Block-based Self-organizing TDMA for Reliable VDES in SANETs

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Abstract

This paper proposes a block-based self-organizing time-division multiple access (BSO-TDMA) protocol for very high frequency (VHF) data exchange system (VDES) in shipborne ad-hoc networks (SANETs). The BSO-TDMA reduces the collisions caused by the simultaneous transmission of automatic identification system (AIS) messages by uniformly allocating channel resources using a block-wise frame. For this purpose, the BSO-TDMA includes two functional operations: (1) frame configuration and (2) slot allocation. The first operation consists of block division and block selection. A frame is divided into multiple blocks, each consisting of fixed-size subblocks, by using the reporting interval (RI) of the ship. Then, the ship selects one of the subblocks within a block by considering the number of occupied slots for each subblock. The second operation allocates the slots within the selected subblock for transmitting AIS messages. First, one of the unoccupied slots within the selected subblock is allocated for the periodic transmission of position reports. Next, to transmit various types of AIS messages, an unoccupied slot is randomly selected from candidate slots located around the previously allocated slot. Experimental simulations are conducted to evaluate the performance of BSO-TDMA. The results show that BSO-TDMA has better performance than that of the existing SOTDMA.

Keywords: AIS, BSO-TDMA, maritime communications, SANET, VDES

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1. Introduction

The progress of maritime systems and maritime communication technology has led to the emergence of autonomous navigation systems that are capable of recognizing, managing, and operating in a ship's surroundings at sea [1–4]. In particular, as the number of ships, volume of international trade, and demand for various maritime services (e.g., maritime navigation, environmental protection, navigational safety, security, logistics, rescue, etc.) increase, autonomous navigation systems that enable the exchange and processing of various data between maritime stations (e.g., ships, shore stations, satellites, etc.) are receiving significant attention [5–7]. The very high frequency (VHF) data exchange system (VDES) supports data transmission and reception between maritime stations in the VHF frequency band, and therefore, it is currently being used for maritime communications and services.

VDES consists of three components: automatic identification system (AIS), application specific message (ASM), and VHF data exchange (VDE) [8–9]. VDES uses these components to support ship-to-ship, ship-to-shore, shore-to-ship, ship-to-satellite, and satellite-to-ship communications in maritime environments. AIS is a crucial component of VDES that broadcasts information such as identifiers, positions, speeds, and courses of ships for collision avoidance between ships [10–12]. ASM transmits and receives specific information related to maritime safety, course management, security, and the environment to support various maritime services [13]. VDE supports high-capacity data transmission in various formats that AIS and ASM cannot support by using VHF data exchange-terrestrial (VDE-TER) and VHF data exchange-satellite (VDE-SAT) components [14–16]. VDE-TER utilizes base stations placed near the coast, and VDE-SAT utilizes low-Earth orbit satellites. AISs exchange essential information for constructing a maritime network among themselves. Consequently, technologies to reliably support AISs are being widely discussed as a crucial issue in maritime communication.

In maritime communication utilizing AIS, networks are classified into infrastructure and ad-hoc networks depending on the use of fixed stations (i.e., shore stations and satellites) [17]. In an infrastructure network, centralized scheduling is performed by the fixed station for communication between maritime stations. When a fixed station is absent or when ship-to-ship connection is required, a shipborne ad-hoc network (SANET) can be established and utilized. In the SANET, each mobile station (i.e., ship) reserves channel resources for its own transmission through distributed scheduling. However, a SANET is difficult to establish because it lacks a control station and the ships are moving. Additionally, collisions may occur frequently because ships attempt to access channels according to their own schedules that take into account the surrounding environment. Therefore, for a SANET utilizing AIS, mechanisms for stable network establishment and conflict mitigation between messages transmitted are indispensable.

Self-organized time-division multiple access (SOTDMA) has been proposed in the AIS standard as a channel access scheme for AIS [18]. SOTDMA uses a medium access control (MAC) protocol based on time-division multiple access (TDMA), and it uses a frame structure comprising multiple slots of equal length. For channel resource allocation, SOTDMA randomly selects slots within the frame by considering the reporting interval (RI) of the mobile station. Consequently, it alleviates collisions that occur when adjacent mobile stations allocate the same slot to each other. However, if the number of neighbor mobile stations within the communication range increases or if neighbor mobile stations have numerous messages to transmit, the mobile station may face challenges in allocating channel resources owing to frequent collisions. To solve these problems, various MAC protocols have been proposed [19–

