Transmission Evaluation of Ship-borne Automatic Identification System (AIS) in Congested Waterways

Kazuhiko Hasegawa, *Member, IEEE*, Kojiro Hata, Kazuhisa Niwa and Junji Fukuto

Abstract— ***AIS (Ship-borne Automatic Identification System) is a system that enables a ship to get information about encountered ships, such as their position, course, speed, name etc. automatically by VHF radio transmission. The system is expected to contribute the improvement of marine traffic control and safety. In some congested waterways overloaded/conflicted transmission of AIS is a potential problem in the planning stage. We have developed a simulator that simulates AIS communication for real or simulated marine traffic flow considering the movement of each ship. AIS communication is evaluated under various AIS transmitting conditions and for various aspects using thus developed AIS Simulator.***

I. INTRODUCTION

THE safety navigation in the congested water is a very important issue. Recently for this issue, ICT is playing an important role. AIS (Ship-borne Automatic Identification System) is one of the systems thus developed. It is installed in each ship and each VTS (Vessel Traffic System) centre (hereafter we may call it just VTS). It transmits the information related to their navigation automatically among ships and VTS centres. It enables us to know the situation of encountered ships far away or behind some obstacles, while it is unable to know in a conventional marine radar or ARPA (Automatic Radar Plotting Aids, a collision prevention aids). AIS, thus, is expected to contribute to prevent collisions and improve safety. At this moment IMO (International Maritime Organization) made it mandatory to install AIS for ships of certain size and over in some years. It has started from 2002 based of amended SOLAS(Safety of Life at Sea) convention and its introduction period will end in 2008.

Manuscript received June 16, 2008. This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid for Scientific Research (C), No. 19510172, 2007-2008, the project of Japan Ship Technology Research Association in the fiscal years of 2006 with support from the Nippon Foundation and Education and Research Promotion Support for the New Employees, Nagasaki University.

K. Hasegawa is with Department of Global Architecture, Osaka University, 2-1, Yamada-oka, Suita, Osaka, 565-0871 Japan (phone:+81-6-6879-7588; fax: +81-6-6879-7594; e-mail: hase@naoe.eng.osaka-u.ac.jp).

K. Hata is with e-Learning Center, Otemae University, 6-42, Ochayasho-cho, Nishinomiya, Hyogo, 662-8552 Japan (e-mail: k-hata@otemae.ac.jp).

K. Niwa is with Research and Development Center for Higher Education, Nagasaki University, 1-14, Bunkyo-machi, Nagasaki, Nagasaki, 852-8521 Japan. (e-mail: niwa@redc.nagasaki-u.ac.jp).

J. Fukuto is with Navigation and System Engineering Department, National Maritime Research Institute, JAPAN, 6-38-1 Shinkawa, Mitaka, Tokyo, 181-0004 Japan (e-mail: fukuto@nmri.go.jp)

On the other hand, VTS is expected to provide information such as route condition, weather and safety related information to ships in each VTS-covering area using AIS binary messages. Furthermore AIS is going to be used for commercial information services and harbour/custom-related matters. Unless mentioned, when we talk as AIS, it is class A AIS. Class B AIS somewhat degraded from class A AIS is going to be introduced for non SOLAS-regulated ships, *i.e.* smaller ships. Here the question is whether VHF radio transmission overloads in the congested waterway or not.

The difficulty to answer the above question is caused by its protocol. AIS transmission interval varies according to each ship's movement. Therefore, the simulator should simulate ships' movement as realistic as possible, and VHF radio transmission and its diffusion characteristics should be taken into an account. We employ two steps to simulate AIS communication. As the first step, the traffic flow data is prepared by Marine Traffic Simulator developed by Hasegawa [1] [2] [3]. Next, based on the traffic flow data, AIS communication is simulated by newly developed AIS Simulator[4]. The evaluation method of AIS communication is also proposed[5]. Moreover, towards future enlargement of AIS adaptation, more quantitative understanding of AIS communication is examined

II. CHARACTERISTICS OF AIS

AIS has 2 channels for communication and each channel has 2,250 slots per minute. Therefore, totally 4,500 slots per minute can be used for exchanging messages. AIS transmits messages appropriately using several protocols according to the situation. The most frequent-used protocol is SOTDMA (Self Organized Time Division Multiple Access).

