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Slot Occupancy-Based Collision Avoidance Algorithm for Very-High-Frequency Data Exchange System Network in Maritime Internet of Things

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Abstract: The maritime industry is undergoing a paradigm shift driven by rapid advancements in wireless communication and an increase in maritime traffic data. However, the existing automatic identification system (AIS) struggles to accommodate the increasing maritime traffic data, leading to the introduction of the very-high-frequency (VHF) data exchange system (VDES). While the VDES increases bandwidth and data rates, ensuring the stable transmission of maritime IoT (MIoT) application data in congested coastal areas remains a challenge due to frequent collisions of AIS messages. This paper presents a slot occupancy-based collision avoidance algorithm (SOCA) for a VDES network in the MIoT. SOCA is designed to mitigate the impact of interference caused by transmissions of AIS messages on transmissions of VDE-Terrestrial (VDE-TER) data in coastal areas. To this end, SOCA provides four steps: (1) construction of the neighbor information table (NIT) and VDES frame maps, (2) construction of the candidate slot list, (3) TDMA channel selection, and (4) slot selection for collision avoidance. SOCA operates by constructing the NIT based on AIS messages to estimate the transmission intervals of AIS messages and updating VDES frame maps upon receiving VDES messages to monitor slot usage dynamically. After that, it generates a candidate slot list for VDE-TER channels, classifying the slots into interference and non-interference categories. SOCA then selects a TDMA channel that minimizes AIS interference and allocates slots with low expected occupancy probabilities to avoid collisions. To evaluate the performance of SOCA, we conducted experimental simulations under static and dynamic ship scenarios. In the static ship scenario, SOCA outperforms the existing VDES, achieving improvements of 13.58% in aggregate throughput, 11.50% in average latency, 33.60% in collision ratio, and 22.64% in packet delivery ratio. Similarly, in the dynamic ship scenario, SOCA demonstrates improvements of 7.30%, 11.99%, 39.27%, and 11.82% in the same metrics, respectively.

Keywords: collision avoidance; maritime Internet of Things; slot occupancy; VDES; VDE-TER

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Citation: Lee, S.-B.; Kwon, J.-H.; Kim, B.-Y.; Shim, W.-S.; Shon, T.; Kim, E.-J. Slot Occupancy-Based Collision Avoidance Algorithm for Very-High-Frequency Data Exchange System Network in Maritime Internet of Things. *Appl. Sci.* **2024**, *14*, 11751. https://doi.org/10.3390/app142411751

Academic Editor: Juan Francisco De Paz Santana

Received: 23 October 2024
Revised: 9 December 2024
Accepted: 12 December 2024
Published: 16 December 2024

1. Introduction

As the number of ships and the volume of global maritime trade increase significantly worldwide, e-Navigation, which ensures maritime safety, security, and environmental protection, has received considerable attention [1–4]. e-Navigation is a next-generation maritime navigation system that aims to meet the requirements of the maritime Internet of Things (MIoT) through the collection, exchange, integration, and mutual cooperation of maritime-related information between ships and coastal stations [5–8]. e-Navigation has been advanced through various technologies such as wireless communication, IoT, and artificial intelligence (AI), and these developments have led to a rapid increase in demand for not only safety applications but also non-safety applications such as infotainment and multimedia services [9–12]. In addition, maritime autonomous surface ships (MASSs) that use automation and remote-control technologies based on a large amount of maritime-related information have emerged [13–15]. This paradigm shift in the maritime industry has led to a rapid increase in maritime traffic [16–18]. Accordingly, the existing automatic identification system (AIS) for maritime communication has reached a point where it can no longer sufficiently accommodate the rapidly increasing maritime traffic due to its limited resources [19–21]. The limited network capacity of AIS causes frequent packet collisions and network congestion, especially in coastal areas where many ship stations are densely packed. Furthermore, this can lead to collisions between ship stations and safety accidents. In response to increasing channel and bandwidth constraints in maritime communications, the International Telecommunication Union (ITU) introduced the very-high-frequency (VHF) data exchange system (VDES) in 2015 [22]. VDES concentrates on addressing these challenges by expanding the transmission capacity of maritime stations, including ship stations, shore stations and satellites, improving the reliability and efficiency of maritime communication networks.

VDES is a time-division multiple access (TDMA)-based maritime communication system designed to facilitate data exchange among ships, ground stations, and satellites. It comprises three main components: AIS, application specific message (ASM), and VHF data exchange (VDE). AIS plays a crucial role in maritime communication by enabling ships to identify each other, track targets, exchange information, and maintain situational awareness via two channels. These capabilities allow AIS to effectively support safe navigation and contribute to the prevention of collisions between ships. ASM is utilized for transmitting various data types, including ship position, speed, direction, identification details, marine safety information, and specific application requirements, using the AIS channel and two additional channels. VDE facilitates high-speed transmission of large data, such as multimedia services, utilizing a broad bandwidth across 12 dedicated channels. Moreover, VDE is separated into VDE-terrestrial (VDE-TER) and VDE-satellite (VDE-SAT), which operate independently. VDE-TER facilitates data transmission in coastal areas by leveraging existing shore station infrastructure, while VDE-SAT uses low-orbit satellites to provide maritime communication for offshore ship stations, thereby enabling access to the MIoT network.

Despite the increase in bandwidth and data rate of maritime communication with the introduction of VDES, ensuring the stable transmission of various MIoT application data through VDE in coastal areas, such as ports and harbors where ships are densely located, remains challenging [23,24]. Specifically, the components of VDES may experience interference due to the utilization of adjacent frequency channels. Consequently, the transmission of VDE-TER data may cause interference, potentially degrading the quality of both the transmission and reception of AIS messages. This interference can lead to an increase in errors and collisions among AIS messages, resulting in unreliable maritime communication and unnecessary delays. Therefore, the standard recommends that when operating VDES in duplex mode co-located with AIS, there should be sufficient isolation between the AIS receiver and VDE transceiver to protect the AIS function from interference. It also suggests implementing a mechanism to synchronize VDE with AIS and ASM. However, the standard does not specify a particular methodology for achieving these requirements.

To reduce collisions of AIS messages in coastal areas, various studies have been conducted previously. Zhang et al. proposed an improved version of the self-organized TDMA-based medium access control (MAC) protocol to reduce the collision probability of ASM channels during data transmission in VDES [25]. This approach aims to minimize interference by optimizing slot allocation. However, it has a limitation in terms of compatibility with AIS. Hu et al. introduced a collision feedback-based MAC protocol, which attempts retransmission after delaying data transmission for a certain period when a collision is detected by the transmitting station [26]. However, this approach results in long delays and resource wastage due to repeated retransmissions. Liang et al. proposed a feedback-based MAC protocol that employs the concept of cognitive radio to reduce collisions in dynamic maritime environments [27]. However, due to the unpredictable characteristic of AIS, which allocates resources and transmits messages in a self-organized TDMA (SOTDMA), collisions between VDES message transmissions among various ship and shore stations remain a challenging issue.

In this paper, we propose a slot occupancy-based collision avoidance algorithm (SOCA) for a VDES network in the MIoT. SOCA is designed to mitigate the impact of interference caused by transmissions of AIS messages on transmissions of VDE-TER data in coastal areas. For this purpose, unlike the existing VDES, SOCA estimates transmission intervals of AIS messages for neighboring stations and updates the expected slot occupancy probabilities of slots in the VDES frame in real time. This allows ship stations to adaptively allocate slots, considering the dynamic changes in the surrounding maritime environment. SOCA includes four steps: (1) construction of the neighbor information table (NIT) and VDES frame maps, (2) construction of the candidate slot list, (3) TDMA channel selection, and (4) slot selection for collision avoidance. In the first step, the ship station constructs the neighbor information table and the VDES frame maps by monitoring VDES channels. The neighbor information table includes the navigational-related information. The VDES frame maps provides transmission schedules of the ship station and its neighboring stations. In the second step, the ship station constructs the candidate slot list of VDE-TER channels and classifies the candidate slots into interference and non-interference slots. In the TDMA channel selection, it selects the TDMA channel that minimizes the impact of VDE-TER data transmission on AIS message transmission. In the collision avoidance slot selection, the ship station selects candidate slots on the chosen TDMA channel that have a low probability of being used by itself or neighboring stations for transmitting AIS messages. To verify the superiority of SOCA, we conducted an experimental simulation. The simulation results demonstrated that SOCA is 13.58%, 11.50%, 33.60%, and 22.64% superior to the existing VDES in aggregate throughput, average latency, collision ratio, and packet delivery ratio, respectively.

