets within each frame, the slot collision rates of both the traditional CSTDMA and the improved CSTDMA increased with the increase of ship stations. The slot collision rates increased quickly at the very beginning. With increase of the ship stations, the growth rate gradually decreased.

(3) When the amount of ship stations and the amount of data packets sent by each ship station within each frame were equal or unequal, the slot collision rates of the improved CSTDMA protocol were obviously lower than the slot collision rates of traditional CSTDMA protocol, with the decrease rate of about 50%. Results indicate that the improved CSTDMA protocol has better communication performance and higher reliability than the traditional CSTDMA protocol.

4 Conclusion

The paper improved detection modes of protocols through research on the traditional CSTDMA protocol. Through design and improvement of the protocol algorithm, information channel parameters of the current AIS were used to simulate actual VHF data communication environments, so the simulation results were more reliable. Through simulation modeling of the network, modeling of the VDES network was conducted in succession from levels such as information channels, processes, nodes and network layers. In this way, communication performance of traditional and improved algorithms of the CSTDMA protocol was simulated. Experimental results indicate that the improved CSTDMA protocol has a lower slot collision rate than the traditional CSTDMA protocol. The improved protocol can satisfy requirements for data transmission performance.

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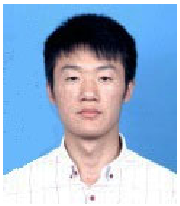

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