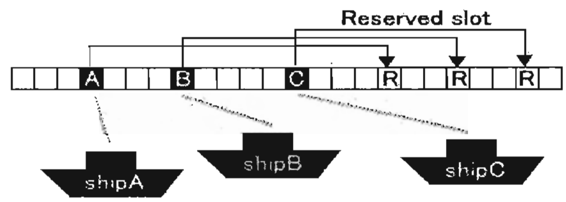

Fig.1 Schematic diagram of SOTDMA

SOTDMA protocol ensures scheduled data transmission by reserving next slot in every data transition interval. As each ship knows the reserved slots, it can choose a vacant slot for its next transmission to avoid the conflict. Although even we adopt this protocol, certain conflict may occur due to the overloaded or some lacks of the transmission. If such lacks of transmission happen, bad influence to the safety of navigation should be considered. We investigate this issue.

III. MARINE TRAFFIC SIMULATOR [1] [2] [3]

Marine Traffic Simulator is a software system to simulate marine traffic flow realistically. Each ship in the traffic flow has her own characteristics, including principal particulars, navigation speed, manoeuvring parameters, OD (origin and destination) and waypoints. Besides, in case of congested area, if necessarily, she will be properly manoeuvre to avoid collision against encountered ships or any obstacles by computerized captain. Marine Traffic Simulator provides realistic traffic flow data to AIS Simulator for any given marine traffic condition and environment.

IV. AIS SIMULATOR[4]

A. Outline of the System

AIS Simulator simulates AIS communication circumstances in the congested waterway using either simulated traffic flow by Marine Traffic Simulator or observed traffic flow data. As the traffic flow data includes position, course, speed etc. of each ship, realistic and precise prediction of AIS communication is available. In addition it is possible to modify the condition such as the number and functions of ship-borne and land AIS stations communication protocol. In this way AIS Simulator can simulate AIS communication under various conditions.

B. System Structure of AIS Simulator

AIS Simulator is divided into three sections. One is AIS simulation section which simulates AIS communication from the given traffic flow data. Second one is database section which accumulates the results. The last one is visualization section, which handles visualization of slot usage and/or area map. The flow diagram of AIS Simulator is shown in Fig.2.

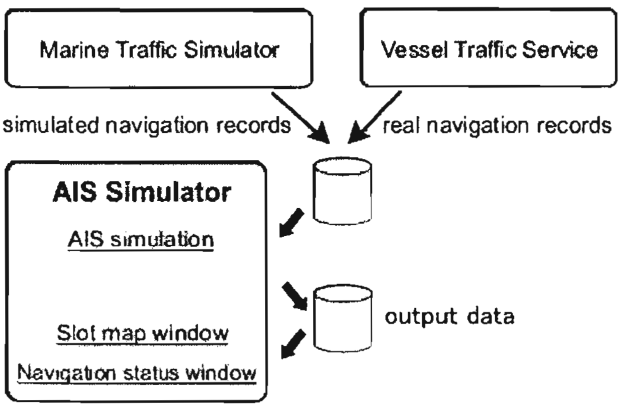

Fig.2 System structure of AIS Simulator.

C. Setting Conditions of AIS in AIS Simulator

1) Communication Protocols [6][7]

To manage the time slot, AIS uses Time Division Multi Access (TDMA) protocol for communication and it includes RATDMA, ITDMA, SOTDMA, FATDMA and CSTDMA. On the other hand, AIS is categorized by its classes. Class A AIS is existing AIS used for SOLAS-regulated ships and Class B AIS is intended for non-SOLAS-regulated ships, however detail protocol is not yet approved. Base Station AIS is used for on-land service station like VTS. Refer to the references[6][7] for more detail description.

2) Types of Messages

AIS messages implemented into AIS Simulator are shown in Table 1.

Table 1 AIS messages implemented in AIS Simulator

Class A AIS	
Message 1	Position report
Message 5	Static and voyage related data(static)
Message 5	Static and voyage related data (voyage)
Message 12	Safety related message
Class B AIS(SOTDMA)	
Message 18	Standard position report
Message 19	Extended position report
Class B AIS(CSTDMA)	
Message 18	Standard position report
Message 24	Class B "CS" static data
Base station	
Message 4	Base station report
Message 8	Binary broadcast message
Message 14	Safety related broadcast message

D. Function of AIS Simulator

1) AIS Simulation

AIS Simulator reads all ships' navigation data for next 1 minute. It starts to scan all ships' 0^{th} slots of channel 1 for the sending and receiving process. When it finishes all 0^{th} slots of channel 1 will be processed. The same procedure will be repeated for 0th slots of channel 2, 1^{st} slots of channel 1, and so on until 2249^{th} slot of channel 2 for every 1 minute until the end of the simulation.