22]. In [19], a distributed MAC protocol based on reservation for ad hoc networks (DR-MAC) was proposed. DR-MAC uses a frame structure that consists of a control slot and multiple data slots. It allows ships to allocate dedicated data slots for data transmission by exchanging control packets (i.e., RTS, CTS, and ACK) in the control slot to prevent collisions. However, it cannot reduce collisions in control slots and requires the transmission of additional control packets, resulting in a significant overhead. In [20], an ad-hoc SOTDMA (ASO-TDMA) protocol for SANET was proposed. ASO-TDMA utilizes a frame structure consisting of multiple subframes. A ship using ASO-TDMA divides the maritime area into multiple hops according to the distance from the base station and selects the subframe corresponding to the hop to which it belongs. However, in ASO-TDMA, ships can only allocate slots within the subframe corresponding to their hop; therefore, significant collisions may occur when multiple ships exist in the same hop. Otherwise, channel utilization may decrease. To solve these problems of ASO-TDMA, enhanced ASO-TDMA (EASO-TDMA) was proposed [21]. EASO-TDMA mitigates collisions that may arise in ASO-TDMA by adaptively adjusting the subframe length based on the number of ships in the hop. However, in EASO-TDMA, a ship randomly selects slots within the corresponding subframe; therefore, even if multiple slots are available for allocation within the subframe, ships may select the same slot, resulting in collisions. In addition, the process of updating the subframe length and reallocating slots in EASO-TDMA has low effectiveness owing to the high implementation complexity. In [22], a feedback-based TDMA (FBTDMA) protocol was proposed to avoid transmission collisions when transmitting information between ships. FBTDMA uses an improved time slot structure of the AIS for feedback on all transmission collisions. The data field in the improved time slot structure is divided into three fields: state flag, message, and feedback. A ship that detects a collision when two or more ships attempt to reserve the slot marks the time slot in which the collision occurred as a collided time slot and records the identifier (ID) of the collided time slot in its VDES devices. Then, in the next frame, this ship broadcasts the message in its transmission slot by including the ID of the collided time slot from the previous frame in the feedback field. As a result, FBTDMA can alleviate transmission collisions in AIS. However, it generates additional overhead by adding the state flag and feedback fields to data packets.

To address the abovementioned issues, in this paper, we propose a block-based self-organizing time division multiple access (BSO-TDMA) protocol for VDES in SANETs. BSO-TDMA aims to reduce collisions by allowing ships to uniformly allocate slots within a frame. In BSO-TDMA, each ship performs channel resource allocation in the first frame after starting the network and in the next frame after changing its RI. To allocate channel resources, the ship sequentially conducts (1) frame configuration and (2) slot allocation. In frame configuration, the frame is first divided into multiple blocks consisting of fixed-size subblocks (i.e., block-wise frame) considering the RI of the ship. Then, the ship selects subblock in the first block based on the number of nominal start slots (NSSs) and nominal slots (NSs) already allocated to each subblock. NSS refers to the first NS, and NS represents a dedicated slot used by the ship to periodically notify neighbor ships of its location and voyage information. In slot allocation, the ship randomly selects one of the unoccupied slots within the selected subblock of the first block to allocate its NSS. Then, the ship searches for candidate slots within a specific interval around NSS and randomly selects an unoccupied slot from candidate slots to allocate a nominal transmission slot (NTS), that is used to transmit various types of AIS messages. In each NTS, the ship allocates NS and NTS for the next block until the end of the block-wise frame. To evaluate the superiority of BSO-TDMA, we performed experimental simulations and compared its performance with that of the existing SOTDMA. The results demonstrated that throughput, packet delivery rate (PDR), and average number of collisions of BSO-TDMA were 11.83%, 13.38%, and 37.07% better than those of the existing SOTDMA, respectively.

The rest of this paper is organized as follows. In Section 2, we present an overview of AIS and SOTDMA. In Section 3, the detailed operation of BSO-TDMA is described. Section 4 presents the simulation configuration and results. Finally, Section 5 presents the conclusions of this paper.

2. Background

2.1 Overview of AIS

In this section, we provide an overview of AIS as described in the AIS standard [18]. AIS is a key component of VDES that plays a vital role in preventing collisions between ships at sea and ensuring maritime safety. AIS allows marine stations to autonomously establish a maritime communication network by periodically broadcasting information that includes the maritime mobile service identity (MMSI), position, speed, course, and ship specification. In addition, it supports data transmission between maritime stations. **Fig. 1** shows the system architecture of the maritime communication network consisting of various maritime stations. In the maritime communication network, stations form an ad-hoc network or infrastructure network and exchange messages with each other by using AIS.

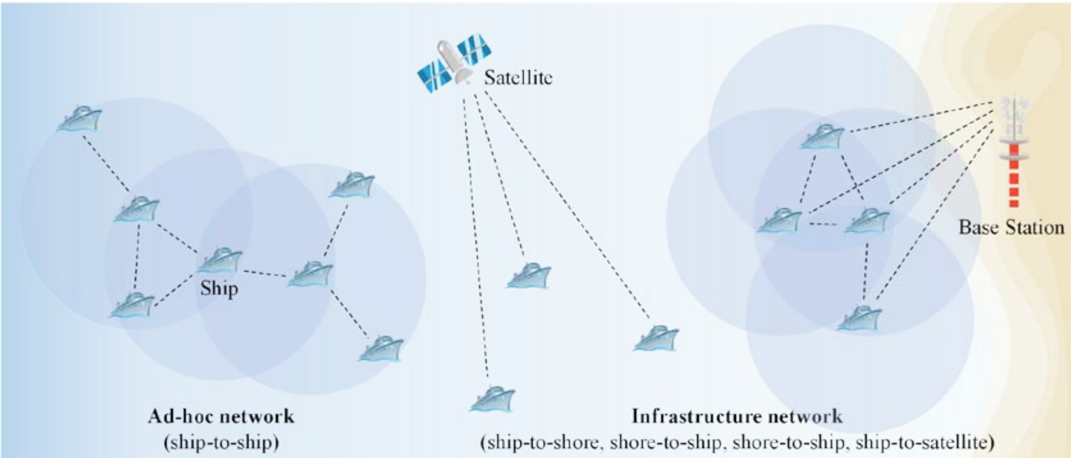


Fig. 1. System architecture of maritime communication network

AIS alternately uses two channels defined as AIS 1 (channel 87B, 161.975 MHz) and AIS 2 (channel 88B, 162.025 MHz) in the VHF maritime mobile band. For long-range AIS, channels 75 and 76 are used. AIS uses the frame structure for channel access, as shown in **Fig. 2**. A frame is equal to 60 seconds and it consists of 2250 slots of the same length. Accordingly, the length of each slot is 26.67 ms. Each slot in the frame is identified by its index (0–2249), and a maximum of 256 bits can be transmitted in each slot. For synchronization between stations, frames of each station are aligned with the coordinated universal time (UTC) minute boundary. Stations can access the channel at the beginning of the slot.

