# Research on Detection Probability of Space-based AIS for Real Scenarios

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**Abstract — Research concerning the detection probability of space-based Automatic Identification System (AIS) currently is as a whole based on the hypothesis that within a satellite footprint area both the ship number and the message transmission time interval are uniformly distributed. Moreover, research results so far are constricted in theory whereas the real scenarios of ship traffic distribution are rarely considered. The paper introduces two statistics, i.e. the ship number in a single Self Organizing Time Division Multiple Access (SOTDMA) cell that follows the Poisson distribution and the AIS message transmission time interval that is highly determined by the type of waters ships are sailing, into the theoretical evolvement and simulation of detection probability. The research finds out that the ship number is the major contributing factor for the detection probability, together with that the scenarios that the separation techniques need to be considered. The separation is not always necessary because it is not all real scenarios that the AIS message received by the AIS-satellite must be the mixed signal. If the space-based AIS is only designed as a supplemental system for the extension of the existing coastal ship monitoring system, the message mixture will completely not occur.**

***Keywords - Ship monitoring; Space-based AIS; SOTDMA; Message mixture; Detection probability; Real scenarios***

## I. INTRODUCTION

The shipborne AIS is a marine navigational broadcasting system working on the Very High Frequency (VHF) radio spectrum for the information communication between ship to ship and ship to shore in real time. Upon the mandatory requirements of the International Convention on the Safety Of Life At Sea (SOLAS Convention), ships engaged on international voyages shall carry AIS terminals (known as Class A AIS equipment) nowadays. It is well recognized that AIS plays an extremely positive role in promoting the maritime safety and security since its introduction into the shipping industry. Moreover, by using the AIS shore-based stations network, the ship traffic along the coast can be effectively monitored. To achieve the surveillance of ships in a global and real-time manner, the space-based AIS has been widely researched recently. This is a system that the micro-size satellites carry AIS transceivers in the Low Earth Orbit (LEO) to directly capture the AIS messages sent from ships and transfer such to the shore station so that the global surveillance of maritime traffic is really achieved from the space.

To avoid the collision between messages transmitted by different shipborne AIS platforms without any organization of the base station, the communication protocol of SOTDMA that is designed for the coordination of the time slot usage in a given cell (a circular area with the radius of approximate 40nm) is applied. However, the footprint area from the AIS sensor installed on a LEO satellite covers a number of SOTDMA cells, there is no coordination scheme between these cells. AIS messages from different SOTDMA cells may simultaneously arrive at the satellite, resulting in the AIS messages mixture, which can lose the content of AIS message. Research concerning the probability that the satellite can correctly detect and decode the AIS message is the key prior work for the design of the whole system of space-based AIS and the determination of the algorithm for separating the mixed AIS messages.

## II. LITERATURE REVIEW

The main theoretical results for the detection probability of space-based AIS are well presented in [1], [2] and [3] provided that within the satellite footprint area both the ship number and the message transmission time interval are uniformly distributed. The further research has been conducted in [4] by using the Full Probability Theorem. With respects of the distribution of message number in a time slot, [5] demonstrates the additional result by using Binomial distribution whereas [6] and [7] use the Poisson distribution. [8] generates the results of the detection probability via different types of satellite antennas for various waters based on the Poisson distribution and the given message transmission time interval. However, the current research concerning the detection probability is as a whole based on the hypothesis that within the satellite footprint area both the ship number and the message transmission time interval are uniformly distributed, i.e. the ship numbers in each SOTDMA cell are completely equal each other and all ships transmit the messages in a totally same time interval. Moreover, research results so far are constricted in theory whereas the real scenarios of ship traffic distribution are rarely taken into account.

Consequently, apart from Section 1 and Section 2 regarding the introduction and the general research review, respectively, the paper is organized as follows: Section 3 simply outlines the basic shipborne AIS technical characteristics; Section 4 introduces in greater details the type and the reason of AIS message mixture; Section 5 focuses upon the theoretical evolvement of detection probability based on considering two statistics, i.e. the ship number in a single SOTDMA cell that follows the Poisson distribution and the message transmission time interval that is highly determined by the waters ships are sailing. Section 6 covers the simulation results and the corresponding analysis for various real scenarios of ship's traffic distribution followed by the conclusion summarized in Section 7.

## III. AIS TECHNICAL CHARACTERISTICS

The SOTDMA specifies that one-minute, also referred to as one frame, is divided into 2250 slots for each of two designated VHF channels to alternatively transmit but simultaneously receive AIS messages.