2) Judgment of Receiving

The judgment of receiving messages is one of the most important processes of AIS simulation. The process will be hereafter explained. In this sub-section we will focus on a ship, to be called as the subject ship *i*.

When a message is sent from one ship to the subject ship *i* and if the subject ship *i* does not engage in transmission processing, this message will be received and this receiving state is called "Receive". If the above is held while transmission processing is done, this message will not be received. Moreover, when a message is sent to the subject ship *i* from two or more ships simultaneously, the subject ship *i* calculates the received power of message from each message-sending ship *j* using the equation (1) .

$$ {}_iP_j = \alpha_i P_j \Big/ {}_iD_j^2 \quad (\alpha = \text{constant}) \tag{1} $$

where ,

${}_iP_j$: Received Power of ship *i* message from Ship *j*

P_j : Power of Ship *j* message

${}_iD_j$: Distance between Ship *i* and Ship *j*

When the message has been simultaneously sent from two or more ships to the subject ship *i*, the received power of a message for each message-sending ship will be compared and largest one will be received. Two of message-sending ships are denoted as *n* and *m* (let the larger received power ship to be ship *n*), and the ratio of the received power to the subject ship *i* is shown as equation (2).

$$ {}_iP_n \Big/ {}_iP_m = \left(\frac{P_n}{{}_iD_n^{\,2}} \right) \Bigg/ \left(\frac{P_m}{{}_iD_m^{\,2}} \right) \tag{2} $$

When it exceeds a threshold value to distinguish either sender, the message of the ship sending larger received power will be received and this reception state is defined "Receive stronger message". When it is below the threshold value, it receives no message and this reception state is defined "Garble". In this study, attenuation of radio wave is not considered, assuming good weather and there is no big reflected wave and other obstacles. In addition, when transmission processing is going on either channel, sending and receiving cannot be processed on the other channel.

3) Average Slot Conflict Rate, Average Slot Garble Rate and Un-transmitted Rate

Average slot garble rate G_T^k and average slot conflict rate C_T^k are defined as follows.

$$ G_T^k = \sum_{t=1}^{T}\sum_{i=1}^{N(t)} {}_iS_g^k(t) \Big/ \sum_{t=1}^{T}\sum_{i=1}^{N(t)} ({}_iS_r^k(t) + {}_iS_g^k(t)) \tag{3} $$

$$ C_T^k = \sum_{t=1}^{T}\sum_{i=1}^{N(t)} {}_iS_{r2}^k(t) \Big/ \sum_{t=1}^{T}\sum_{i=1}^{N(t)} ({}_iS_r^k(t) + {}_iS_g^k(t)) \tag{4} $$

where, ${}_iS_s(t)$, is the total number of slots which a ship *i* uses for transmission at a certain time *t* (1 minute interval), ${}_iS_r(t)$ is the total number of slots which a ship *i* uses for reception, ${}_iS_{r1}(t)$ is the total number of slots in ${}_iS_r(t)$ where collision has not occurred and ${}_iS_{r2}(t)$ is the total number of slots in ${}_iS_r(t)$ where collision has occurred, ${}_iS_g(t)$ is the total number of slots where garble occurs, s ${}_iS_u(t)$ is the total number of unused slots, $N(t)$ is the number of ships of the whole gaming area and T is the total gaming time at simulation trial (k).

Apart from the above-mentioned indices, it is also important to focus on a certain ship and to know how much percentage of the subject ship's messages is received by other ships even in their reachable distance. We can define this as un-transmitted rate ${}_iU^k(t)$ in equation (5).

$$ {}_iU^k(t) = {}_im_g^k(t) / M(t) \tag{5} $$

Where $M(t)$ is the number of ships inside the radio wave reachable area at a certain time *t* (discrete time interval which is decided by the subject ship's motion state and the type of the message) and ${}_im_g^k(t)$ is the total number of other ships in the area which are not received this message in the simulation trial (k).