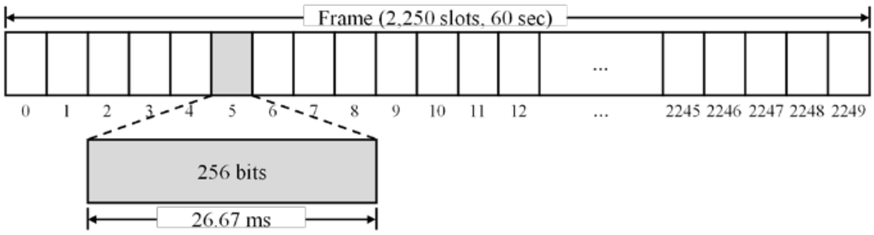


Fig. 2. Frame structure of AIS

In AIS, SOTDMA, random access TDMA (RATDMA), incremental TDMA (ITDMA), and fixed access TDMA (FATDMA) are used for slot allocation of stations. SOTDMA is used for slot allocation for scheduled repetitive transmissions. RATDMA is used to randomly allocate the first transmission slot of stations within a specific interval ahead in the first frame. ITDMA is used to temporarily change the transmission period of messages that must be transmitted periodically and to allocate slots for transmitting safety-related messages. FATDMA is only used for slot allocation for repetitive message transmission by the base station. These TDMA-based MAC protocols are used differently depending on the operation mode of the station. AIS supports three modes of operation: autonomous, assigned, and polled. The station operates in autonomous and continuous mode by default and determines its transmission schedule. The station operating in the assigned mode adjusts its transmission schedule by considering the slots allocated by the base station or competent authority. A station operating in the polled mode should not conflict with the operation of the other modes and should automatically respond to interrogation messages from other stations.

2.2 Channel Resource Allocation using SOTDMA

In AIS, ships perform channel resource allocation to periodically broadcast information (i.e., position report) including their position, speed, and course by using SOTDMA. Before joining the network, the ship determines the parameters (i.e., RI, report rate (Rr), nominal increment (NI), and selection interval (SI)) required for channel resource allocation and then performs channel monitoring for one minute. RI represents the time period in which the ship transmits its position, voyage, and safety-related messages. As shown in **Table 1**, RI varies depending on the ship's speed and course change (i.e., ship's dynamic conditions). Rr represents the number of position reports that should be transmitted within one frame. NI represents the interval between NSs. SI represents a collection of slots around each NS. Rr, NI, and SI are calculated by (1)–(3).

Table 1. Parameters related to ship's dynamic conditions

Ship's dynamic conditions	RI (sec)
Ship at anchor or moored and not moving faster than 3 knots	180
Ship at anchor or moored and moving faster than 3 knots	10
Ship moving at 0–14 knots	10
Ship moving at 0–14 knots and changing course	10/3
Ship moving at 14–23 knots	6
Ship moving at 14–23 knots and changing course	2
Ship moving at >23 knots	2
Ship moving at >23 knots and changing course	2

$$Rr = 60 / RI \quad (1)$$

$$NI = 2250 / Rr \quad (2)$$

$$SI = 0.2 \times NI \quad (3)$$

The ship constructs a frame map by reflecting information such as the existence of ships and base stations participating in the existing network and channel activity (i.e., slot allocation information) obtained through channel monitoring. The frame map includes slot usage information, indicating the allocated slots (NSS, NSs, and NTSs) within the frame for all adjacent stations (i.e., ships and base stations). After channel monitoring, the ship randomly selects a slot that is unoccupied from the front portion (0–149 slots) of the first frame to allocate the NSS, and then, it allocates the NTS by randomly selecting a slot within the SI centered around the NSS. Each NTS has a slot time-out that is randomly selected within the range of 3–7, and it decreases by 1 for each frame that elapses. The allocated NTS is maintained continuously for several frames until the slot time-out reaches 0, at which point a new NTS should be selected. For every NTS (i.e., current NTS), the ship allocates the next NTS corresponding to the next NS. Specifically, the ship randomly selects a slot within the SI centered around the next NS and allocates it as the next NTS. The ship updates its frame map whenever it allocates its NSS, NSs, and NTSs. **Fig. 3** shows an example of the frame map. In the figure, the patterned slots represent slots previously occupied by neighbor stations, and the shaded slots represent NSS, NSs, and NTSs allocated by the ship itself.