The remainder of this paper is organized as follows: Section 2 provides the overview of VDES and discusses the related works. Section 3 describes a design of SOCA in detail. Section 4 shows the simulation configuration and results. Finally, we conclude this paper in Section 5.

2. VDES Overview and Related Work

In this section, we provide a brief overview of VDES, including its components, channels, and frame structure. We also review related studies on MAC protocols for VDES networks in MIoT, focusing on collision avoidance strategies and addressing their limitations to enhance maritime communications.

2.1. VDES Overview

VDES is a multi-component system for maritime communications consisting of AIS, ASM, and VDES, enabling data exchange between maritime stations, ship-to-ship, ship-to-shore, shore-to-ship, ship-to-satellite, and satellite-to-ship. VDES comprises terrestrial and satellite components, VDE-TER and VDE-SAT, which are interoperable and compatible. It is designed to operate in the VHF maritime mobile band (156.025–162.025 MHz) and supports both simplex and duplex modes. To avoid collisions, ship stations must transmit VDES messages according to the following priority order: AIS > ASM > VDE. Figure 1 illustrates the VDES functions and frequency usage.

AIS, the core system of VDES, is primarily utilized to prevent collisions and enhance safe navigation by enabling ships to identify various maritime stations. It mainly operates through two channels (AIS 1, AIS 2). AIS periodically transmits information crucial for ship recognition and navigation, static and dynamic information, and voyage-related data. This information includes the identifier (ID) of the ship, as well as its type, location, speed, and navigation details. In coastal regions, AIS is employed to gather navigation data of ships. Conversely, in offshore areas, long-range AIS ensures safe navigation of ships, even in areas lacking infrastructure, by communicating with satellites. Nevertheless, AIS channels, with a bandwidth of 25 kHz and a transmission rate of 9.6 Mbps, have already become overloaded in some large and congested ports where ships are closely clustered.

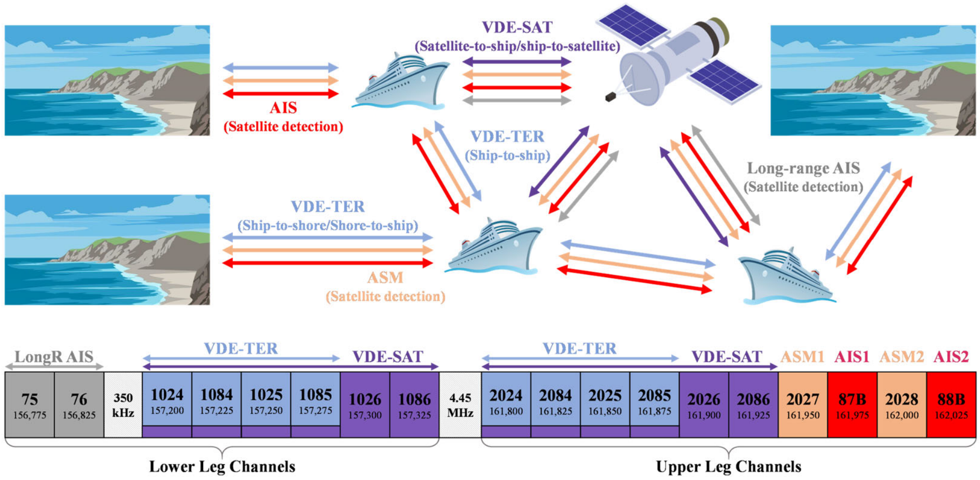


Figure 1. VDES functions and frequency usage.

Accordingly, ASM and VDE were introduced to overcome the resource constraints of AIS and to meet the increasing requirements of various applications. ASM plays a key role in preventing traffic overload of AIS channels and loss of AIS messages important for maritime safety by allowing application messages previously transmitted on the AIS channel to be transmitted on two other channels (ASM 1 and ASM 2). The bandwidth of ASM channels is 25 kHz, the same as AIS, but the data rate is 19.2 kbps, which is twice that of AIS. Environmental, safety, and regulatory information is mainly transmitted through ASM.

However, there were limits to accommodating the increasing number of ships and maritime application messages. Therefore, VDE was additionally introduced to enable the exchange of various data to meet the requirements of e-Navigation and MASS services through 12 additional channels and high data rates. Multimedia information such as real-time weather data, audio, images, and video is transmitted through VDE. VDE is divided into VDE-TER and VDE-SAT. VDE-TER supports bandwidths of 25, 50, and 100 kHz and data rates from 38.4 kbps up to 307.2 kbps. On the other hand, VDE-SAT supports bandwidths of 50, 100, and 150 kHz and data rates from 2.1 to 56.4 kbps. The default bandwidths of VDE-TER and VDE-SAT are 100 kHz and 50 kHz, respectively.

As a result, VDES enhances the efficiency of ship operations at sea, maritime traffic management, and maritime safety by utilizing components with various characteristics. It enables seamless data exchange and service operation for more ship stations by expanding bandwidth and offering high data rates.

Figure 2 illustrates the VDES frame structure. VDES employs a frame structure with a duration of one minute, synchronized to coordinated universal time (UTC). The frame consists of a total of 2250 slots. Each slot is approximately 26.67 ms long and can transmit packets of up to 256 bits. The slots in the frame are numbered from 0 to 2449. In VDE-TER, the VDES frame is divided into 25 sub-frames, which are TDMA frames. The TDMA frame numbers range from 0 to 24. Each TDMA frame consists of 15 hexslots, where each hexslot comprises 6 consecutive slots and lasts for 160 ms. The hexslot number increases by 1 every 6 slots. Time progresses from top to bottom and from left to right within the TDMA frame. Furthermore, each slot within a hexslot has a distinct TDMA channel offset, resulting in the utilization of six TDMA channels in a TDMA frame. Each horizontal slot line within a TDMA frame represents a TDMA channel.

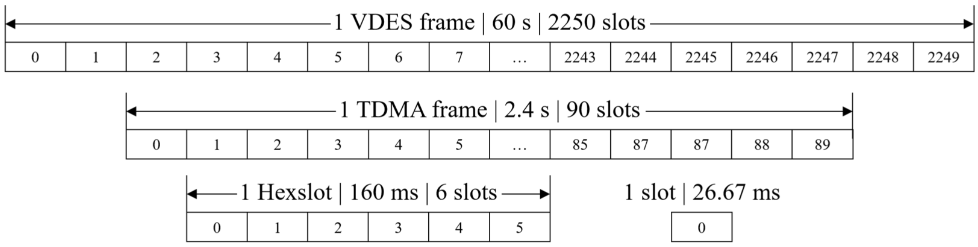


Figure 2. VDES frame structure.

Furthermore, in VDE-TER, one slot function is allocated to each slot in a TDMA frame. The same slot function can be allocated to several consecutive slots. Six slot functions are defined in VDE-TER: bulletin board signalling channel (BBSC), random access channel (RAC), announcement signalling channel (ASC), data signalling channel (DSCH), data channel (DC), and ranging channel (RC). These slot functions can be repeated within a TDMA channel. Note that the VDES standard provides a default slotmap for VDE-TER, depicted as Figure 3.