TABLE I. CLASS A AIS EQUIPMENT TECHNICAL CHARACTERISTICS PARAMETER

| Parameter | Characteristics standard |
|---|---|
| Baseband | 161.975MHz, 162.025MHz |
| Wavelength | 1.85m (162MHz) |
| Transmitter power | 12.5W(by default), 1W |
| Bandwidth | 25.0kHz |
| Data encoding | Non return zero inverted (NRZI) |
| Modulation | GMSK/FM |
| Modulation index | 0.5 |
| Transmit Bandwidth-Time product | 0.4 |
| Receive Bandwidth-Time product | 0.5 |
| Bit rate | 9600bits/s ± 50ppm |
| Frame length | 1min |
| Slot length | 26.7ms(256bits) |
| Capacity | 4500 slots/min |
| Receiver sensitivity | -107 dBm |

Each time slot is then equal to 26.67ms long for 256-bit message communication. AIS automatically and autonomously determines the slots unused to transmit its messages at the rate of 9600bits/s using a binary Gaussian filtered Minimum Shift Keying/Frequency Modulation (GMSK/FM) and meanwhile reserves other slots for next message transmission. Multiple slots for the transmission of the longer AIS message are also allowed. The SOTDMA scheme that requires AIS to reserve their transmission slots ahead of time is able to ensure that AIS messages are not transmitted at the same time slots within a SOTDMA cell. The detailed technical characteristics for the Class A AIS equipment are listed in Table I. [9].

AIS message data transfer uses a bit-oriented protocol based on the High-level Data Link Control (HDLC). The transmission packet with the total length of default packet is 256 bits equivalent to one slot including seven parts shown in Fig. (1). In the buffer part, the distance delay with 12 bits long equivalent to 202.16nm is reserved for avoiding AIS messages collisions within a SOTDMA cell due to the different signal path lengths, i.e. in theory the SOTDMA protocol provides the Class A AIS equipment with the protection for the difference of a propagation range up to 202.16nm.

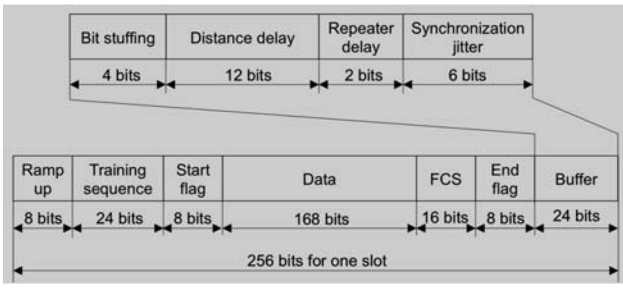


Fig.1 AIS Message Buffer Structure [9]

## IV. SPACE-BASED AIS MESSAGE MIXTURE

The space-based AIS message mixture is depicted as the satellite simultaneously receives two or more messages transmitted from ships within the same time period and among these messages are totally or partially overlapped. There are two different types of space-based AIS message mixture: the message mixture in the same slot ("the same slot mixture") and the message mixture in the adjunct slots ("the adjunct slots mixture").

### A. *Message Mixture in the Same Slot*

The message mixture in the same slot takes place while the satellite simultaneously receives two or more complete AIS messages transmitted from ships in a time slot. The total overlapping will occur in this type of mixture. Reasons for this type of mixture are twofold: 1) ships located in different positions have the same distances with the same satellite and transmit the same AIS message at the same time, see Ship A and B in Fig. (2); 2) ships located in different positions have the different distances with the same satellite and transmit the same AIS message at the different time, but the messages arrive at the same satellite at the same time due to the distance difference, see Ship C and D in Fig. (2).

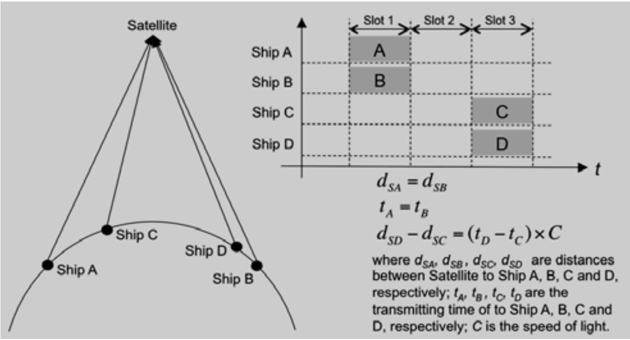

Fig. 2 Message Mixture in the Same Slot

### B. *Message Mixture in the Adjunct Slots*

The message mixture in the adjunct slots takes place while the satellite simultaneously receives two or more complete AIS messages transmitted from ships in two adjunct time slots. The partial overlapping will occur in this type of mixture. Reasons for this type of mixture are also twofold: 1) ships located in different positions have the same distances with the same satellite and transmit the same AIS message at the same time, but the differences of transmission time range from the allowed delay time period (i.e. 12 bits long) to a slot time period, see Ship A and B in Fig. (3); 2) ships located in different positions have the different distances with the same satellite and transmit the same AIS message at the same time, but the time period differences that messages arrive at the same satellite range from the allowed delay time period to a slot time period due to the distance difference, see Ship C and D in Fig. (3).