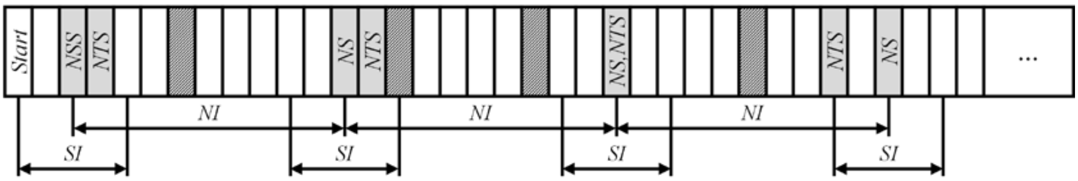


Fig. 3. Example of frame map

3. Design of BSO-TDMA

BSO-TDMA is designed to mitigate collisions in maritime communication using AIS by allowing ships to allocate different time slots within a frame. In BSO-TDMA, the ship performs channel monitoring for one minute before joining the network, and it constructs and maintains a frame map containing slot usage information of all neighbor stations within its communication range. For channel resource allocation, after the channel monitoring or whenever RI changes, the ship defines the frame as a block-wise frame that is logically divided into several blocks according to its RI. It also allocates slots (i.e., NSS, NS, and NTS) for message transmission based on the block information and frame map. Specifically, the ship sequentially conducts (1) frame configuration and (2) slot allocation to allocate channel resources.

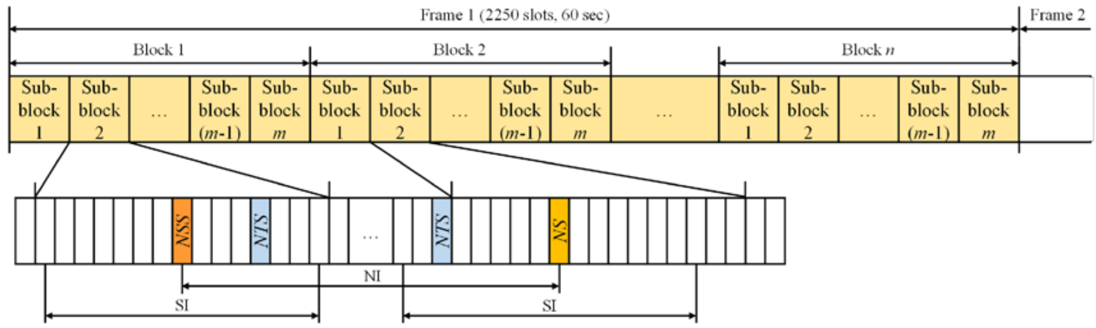


Fig. 4. Frame structure of BSO-TDMA

The frame configuration consists of block division and block selection. In block division, the frame is divided into several blocks. **Fig. 4** shows the frame structure of BSO-TDMA. As shown in the figure, the frame length of BSO-TDMA is 2250 slots (60 sec); it is the same as that of the existing SOTDMA. However, unlike a ship using the existing SOTDMA, the one using BSO-TDMA logically divides the first frame subsequent to channel monitoring or RI change into *n* blocks. The ship thus uniformly allocates slots within the frame. The number of blocks within the frame is equal to Rr, and the length of each block is equal to NI. Each block consists of *m* subblocks of length SI. Rr, NI, and SI are calculated by (1)–(3), respectively. The set of blocks within the frame ($\mathbf{BL}$) and the set of subblocks within each block ($\mathbf{SBL}$) are represented by (4) and (5), respectively.

$$\mathbf{BL} = [bl_1, bl_2, \cdots, bl_n] = [1, 2, \cdots, n] \tag{4}$$

$$\mathbf{SBL} = [sbl_1, sbl_2, \cdots, sbl_m] = [1, 2, \cdots, m] \tag{5}$$

where bl_n indicates the index of the *n*-th block within the frame, and sbl_m indicates the index of the *m*-th subblock within each block.

After the block division is completed, the ship performs block selection and selects a subblock within the selected block to which NSS will be allocated. The ship initially sets the block index to bl_1. From the beginning of the frame, the next block index is selected whenever NI has elapsed. The block index is initialized to bl_1 at the beginning of each frame. Afterwards, the ship counts the number of NSSs and NSs for neighbor stations allocated in each subblock and randomly selects one of the subblocks with the smallest number of slots (i.e., NSS and NSs). For this purpose, the ship maintains a list of the number of allocated NSSs and NSs within each subblock ($\mathbf{BCC}$), which is represented by (6).

$$\mathbf{BCC} = [bcc_1, bcc_2, \cdots, bcc_m] \tag{6}$$

where bcc_m indicates the number of NSSs and NSs allocated within the *m*-th subblock. The ship updates its $\mathbf{BCC}$ when it allocates its own NSS and NS or receives new NSS and NS allocation information from neighbor stations. For example, if the ship allocates its own NSS within the *i*-th subblock, bcc_i is increased by 1.

In slot allocation, the ship allocates NSS by selecting a random slot among unoccupied slots within the selected subblock. After the NSS allocation is completed, the ship constructs a set of candidate slots for NTS allocation ($\mathbf{CS}_{nss}$). $\mathbf{CS}_{nss}$ comprises slots centered around the allocated NSS and is represented by (7).

$$\mathbf{CS}_{nss} = \left[cs_{nss,1}, cs_{nss,2}, \cdots, cs_{nss,k} \right] \tag{7}$$

where $cs_{nss,k}$ indicates the slot index of the k-th candidate slot associated with the allocated NSS, and k is equal to SI. The slot index of the i-th candidate slot for the allocated NSS is calculated by (8).

$$cs_{nss,i} = i + \left(nss - 1 \right) - \left(\frac{SI - 1}{2} \right) \tag{8}$$

where nss indicates the slot index of the allocated NSS.