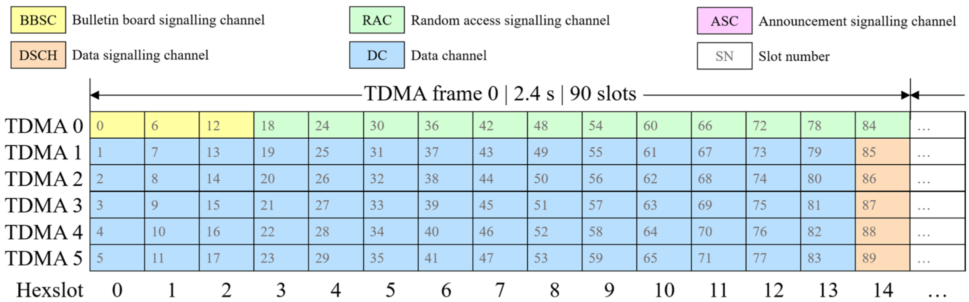


Figure 3. VDE-TER default slotmap.

2.2. Related Work

Numerous studies have been conducted to mitigate collisions between AIS messages and other transmissions in MIoT. In [25], Zhang et al. proposed a priority determination mechanism that determines transmission priority depending on the message type. However, this mechanism causes long delays in low-priority message transmissions, particularly in dense environments with intense competition for slots and channels.

In [26], Hu et al. proposed a feedback-based TDMA (FBTDMA) protocol that includes a collision feedback mechanism and a modified time slot structure. A collision feedback mechanism uses feedback signals to notify the neighboring ship stations immediately when a collision occurs. However, this causes additional message overhead for collision feedback, resulting in long delays and network overload. In addition, the modified time slot structure increases the complexity of system design and implementation, as it requires sophisticated frame segmentation and inconsistent slot length. In [27], Liang et al. proposed a feedback-based improved hexslot MAC (FIH-MAC) protocol in which the ship stations periodically monitor and update their neighbors' channel state information (CSI) to assess channel availability for message transmissions. However, since this protocol heavily relies on accurate CSI, incorrect estimation of CSI can significantly increase the probability of collisions. In addition, the process of monitoring and updating CSI may incur additional communication overhead and communication delays. Furthermore, the authors assume that the CSI is obtained via cognitive radio, which requires complex radio processing techniques for implementation. In [28], Chen et al. modified the existing carrier-sense TDMA (CSTDMA) protocol. With this modified protocol, ship stations continuously monitor the occupancy of near-future slots when slot allocations are required for message transmissions. However, this approach makes collisions highly likely, even if only one adjacent ship station simultaneously attempts to transmit a message.

A hybrid MAC protocol, which combines contention-free and contention-based mechanisms, can be applied to the maritime communication networks. In [29], Yang et al. proposed a topology and traffic adaptive medium access control (TTA-MAC) protocol. TTA-MAC uses a frame structure comprising contention-free and contention-based periods. Under high-traffic conditions, the contention-free period is extended by increasing the slot allocation ratio within the frame. However, in high-traffic conditions, ship stations may experience frequent collisions due to the inclusion of the contention-based period within the frame. Additionally, the use of a hybrid MAC with a dynamic frame structure incurs extra computational overhead and requires additional control message exchanges.

These studies demonstrate various resource allocation strategies to mitigate collisions between AIS messages and other transmissions in maritime communications. Despite these efforts, they still encounter significant challenges in terms of performance degradation, including prolonged delays, excessive message overhead, and frequent collisions in dense environments. Moreover, there are further challenges related to compatibility with existing VDES systems and implementation complexity.

3. Design of SOCA

SOCA is designed to mitigate the impact of VDE-TER data exchange on the AIS message transmission in coastal areas with a high density of ship stations. To achieve this, SOCA focuses on effectively allocating slots for VDE-TER data transmission by selecting candidate slots that have a low probability of being potentially used for AIS message transmission. SOCA is a MAC layer enhancement of the VDES standard and, therefore, uses the VDES protocol as its baseline MAC scheme. Specifically, SOCA comprises four steps: (1) construction of the NIT and VDES frame maps, (2) construction of the candidate slot list for VDE-TER, (3) TDMA channel selection, and (4) collision avoidance slot selection. In the following, we provide a detailed description of the operations involved in SOCA.

3.1. Construction of Neighbor Information Table (NIT) and VDES Frame Maps

The ship station conducts VDES channel monitoring for an initial duration of one minute to participate in the VDES network. By monitoring VDES channels, the ship station collects information such as channel activity and ID, speed, position, and scheduling information (i.e., slot usage) of neighboring stations. Subsequently, the ship station constructs the NIT containing the collected information. In particular, the ship station estimates the report rate (Rr), nominal increment (NI), and selection interval (SI) of neighboring stations using the reporting interval (RI) included in the received AIS messages, updating them in the NIT in real time. The RI of a ship station is determined by its speed [19]. RI, Rr, NI, and SI are parameters used by the AIS to allocate resources for AIS message transmission (i.e., nominal slot (NS) and nominal transmission slot (NTS)). Additionally, the ship station constructs VDES frame maps using information obtained from its neighboring stations. Specifically, VDES frame maps include the AIS frame map, the ASM frame map, and the VDE-TER slotmap. Note that the VDE-SAT is out of the scope of SOCA; therefore, the VDE-SAT slotmap is not included in the VDES frame maps. The NIT is updated only when AIS messages are received, and the VDES frame maps are continuously updated upon receiving VDES messages (i.e., AIS, ASM, and VDE messages). After completing the construction of the NIT and VDES frame maps, the ship station proceeds to construct a candidate slot list for the TDMA channels designated for VDE-TER.

3.2. Construction of Candidate Slot List

The ship station constructs a candidate slot list for the TDMA channels by considering the NIT and VDES frame maps. This overall candidate slot list encompasses the individual candidate slot lists for each TDMA channel. The individual candidate slot list for each TDMA channel can consist of free, available, and allocated slots, in compliance with the candidate slot selection rules specified in the VDES standard [22]. The candidate slot list (**S**) for the TDMA channels can be represented by

$$\mathbf{S} = \left[\mathbf{CS}_1, \mathbf{CS}_2, \cdots, \mathbf{CS}_i, \cdots, \mathbf{CS}_{N_{ch}}\right], \quad (1)$$

where $\mathbf{CS}_i$ represents the candidate slot list of the i-th TDMA channel. N_{ch} represents the total number of TDMA channels within a TDMA frame. $\mathbf{CS}_i$ can be represented by

$$\mathbf{CS}_i = \left[sn_{i,1}, sn_{i,2}, \cdots, sn_{i,j}, \cdots, sn_{i,n_{cs},i}\right] \; (0 \le n_{cs,i} \le 15), \quad (2)$$

where $sn_{i,j}$ represents the slot number of the j-th candidate slot in the candidate slot list for the i-th TDMA channel. $n_{cs,i}$ represents the number of candidate slots in the i-th TDMA channel.

Upon completing the construction of the candidate slot list for the TDMA channels, the ship station classifies the candidate slots for each TDMA channel into interference and non-interference slots and calculates the number of each for every TDMA channel. The interference slot refers to the candidate slot that is included in the SI of its own or at least one neighboring station, while the non-interference slot is not included in any of these SIs. Subsequently, it constructs lists $\mathbf{N}_{IS}$ and $\mathbf{N}_{NIS}$, containing the number of interference slots and non-interference slots for each TDMA channel, respectively. $\mathbf{N}_{IS}$ and $\mathbf{N}_{NIS}$ can be represented by

$$\mathbf{N}_{IS} = \left[n_{IS,1}, n_{IS,2}, \cdots, n_{IS,i}, \cdots, n_{IS,N_{ch}}\right], \quad (3)$$

$$\mathbf{N}_{NIS} = \left[n_{NIS,1}, n_{NIS,2}, \cdots, n_{NIS,i}, \cdots, n_{NIS,N_{ch}}\right], \quad (4)$$

where $n_{IS,i}$ and $n_{NIS,i}$ refer to the number of interference slots and non-interference slots included in $\mathbf{CS}_i$, respectively. The ship station then performs TDMA channel selection for its VDE-TER data transmission.