4) Visualization of Communication Process

Two GUIs of Slot Map Window and Navigation Status Window are provided in .AIS Simulator. It helps visual understanding of AIS communication easily. A sample Slot Map Window is shown in Fig.3.

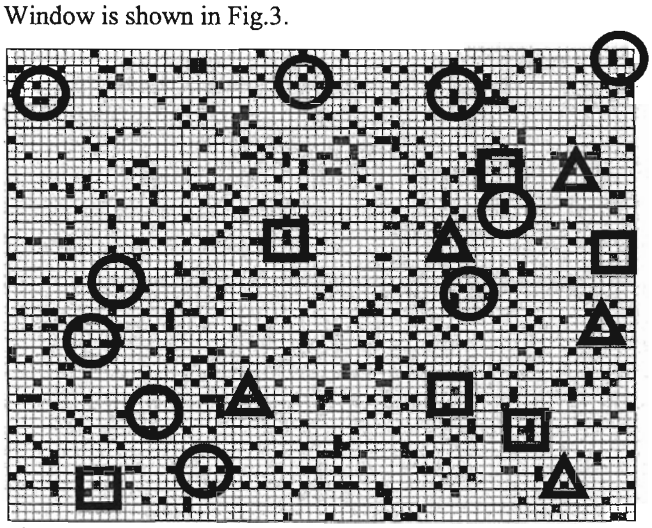

Fig.3 A sample Slot Map Window.

One frame, namely, 2,250 slots per channel is shown in the total 4,500 squares, where first and second rows correspond to the first 75 slots starting from the left for channels 1 and 2 respectively. Each square is spotted in colour to identify its usage condition. In the figure, blue mark which is emphasized by adding triangular mark for black-and-white print. red mark emphasized by circle and yellow mark emphasized by square, green mark without emphasized mark denote 'own ship's usage', 'missing by garble' and 'conflicted, but received larger power' and 'other ships' usage' respectively. It animates according to the simulation and at a glance it is very easy to understand the slot usage condition.

On the one hand, Navigation status window is the tool which enables to evaluate the communication situation in the whole gaming area. A sample Navigation Status Window is shown in Fig.4. In the picture each dot is coloured according to its communication status and in this case, we can find the conflict area is concentrating in the middle of Tokyo Bay.

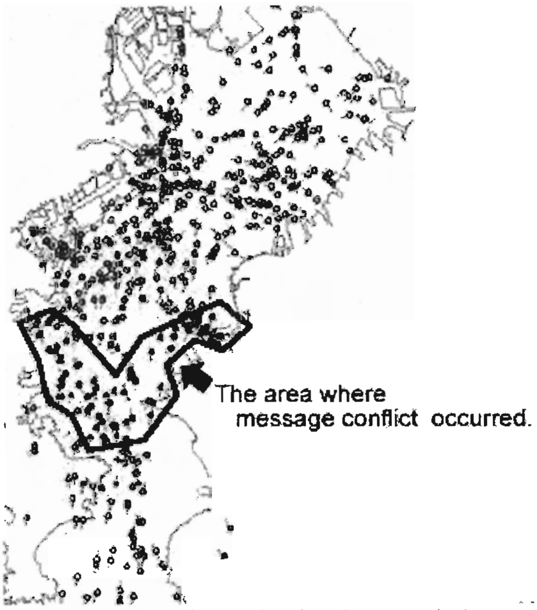

Fig.4 A sample Navigation Status Window

V. Evaluation of AIS System by Simulation

A. Evaluation Method

Tokyo Bay is one of the most congested areas in the world. It is valuable if we evaluate the AIS communication in this area, discussing several matters, such as how many conflicts and garbles may occur, what is the influence of the traffic density or navigational instructions or any other alterations. The installation of Class B AIS is also under consideration in this area. There are many points to be discussed before installation, such as "which type of protocol is most suitable?" and "up to which size of ships to be applied?". To answer these questions, AIS Simulator will play an important role. We have applied these problems for Tokyo Bay.

The simulation conditions are shown in Table 2. Main points are tonnage regulation and protocols to be applied for Class B AIS.

To reduce redundancy due to randomness of traffic flow, 24 hour simulation was executed 3 times. Statistical effectiveness is thus confirmed and mean and maximum values are used for the evaluation.