Thereafter, the ship randomly selects one of the unoccupied candidate slots in $\mathbf{CS}_{nss}$ by referring to the frame map and allocates it as its NTS. The allocated NTS is maintained continuously for several frames. For this purpose, the ship randomly determines the slot time-out within the range of 3–7 and assigns it to the NTS. The slot time-out decreases by 1 whenever the frame index increases by 1. If the slot time-out reaches 0, the ship reallocates the NTS.

The ship subsequently transmits its AIS messages in the NSS and NTS allocated within the selected block. A ship listens to AIS messages from neighbor stations in slots excluding its NSS and NTS within the selected block. When new slot allocation and deallocation information is obtained from AIS messages from neighbor stations, the ship updates the frame map and $\mathbf{BCC}$. If the bcc of the selected subblock is increased before transmitting the AIS message in its NSS, the ship reallocates its NSS and NTS. In other words, the ship performs block selection and slot allocation again using the updated frame map and $\mathbf{BCC}$. These operations are repeated until the NSS and NTS are successfully allocated within the current frame. If the slot allocation fails even in the last block of the current frame, the ship randomly selects one of the subblocks of blocks and allocates its NSS and NTS before starting the next frame.

At each NTS, the ship determines the slot indices of the next NS and the next NTS to be allocated in the next block and broadcasts its AIS message containing the slot indices. The slot index of the next NS is calculated by adding NI to the slot index of the NS associated with the current NTS. If the current NS is the first NS, the slot index of the current NS is nss . The slot index of the next NTS is determined by the ship randomly selecting an unoccupied candidate slot within the set of candidate slots corresponding to the next NS ($\mathbf{CS}_{nextNS}$). $\mathbf{CS}_{nextNS}$ is represented by (9), and k is equal to SI. The slot index of the i-th candidate slot ($cs_{nextNS,i}$) in $\mathbf{CS}_{nextNS}$ is calculated by (10).

$$\mathbf{CS}_{nextNS} = \left[cs_{nextNS,1}, cs_{nextNS,2}, \cdots, cs_{nextNS,k} \right] \tag{9}$$

$$cs_{nextNS,i} = i + \left(ns_{next} - 1 \right) - \left(\frac{SI - 1}{2} \right) \tag{10}$$

4. Performance Evaluation

We performed experimental simulations using the MATLAB simulator to evaluate the performance of BSO-TDMA. The simulation results of BSO-TDMA were compared to those of the existing SOTDMA to verify the superiority of BSO-TDMA. We describe the simulation configuration and simulation results in detail in the following subsections.

4.1 Simulation Configuration

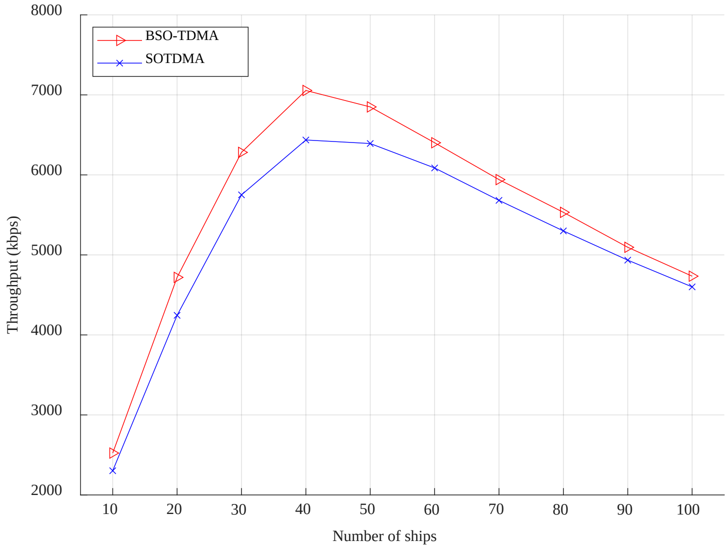
In the simulation, we considered an ad-hoc network consisting of multiple ships sailing at the same fixed speed (i.e., fixed reporting interval). We assume that all ships in the network are randomly deployed within the same communication range, set to 20 nautical miles (NM). All ships in the network are assumed to always have AIS messages to transmit (i.e., saturation condition). In the simulation, the number of ships and RI vary from 10 to 100 and 2 to 6, respectively. The performance of BSO-TDMA was compared with that of existing SOTDMA in terms of throughput, PDR, and average number of collisions. The simulation was iterated 200 times. The detailed simulation parameters are listed in **Table 2**.