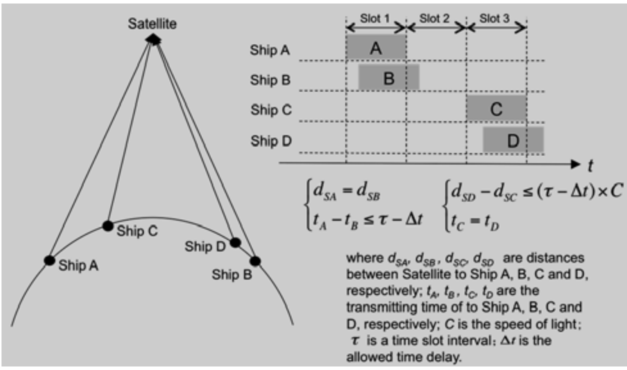

Fig. 3 Message Mixture in the Adjunct Slots

## V. DETECTION PROBABILITY FOR SPACE-BASED AIS

The detection probability for space-based AIS is a probability that within a satellite observation time period, the satellite can correctly detect the AIS messages sent from all ships monitored in its footprint area, namely within this observation time period, the probability that all AIS messages do not conflict. Obviously, this detection probability includes the probability that neither the same slot mixture nor the adjunct slots mixture occurs. As both types of message mixture can be considered as two independent events, the detection probability for space-based AIS can be presented as:

$$P = P_S \times P_A \tag{1}$$

where $P_S$ is the probability that no same slot mixture occurs, $P_A$ is the probability that no adjunct slots mixture occurs.

Practically, the satellite system can be regarded as an effective and reliable surveillance system for monitoring ship traffic provided that the detection probability is not less than 99%.

### A. *Probability That No Same Slot Mixture Occurs*

#### 1) *Probability Based on Uniform Distribution*

Suppose there are totally $N$ ships within an observation time of an AIS-satellite, then in a SOTDMA cell, the average number of transmitting message in the same time slot by using the same channel, $\lambda$, can be calculated as:

$$\lambda = \frac{N\tau}{n_C T} \tag{2}$$

where $n_C$ is the AIS channel number, $\tau$ is the time length of a slot, $T$ is the time interval of message transmission.

As ships transmit the AIS message at random, the message number received in the same slot by the same channel approximately follows the Poisson distribution, then the probability that the AIS-satellite can simultaneously receive $x$ messages in the same slot is:

$$P(x) = \exp(-\lambda)\frac{\lambda^x}{x!} \tag{3}$$

So in this slot, the probability that no same slot mixture occurs is:

$$P_m = 1 - \sum_{x=2}^{m} P(x) = P(0) + P(1) = (1+\lambda)\exp(-\lambda) \tag{4}$$

Then, within an observation time of an AIS-satellite $T_{obs}$, the number of AIS message sent by ships are $T_{obs}/T$ in total, resulting in the probability that all these messages which the same slot mixture does not occur is:

$$P_{obs} = 1 - (1 - P_m)^{\frac{T_{obs}}{T}} \tag{5}$$

Thus, the probability that no same slot mixture occurs in theory is the function of the observation time of an AIS-satellite $T_{obs}$, ship number $N$ and message transmission time interval $T$. For a specific space-based AIS, $T_{obs}$ is constant.

So the probability that no same slot mixture occurs is mainly related to the ship number $N$ and message transmission time interval $T$. It is apparent that the probability that no same slot mixture occurs declines as the ship number rises and message transmission time interval becomes quicker. Fig. 4 shows that under the conditions of $T_{obs}=300s$ and the detection probability being 99%, compared to those of $T=6s$ and $T=10s$, the number of the ship that can be correctly detected by the AIS-satellite as $T=2s$ is much lesser.

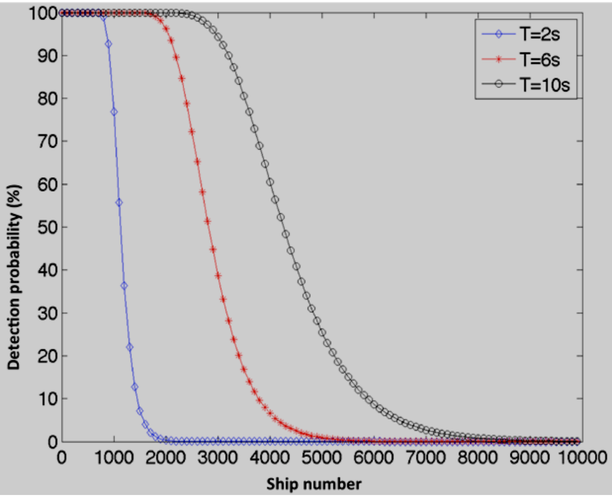


Fig. 4 Detection Probability vs. Ship Number and Message Transmission Time Interval

Again, Formula (5) is derived from two hypotheses that each SOTDMA cell has the same number of ships and all AIS messages are sent in a same time interval. However, the distribution of ship number and message transmission time interval in the real case may be far from these hypotheses. To enable the detection probability for the space-based AIS to be consistent with the real case as closer as possible, the distribution for ship number and message transmission time interval in the real case shall hence be considered in details.