Table 2 Simulated conditions of AIS

<table>
<tr><th>Gross tonnage</th><th>Case1</th><th>Case2</th><th>Case3</th><th>Case4</th><th>Case5</th></tr>
<tr><td>5~300</td><td rowspan="2">non</td><td>non</td><td rowspan="2">Class B (CSTDMA)</td><td>Class B (CSTDMA)</td><td>Class B (SOTDMA)</td></tr>
<tr><td>300~500</td><td rowspan="6">Class A</td><td rowspan="6">Class A</td><td rowspan="6">Class A</td></tr>
<tr><td>500~1,000</td><td rowspan="5">Class A</td><td rowspan="5">Class A</td></tr>
<tr><td>1,000~3,000</td></tr>
<tr><td>3,000~6,000</td></tr>
<tr><td>6,000~10,000</td></tr>
<tr><td>10,000~</td></tr>
</table>

B. Evaluation of Communication Capacity

The communication capacity is evaluated in order to inspect whether it afford to the future increase of traffic density or new services through AIS. It is evaluated by the slot usage rate for each case as shown in Fig. 5.

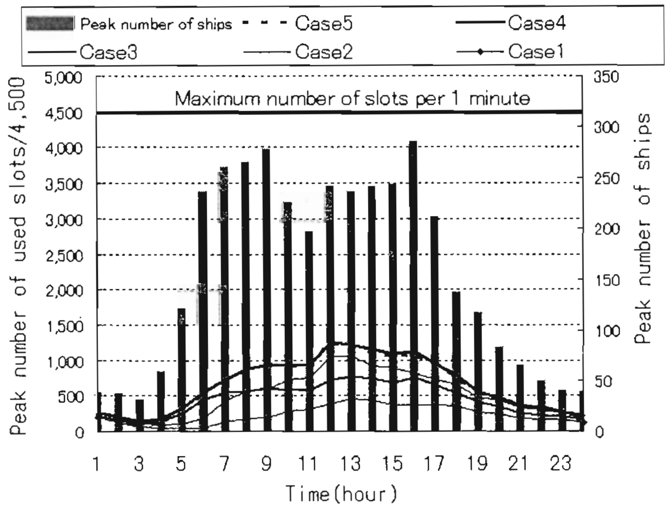

Fig. 5 Slot usage rate and the number of ships

The maximum capacity of slots which can be used per 1 minute is 4500 which is illustrated by the straight line in the top of the figure. Regarding the value in the bar chart, which represents the maximum of the ships existing simultaneously to the area every single hour, it is said that the busiest time in Tokyo Bay is in the morning and in the evening and it is between 200 and 300 and that it is somewhat proportional to the maximum number of used slots. However, it is not proportional, so that we cannot estimate the maximum capacity of AIS transmission just only from the number of ships. It is one of important conclusions and the necessity of AIS Simulator is confirmed.

Regarding the maximum number of used slots, it is about 1,300 or approximately 1/3 of its maximum capacity even in the hardest cases 4 and 5. So we can conclude it will correspond to the future increase of the traffic density and/or new services.

C. Evaluation of Garble Rate

In order to investigate the influence of garble rate due to the number of ships or AIS installation conditions, it is illustrated based on the number of ships servicing AIS transmission for Cases 3, 4 and 5 as shown in Fig 6.