Table 2. Simulation parameters

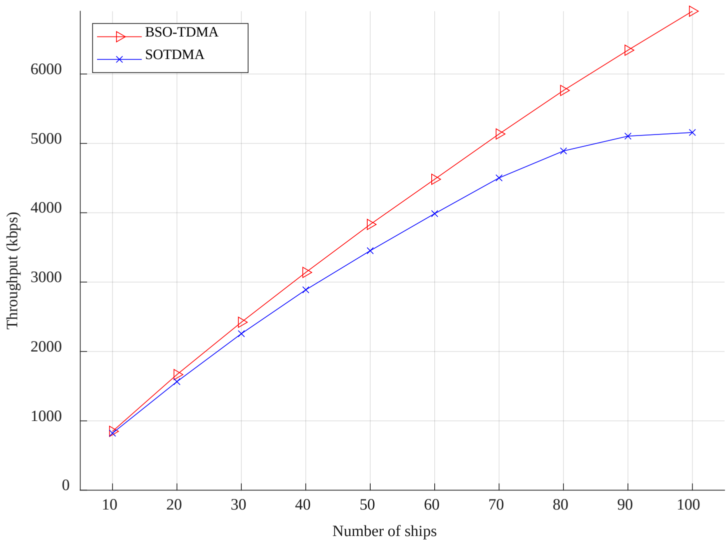
Parameter	Value	Parameter	Value
Number of ships	10–100	*RI*	2, 6
Communication range	20 NM	*Rr*	30, 10
Packet size	256 bits	*NI*	75, 225
Data rate	9,600 bps	*SI*	15, 45
Frame length	2,250 slots	*n*	30, 10
Slot length	26.67 ms	*m*	5

4.2 Simulation Results

Figs. 5(a) and **(b)** illustrate the variations in the throughput when RI is 2 and 6, respectively. In the figure, the throughput of BSO-TDMA is higher than that of SOTDMA regardless of the RI of the ship and the number of ships in the network. This is because BSO-TDMA reduces ships selecting the same slots through the frame configuration. In **Figs. 5(a)** and **(b)**, the throughput of BSO-TDMA and SOTDMA increases until the number of ships is 40 and 100, respectively. This is because as the number of ships increases, the number of slots allocated for transmission by ships within the frame and the number of AIS messages transmitted within the network increase. However, in **Fig. 5(a)**, when the number of ships exceeds 40, collisions between transmitted AIS messages increase owing to the increase in overlapping allocated slots by ships, thereby reducing the throughput of BSO-TDMA and SOTDMA. Additionally, until the number of ships is 80, the throughput of BSO-TDMA and SOTDMA is higher when RI is 2 than when it is 6. In addition, regardless of the channel resource allocation scheme, the throughput of the network comprising ships with RI of 2 is higher than that of the network comprising ships with RI of 6. The smaller the RI, the more frequently the ship transmits its AIS messages in the allocated slots at shorter intervals within the frame. Quantitatively, when RI is 2 and 6, the throughput of BSO-TDMA is 6.58% and 17.07% higher than that of SOTDMA, respectively.



(a)



(b)

Fig. 5. Throughput: (a) *RI* = 2 and (b) *RI* = 6

Figs. 6(a) and **(b)** illustrate the variations in the PDR when RI is 2 and 6, respectively. We define PDR as the ratio of the number of AIS messages received by the receiving ship to the total AIS messages transmitted by the transmitting ship. The PDR of BSO-TDMA and SOTDMA tend to decrease as the number of ships increases owing to the increase in collisions between AIS messages. Regardless of the number of ships, when the RI of the ship increases, the PDR of both BSO-TDMA and SOTDMA increases. This is because an increase in RI results in a decrease in the number of slots allocated within the frame and an increase in the number of candidate slots considered to select NTSs. As a result, it reduces ships choosing the same slot as each other to transmit their messages. Meanwhile, the PDR of BSO-TDMA is higher regardless of the number of ships and RI compared with that of SOTDMA. This is because the ship using BSO-TDMA randomly selects one of the subblocks to which NSSs of other ships are not allocated and allocates its NSS, considering its own frame map and **BCC**. Therefore, in BSO-TDMA, the same NSS selection between ships and overlap between SIs centered around each NS are less than in SOTDMA, resulting in more AIS messages being sent successfully. A ship using SOTDMA entails more overlapping slots than one using BSO-TDMA because it randomly selects its NSS from an interval limited to 150 slots within the frame. It results in frequent collisions between AIS messages transmitted by ships. Quantitatively, when RI is 2 and 6, the PDR of BSO-TDMA is 12.78% and 13.98% higher than that of SOTDMA, respectively.