*2) Distribution of Ship Number*

The ship number in total is highly related to the number of SOTDMA cell within an observation time and the ship number in each SOTDMA cell. Nonetheless, the ship number of each SOTDMA cell is closely determined by the type of waters in which this SOTDMA cell is located. For example, ships in a SOTDMA cell located in the port waters are much more than those in a SOTDMA cell located in the coast waters or the ocean waters. But the ship number in a SOTDMA cell approximately follows the Poisson distribution no matter in which type of waters this SOTDMA cell is located. Thus, the ship number in total within an observation time can be expressed as:

$$N(L,K,n)=\sum_{i=1}^{l}\sum_{j=1}^{k}POISS_{ij}(n_i) \tag{6}$$

where, $L$ is the number of type of waters within an observation time, $K$ is the number of SOTDMA cells in each type of waters, $POISS_{ij}(n_i)$ is the ship number which follows Poisson distribution for the No. $j$th SOTDMA cell located in the No. $i$th type of waters, $n_i$ is the average number of ships for all SOTDMA cells located in $i$th type of waters.

*3) Analysis of Message Transmission Time Interval*

The AIS message transmission time interval is associated with the ship navigational status, speed and course and can be summarized as [9]:

$$T(\Theta,V,ROT)=\begin{cases}180s,\Theta=at\ \ anchor;\\ 10s,0\le V\le 14kn\ \ and\ \ ROT=0;\\ 3.33s,0\le V\le 23kn\ \ and\ \ ROT\ne 0;\\ 6s,14\le V\le 23kn\ \ and\ \ ROT=0;\\ 2s,14\le V\le 23kn\ \ and\ \ ROT\ne 0;\\ 2s,V>23kn\ \ and\ \ ROT=0;\\ 2s,V>23kn\ \ and\ \ ROT\ne 0;\end{cases} \tag{7}$$

where $\Theta$ is ship navigational status, $V$ is the ship speed and $ROT$ is ship rate of turning.

Suppose the message transmission time interval for each SOTDMA cell is identical, so the message transmission time interval for the SOTDMA cells within a satellite observation time in practice can be determined via Formula (7) and the type of waters in which the SOTDMA cells are located. In general, if the SOTDMA cells within an observation time are located in different types of waters, then the AIS message transmission time interval within an observation time can be written as:

$$T(p,i)=\sum_{i=1}^{L}p_iT_i \tag{8}$$

where $L$ is the number of type of waters within an observation time, $p_i$ is the proportion of the No. $i$th types of waters within the footprint area, $T_i$ is the AIS message transmission time interval for the SOTDMA cell located in the No. $i$th type of waters.

So by considering Formula (5), (6) and (8), the general Formula for expressing the probability that all AIS messages which the same slot mixture does not occur within an observation time can be rewritten as:

$$P_S=1-(1-(1+\frac{N(L,K,n)\tau}{n_CT(p,i)})\exp(-\frac{N(L,K,n)\tau}{n_CT(p,i)}))^{\frac{T_{obs}}{T(p,i)}} \tag{9}$$

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### B. *Probability that No Adjunct Slots Mixture Occurs*

The overlapping factor $s$ need be introduced for researching the probability that no message mixture in the adjunct slots occurs. The overlapping factor $s$ is defined as the ratio between the probability that the adjunct slots mixture occurs to the probability that the same slot mixture occurs. [10] illustrates that the overlapping factor $s$ is the function of the altitude of satellite orbit and $s=0.7$ as the satellite is orbiting at 600-1000km high.

Thus, the detection probability of the space-based AIS while considering the probability that both types of message mixture occurs can be generated as:

$$P_S = 1-(1-(1+\frac{N(L,K,n)\tau(1+s)}{n_C T(p,i)})\exp(-\frac{N(L,K,n)\tau(1+s)}{n_C T(p,i)}))^{\frac{T_{obs}}{T(p,i)}} \quad (10)$$

## VI. SIMULATION AND ANALYSIS

To demonstrate the detection probability of space-based AIS in real scenarios, the simulation parameters are initialized in Table II.