3.3. TDMA Channel Selection

The ship station selects the TDMA channel to ensure that the VDE-TER data transmission has minimal impact on the AIS transmission. Algorithm 1 presents the procedure for selecting a TDMA channel for VDE-TER data transmission. The algorithm takes n_{req}, $\mathbf{N}_{IS}$, and $\mathbf{N}_{NIS}$ as inputs. n_{req} represents the number of required slots to transmit a VDE-TER data packet and is calculated by

$$n_{req} = \left\lceil \frac{l_{data}}{l_{maxPkt}} \right\rceil, \quad (5)$$

where l_{data} represents the size of a data packet to be transmitted via VDE-TER. l_{maxPkt} represents the maximum size of a packet that can be transmitted within a single slot of the TDMA frame. The output of the algorithm is the channel number of the TDMA channel selected by the ship station, denoted as ch.

The algorithm first defines ch and initializes it to zero. It also defines $\mathbf{CH}_{preferred}$, $\mathbf{CH}_{available}$, and $\mathbf{CH}_{maxNIS}$, and initializes them as empty lists. $\mathbf{CH}_{preferred}$ and $\mathbf{CH}_{available}$ refer to the lists of preferred and available TDMA channels, respectively, to be selected by the ship station. The preferred TDMA channel indicates the TDMA channel that has at least as many non-interference slots as the number of required slots for the ship station. The available TDMA channel indicates the TDMA channel in which the total number of non-interference and interference slots are equal to or greater than the number of required slots for the ship station.

Afterward, the algorithm iterates over the total number of TDMA channels, checking the following conditions for each TDMA channel. If the number of non-interference slots for a given TDMA channel is greater than or equal to the required number of slots, the TDMA channel number is appended to $\mathbf{CH}_{preferred}$. If this condition is not met, but the total number of non-interference and interference slots is greater than or equal to the required number of slots, the TDMA channel number is appended to $\mathbf{CH}_{available}$. Subsequently, the algorithm first checks if $\mathbf{CH}_{preferred}$ is not empty. It extracts the TDMA channels with the maximum number of non-interference slots from $\mathbf{CH}_{preferred}$ and appends them to $\mathbf{CH}_{maxNIS}$. If $\mathbf{CH}_{preferred}$ is empty and $\mathbf{CH}_{available}$ is not empty, it conducts the same process for $\mathbf{CH}_{available}$. The algorithm then selects the TDMA channel from $\mathbf{CH}_{maxNIS}$ that is farthest from the AIS 1 channel and set its channel number to ch. If both $\mathbf{CH}_{preferred}$ and $\mathbf{CH}_{available}$ are empty, this indicates that none of the TDMA channels in the current TDMA frame can provide sufficient resources for the ship station to transmit VDE-TER data. Accordingly, the ship station waits until it gains access to the next RAC slot, after which it reinitiates TDMA channel selection. Finally, the algorithm returns the selected TDMA channel.

Algorithm 1. TDMA channel selection

Input: n_{req}
Output: ch
Initialize:
$ch \leftarrow 0$
$\mathbf{CH}_{preferred} \leftarrow [\,]$
$\mathbf{CH}_{available} \leftarrow [\,]$
$\mathbf{CH}_{maxNIS} \leftarrow [\,]$
Procedure:
for $i = 1$ to N_{ch} **do**
  if $\mathbf{N}_{NIS}(i) \geq n_{req}$
    $\mathbf{CH}_{preferred} \leftarrow i$
  else if $\mathbf{N}_{NIS}(i) + \mathbf{N}_{IS}(i) \geq n_{req}$
    $\mathbf{CH}_{available} \leftarrow i$
  end if
end for
if $\mathbf{CH}_{preferred}$ is not empty
  $\mathbf{CH}_{maxNIS} \leftarrow maxNIS\left(\mathbf{CH}_{preferred}\right)$
else if $\mathbf{CH}_{available}$ is not empty
  $\mathbf{CH}_{maxNIS} \leftarrow maxNIS(\mathbf{CH}_{available})$
else
  Wait for the next RAC slot.
end if
$ch \leftarrow maxFreqDiff(\mathbf{CH}_{maxNIS})$
return ch

3.4. Slot Selection for Collision Avoidance

After the TDMA channel selection is completed, the ship station conducts collision avoidance slot selection on the selected TDMA channel. To reduce collisions with AIS caused by VDE-TER data transmission, the ship station should prioritize candidate slots that are not potentially occupied by itself or its neighboring stations for AIS message transmission. We define the probability of a candidate slot being occupied by the ship station itself or its neighboring stations for AIS message transmission as the expected slot occupancy probability. A candidate slot is considered more interference-resilient if it has a lower expected slot occupancy probability. The ship station calculates the expected slot occupancy probability for candidate slots within the selected TDMA channel to perform collision avoidance slot selection for VDE-TER data transmission. The expected slot occupancy probability for the candidate slot (p_k) in the TDMA channel selected by the ship station is given by

$$p_k = 1 - \prod_{m \in \mathbf{STA}} (1 - p_{m,k}), \tag{6}$$

where k denotes the slot number of the candidate slot. **STA** represents the set consisting of the ship station and its neighboring stations. $p_{m,k}$ represents the probability that slot k can be used by ship station m to transmit an AIS message, as given by

$$p_{m,k} = \frac{1}{l_{SI_m}} \cdot \delta_{k \in \mathbf{SI}_m}, \tag{7}$$

where l_{SI_m} represents the length of the SI for the ship station m. $\mathbf{SI}_m$ represents the set of slot numbers within the SIs of the current TDMA frame for the ship station m. $\delta_{k \in \mathbf{SI}_m}$ indicates whether slot k is within $\mathbf{SI}_m$, being 1 if exists and 0 otherwise. Following the calculation of the expected slot occupancy probabilities for all candidate slots within the selected TDMA channel, the ship station performs normalization on these probabilities. The normalized expected slot occupancy probability of slot k (p'_k) is given by

$$p'_k = \frac{p_k}{\sum_{j \in \mathbf{CS}_{ch}} p_j}, \tag{8}$$

where $\mathbf{CS}_{ch}$ represents the candidate slot list for the TDMA channel selected by the ship station. p_j represents the expected slot occupancy probability of the candidate slot with slot number j in $\mathbf{CS}_{ch}$. The ship station maintains a list of the normalized expected slot occupancy probabilities for all candidate slots in the selected TDMA channel ($\mathbf{P}_{ch}$). $\mathbf{P}_{ch}$ can be represented by

$$\mathbf{P}_{ch} = \left[p'_{1,ch}, p'_{2,ch}, \cdots, p'_{i,ch}, \cdots, p'_{n_{cs},ch} \right], \tag{9}$$

where $p'_{i,ch}$ and $p'_{n_{cs},ch}$ represent the normalized expected slot occupancy probability of the i-th candidate slot and the number of candidate slots within the TDMA channel selected by the ship station.

Finally, the ship station conducts collision avoidance slot selection based on the normalized expected slot occupancy probabilities of all candidate slots in the selected TDMA channel. Algorithm 2 presents the procedure for the collision avoidance slot selection. The algorithm takes n_{req}, $\mathbf{CS}_{ch}$, and $\mathbf{P}_{ch}$ as inputs. The output of the algorithm is a list, denoted as **SN**, containing the slot numbers of the candidate slots selected from $\mathbf{CS}_{ch}$.