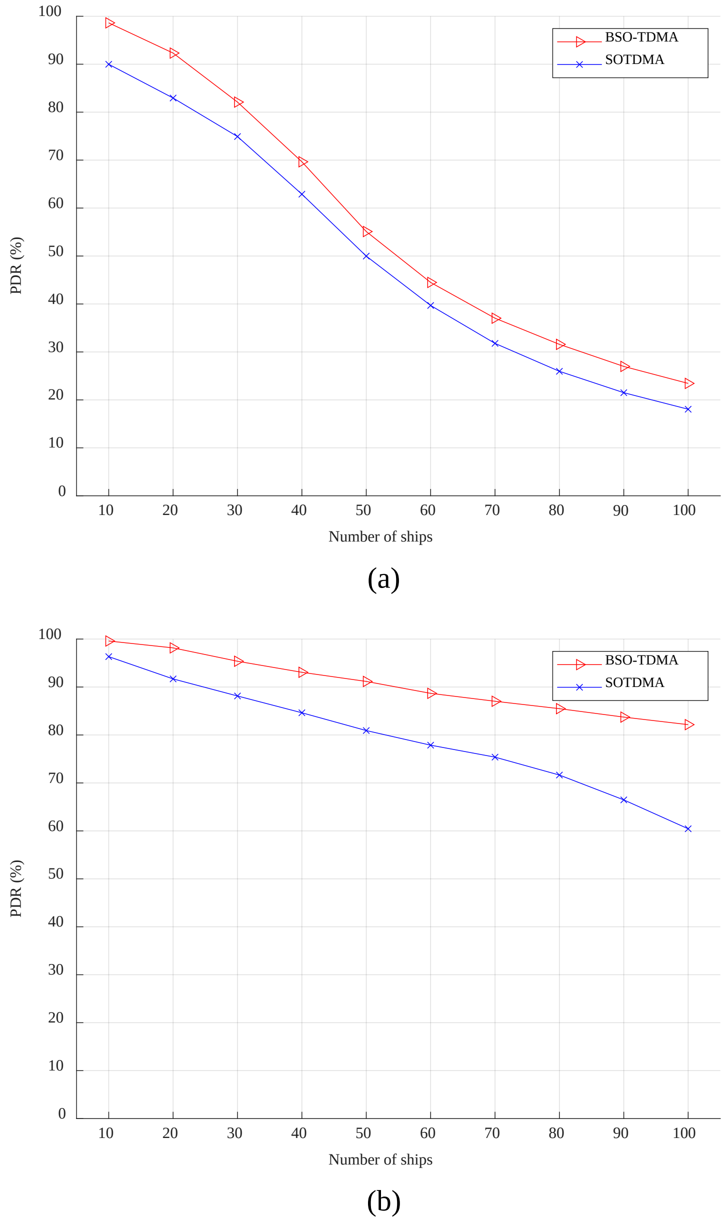
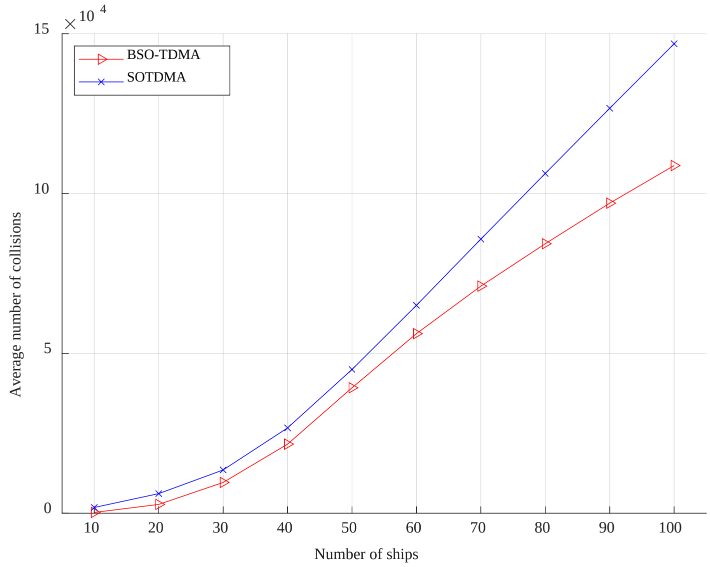
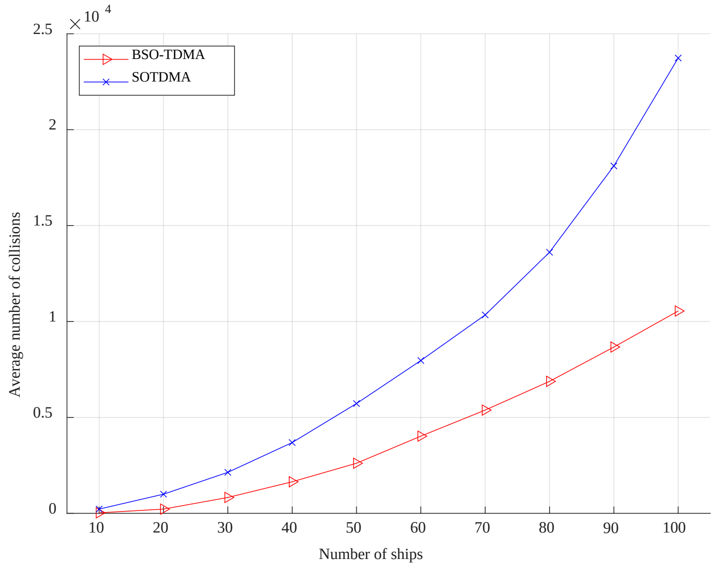


Fig. 6. PDR: (a) RI = 2 and (b) RI = 6

Figs. 7(a) and **(b)** illustrate the variations in the average number of collisions when RI is 2 and 6, respectively. In the figure, the average number of collisions for BSO-TDMA and SOTDMA increases as the number of ships increases owing to the increase in the number of slots that need to be allocated within the frame. Accordingly, regardless of the channel resource allocation scheme, the overlap between SIs centered around each NS selected by ships commonly increases. Further, the overlap between SIs increases collisions in the network by causing ships to select the same NTSs as each other. As the RI increases, the average number of collisions for BSO-TDMA and SOTDMA decreases. This is because an increase in RI reduces the number of slots allocated within the frame, resulting in an effect similar to that of a decrease in the number of ships in the network. Additionally, regardless of RI, the average number of collisions of BSO-TDMA is lower than that of SOTDMA. BSO-TDMA reduces collisions by allowing ships to allocate slots dispersedly rather than concentrated in specific ranges within the frame by using **BCC** . Quantitatively, when RI is 2 and 6, the average number of collisions in BSO-TDMA is 21.32% and 52.83% lower than that in SOTDMA, respectively.