TABLE II. INITIALIZED SIMULATION PARAMETERS

| Parameter | Value |
|---|---|
| Satellite orbital altitude | 600km |
| Satellite antenna type | Omnidirectional |
| Satellite observation time | 300s |
| Radius of a SOTDMA cell | 40nm |
| Waters types | Ocean waters (100nm far from coastal line)<br>Coast waters (10-100nm from coastal line)<br>Port waters (0-10nm from coastal line) |
| Simulation number | 1000 for each scenario |
| Average number of ships | 3 for a SOTDMA located in ocean waters<br>20 for a SOTDMA located in coast waters<br>300 for a SOTDMA located in port waters |

Theoretically, the maximum radius of footprint area for a 600km-altitude-satellite is about 1437nm, which is able to cover about 1290 SOTDMA cells. As stated in Section 3, the distance delay with 12 bits long is reserved, which ensures that the AIS message collisions can be avoided if the different signal path lengths of these messages are less than 202nm. For a 600km-altitude-satellite, the maximum radius of its footprint area can only be about 400nm provided that the different signal path lengths of any two messages within this footprint area of this satellite are not more than 202nm [11]. Thus, for a 600km-altitude-satellite, only the same slot mixture possibly occurs if the maximum radius of its footprint area is designed as being 400nm. In the following simulations, the maximum radius of the satellite footprint area is set as being 400nm for the scenario that only the same slot mixture is considered, whereas being 1437nm for the scenario that both types of message mixture are considered.

### A. *Single Type of Waters in Footprint Area*

For the scenario that only the same slot mixture is considered, if the satellite footprint area only covers ocean waters or coast waters, the detection probability can be 100%, i.e. no message collisions occur, see Fig. (5). However, if the satellite footprint area only covers port waters, although the AIS transmission time interval becomes shorter, the detection probability is less than 10% due to the sharp increase of the ship number, which indicates that the ship number has a greater impact on the detection probability as opposed to the message transmission time interval.

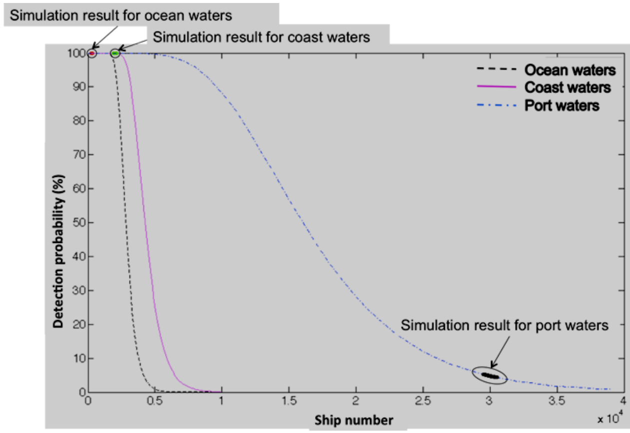


Fig. 5 Detection Probability of Same Slot Mixture for Single Type of Waters

For the scenario that both types of message mixture are considered, if the satellite footprint area only covers ocean waters, the detection probability can be 100%, i.e. no message collisions occur, see Fig. (6). But if the satellite footprint area only covers coast waters, the increase of the ship number causes the reduction of the detection probability to be less than 93% despite the faster AIS transmission. Even worse, if the satellite footprint area only covers port waters, the detection probability is 0%, i.e. all AIS messages received by the satellite are mixed.

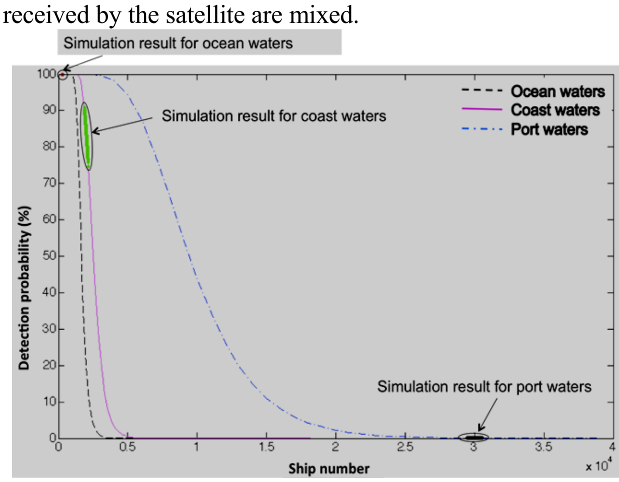


Fig. 6 Detection Probability of Both Types of Mixture for Single Type of Waters

*B. Mixed Types of Waters in Footprint Area*

*1) Mixed Type of Ocean and Coast waters*

The ratio between ocean waters and coast waters within the satellite footprint area is selected in 9 situations: 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8 and 1:9. For the scenario that only the same slot mixture is considered, if the satellite footprint area covers mixed type of ocean waters and coast waters, the detection probability can be 100% irrespective of the ratio between ocean waters and coast waters, i.e. no message collisions occur, see Fig. (7).