Algorithm 2. Slot selection for collison avoidance

```
Input: n_req, CS_ch and P_ch
Output: SN
Initialize:
    SN ← [ ]
    val ← 0
    idx ← 0
Procedure:
    for i = 1 to n_req do
        [val, idx] ← min(P_ch)
        SN ← CS_ch(idx)
        Remove val from P_ch
    end for
    return SN
```

The algorithm first defines **SN** and initializes it to an empty list. It also defines *val* and *idx*, initializing both to zero. The algorithm then iterates over the number of required slots for VDE-TER data transmission, extracting the minimum value (*val*) and its index (*idx*) from $\mathbf{P}_{ch}$. It extracts the slot number of the candidate slot with the minimum value from $\mathbf{CS}_{ch}$ using *idx* and appends it to **SN**. It then removes *val* from $\mathbf{P}_{ch}$. Finally, the algorithm terminates the collision avoidance slot selection procedure by returning **SN**.

4. Performance Evaluation

We conducted experimental simulations to evaluate the performance of SOCA using the MATLAB R2023b simulator. The simulation results were compared with the slot allocation scheme of the existing VDES to demonstrate the superiority of SOCA. In the following subsections, we provide a detailed description of the simulation configuration and the simulation results obtained.

4.1. Simulation Configuration

In the simulation, the VDES network consists of a shore station and multiple ship stations located in a coastal area. To evaluate the performance of SOCA under various maritime environments, we consider static and dynamic ship scenarios, as illustrated in Figure 4.

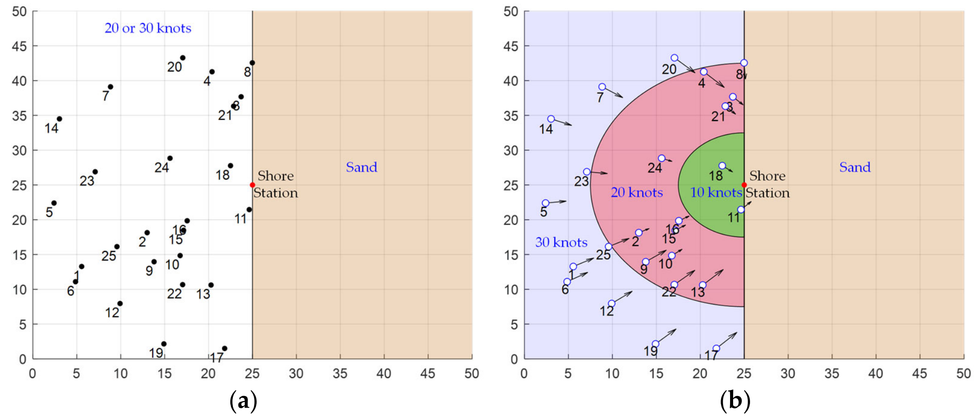


Figure 4. Example of ship scenarios: (**a**) static ship scenario and (**b**) dynamic ship scenario.

In both scenarios, all ship stations are assumed to be randomly positioned within a 25 × 50-nautical-mile (NM) area. The number of ship stations in the simulation varies from 5 to 50, and the communication range for both the shore station and ship stations is set to 50 NM. Additionally, it is assumed that each ship station generates n_{pkt} VDE-TER data packets of uniform size at the beginning of every VDES frame and transmits them the shore station via VDE-TER.

In the static ship scenario, it is assumed that all ship stations maintain the same sailing speed, resulting in identical values for RI, Rr, NI, and SI across all ship stations. The RI, which determines the transmission period of AIS message, is set to 2 or 6, depending on the speed of ship stations, as shown in Table 1 [19]. The simulations are conducted separately for two cases: RI set to 2 with an assumed ship speed of 30 knots, and RI set to 6 with an assumed ship speed of 20 knots. In the dynamic ship scenario, it is assumed that the speed of each ship station varies depending on its distance from the shore station: 10 knots within 15 NM, 20 knots between 15 and 35 NM, and 30 knots beyond 35 NM. Consequently, the parameters *RI*, *Rr*, *NI*, and *SI* vary across stations. Note that the values of *Rr*, *NI*, and *SI* are updated based on the changes in *RI* and are calculated by

$$Rr = 60/RI, \tag{10}$$

$$NI = 2250/Rr, \tag{11}$$

$$SI = 0.2 \times NI. \tag{12}$$

Table 1. Parameters related to ship conditions.

Ship Conditions	RI (s)
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

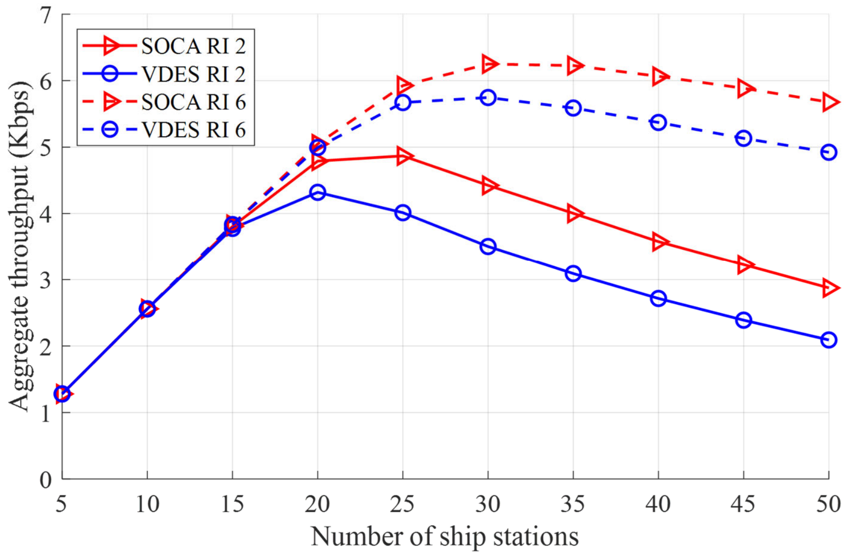
The performance of SOCA is compared to that of the existing VDES slot allocation scheme in terms of aggregate throughput, average latency, collision ratio, and packet delivery ratio. The simulation was repeated 100 times, and the detailed simulation parameters are listed in Table 2.

Table 2. Simulation parameters.

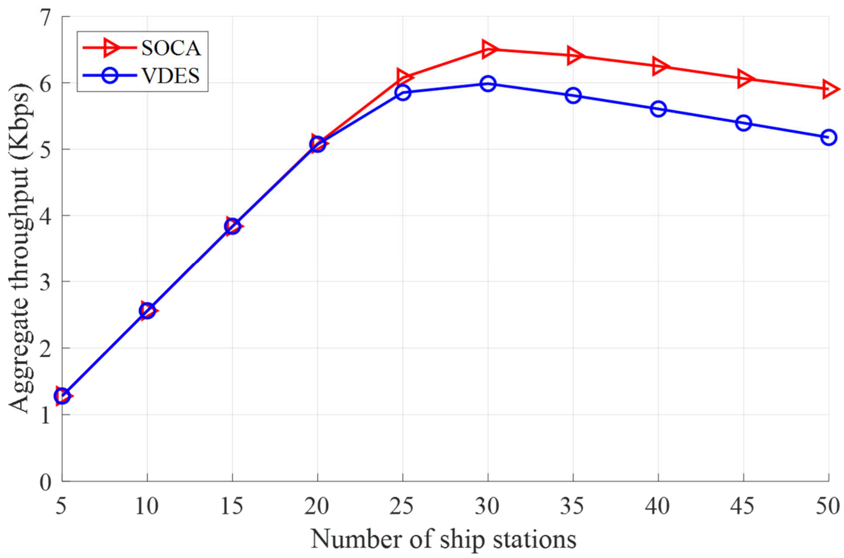
Parameter	Value	Parameter	Value
Number of ship stations	5–50	TDMA frame length	90 slots
Communication range	50 NM	Slot length	26.67 ms
Data rate of AIS	9.6 kbps	RI	2, 6
Data rate of VDE-TER	38.4 kbps	Rr	30, 10
AIS message size	32 bytes	NI	75, 225
VDE-TER data size	640 bytes	SI	15, 45
Frame length	2250 slots	n_{pkt}	5