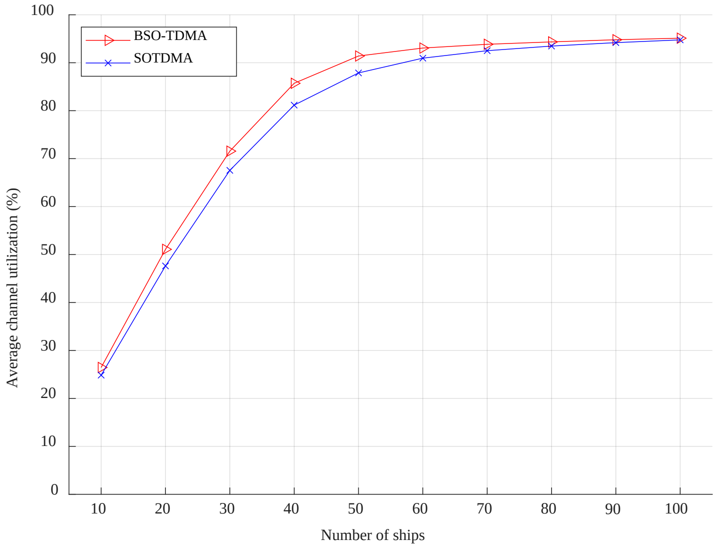
(a)



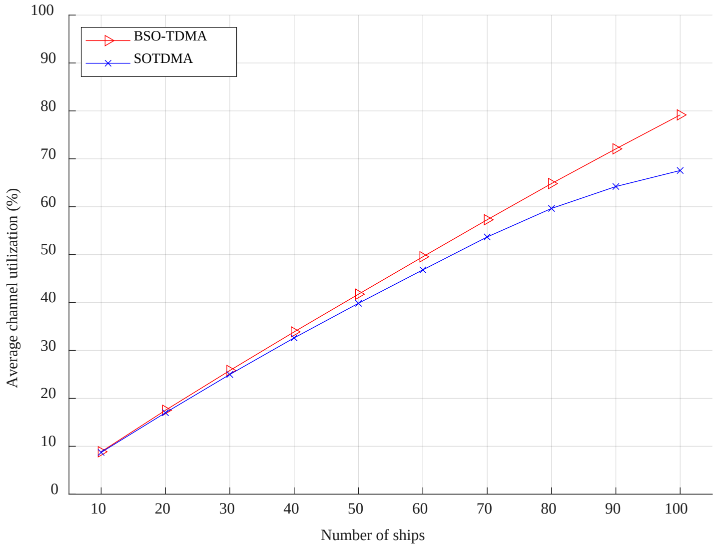
(b)

Fig. 7. Average number of collisions: (a) *RI* = 2 and (b) *RI* = 6

Figs. 8(a) and **(b)** illustrate the variations in average channel utilization when RI is 2 and 6, respectively. We define channel utilization as the ratio of the number of slots allocated for transmission by ships within the frame to the number of total slots within the frame. In **Fig. 8(a)**, as the number of ships increases, the average channel utilization of BSO-TDMA and SOTDMA tends to increase up to 60 and 70 ships, respectively, following which it does not increase. This is because the number of slots that need to be allocated within the frame increases; however, the number of slots that can be allocated within the frame is limited. Additionally, even if the total number of slots that need to be allocated by ships exceeds the frame length, unoccupied slots remain within the frame owing to the random slot allocation of ships. Therefore, the average channel utilization of BSO-TDMA and SOTDMA does not reach 100%. The average channel utilization of BSO-TDMA is higher than that of SOTDMA, regardless of the number of ships and RI. In BSO-TDMA, ships perform slot allocation by referring to their BCC; therefore, slots for the transmissions of ships are allocated less intensively to specific ranges within the frame and overlap less. Meanwhile, when the number of slots of ships to be allocated within the frame significantly exceeds the frame length, the average channel utilization of BSO-TDMA and SOTDMA becomes almost similar. This is because the overlap between NSs allotted within the frame and SIs centered around each NS causes most candidate slots to be allocated as NTSs. Quantitatively, when RI is 2 and 6, the average channel utilization of BSO-TDMA is 2.89% and 8.58% higher than that of SOTDMA, respectively.



(a)



(b)

Fig. 8. Average channel utilization: (a) $RI = 2$ and (b) $RI = 6$

5. Conclusion

In this paper, we propose BSO-TDMA, to allow ships to uniformly allocate slots within a frame, thereby reducing collisions in SANET. In BSO-TDMA, frame configuration and slot allocation are performed sequentially for channel resource allocation. In the former, the ship divides a frame into multiple blocks consisting of fixed-size subblocks and randomly selects one subblock within the block considering the BCC. In the latter, the ship selects one of the slots within the selected subblock to allocate NSS or NS and randomly selects unoccupied slots among the candidate slots to allocate NTS. To evaluate the performance of BSO-TDMA, we conducted experimental simulations and compared the results with those of the existing SOTDMA. In the simulation, two different RIs were set to investigate the impact of RI on the BSO-TDMA performance. The results showed that BSO-TDMA had better performance on average compared to that of the existing SOTDMA. Specifically, for each RI case (i.e., RI = 2 and RI = 6), the BSO-TDMA had 6.58% and 17.07% higher throughput, 12.78% and 13.98% higher PDR, and 21.32% and 52.83% fewer collisions than those of the existing SOTDMA, respectively.

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