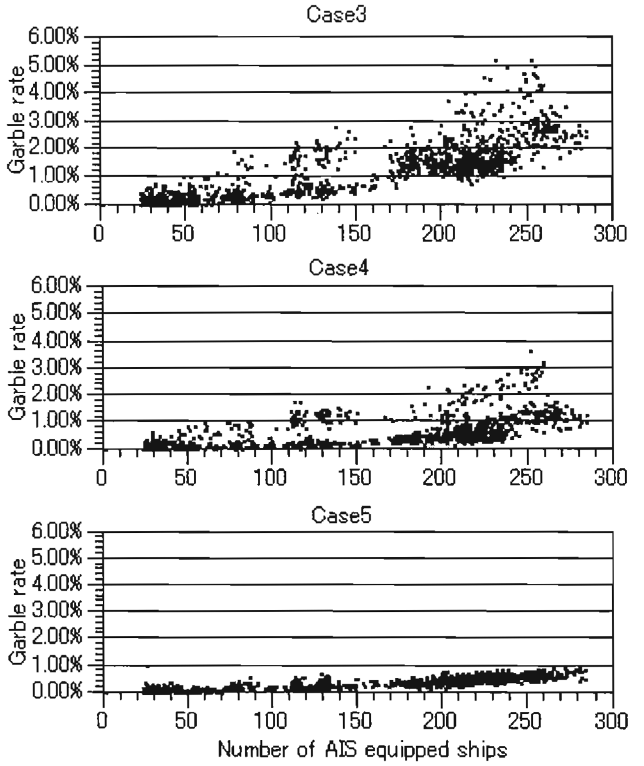

Fig. 6 Garble rate versus number of AIS equipped ships

Roughly speaking, the garble rate is proportional to the number of ships for every case. However, for Cases 3 and 4 which use CSTDMA for message transmission for Class B AIS, this tendency is remarkable. In case of CSTDMA protocol, it is expected that the collision of a message may easily occur and this interference increases according to the increase of ships, because in this protocol transmission will be done without reserving the next slot, while in case of SOTDMA, it reserves the next slot. It is strongly recommended to apply SOTDMA for Class B AIS protocol in the case of an area with a large number of ships..

On the other hand, the results for Cases 1 and 2 are omitted, because most of the messages are successfully transmitted. If only Class A is considered, there is no big difference in garble rate independent of the tonnage regulation. It, however, should be noticed that this conclusion is strongly related to Japanese domestic ship tax system. The most Japanese domestic ships are around but less than 500 tons due to the tax system, so even if the tonnage regulation may drop to 300 tons, small number of ships will be affected..

D. Evaluation of Un-transmitted Rate

Un-transmitted rate is investigated choosing one Class A AIS-equipped ship and one Class B AIS-equipped ship. These ships were chosen so that they appear as long time as possible between 10:00-14:00 moving northbound in the simulation. In Figure 7 the maximum value of un-transmitted rate in the 3 trials is shown for the distance from the subject ship. If the subject ship is equipped with Class B AIS, un-transmitted rate increases drastically (Cases 3 and 4). This is the same tendency with the garble rate. On the other hand, if the subject ship is equipped with Class A AIS, almost 100% transmission is successfully done within 15nm, while the increase of the un-transmitted rate is observed for ships exceeding 25 nm from the subject ship. However, for all cases, as the maximum un-transmitted rate is 2.0% or less, it is evaluated that no severe situation for the un-transmitted rate may occur.

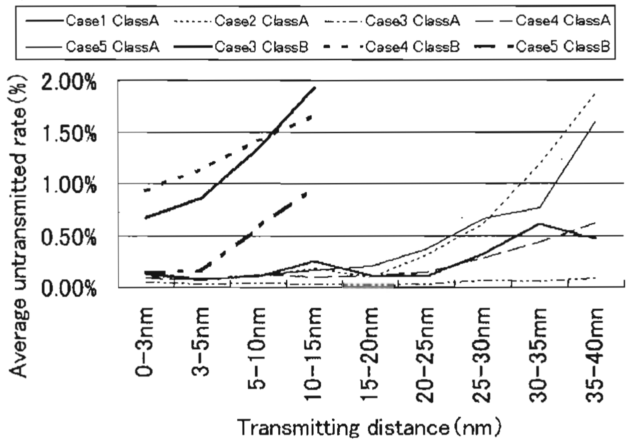

Fig.7 Relation between average un-transmitted rate and transmitting distance

Figures 8 and 9 show the un-transmitted rate versus the number of AIS equipped ships within the reachable range for Class A and Class B respectively. The result was analyzed from the simulation of Case 3.

In Fig. 8, it is found that 170- 240 ships exist in the Class A AIS reachable range, but the un-transmitted rate is quite low. On the other hand, in the case of Class B as shown in Fig.9, the un-transmitted rate reaches over 20% and below 50%, independent of the number of ships. The message recording the highest un-transmitted rate is 46% (62 ships) out of 134 ships existed. However, the frequency of the message whose un-transmitted rate exceeds 20% is only 3 % of all messages and considering from the result of Fig.7, it can be concluded that there is severe risk of introducing Class B AIS in Tokyo Bay or at the equivalent traffic condition.