4.2. Simulation Results

Figure 5a,b illustrate the variations in aggregate throughput in static and dynamic ship scenarios, respectively. In Figure 5a, the aggregate throughput initially increases as the number of ship stations grows; however, it gradually declines after reaching a certain number of ship stations. Up to 15 ship stations, the aggregate throughput increases similarly regardless of the RI value. This is because the VDES frame can accommodate all VDE-TER data packets transmitted by the ship stations, resulting in an increased total number of packets received by the shore station. However, as the number of ship stations exceeds 15, traffic surpasses the capacity of the VDES frame, causing aggregate throughput to gradually increase and then decrease. In particular, the aggregate throughput is lower and drops more sharply with RI set to 2 than with RI set to 6. This occurs because a smaller RI results in more frequent AIS message transmissions. As a result, VDE-TER data, having lower priority than AIS messages, are more frequently unable to be transmitted. In SOCA, non-interference slots with lower expected slot occupancy probabilities are preferentially selected for VDE-TER data transmissions, whereas the existing VDES randomly selects candidate slots without accounting for interference. Consequently, SOCA results in fewer overlapping slots than the existing VDES, leading to higher aggregate throughput, as shown in the figure. Specifically, the overlapping slot refers to a slot that is redundantly allocated for both AIS message transmissions and VDE-TER data transmissions. Therefore, overlapping slots may result in collisions between AIS message transmissions and VDE-TER data transmissions, or in VDE-TER data transmissions being deferred. Quantitatively, SOCA achieves 19.06% and 8.11% higher aggregate throughput with RI values of 2 and 6, respectively, compared to the existing VDES.



(**a**)



(**b**)

Figure 5. Aggregate throughput: (**a**) static ship scenario and (**b**) dynamic ship scenario.

In Figure 5b, the aggregate throughput in the dynamic ship scenario is generally higher than in the static ship scenario. This is because, in the dynamic ship scenario, the RI values of ship stations change, which leads to reduced collisions between AIS messages. This reduction in collisions decreases unnecessary slot usage caused by AIS message retransmissions, thereby increasing the opportunities for ship stations to transmit VDE-TER data. Consequently, successful VDE-TER data transmissions increase, resulting in 48.19% and 2.88% higher aggregate throughput in the dynamic ship scenario compared to the static ship scenario when the RI is set to 2 and 6, respectively. Furthermore, in the dynamic ship scenario, SOCA achieves 7.30% higher aggregate throughput compared to the existing VDES.

Figure 6a,b illustrate the variations in average latency in static and dynamic ship scenarios, respectively. In Figure 6a, the average latency increases as the number of ship stations grows. This is primarily due to intensified competition among ship stations for access to RAC slots used in allocating slots for VDE-TER transmission. The increased contention for RAC slots delays the transmission of request messages for slot allocation. This delay, in turn, increases the transmission waiting time for VDE-TER data packets, significantly impacting the average latency. The average latency is shorter when the RI is set to 6 compared to when it is set to 2. This is because fewer AIS message transmissions occur across the network with a larger RI, reducing delays in VDE-TER data transmission. In the figure, SOCA consistently demonstrates shorter average latency regardless of the RI. This is because SOCA reduces overlapping slots by selecting TDMA channels with sufficient non-interference slots to minimize collisions, thereby reducing the retransmission of AIS messages. However, the existing VDES randomly selects TDMA channels, which often results in insufficient available slots or the allocation of slots that are more likely to experience interference during VDE-TER data transmission. Accordingly, it leads to longer latency compared to SOCA. Quantitatively, when RI is 2 and 6, SOCA achieves 12.63% and 10.36% lower average latency, respectively, compared to the existing VDES.

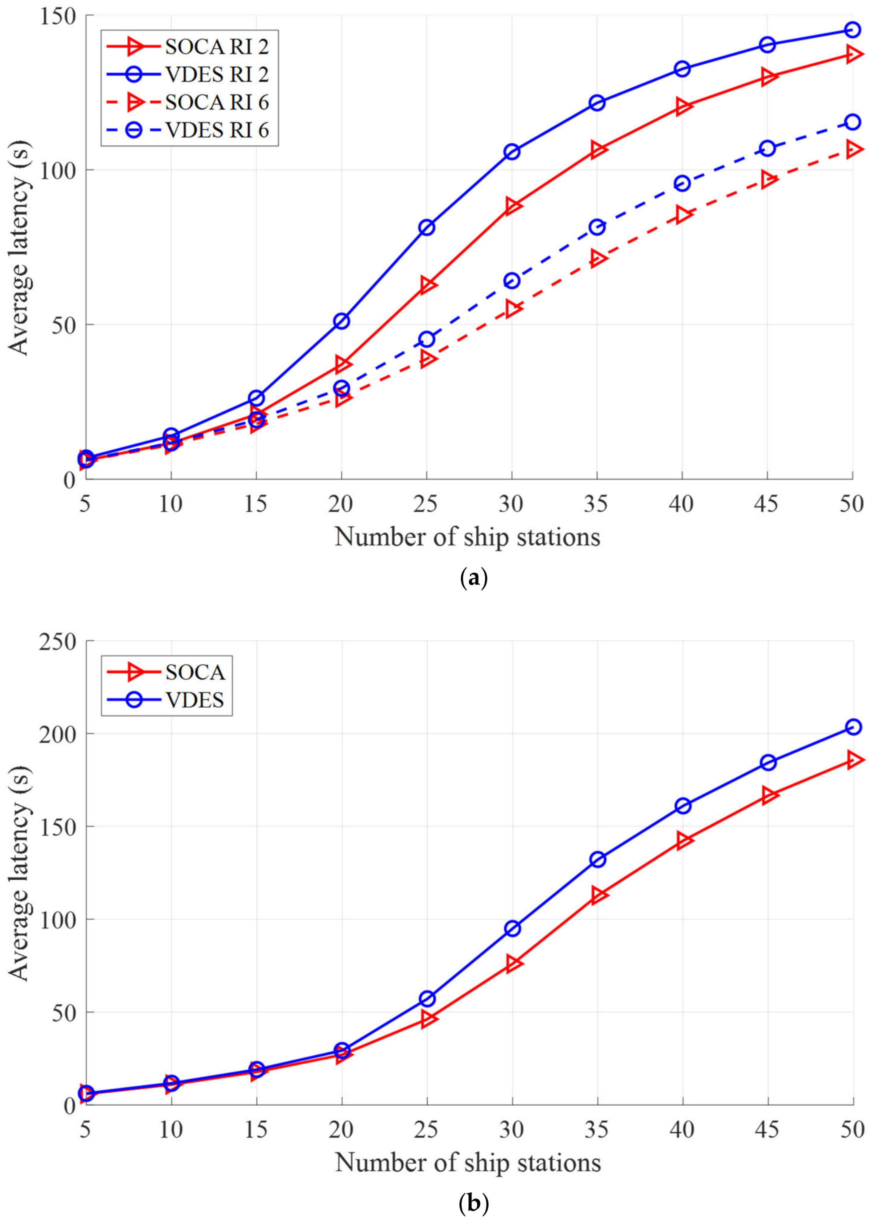


Figure 6. Average latency: (**a**) static ship scenario and (**b**) dynamic ship scenario.