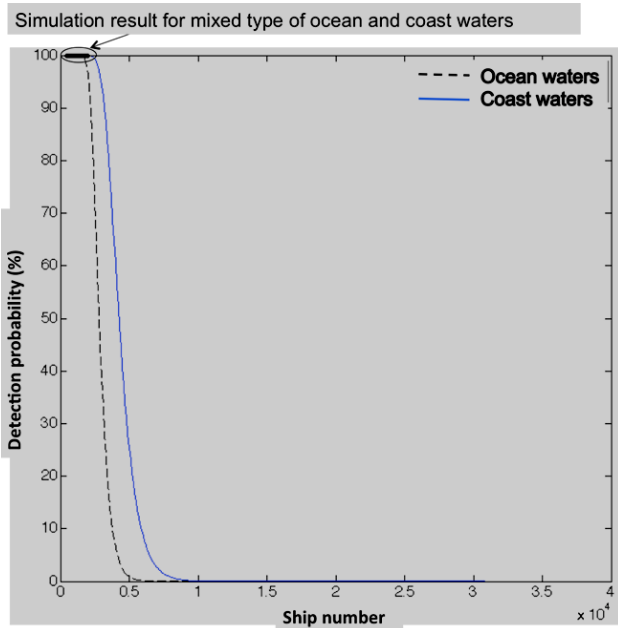


Fig.7 Detection Probability of Same Slot Mixture for Mixed Type of Ocean and Coast Waters

For the scenario that both types of message mixture are considered, if the ratio between ocean waters and coast waters ranges from 9:1 to 6:4, the detection probability can be 100%, i.e. no message collisions occur, see Fig. (8). However, the detection probability can only be 80%-99% if the ratio between ocean waters and coast waters ranges from 5:5 to 1:9, which indicates that the increase of the ship number that causes the reduction of the detection probability has a greater impact than the slower message transmission that causes the increase of the detection probability.

*2) Mixed Type of Coast and Port Waters*

Similarly, the ratio between coast waters and port waters within the satellite footprint area is also selected in 9 situations: 9:1, 8:2, 7:3, 6:4, 5:5, 4:6, 3:7, 2:8 and 1:9. No matter in the scenario that only the same slot mixture is considered or in the scenario that both types of message mixture are considered, the detection probability declines as the portion of port waters increases regardless the ratio between coast waters and port waters, see Fig. (9) and (10). Moreover, the detection probability for the scenario that both types of message mixture are considered has a greater reduction compared to that for the scenario that only the same slot mixture is considered, i.e. 0%-21% vs. 23%-95%, which indicates that the increase of the ship number that causes the reduction of the detection probability has a greater impact than the slower message transmission that causes the increase of the detection probability.

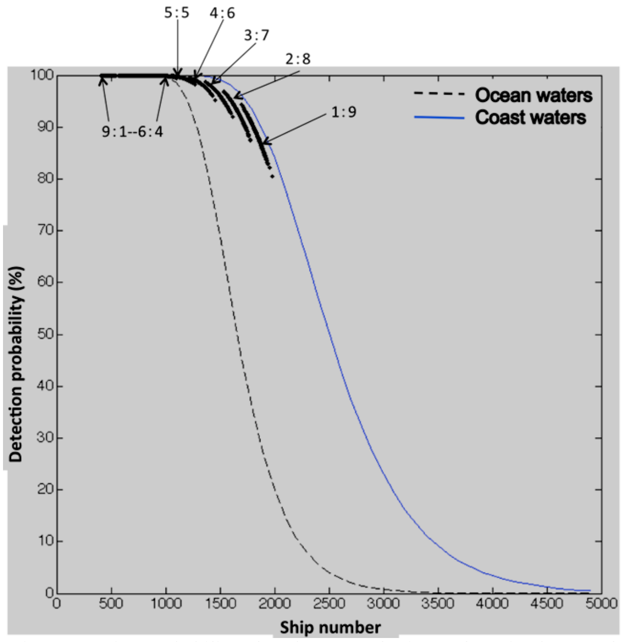


Fig.8 Detection Probability of Both Types of Mixture for Mixed Type of Ocean and Coast Waters

*3) Mixed Type of Ocean, Coast and Port Waters*

The ratio among ocean, coast waters and port waters within the satellite footprint area is also selected in 9 situations: 9:0.5:0.5, 8:1:1, 7:1:2, 5:2:3, 3:3:4, 2:3:5, 1:3:6, 1:1:8 and 0.5:0.5:9. No matter in the scenario that only the same slot mixture is considered or in the scenario that both types of message mixture are considered, the detection probability goes down as the portion of coast and port waters increases regardless the ratio among three types of waters, see Fig. (11) and (12).