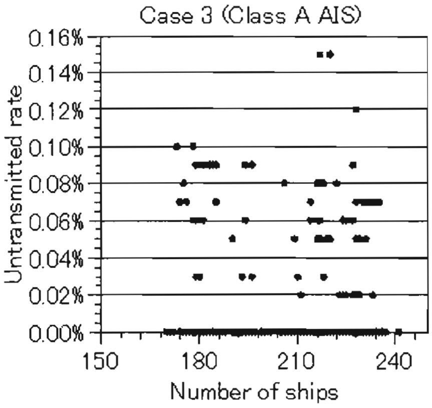

Fig. 8 Relation between un-transmitted rate and number of AIS equipped ships reachable from a specified ship equipped Class A AIS (Case3)

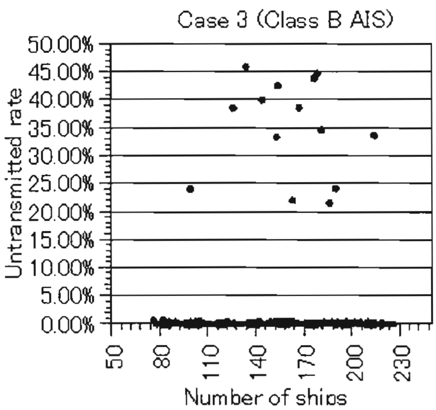

Fig. 9 Relation between un-transmitted rate and number of AIS equipped ships reachable from a specified ship equipped Class B AIS (Case3)

VI. Conclusions

AIS Simulator which simulates the AIS communication in the congested sea area was developed. Using AIS Simulator, evaluation of the communication capacity of AIS was successfully done.

AIS Simulator can simulates under any given navigation environments with easy visible outputs with Slot Map Window and Navigation Status Window. It can simulate varying AIS communication protocols or traffic conditions with several evaluation indices. An example of applying AIS Simulator is introduced for Tokyo Bay.

The main conclusions drawn in this paper are as follows:

(1) The largest occupation of slots in Tokyo Bay is 1,300 slots.

(2) The garble rate is roughly proportional to the number of ships and the distance between the sending and receiving ships. The un-transmitted rate becomes high for Class B AIS, but it is allowable level.

(3) Changing tonnage regulation of Class A AIS from up to 500 tons to up to 300 tons have no severe influence from the viewpoint of AIS communication capacity and unsuccessful transmission..

(4) It is discussed the superiority and the inferiority of SOTDMA and CSTDMA quantitatively when they are used as the communication protocol of Class B AIS. An important knowledge is provided for the future implementation.

Acknowledgment

The authors would like to acknowledge Eleni-Marina Asimakopoulou, IAESTE trainee from Greece and Shinpei Watanabe for their support to this research.

References

[1] K.Hasegawa, Some Recent Developments of Next Generation's Marine Traffic Systems , IFAC Conference on Computer Applications in Marine Systems (CAMS'04), Ancona, Italy, pp. 13-18 , 2004

[2] K.Hasegawa, K.Hata, M.Shioji, K.Niwa, S.Mori, H.Fukuda, Maritime Traffic Simulation in Congested Waterways and Its Applications , The 4th Conference for New Ship and Marine Technology (New S-Tech2004), Chine, pp.195-199 , 2004

[3] K.Hasegawa, K.Hata, M.Shioji, K.Niwa, S.Mori, H.Fukuda: Simulation-based Master plan Design and ITS Safety Assessment For Congested Waterways Management, The 2nd International Conference on Design for Safety, Japan, pp.265-270, 2004

[4] K.Hata, K.Hasegawa, K.Niwa: AIS Simulator, Journal of the Japan society of Naval architects and Ocean engineers. No.6, The Japan society of Naval architects and Ocean engineers, Japan, pp.91-98, 2007

[5] K.Hata, J.Fukuto, K.Hasegawa, K.Niwa : Evaluation of AIS communication using AIS Simulator, The journal of Japan Institute of Navigation. No.117, Japan Institute of Navigation, Japan, pp.27-33, 2007

[6] ITU: Technical characteristics for a universal shipborne automatic identification system using time division multiple access in the VHF maritime mobile band, ITU-R M.1371-1, ITU, 2001

[7] IEC: Maritime navigation and radiocommunication equipment and systems - Class B shipborne equipment of the automatic identification system (AIS) - Part 1: Carrier-sense time division multiple access (CSTDMA) techniques, IEC 62287-1 Ed.1, IEC, 2006