In Figure 6b, the average latency in the dynamic ship scenario is affected by the number of ship stations, similar to the static ship scenario. However, in the dynamic ship scenario, the average latency increases gradually and then rises sharply when the number of ship stations exceeds 20, compared to the static scenario. When the number of ship stations is

20 or fewer, the proportion of the slowest ship stations (i.e., those moving at 10 knots) is small, resulting in a negligible impact on VDE-TER data transmission delay. Specifically, a larger RI increases the transmission interval of AIS messages, thereby reducing the transmission opportunities available to ship stations. That is, the number of NTSs available for transmitting both AIS messages and VDE-TER data decreases. Conversely, as the number of the slowest ship stations increases, the average number of NTSs per ship station decreases, which lengthens the VDE-TER data transmission interval and significantly increases the average latency. Accordingly, the average latency in the dynamic ship scenario is longer than in the static ship scenario. Quantitatively, the average latency in the dynamic ship scenario is 9.39% and 54.99% higher than in the static ship scenario when the RI is set to 2 and 6, respectively. In addition, in the dynamic ship scenario, SOCA achieves a 11.99% higher average latency than that of the existing VDES.

Figure 7a,b illustrate the variations in the collision ratio in static and dynamic ship scenarios, respectively. The collision ratio refers to the proportion of the average number of collided slots within a single frame ($n_{avgColSlot}$) to the total number of slots in that frame, and can be expressed as

$$\text{Collision Ratio} = n_{avgColSlot}/2250 \tag{13}$$

In Figure 7a, the collision ratio is affected by the number of ship stations since frequent AIS message transmissions can increase collisions with messages transmitted over TDMA channels. Accordingly, as the RI decreases, collisions increase due to the higher number of AIS messages transmitted in the network. As a result, the collision ratio is higher when the RI is 2 compared to when the RI is 6. In the figure, the collision ratio of SOCA is lower than that of the existing VDES because SOCA identifies non-interference slots based on the NIT and allocates slots for VDE-TER data transmission accordingly. When the number of non-interference slots is sufficient relative to the number of slots required for transmission by ship stations (i.e., when the number of ship stations is small), the collision ratio of SOCA approaches 0%. In contrast, the existing VDES does not account for the overlap between the SIs of ship stations and the expected slot occupancy probabilities of candidate slots, resulting in a relatively higher collision ratio than SOCA. Quantitatively, when RI is 2 and 6, the collision ratio of SOCA is 27.61% and 39.59% lower than that of the existing VDES, respectively.

In Figure 7b, the collision ratio in the dynamic ship scenario increases as the number of ship stations grows, similar to the static ship scenario. However, the collision ratio in the dynamic ship scenario is consistently lower than in the static ship scenario, regardless of the RI and network size. This is because the ship stations move at different speeds, resulting in varying transmission intervals of AIS messages. Consequently, collisions between AIS messages are reduced, leading to fewer AIS message retransmissions and a lower overall collision ratio in the network. Quantitatively, the collision ratio in the dynamic ship scenario is 62.90% and 10.11% lower than in the static ship scenario when the RI is set to 2 and 6, respectively. Furthermore, in the dynamic ship scenario, SOCA achieves a 39.27% lower collision ratio than that of the existing VDES.

Figure 8a,b illustrate the variations in the packet delivery ratio in static and dynamic ship scenarios, respectively. The packet delivery ratio is defined as the ratio of the number of successful VDE-TER data transmissions to the total number of VDE-TER data transmissions. In Figure 8a, the packet delivery ratio decreases as the number of ship stations increases, regardless of the RI. This decline is primarily due to increased collisions between AIS messages. These collisions lead to retransmissions of AIS messages, creating numerous overlapping slots in the VDES frame and resulting in further collisions between AIS messages and VDE-TER data transmissions. In particular, the packet delivery ratio decreases more rapidly when the RI is set to 2 compared to when it is set to 6. This is because the frequent transmission of AIS messages by ship stations significantly increases the number of AIS messages in the network. Overall, SOCA achieves a higher packet delivery ratio than the existing VDES. SOCA identifies the durations during which the AIS messages of neighboring ship stations will be transmitted based on its NIT and avoids transmitting VDE-TER data in those durations whenever possible. By doing so, SOCA ensures high reliability in data transmission and enables a large number of ship stations to utilize channel resources more efficiently. In contrast, the existing VDES allocates slots for VDE-TER data transmission without accounting for interference caused by transmissions from neighboring ship stations. Consequently, the existing VDES suffers from frequent collisions and retransmissions, leading to a degradation in overall network performance. Quantitatively, when RI is 2 and 6, the packet delivery ratio of SOCA is 32.29% and 12.99% higher than that of the existing VDES, respectively.

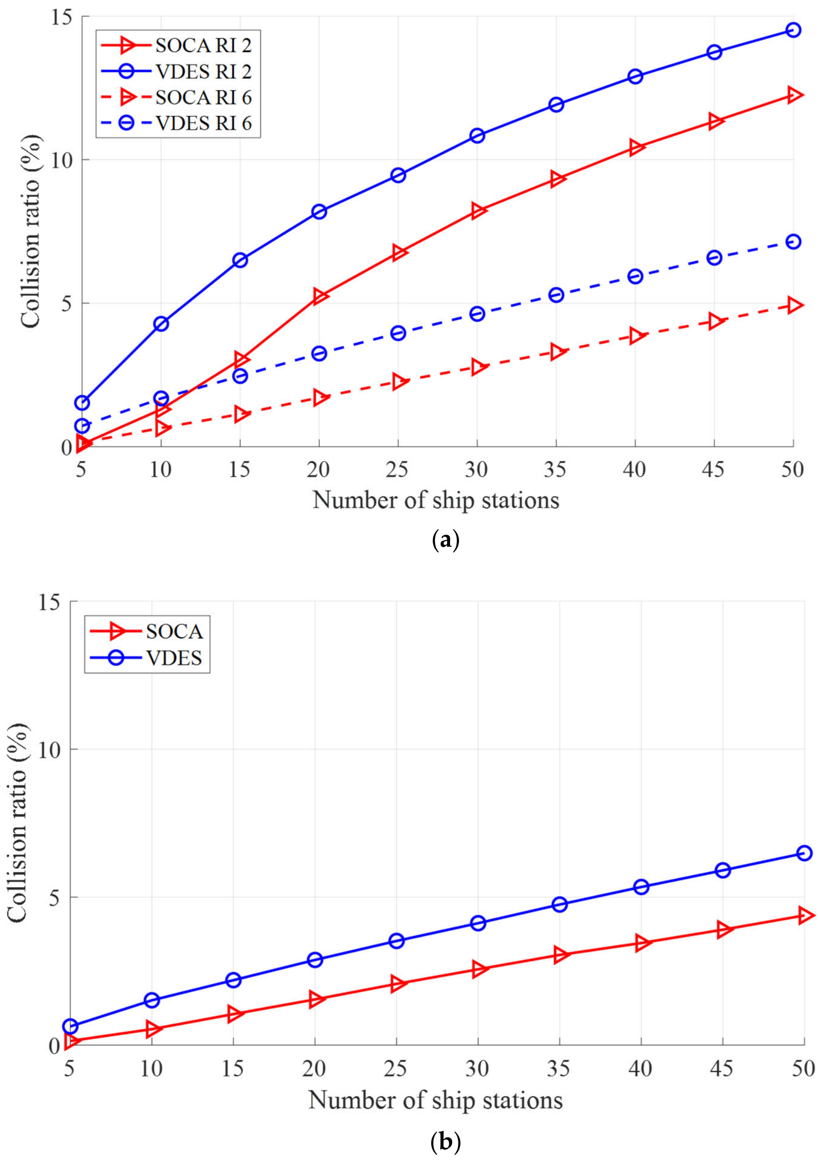


Figure 7. Collision ratio: (**a**) static ship scenario and (**b**) dynamic ship scenario.