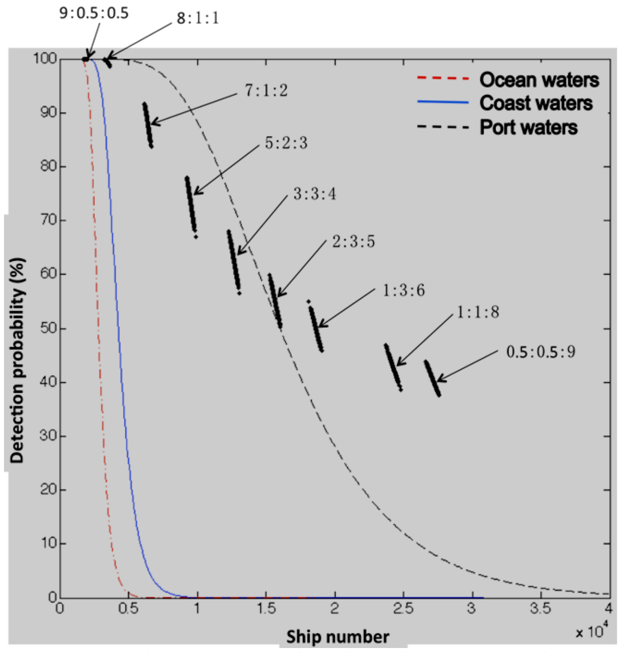


Fig.9 Detection Probability of Same Slot Mixture for Mixed Type of Coast and Port Waters

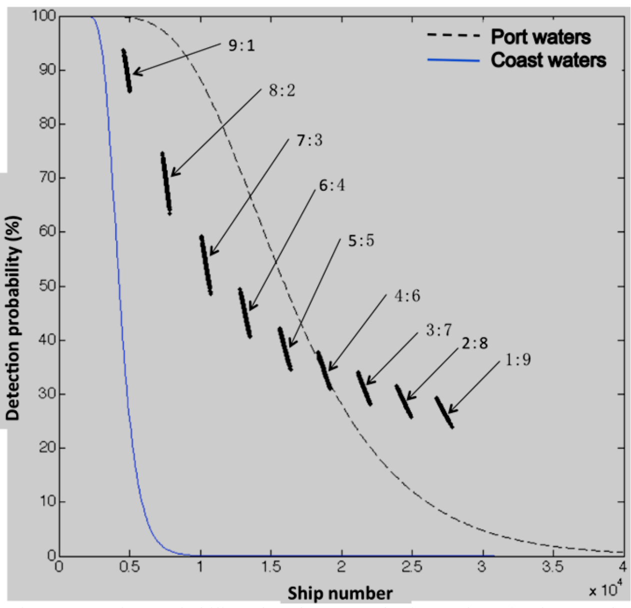


Fig.10 Detection Probability of Both Types of Mixture for Mixed Type of Ocean and Coast Waters

Moreover, the detection probability for the scenario that both types of message mixture are considered has a greater reduction compared to that for the scenario that only the same slot mixture is considered. In most situations, the detection probability is less than 99% except the situation that the ratio among three types of waters is 9:0.5:0.5 for the scenario that only the same slot mixture is considered. Similar to the aforementioned simulations, the increase of the ship number that causes the reduction of the detection probability has a greater impact than the slower message transmission that causes the increase of the detection probability.