In Figure 8b, the packet delivery ratio in the dynamic ship scenario is higher than in the static ship scenario, regardless of the RI. In the dynamic ship scenario, fewer AIS messages are transmitted than when the RI values of all ship stations are set to 6. Accordingly, collisions and retransmissions caused by AIS messages are reduced because the ship stations do not transmit AIS messages with the same transmission interval. As a result, the channel resources occupied by transmission of AIS messages are reduced, allowing more VDE-TER data to be transmitted successfully. Therefore, the shore station in the dynamic ship scenario receives more VDE-TER data than in the static ship scenario. Quantitatively, the packet delivery ratio in the dynamic ship scenario is 46.94% and 2.31% higher than in the static ship scenario when the RI is set to 2 and 6, respectively. Furthermore, in the dynamic ship scenario, SOCA achieves a 11.82% higher packet delivery ratio than that of the existing VDES.

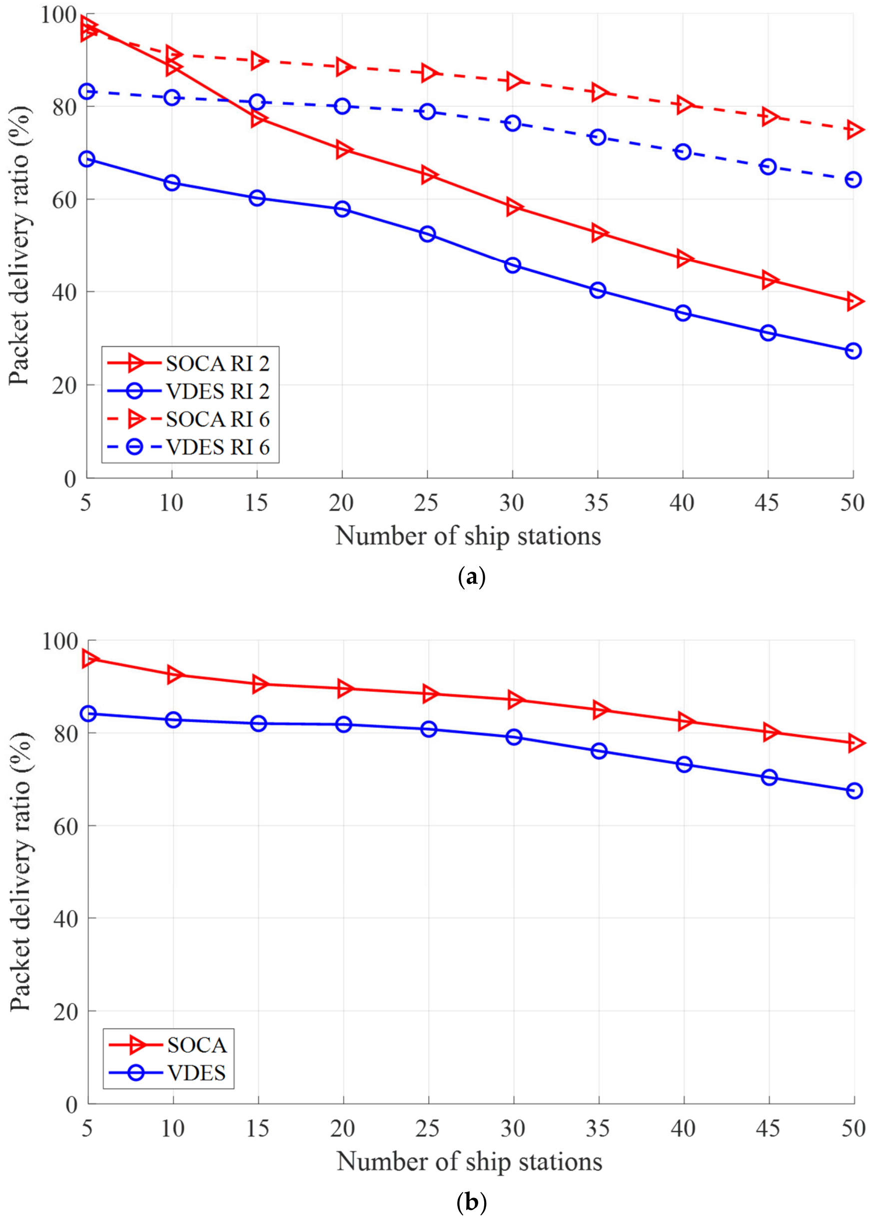


Figure 8. Packet delivery ratio: (**a**) static ship scenario and (**b**) dynamic ship scenario.

5. Conclusions

In this paper, we proposed the SOCA for the VDES network in the MIoT to mitigate the impact of interference caused by transmissions of AIS messages on transmissions of VDE-TER data in coastal areas with a high concentration of ship stations. SOCA operates with four steps: (1) construction of the NIT and VDES frame maps, (2) construction of the candidate slot list, (3) TDMA channel selection, and (4) slot selection for collision avoidance. To demonstrate the superiority of SOCA, we conducted experimental simulations under static and dynamic ship scenarios. In the static ship scenario, SOCA outperforms the existing VDES, achieving improvements of 13.58% in aggregate throughput, 11.50% in average latency, 33.60% in collision ratio, and 22.64% in packet delivery ratio. Similarly, in the dynamic ship scenario, SOCA demonstrated improvements of 7.30%, 11.99%, 39.27%, and

11.82% in the same metrics, respectively. The results show that SOCA has the potential to overcome the limitations of slot allocation in the existing VDES, such as frequent collisions caused by AIS messages and transmission delays of VDE-TER data, in high-density and dynamic maritime communication networks.

SOCA is a MAC layer enhancement of standard VDES, ensuring compatibility with the VDES system and simplifying potential implementation issues. From this perspective, it is expected to be a promising solution for future large-scale MIoT applications, such as autonomous ships, real-time maritime traffic management, and remote ship monitoring, all of which demand substantial data exchange. Meanwhile, the simulation environment in this study does not fully reflect the complexity of the real-world maritime conditions. Therefore, we consider it future work to study an enhancement of SOCA that incorporates more realistic conditions for maritime ad hoc networks, enabling ship stations to exchange MIoT application data via VDE-TER, even in long-range offshore environments.

Author Contributions: Conceptualization: S.-B.L., J.-H.K. and E.-J.K.; methodology: S.-B.L., J.-H.K. and E.-J.K.; software: S.-B.L., J.-H.K. and E.-J.K.; validation: S.-B.L., B.-Y.K., W.-S.S., T.S. and E.-J.K.; formal analysis: S.-B.L., B.-Y.K., W.-S.S., T.S. and E.-J.K.; investigation: J.-H.K. and E.-J.K.; resources: B.-Y.K., W.-S.S., T.S. and E.-J.K.; data curation: J.-H.K., B.-Y.K., W.-S.S. and T.S.; writing—original draft preparation: S.-B.L., J.-H.K. and E.-J.K.; writing—review and editing: S.-B.L., J.-H.K. and E.-J.K.; visualization: S.-B.L.; supervision: E.-J.K.; project administration: E.-J.K.; funding acquisition: W.-S.S. and E.-J.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by a grant from Republic of Korea National R&D Project "Development of Internet like maritime network technology and diversification of LTE-Maritime user equipment" funded by Ministry of Oceans and Fisheries (KS211523).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AI	Artificial intelligence
AIS	Automatic identification system
ASC	Announcement signalling channel
ASM	Application specific message
BBSC	Bulletin board signalling channel
DC	Data channel
DSCH	Data signalling channel
ID	Identifier
ITU	International Telecommunication Union
MAC	Medium access control
MASS	Maritime autonomous surface ship
MIoT	Maritime Internet of Things
NI	Nominal increment
NIT	Neighbor information table
NM	Nautical mile
NS	Nominal slot
NTS	Nominal transmission slot
RAC	Random access channel
RC	Ranging channel
RI	Reporting interval
Rr	Report rate
SI	Selection interval
SOCA	Slot occupancy-based collision avoidance

SOTDMA	Self-organized time-division multiple access
TDMA	Time-division multiple access
UTC	Coordinated universal time
VDE	Very-high-frequency data exchange
VDES	Very-high-frequency data exchange system
VHF	Very high frequency
VDE-SAT	VDE-satellite
VDE-TER	VDE-terrestrial

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