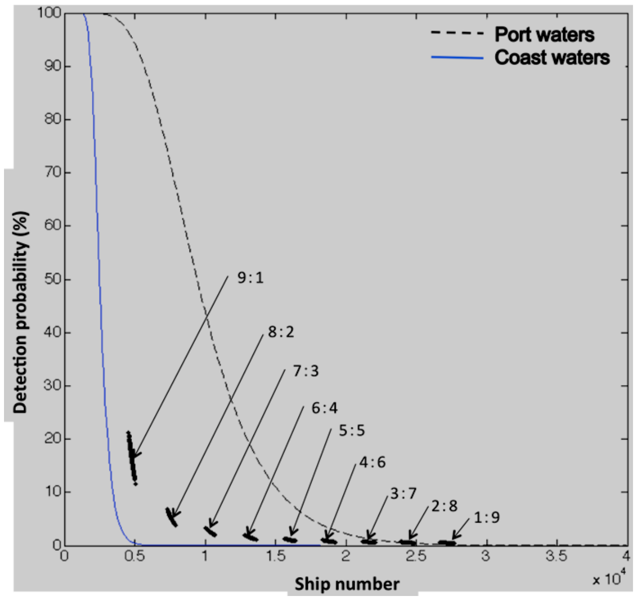


Fig.11 Detection Probability of Same Slot Mixture for Mixed Type of Ocean

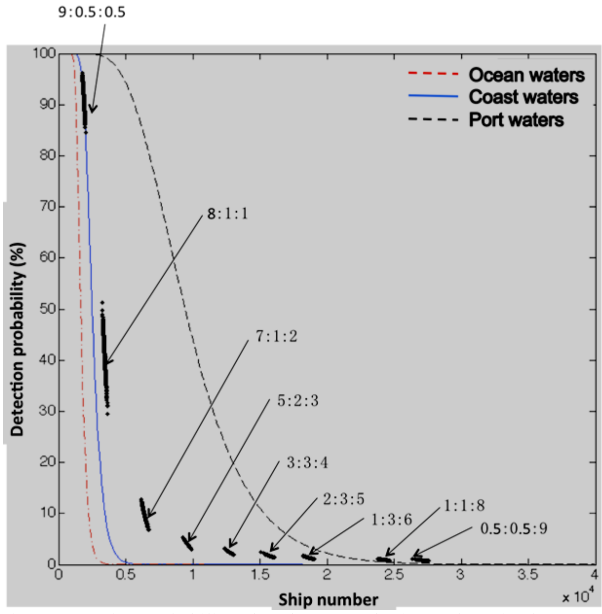


Fig.12 Detection Probability of Both Types of Mixture for Mixed Type of Ocean, Coast and Port Waters

## C. *Summary*

In a word, while considering the combination of the type of waters within the satellite footprint area and the type of message mixture, the detection probability of the space-based AIS in various real scenarios based on the simulation and the relevant remarks on the further separation considerations can be summarized in Table III.

TABLE III. DETECTİON PROBABİLİTY OF SPACE-BASED AIS İN VARİOUS REAL SCENARİOS

| Types of Waters Covered in Satellite Footprint Area | | Type of Message Mixture | Detection Probability | Remarks |
|---|---|---|---|---|
| Single type of waters | Ocean waters | Only message mixture in the same slot | 100% | No need to consider the mixed message separation |
| | | Both types of message mixture | 100% | No need to consider the mixed message separation |
| | Coast waters | Only message mixture in the same slot | 100% | No need to consider the mixed message separation |
| | | Both types of message mixture | <93% | Need to consider the mixed message separation |
| | Port waters | Only message mixture in the same slot | <10% | Need to consider the mixed message separation |
| | | Both types of message mixture | 0% | Need to consider the mixed message separation |
| Mixed type of waters | Ocean and coast waters | Only message mixture in the same slot | 100% | No need to consider the mixed message separation |
| | | Both types of message mixture | 100% | No need to consider the mixed message separation while waters ratio is 9:1-6:4 |
| | | | 80%-99% | Need to consider the mixed message separation while waters ratio is 5:5-1:9 |
| | Coast and port waters | Only message mixture in the same slot | 23%-95% | Need to consider the mixed message separation |
| | | Both types of message mixture | 0%-21% | Need to consider the mixed message separation |
| | Ocean, coast and port waters | Only message mixture in the same slot | 99% | No need to consider the mixed message separation while waters ratio is not more than 8:1:1 |
| | | | 38%-92% | Need to consider the mixed message separation while waters ratio is more than 8:1:1 |
| | | Only message mixture in the same slot | 0%-96% | Need to consider the mixed message separation |

## VI. CONCLUSION

Since the footprint area of the space-based AIS covers a large number of SOTDMA cells, the AIS messages received by an AIS-satellite will possibly be mixed, which can cause the loss of information content if no separation methods are further used. The ship number within the satellite observation time is the major contributing factor for the detection probability. But in practice, it is not all scenarios that the AIS message received by the space-based AIS is the mixed signal. For instance, if the space-based AIS is designed as a supplemental system for the extension of the existing coastal ship monitoring system which the AIS shore-based stations network is used, namely the space-based AIS is only used to monitor ships sailing in the ocean waters, the detection probability can be 100%, i.e. there is no need to further use the appropriate methods to separate the mixed messages. Similarly, if the space-based AIS is designed only to focus on considering the message mixture in the same slot, then it can completely and correctly detect the AIS messages coming from the mixed type of ocean and coast waters. However, in most scenarios, the space-based AIS suffers from the serious phenomenon of mixed messages, *inter alia*, when the ships sailing at port waters or mixed waters of port and coast are monitored. Thus, it is quite necessary to further research the appropriate techniques to separate the mixed messages for the purpose of increasing the detection probability of the space-based AIS in various scenarios.

## CONFLICT OF INTEREST

The author confirms that this article content has no conflicts of interest.

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